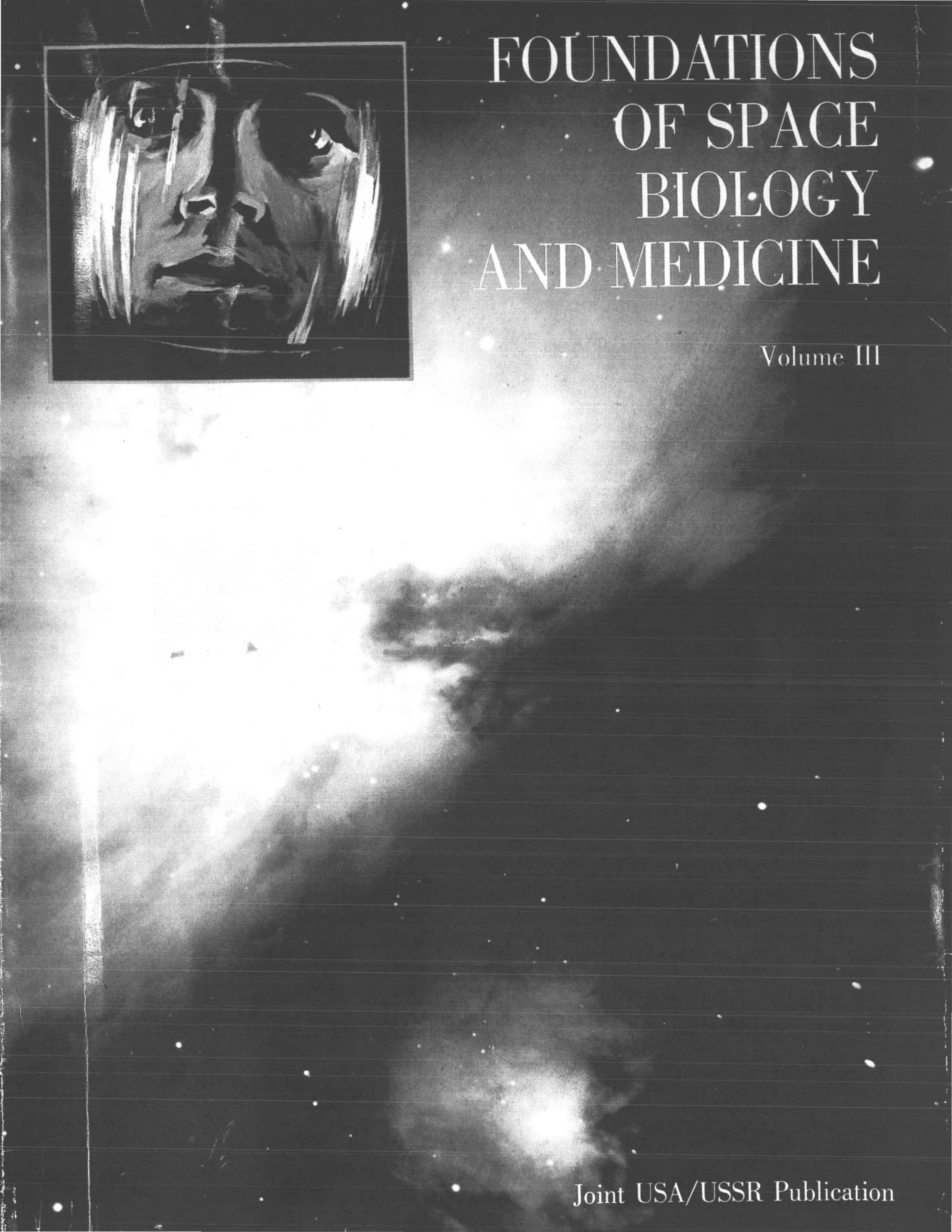

FOUNDATIONS OF SPACE BIOLOGY AND MEDICINE

Volume III

Joint USA/USSR Publication

Foundations of Space Biology and Medicine is a joint publication produced in accordance with an agreement on space cooperation between the National Aeronautics and Space Administration USA and the Academy of Sciences of the USSR.

This publication represents a comprehensive review prepared by Soviet and American experts.

The work is being published simultaneously in both countries. A Joint Editorial Board, meeting alternately in the Soviet Union and the United States, planned the publication, selected the authors, and guided the preparation of the manuscript. Of the 45 chapters, 19 were written by US authors, 20 by Soviet authors, and 6 were written jointly.

The publication consists of three volumes:

Volume I—Space as a Habitat
Volume II—Ecological and Physiological Bases of Space Biology and Medicine (2 books)
Volume III—Space Medicine and Biotechnology

The three volumes summarize the results of medical and biological research in space accumulated so far and suggest prospects for future research. The publication is addressed not only to the specialists but also to a wide range of readers—physicians, biologists, engineers, and other individuals who are interested in the problems of space exploration and exploitation.

The joint review of space biology and medicine is believed to be of value not only for its scientific and technical content but also as concrete evidence that scientific groups in two nations can work together effectively to achieve a common goal.

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NATIONAL AERONAUTICS
AND SPACE ADMINISTRATION

FOUNDATIONS
OF SPACE
BIOLOGY
AND MEDICINE

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Совместное советско-американское издание

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OF SPACE
BIOLOGY
AND MEDICINE

Joint USA/USSR Publication
in Three Volumes

General Editors

MELVIN CALVIN (USA) and OLEG G. GAZENKO (USSR)

Volume III

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Volume III

SPACE MEDICINE AND BIOTECHNOLOGY

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INTRODUCTION

The third volume of *Foundations of Space Biology and Medicine*—"Space Medicine and Biotechnology"—is a logical completion for the three-volume publication. It is dedicated to the most practical aspects of supporting the life and health of the crews of manned spacecraft and is based on the information in Volumes I and II on space, spaceflight dynamics, and the influence of spaceflight factors on the human organism.

Some doubt is still occasionally expressed in regard to the expediency and practicality of manned space flight to the distant planets and the creation of manned space stations; however, practical steps toward the performance of missions of this type are analyzed in Volume III.

We hope that our optimistic approach to the prospects for further development of piloted spacecraft will arouse enthusiasm in the readers of this work, bringing closer the practical utilization of the information this volume contains.

Volume III consists of 5 parts and 17 Chapters.

Part 1 is the most comprehensive, with seven chapters dedicated to particular problems of life support for astronauts on-board spacecraft. Chapter 1 discusses man's requirements for food, oxygen, and water, the interrelationship of these requirements to the level of energy expenditures and the end products of metabolism. This informs the reader of what must be supplied to the astronauts and in what quantity, the products that must be isolated and in what quantity, and finally, the materials that can be used for subsequent recycling of water, oxygen, and food.

Chapters that follow contain information on possible means of meeting the needs of man for water, food, and oxygen; methods for isolation and storage of waste products; astronauts' clothing and their personal hygiene; problems of living in spacecraft cabins; and finally, space suits designed to protect man from the vacuum and other hazards of space. In each of these chapters, we not only analyze the experience of Soviet and American space projects, but also describe other possible means of life support, which can be used in the future for planning more complex and extended operations in space.

Current solutions of particular problems of life support of astronauts still do not equate to the creation of a system, particularly a system in which the individual units are interconnected, so that the end products of some units can serve as the raw materials for the operation of others. Therefore, combined analysis of life-support systems is required for flights of various durations, and this forms the subject matter of Part 2 in this volume. In this part, life-support systems are described which are effective for flights that are short-term, of moderate duration, and possibly unlimited duration.

There are three chapters in Part 2. Chapter 8 presents life-support systems based on storage of consumable materials. These systems are effective only for flights lasting up to 20 or 30 days. Further increases in flight duration require recycling of consumable materials. The most effective method is regeneration of drinking water from atmospheric moisture condensate and urine. Regeneration of water yields great savings in the weight of expendable material and at the same time does not require large expenditures of energy. The technology for regeneration of water is comparatively simple and can be accomplished by light, portable installations. Carbon dioxide sorbents which can be regenerated can yield significant savings for flights of moderate duration, while expeditions of many months' duration make the regeneration of oxygen from carbon dioxide and metabolic water desirable.

Life-support systems based on the regeneration of expendable materials are described in Chapter 9.

Chapter 10 is focused on the use of biosynthesis for regeneration of oxygen and food in spacecraft cabins. Biosynthesis becomes desirable (from the standpoint of savings in energy and weight) only when the duration of a space flight is greater than 1.5–3 years. The time necessary for flights to planets in the solar system is of this order of magnitude. Furthermore, familiar plants and fresh, natural foods on-board the spacecraft are expected to have a favorable psychological influence on the astronauts. Therefore, the possibility cannot be excluded of partial utilization of biosynthesis for shorter voyages as well. A great deal will depend on the technical successes achieved in the development of biosynthesis. These considerations have convinced us of the necessity for studying the current state and prospects for development of biological life-support systems. Thus, Part 2 has led to a detailed analysis of the complete physiological interaction of man with his environment—a basic analysis which has already exposed the unified nature of terrestrial ecology.

Part 3 of this volume is dedicated to certain practical problems of spaceflight safety. In Chapter 11, the methods and equipment used to protect the crew from the damaging effects of penetrating radiation are examined.

Chapter 12 is a discussion of equipment and methods used for medical aid to astronauts during a flight, as well as preventive preflight and postflight steps.

Chapters 13 and 14 present materials on methods of protecting spacecraft crews in emergency situations, such as landing in an unplanned area, failure of the cabin seal, and fire.

Part 4 is a description of the medical and psychophysiological problems of selection and training of astronauts. The two chapters (15 and 16) of this part present the principles and specific methods which have been used as a basis for the selection and training of astronauts for the Soviet and American programs of manned space flight. The authors analyze the effectiveness of the measures taken in order to improve them for the future.

The last chapter, 17, in Part 5, is a discussion of the prospects for manned space flights in the next few years. The author formulates the tasks now before space medicine, based on analysis of some of the characteristics of upcoming flights. Thus, this chapter is actually a conclusion to all of Volume III.

Highly qualified specialists from the USSR and the USA prepared the material in Volume III. Most of the authors have had personal experience in spaceflight support and, naturally, have their own points of view concerning the problems discussed. We have attempted, inasmuch as possible, to leave the manuscripts in the form in which they were presented, even when our opinions were not in agreement with those of the authors, or when the authors of the chapters stated contradictory opinions concerning the same problem.

The manuscripts were corrected with the agreement of the authors; this amounted primarily to clarification of terminology (stemming particularly from translation), and elimination of materials exceeding the scope of a chapter

The most difficult task was to correlate the chapters, eliminating repetition, and avoiding omissions. We realize that we may have partially failed in this effort. The reasons for this were, understandably, the difficulties of coordinating these problems with the authors, and the exigency to publish the work before its content becomes out-of-date.

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Part 1

METHODS OF PROVIDING LIFE SUPPORT FOR ASTRONAUTS

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Chapter 1

BASIC DATA FOR PLANNING LIFE-SUPPORT SYSTEMS

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Breathable atmosphere, tolerable temperature, and a supply of substances involved in metabolism are minimal requirements for human operations in space. Systems for meeting these needs must provide for the inflow of oxygen, water, and nutrients; for disposal of carbon dioxide and other wastes and body secretions in liquid, solid, and gaseous form; and for heating and cooling. These input and output factors vary according to the physical activity, size, and sex of the astronauts. They are interrelated in the sense that oxygen and water requirements depend on energy need and the form in which it is supplied; the volume and nature of end products of human metabolism differ according to the food form in which energy needs are met. The choice among engineering solutions to life-support requirements also affects the dimension of the needs; for example, the amount of water used for body cooling varies under different conditions of air temperature and flow.

Naturally, the ideal system would provide for life support with a generous margin of safety, perhaps including redundant systems. Yet the system must not be so cumbersome that it would limit the scope of the primary scientific and technical objectives of a space mission. Thus, there is continued desire to mold the mutable biologic parameters, to strain the biologic limits of tolerance, in order to better fit an expedient mechanism for supplying or regenerating the materials needed for life [33].

Life-support systems for initial space flights were, of necessity, designed according to materials and energy balances of normal men living in terrestrial environment. Manned flights have provided some of the desired information on human metabolic behavior and adjustment to conditions in spacecraft, free space, and the lunar environment; thus, planning may now proceed with greater assurance and precision, based on these accumulated data and experiential evidence. But in-flight research has lagged behind perceived needs for information and certain recognized issues remain unresolved. Since each new mission presents and sometimes reveals new problems, the planning remains imperfect.

In this chapter, the optimal operating range and known metabolic limits of terrestrial man are reviewed briefly, and major findings from actual space flights summarized. (Detailed results of investigations of the nutritional status of astronauts are discussed in Volume III, Part 1, Chapter 2.) The intention here is to provide a quick reference for those involved with space systems, but not to instruct in the basic disciplines of physiology and nutrition.[1]

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[1] The subject matter reviewed, paraphrased, or quoted without further citation in this chapter was compiled originally by Dr. I. G. Popov of the USSR, and Professors M. Kleiber, N. Pace, S. Margen, and D. Calloway of the University of California. The US contributions have been published in full [7].

ENERGY REQUIREMENT

Although man requires about 40 specific organic compounds and minerals in his daily diet, the combined weight is small—about 50 to 100 g. The need for relatively nonspecific sources of energy determines the weight and volume of the food supply.

Metabolic energy is released through chemical oxidation of foodstuffs, or through oxidation of the body's own organic substances, if the dietary energy intake is insufficient to meet the metabolic energy requirements. Molecular oxygen serves as the ultimate electron acceptor for oxidative processes in man; it is consumed along with organic materials to yield heat and other forms of energy, with carbon dioxide and water the major chemical end products. Thus, the need for energy also sets the requirement for oxygen. It is a major factor in the water requirement for body cooling as well.

Energy requirement is not a constant. It varies from one individual to another and in a given person from day to day, depending on how he spends his time and under what conditions. It is useful to consider separately the magnitude of, and factors affecting, the energy expended for resting or basal metabolism, for physical activity, and for maintenance of body temperature.

Basal Metabolic Rate

The basal metabolic rate (BMR) is defined as the heat production by an individual in the postabsorptive state who is resting awake in the reclining position in a comfortable thermal environment, and is usually expressed as kilocalories (kcal) per square meter of body surface per hour. (One kcal equals 4.184 kiloJoules.) Body surface area is computed from the formula of DuBois and DuBois:

$$\text{Surface area, m}^2 = 0.007\,184 \times (\text{body weight, kg})^{0.425} \times (\text{body height, cm})^{0.725}$$

The major factors accounting for differences among individuals in the metabolic energy expenditure at rest are: age, body size and composition, and sex. Resting metabolism is primarily a function of the continuous work of the internal organs (liver, kidneys, and the like) and the nervous system, with smaller contributions per unit of weight from resting muscle and other tissues. Thus, BMR increases with increasing body mass but at different rates according to the type of mass involved. At a given weight, women have a smaller fat-free body mass than men, and older adults have less active lean tissue than younger adults. BMR is, accordingly, lower in women than men and in older adults of both sexes [3]. BMR of the healthy male normally falls from a value of 40 $\text{kcal/m}^2 \cdot \text{h}^{-1}$ body surface at age 20, to 36 $\text{kcal/m}^2 \cdot \text{h}^{-1}$ at age 50. For a man of about 70 kg weight and 1.8 m^2 surface area, these figures summate to 1728 and 1555 kcal/d, respectively.

Utilization of food results in an increase in metabolic heat production because of the energy associated with processes of digestion and assimilation of nutrient substances. With a normal diet this "specific dynamic effect" may amount to 8–10% of total energy intake. Resting energy expenditure, measured at usual times after meals under ordinary conditions, is about 10% higher than BMR. Metabolic rate usually falls during deep sleep to about 10% below the BMR.

Of the 1600 kcal basal metabolism, little is referable to direct gravity effects, so that little direct effect of gravitational change would be expected. However, secondary effects of prolonged weightlessness may reduce BMR. These weightlessness effects would include disuse muscular atrophy, altered tissue hydration, and altered endocrine states. Prolonged bed rest may, to a certain extent, simulate the effect of weightlessness. Reported results of such studies [12, 27] include a reduction of about 10% in BMR after 3 weeks or so of continuous bed rest, which may be related to the observed negative nitrogen balance and decreased fitness indicative of a loss of muscle mass.

Maintenance of Body Temperature

Man is able to maintain a body core temperature of about 38° C in spite of large variations in his metabolic heat production and in the thermal characteristics of his environment. Body heat-balance is computed as:

$$M = E \pm R \pm C \pm K \pm W \pm S$$

where M is the metabolic heat-production rate, E the evaporative heat loss, R the radiant heat exchange (+ for net loss), W the useful work accomplished (+ for work against external forces), and S the storage of body heat (+ for net gain by the body), all expressed in watts per square meter of body surface area. When S equals zero, heat balance is maintained, and body temperature remains constant.

The rate of heat production necessary to maintain body temperature constant may be called the thermostatic heat requirement [18]. According to Fourier's law of heat flow, this thermostatic heat requirement can be expressed as:

$$\frac{\Delta Q}{\Delta t} = \frac{T_B - T_E}{R}$$

where $\frac{\Delta Q}{\Delta t}$ is the rate of heat flow, T_B is the temperature of the interior of the body, T_E is the effective temperature of the environment and R is the resistance to heat flow. If the resistance to heat flow, R, is taken to be independent of changes in environmental temperature, then the thermostatic heat requirement is proportional to the difference between the effective environmental temperature and the interior body temperature.

At a low environmental temperature, metabolic rate of animals and inadequately clothed man decreases as the environment becomes warmer, i.e., the metabolic rate follows the thermostatic heat requirement. When the environment is heated above a lower critical temperature, the metabolic rate does not decrease further but remains at a low level, which for fasting and resting man is called the BMR. When the environment becomes hotter than an upper critical temperature and when cooling mechanisms are insufficient for heat removal, the body temperature increases as does the metabolic rate (following Van't Hoff's law [18]). When such a condition of positive feedback (increase in temperature-increase in metabolic rate) continues, the animal dies of heat stroke. The range between the lower and upper critical temperatures is the metabolically indifferent temperature.

Man moderates the environmental conditions by selection of clothing and, if possible, manipulation of air temperature, humidity, and flow, so that skin temperature is maintained at about 33°C without calling into play the mechanisms for increasing metabolic heat production or heat loss. If the microclimate is thus kept thermally neutral, the BMR is not expected to be determined by thermostatic heat requirement.

Departure from a comfortable thermal environment, toward either hot or cold, will increase energy needs. If the environment is overheated or metabolic heat production rises (as with hard work), extra energy is required due to sweating and increased cardiovascular work, and to any increase in body core temperature. Casual cold exposure leads to shivering and continued exposure to nonshivering thermogenesis, both of which use energy.

Physical Activity

The normal activities of man have additional energetic requirements, which include an erect posture in a gravitational habitat and exercise. In the vertical state, special tonic muscular activity and circulation against a hydrostatic pressure result in greater oxygen consumption and metabolic heat production (e.g., reclining 70 kcal/h, sitting 100 kcal, standing 110 kcal). With movement of mass over distance there is further increase in energy expenditure proportional to the work performed.

For example, a 70-kg man walking for 1 h at 4.8 km/h (3 mph) on the level at 1 g spends 250 kcal; if he runs the same track at 8 km/h (5 mph), his expenditure increases to 570 kcal. Physical activity is the most important variable determining total energy needs of individuals of like sex, age, and weight [2].

When a person is physically active, additional oxygen is required for utilization of energy substrates, thus increasing pulmonary ventilation rate over resting values (Table 1). Very light work, such as tasks involving upper torso movement while seated (movement of 50 kg one m in one min) doubles the resting ventilation rate, while heavy work (700 kg m/min) increases it sixfold. The maximum effort an individual can expend varies with his musculature and fitness, and is reflected in his maximum pulmonary ventilation and oxygen uptake rates.

TABLE 1.—*Classification of Energy Expenditures and Associated Oxygen Requirements*

(Male 60–70 kg, 170–180 cm [5])

Activity category	Level of work kgm/min	Pulmonary ventilation l/min	Oxygen requirement l/min	Expenditure of energy kcal/min
Basal rate		5	0.2–0.25	1.0–1.25
At rest		5–10	0.25–0.3	1.25–1.5
Work				
Very light	less than 50	10–15	0.3–0.5	1.5–2.5
Light	50–300	15–20	0.5–1.0	2.5–5.0
Medium	300–550	20–35	1.0–1.5	5.0–7.5
Heavy	550–900	35–50	1.5–2.0	7.5–10.0
Very heavy	900–1150	50–65	2.0–2.5	10.0–12.5
Extremely heavy	1150–1250	65–85	2.5–3.0	12.5–15.0
Exhausting	over 1250	over 85	over 3.0	over 15.0

TABLE 2.—*Energy Expenditure in Various Activities During a 120-Day Experiment in a Simulated Spacecraft* [5]

Activity	Duration, h	Energy expenditures, kcal			
		Per min		Per period	
		Range	Mean	Range	Mean
All kinds of research, repairing and constructing instruments, analyzing information, filming and photographing, reading scientific literature during limited movement	7.30-8.00	1.21–2.14	1.62	545–1027	753
Preparing food, serving, and cleaning the table, washing and drying dishes	4.30	2.2–5.21	3.43	594–1407	926
Light cleaning of room (sweeping floor with broom)	0.15	2.5–7.49	4.5	38–112	67
Heavy cleaning of room (washing floor, damp mopping partitions)	0.30	3.5–7.9	5.5	105–237	165
Set of gymnastic exercises throughout the day	0.15–0.45	5.0–11.7	8.2	81–527	246
Compulsory daily work on a cycle measuring energy with 500 kg-m/min	0.30	5.4–10.24	7.34	162–307	220
Sleep at night, after dinner; rest lying down throughout the day	10.00[1]			660–896	767
Total					3144

[1] Energy expenditures during sleep were assumed to be 70 kcal/h at 70 kg body weight.

Exhausting work of over 1250 kg m/min cannot be sustained because at maximum ventilation rate, the amount of oxygen taken up is insufficient to meet energetic needs; in work of this nature the individual is said to accumulate an oxygen debt, which must be repaid by continued increased oxygen uptake at rest after completion of the work. The maximum effort that can be sustained for long periods is about half the individual's maximum capacity, called steady-state work. If a task requires 50% more energy than an individual's steady-state level, then he must work on a cycle of 10 min work and 5 min rest, or the like.

Total energy requirement can be computed from measurement of the energy cost of specific work tasks and knowledge of the amount of time spent at each activity level. Data from an experiment in which several men lived for 120 days in a simulated spacecraft are illustrative [5] (Table 2). Assigned research tasks occupied about 8 h daily and were performed at a cost of 1.6 kcal/min or 753 kcal/d; energy expenditure during 10 h sleep and rest was 767 kcal; other more vigorous tasks brought total energy expenditure to 3144 kcal/d for a 70-kg man.

Except for extravehicular operations, astronaut tasks have proved to be chiefly quiet, seated activities involving neuromuscular coordination but little physical work. Energy expenditure of Vostok male astronauts was 2040 to 2340 kcal/d and that of the female astronaut was 2010 kcal [34]. Average energy expenditures were 2410, 2010, and 2220 kcal/d for the two-man crews of Gemini 4, 5, and 7, respectively [3].

The energy cost of work performed outside spacecraft has been more difficult to predict because of uncertainty concerning the effect of gravitational changes. (See Volume II, Part 2, Chapters 4 and 8.) While weightlessness eliminates loading, reducing energetic requirements, it also greatly reduces friction. Consequently, for some tasks the reactive force must be supplied by the musculature. This can lead to a net increase in energy requirement for the performance of tasks such as those involving pushing or torquing.

During extravehicular operations in free space, telemetered heart rate of US astronauts has been maintained at or below 140 beats/min which, in laboratory studies, predicts an energy expenditure of 8 kcal/min or about 500 kcal/h [16]. Lunar extravehicular activity is somewhat less energetic, about 300 kcal/h [4]. Apparently the lunar gravitational force has a beneficial effect on locomotion that more than compensates for weight due to one-sixth *g*.

Energy Allowance for Space Missions

The energy requirement presently predicted for sedentary in-cabin missions is below 2500 kcal/d for a 70-kg man (about 36 kcal/kg · d^{-1} or 100 kcal/h [35]). The normal space food allowance should be increased according to the specified activity program of a mission, by substituting the observed higher work-energy figures for the 100 kcal/h allotted for the sedentary space mission. Only rarely would energy expenditure ever exceed 5000 kcal/d under any sustainable conditions of work [25].

It has been customary and is advisable to increase the computed allowance by 10%–15% in planning for actual space missions. For missions that include some programed exercise or moderate extravehicular activity, the total daily allowance for a male astronaut should be about 2800 kcal of physiologically available energy[2] This is the same as the average recommended energy allowance for US men in usual occupations [29] and below the recommended level of 3000 kcal/d for males in the lightest occupational group in the USSR [30]. Allowances for women would be less because of their size and lower BMR. Normal US and USSR allowances for female adults are 2000 kcal and 2700 kcal, respectively.

Should it be necessary to operate in a hot environment, under conditions where the air surrounding the body is above 30° C, energy allowances should be increased by 0.5% for each degree of temperature elevation between 30° and 40° [29]. Similarly, if the crew is inadequately protected from cold, allowances should be increased by 0.5% per degree of decline below 20° C in the microclimate.

Metabolism and Gas Exchange

On the basis of the following type-reaction for glucose

$$C_6H_{12}O_6 + 6\,O_2 \rightarrow 6\,CO_2 + 6H_2O$$

it can be computed that the oxidation of 1.0 g carbohydrate releases 4.1 kcal heat, consumes 0.75 l STPD oxygen, and produces 0.75 l STPD carbon dioxide and 0.60 ml water (Table 3).

Similarly, for a typical fat, triolein, reaction

$$C_{57}H_{104}O_6 + 80\,O_2 \rightarrow 57\,CO_2 + 52\,H_2O$$

it may be calculated that the oxidation of 1.0 g fat releases 9.3 kcal heat, consumes 2.02 l STPD oxygen, and produces 1.44 l STPD carbon dioxide and 1.06 ml water.

---

[2] The energy available to the body is the gross energy of the diet minus the losses in urine and feces.

TABLE 3.—*Energetic Relationships of Typical Fats, Proteins, and Carbohydrates*[1]

Energy—physical properties	Fat	Protein	Carbohydrate
Metabolizable energy, kcal/g [2]	9.3	4.1 [3]	4.1
Density, g/ml	0.9	1.3	1.5
Energetic density, kcal/ml	8.4	5.3	6.2
Weight per 1000 kcal, g			
metabolized	107	244	244
in diet, approx.	112	256	245
Water of oxidation, g			
per g	1.07	0.41	0.60
per 1000 kcal	115	100	146
Gas exchange			
per g			
oxygen used, g	2.88	1.38	1.18
carbon dioxide produced, g	2.80	1.53	1.63
per 1000 kcal			
oxygen used, g	310	336	289
carbon dioxide produced, g	301	373	398
Respiratory Quotient (CO_2/O_2)			
by volume	0.71	0.81	1.00
by weight	0.97	1.11	1.38
Energy yield per l oxygen used, kcal	4.6	4.5	5.2

[1] Adapted from reference [7].

[2] One kcal equals 4.184 kJ.

[3] Potential energy is lost in urine, chiefly as urea, hence this value is reduced from the 5.6 kcal obtained with complete oxidation.

Also, considering the reaction of a typical dipeptide unit, -alanyl-alanyl-

$$2\,C_3H_5ON + 6\,O_2 \rightarrow 5\,CO_2 + 3\,H_2O + (NH_2)_2CO$$

it may be estimated that the partial oxidation of 1.0 g protein in the body releases 4.1 kcal heat, consumes 0.95 l STPD oxygen, and produces 0.79 l STPD carbon dioxide, 0.38 ml water, and 0.42 g urea.

The respiratory quotient (RQ) is defined as the ratio of volume of carbon dioxide produced per unit time to volume of oxygen consumed in the same period. Normally, the RQ is in the vicinity of 0.83. Under these normal circumstances, liberation of 1.0 kcal metabolic heat requires the consumption of 0.206 l oxygen and results in production of 0.171 l carbon dioxide.

It is possible to manipulate the RQ to some extent by varying the proportion of fat and carbohydrate in the diet, holding protein constant. The RQ during pure fat oxidation is approximately 0.7. (The value is above this for fatty acids of shorter chain length.) RQs near this figure have been obtained during fasting and with extremely high-fat diets. The RQ is 1.0 when sugars are oxidized exclusively; values are above 1.0 when energy is being stored as body fat, e.g., when palmitic acid is formed from glucose:

$$4C_6H_{12}O_6 + O_2 \rightarrow C_{16}H_{32}O_2 + 8CO_2 + 8H_2O$$

Diets high in carbohydrate content or those that exceed energy needs may thus result in RQs approaching 1.0. However, the exact theoretical values are not recorded because protein is always being metabolized to some extent; the RQ for protein oxidation is about 0.8.

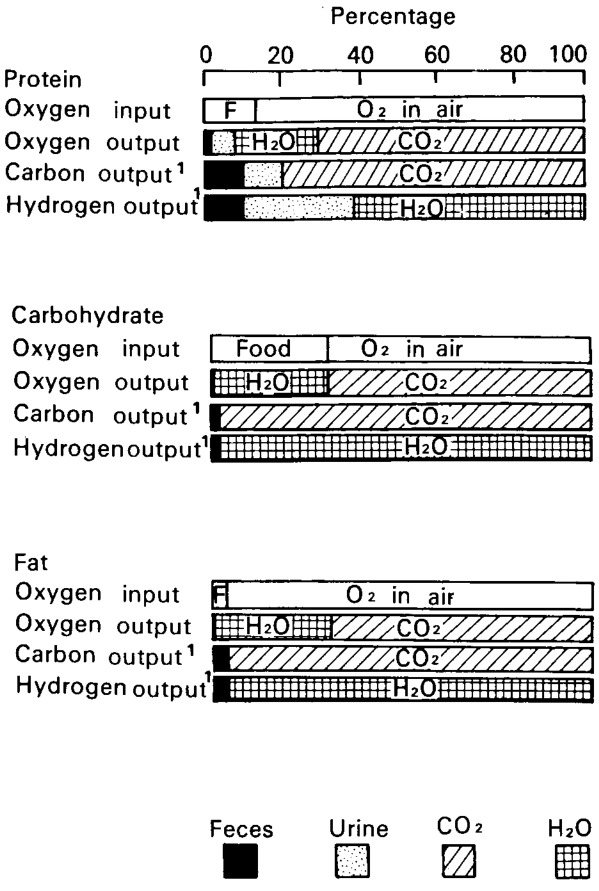
ENERGY NUTRIENTS

The extent to which RQ can be altered in a space mission will be determined by the physiologic limits of tolerance to each of the three major energy nutrients: fat, carbohydrate, and protein. There is a minimum requirement for these nutrients below which intake cannot be permitted to fall if health is to be maintained, and a maximum limitation for type or amount of each. Tolerance is not uniform and the ability of each crewmember to adjust to distorted dietary patterns would have to be tested. A period of preflight conditioning would be mandatory if extreme diets were to be used.

Fat

Fat is the most concentrated form of metabolizable energy, both by weight and volume (Table 3). While more oxygen is required for metabolism of fat than carbohydrate or protein, the total weight of materials needed per 1000 kcal is only 422 g with fat compared to 534 g with carbohydrate and 592 g with protein. Food fats are almost entirely in the form of triglycerides with even numbers of carbon atoms in the constituent fatty acids.

Minimum requirement. The cis forms of certain polyunsaturated fatty acids must be provided



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[1] Input for carbon and hydrogen is all food.

FIGURE 1.—Approximate material balances in human metabolism.

as such in the diet and, as far as is known, this constitutes the only dietary requirement for fat. Linoleic acid (9, 12-octadecadienoic acid) can fulfill all of the proved essential requirement; arachidonic acid can also be used but it is not found in significant amounts in most diets. The minimum need can probably be met by a diet in which 1% of the total energy is provided by linoleic acid (3–6 g/d) [5], and 2% is thought to be a safe allowance [29]. Even if the diet were totally fat-free, clinical symptoms of essential fatty acid deficiency might not appear for weeks or months, because tissues of well-nourished adults provide a large reserve.

Maximum tolerance. Individuals accustomed to high-carbohydrate diets usually experience transient discomfort (nausea, headache, diarrhea) with abrupt change to a diet that exceeds about 150 g fat/d [7]. The initial adjustment period is characterized by presence in the urine of incompletely oxidized end products, mainly of fat metabolism. These normal intermediates are formed more abundantly than they can be used without an adequate supply of carbohydrate. These products are acidic and lead to loss of alkaline buffers and body water. The partially oxidized products—acetoacetic acid, β-hydroxybutyric acid, and acetone—collectively are called ketone bodies and the metabolic state, ketosis or ketoacidosis. Metabolic acidosis can be prevented or counteracted by simultaneous administration of additional base (as $NaHCO_3$), although the base does not alter ketone production.

Ketones continue to appear in the urine even after several weeks of experimental feeding of high-fat diets, but the amount usually diminishes with persistent high-fat feeding. Ketonuria is low in the obese and absent from fully adapted Eskimos. Excretion of ketones in the urine, and to a small extent from the lungs, involves some loss of potential energy, in the order of 40 kcal/d under conditions of high production.

A dietary mixture that will just permit or prevent the appearance of ketone bodies in the urine of healthy subjects can be computed roughly by assuming all fatty acids (90% triglyceride weight) and about half protein to produce ketones (K); and all glycerol (10% triglyceride weight), starch and sugar, and half protein to serve as antiketogenic (AK) substances. For most subjects, the ketotic threshhold is found to coincide with a K/AK weight ratio of 1.0 to 1.5.

Fecal fat content is increased above the normal figure of less than 5 g/d when the diet includes a large amount of fat, but the percentage absorbed is unchanged. In a number of studies, absorption ranged from 91 to 98% of ordinary food fats. The presence of large amounts of long-chain saturated fatty acids (e.g., stearic, palmitic) is known to reduce digestibility, and the presence of shorter chain-acids (below C12) to result in improved absorption, at upper limits of intake.

High levels of dietary fat have been implicated in accelerated rates of erythrocyte breakdown but no increase in the metabolic end products of hemoglobin has been observed in recent studies of men fed diets high in fat. However, both rate of absorption and fatty acid chain length would be important variables, affecting the level and transport form of lipids in the circulation; these factors have not been studied.

To determine the desirable proportion of unsaturated fats to be recommended for inclusion in high-fat diets for extended space missions, consideration must be given to the evidence linking dietary fat with cardiovascular disease [28, 30]. Although a causal association between fat, fat saturation, and human health has not been proved unequivocally, the weight of evidence suggests that it would be prudent to shift consumption toward a higher proportion of polyunsaturated fatty acids in the diet. A weight ratio of 1.1 to 1.5 polyunsaturated to 1.0 saturated acids is suggested. There is no evidence of harm from following this ratio, provided an increased need for tissue antioxidants is also met. (See discussion of vitamin E under **Fat-Soluble Vitamins** in the next section.)

Fat allowance for space missions. The diet could include as much as 75–80% energy in the form of fat, or up to 250 g/d. Analysis of inadequate evidence suggests that under these conditions, the average chain length of fatty acids should be about 16 carbon atoms with at least 1.2 g polyunsaturated for each 1.0 g saturated acid. Palatability might be a problem, and gastric emptying would be slower than with ordinary diets. The lower limit of fat intake is 7 g linoleic acid, which would be provided by 15 g corn oil.

Recommended intake of fat is 70–90 g/d [1, 33]. The USSR recommendation is that 60% fat be derived from animal sources [1]. This would coincide with prevailing US opinion only if the animal fat were derived, to a great extent, from animals with less saturated body fat (e.g., fish, poultry) than beef and mutton.

Carbohydrate

Carbohydrate is the major source of energy in most conventional diets. Utilizable dietary carbohydrates are mainly hexoses or larger molecules made from them. Sugar alcohols, glycerol, and partially oxidized forms (e.g., lactic, pyruvic, and citric acids) can also be used via carbohydrate pathways. These alcohols and acids do not occur in energetically significant amounts in most diets but could be produced synthetically aboard spacecraft. (See Volume III, Part 1, Chapter 2.)

Minimum requirement. Glucose is the usual substrate for the nervous system (brain RQ = 1.0) and red blood cells, but it is generally accepted that carbohydrate need not be present in the diet, since it can be formed from the glycerol moiety of fats and by gluconeogenesis from protein. The requirement at the tissue level has been estimated in the order of 140 g/d: 100 g for the central nervous system and 40 g for erythrocytes. However, if carbohydrate is totally absent from the diet or animals are fasted, after a time the brain adapts to utilization of ketone bodies and tissue requirement becomes less.

A diet that met the proposed energy needs but that was free of carbohydrate could include 250 g fat (80% kcal) and 140 g protein. This diet would provide 25 g glycerol and about 70 g glucogenic amino acids, or about 95 g materials that could enter carbohydrate pathways. The K/AK ratio would be about 3 and the individual would be expected to excrete some ketone bodies. Diets of this composition have not been tested in man. The nearest approximation is an all-meat diet which is higher in protein content than the example, and includes a small amount of tissue glucose and glycogen; this diet was used by the explorers Steffanson and Andersen without untoward effects [23].

The metabolic pattern during fasting is a reasonable model for a carbohydrate-free diet, since all energy is then being derived from adipose tissue and lean muscle. During fasting, there is loss of extracellular fluid and sodium with a decrease in blood volume and heart size, and blood uric acid level is elevated. Carbohydrate dosages between 50 and 100 g/d are sufficient to prevent these changes. It would seem desirable to include this small amount of carbohydrate in the diet.

There is no demonstrated requirement for nondigestible carbohydrates (*fiber* or *bulk*) in the human diet. Intestinal bacteria utilize most food carbohydrates not digested by man with production of gas and a number of small organic compounds that promote laxation; normal bowel function is maintained adequately in experimental studies of fiber-free diets [8]. Hypotheses have been advanced that link certain chronic disorders (noninfective diseases of the large bowel and vascular diseases) to reduced fiber intake [4a], but a cause-effect relationship has not been proved. Certain Soviet specialists [5] recommend inclusion of a small amount of nonassimilable carbohydrates in the diet of cosmonauts. Addition of 2 to 3 g fiber in the form of crude plant materials would not be harmful and could be beneficial.

Maximum tolerance. The maximum permissible intake of carbohydrate is unknown. The theoretical absorptive capacity for glucose is far in excess of the total daily energy requirement, about 200 to 300 g/h or 15 000 kcal in 16 hours. However, when hypertonic materials are introduced into the gastrointestinal tract in large amounts, gastric emptying is delayed and there is transfer of water into the tract to dilute the substance given. This can lead to symptoms such as nausea, diarrhea, and fainting. In sensitive subjects, this syndrome can be induced by as little as 100 g glucose. At equal energy levels, solutions of glycerol, glucose, and sucrose would have decreasing osmolalities because of differences in molecular weight. If sugars are used, adequate dilution should be assured, and it would be preferable to include a large proportion of starch in the diet.

Glucose will be excreted in the urine if the blood level exceeds the maximum reabsorptive capacity of the kidney, so that a diet based on maximum amounts of simple sugars should be given on a schedule of more frequent, smaller meals. The renal threshold for glycerol is lower than that for glucose, and wastage in the urine would probably limit the utility of this compound.

The reaction of some individuals to substitution of carbohydrate for fat in the diet is a marked increase in serum-triglyceride concentration. Normal persons show this elevation of blood lipid only when carbohydrate is increased to about 85% total energy intake [21]. This undesirable response is often more severe with sucrose than with starch.

Carbohydrate allowance for space missions. Astronaut diets could include 85 or 90% energy in the form of usual food carbohydrates, provided the diet is not hypertonic and the crew is examined for tendency toward carbohydrate-induced hyperlipidemia. Carbohydrate would be advantageous if there is risk of hypoxia, because of its low oxygen requirement in metabolism [17]. There is no true minimum requirement for carbohydrate, but 100 g/d is a safe, lower level of intake. The recommended intake is 400 to 500 g/d [1, 33], with a large proportion as starch.

Protein

Proteins are composed of about 20 different amino acids, nine of which are needed in the daily diet of man. Most proteins contain about 16% nitrogen, mainly as alpha-amino groups. Because man cannot oxidize nitrogen completely, the full potential energy value of protein is never realized biologically. The major metabolic end product, urea, has a potential energy value of 2.5 kcal/g.

Minimum requirement. Dietary protein must provide minimum amounts needed of the nine indispensable amino acids, and enough more amino nitrogen for synthesis of those present in tissues but not required as such in the diet. This second, nonspecific need can be met by supplying more of the indispensable amino acids, other amino acids, urea, or ammonium citrate.

The minimum need for eight of the amino acids to maintain nitrogen balance in healthy young men has been determined; a safe allowance is considered to be twice the amount needed by the highest requirer in the studies [5, 26, 29, 30]. Data available for women are not remarkably different. Allowances are (g per day): tryptophan, 0.5; leucine, 2.2; isoleucine, 1.4; valine, 1.6; threonine, 1.0; lysine, 1.6; methionine (+ cystine), 2.2; and phenylalanine (+ tyrosine), 2.2. The ninth amino acid, histidine, was not shown to be essential by the technique originally used. It is required by human infants, however, and by nephritic patients maintained on limited diets for long periods. There is no known synthetic mechanism in man and histidine may be presumed to be essential in the long term. An allowance of 2.0 g/d has been suggested [5]. A tenth amino acid, arginine, can be synthesized; the synthetic rate could be limiting under some circumstances but this has not been demonstrated so far for an adult male. An intake of 6.0 g/d has been suggested [5].

The minimum requirement for protein is substantially larger than the sum of the minimum requirements of the nine indispensable amino acids. An average figure of 0.5 g protein/kg body weight/d is generally accepted as minimum [26], or about 6 g amino nitrogen for a typical male adult. This figure is adequate only when the need for energy and other essential nutrients is also met, and protein is not required for carbohydrate synthesis (v.s.).

There is no consensus on whether or not there is benefit from more protein in the diet than the absolute minimum needed for nitrogen balance. In animals, a more generous protein intake protects against the effects of such potential hazards as infection and certain toxic materials. Increasing the dietary protein would not prevent loss of muscle protein due to lack of exercise and hypogravitational living. Because of the uncertainty, it is probably desirable to provide at least 50 g protein in the space diet as a small margin of safety.

Maximum tolerance. Until recently, human tolerance to protein had not been tested. Customary "high-protein" intakes did not exceed 200-250 g protein, which is only double the usual intake in the USSR and USA, and one-third the energy supplied by the diet. Individuals given these conventional high-protein diets have shown no pathologic changes. Blood urea content is increased and urinary volume and/or osmolality are higher than usual due to the excretory load of urea. The urine contains more sulfur and phosphorus, the pH is low, and uric acid output is increased.

All these changes were magnified in men fed diets for 1 month in which 85% energy was derived from protein [9, 22]. Percentage digestibility of protein was normal, so that fecal nitrogen content was proportionately increased to about 9 g/d. Urine volume was 4 to 5 l and contained three times the normal amount of uric acid and calcium. Ketones were present in the urine throughout the study. Thus, very high protein intake resulted in loss of calcium, increases in energy loss (in feces and urine), water requirement, and risk of formation of renal urate stones.

Protein allowance for space missions. If water supplies are adequate and an abundant supply of cations is included in the diet, as much as 300 g protein might be allowable. Urine volume should be large (2.5–3 l) to assure clearance of urea and solubility of uric acid. Because renal filtration and urinary flow would be increased, excretion of many water-soluble substances (vitamins, minerals) might be increased. A minimum intake of 50 g high-quality protein is suggested. If the diet is high in fat, higher intake may be needed to prevent ketosis and promote nitrogen balance.

Preferred diets usually derive 11–15% energy from protein. The recommended daily allowance in the US, 0.8 g/kg body weight [29], is less than the 12–14% energy intake recommended in the USSR [5, 30]. The allowance for the Soviet population was established at twice the estimated minimum requirement to offset unfavorable effects of the environment [30], while the US allowance includes a less generous, but adequate margin of safety for normal living [29]. The USSR specifies that at least half the protein should be of animal origin, increasing to 60% for persons engaged in tense mental work [30]. These allowances of 55 to 120 g/d are adequate for both men and women. The higher levels probably will provide a more satisfying diet in view of the preferred and habitual intakes of present space crews.

VITAMIN AND MINERAL REQUIREMENTS

The micronutrients regulate all life processes; some are structural components of tissues as well. The skeleton constitutes a substantial reserve of calcium and phosphorus, and a well-nourished body has adequate stores of some of the trace minerals and fat-soluble vitamins. Essentially, there is no tissue storage of many nutrients, however. Symptoms of deficiency will appear after days, weeks, or months of dietary inadequacy, depending on the nutrient in question. The first detectable evidences of deficiency are often biochemical abnormalities in the metabolic pathways; clinical symptoms appear much later. The lowest amount of a nutrient that will prevent the first detectable alteration is usually accepted as the minimum requirement.

For some nutrients, such as calcium, a minimum requirement cannot be set in this way. The skeleton will be depleted to maintain the more essential soft tissue functions of the mineral, so that biochemical changes will not be observed but the skeleton may be so raided that it becomes too fragile to support the body weight. For nutrients of this class, it is customary to stipulate requirement as the least amount that will maintain balance between the amount in the diet and that lost from the body. This is a satisfactory criterion of adequacy only if the body content of the nutrient was adequate initially and if there has not been an undesirable shift of the nutrient within body compartments.

Absorption and utilization of some nutrients vary with habitual intake and/or body stores. For example, iron is better absorbed by those whose body stores are low, and calcium absorption varies according to customary dietary intake. Certain vitamins are manufactured by intestinal bacteria, some useful and some not, so that the amount found in the excreta may be in excess of that in the diet, irrespective of adequacy of the diet or tissue reserves of the nutrient (such as pantothenic acid). For these reasons and others, habitual intakes of healthy populations are accepted as the best available guides to the requirement of many nutrients.

The needs of individuals within a like population are not alike and changes in the environment add to the variance. Thus, the recommended daily allowance of nutrients is always higher than the predicted minimum need. Depending on the precision with which the minimum requirement is known, the variance within the population, and the criticality of the known functions of the nutrient, allowances may provide more or less generous margins of safety [25, 29, 30].

Water-Soluble Vitamins

The weight requirement of vitamins is negligible, so that life-support systems can provide ample amounts of the nontoxic water-soluble nutrients. The allowances recommended for healthy adults in the USA and USSR, listed in Table 4, should provide adequately for the needs of astronauts fed normal diets.

The need for certain vitamins varies with energy expenditure, requiring larger amounts for missions that impose higher energy demands. These vitamin requirements, mg per 1000 kcal, are: thiamine, 0.5; riboflavin, 0.55; and niacin, 6.6. The need for vitamin B_6 increases with increasing protein intake—2 mg/100 g protein. The allowance for choline could be reduced, but in that case, the need for the essential amino acid methionine, as a donor of methyl groups, would be increased. All these water-soluble vitamins can be given to healthy individuals in amounts many times greater than the recommended allowance without harm or benefit; the excess is excreted in the urine.

Opinions differ on the essentiality of some water-soluble substances found in common foods. The USSR suggests allowances of pangamic acid (2.5 mg/d), rutin and related bioflavonoids (50 mg/d), and inositol (1.0 g/d) [5]. These substances are not recognized in the USA as essential components of otherwise adequate diets for adults. None of these compounds is harmful at the suggested intakes or levels encountered in ordinary foods.

Fat-Soluble Vitamins

Because fat-soluble vitamins are stored in the tissues, the need for them in the day-to-day diet might be considered less critical than for other nutrients. Tissue reserves of vitamin A would be adequate for several weeks of poor intake in a previously well-nourished person, and there is no apparent need for vitamin D in the diet of adults who have even minor exposure to sunlight. Since vitamin K is synthesized by

TABLE 4.—*Recommended Daily Dietary Allowances of Vitamins and Minerals in Space Diets*

Nutrient	Recommended daily allowance male, 70 kg		Nutrient	Recommended daily allowance male, 70 kg	
	USSR [1]	USA [2]		USSR	USA
Water-soluble vitamins			Macrominerals		
Ascorbic acid, mg	75–105	45	Calcium, g	0.8	0.8
Biotin, μg	150–300	150–300	Phosphorus, g	1.2	0.8
Choline, g	1.0–1.5 [3]	0.5–1.0	Magnesium, mg	400–600	350
Folacin, mg	1–2 [3]	0.4	Sodium, g	4–6 [4]	3 [5]
Niacin, mg	20–25	18	Chlorine, g	5–7	4 [5]
Pantothenic acid, mg	10–12 [3]	10–15	Potassium, g	2.5–5 [4]	3–5 [5]
Riboflavin, mg	2.4–3.4	1.6	Trace minerals		
Thiamin, mg	1.8–2.5	1.4	Copper, mg	2 [4]	2
Vitamin B_6, mg	2.1–2.9	2.0	Chromium, mg	2–2.5 [4]	0.5 [6]
Vitamin B_{12}, μg	1 [3]	3	Fluorine, mg	0.5–1.0	1.0–1.5 [6]
Fat-soluble vitamins			Iodine, μg	100–200	130
Vitamin A, IU	5000	5000	Iron, mg	15	10
Vitamin D, IU	0	0	Manganese, mg	5–10 [4]	5 [6]
Vitamin E, IU	3–9 [4]	15	Molybdenum, mg	0.5 [4]	0.25 [6]
Vitamin K_1, mg	up to 2 [3]	2	Selenium, μg	500 [4]	10 [6]
			Zinc, mg	10–15 [4]	15

[1] Values from reference [30] unless noted. Lower value for light occupation under ordinary conditions, higher value for heaviest physical work.

[2] Values for reference [29] unless noted.

[3] From reference [5].

[4] Am't in 3000-kcal diet, after Pokrevskiy 1964 [5].

[5] See text.

[6] Minimum requirement estimated by Margen [7].

intestinal bacteria, deficiency symptoms might not appear for some time unless there were interference with intestinal absorption or if antibiotic drugs were given. Vitamin E reserves would probably be the first to show depletion, particularly if the atmosphere has an increased partial pressure of oxygen and/or if the diet is high in polyunsaturated fatty acids. Since these situations impose increased demand for the nutrient to serve its nonspecific antioxidant function, the rate of change would depend on the amount of other biologically active fat-antioxidants present in the food supply (e.g. BHT (butylated-hydroxytoluene), propyl gallate). However, the safer course would be to include the normal recommended allowances of these nutrients in the daily space diet (Table 4).

In contrast with the water-soluble vitamins, excessive doses of certain fat-soluble vitamins are to be avoided because of potential toxicity [29]. Habitual vitamin A intake should not exceed 10 000 IU/d, although the carotenoid precursors are nearly harmless. (Pigmentation of the skin occurs with excessive intake of beta-carotene and one case of hepatic injury has been reported.) Only in the unlikely circumstance that astronauts are completely shielded from ultraviolet radiation for long periods would vitamin D be needed in the diet and in that case, not more than 400 IU/d. The naturally occurring plant form of vitamin K, phylloquinone, is not harmful but the synthetic form, menadione, is toxic to premature infants. Since there is no information on toxicity of menadione in adults, it would be wise to use the natural compound.

Vitamin E has not been shown to have toxic effects at dosages 1000 times the recommended intake; nor have benefits from high intakes been proved. Because oxygen concentration in spacecraft may be higher than in Earth atmosphere, and because the nutrient is harmless, it would be prudent to double the recommended vitamin E allowance for astronauts.

Minerals

Recommended daily allowances for the minerals are in Table 4 but considerable uncertainty exists in applying these allowances to space diets.

The large mass of calcium in bone is constantly undergoing turnover, being degraded and reformed. In health, the rates of these processes are balanced. Any condition which accelerates the breakdown of bone or decreases its buildup will ultimately lead to demineralization of the skeleton. Bed rest studies indicate that weight bearing on the long bones is necessary to keep the processes in balance [27]. Stressful experiences also lead to increased loss of calcium. Diminished bone density has been noted in US astronauts but there has been no change in calcium levels in the blood. If the process continued unabated, there would be risk of formation of renal stones as the excess calcium is dumped into the urine, and increased bone fragility.

There is no basis for assuming that increased dietary calcium would prevent demineralization, because the problem is physiologic regulation, but inadequate intake would worsen the condition. It is important that normal allowances be met and that the astronaut's intake in-flight is not less than his habitual intake to which his absorptive mechanism is adjusted. Intakes of calcium, phosphorus, and magnesium should be kept in balance, with a Ca/P ratio of 1 and a Ca/Mg ratio of approximately 2.

The electrolytes also pose special problems because of uncertainty about the effects of space conditions on body water compartments. Diuresis with loss of body water has been noted regularly in subjects at bed rest and in astronauts [27]. When at bed rest, there is concomitant negative sodium balance that cannot be corrected by sodium intake. With a diminished body sodium pool, output of adrenocortical hormones (especially aldosterone) would rise with a net effect of sodium retention and potassium loss. The outcome might be reduced body water and blood volume, diminished pools of sodium and potassium, and normal or increased osmolarity in the fluid compartments. It would be expected that body chloride would follow the same pattern as sodium. These changes could have potentially serious effects on the cardiovascular system. To permit the full spectrum of regulatory control, sodium intake should be not less than 3 g/d and potassium at least equal to sodium.

With inadequate body cooling during hard physical work or in the heat, there is additional loss of sodium and chloride in sweat. To compensate for this loss, an additional 1.0 g sodium chloride should be taken for each liter of water required above the nominal 2.5 for sedentary missions.

Trace Minerals

The trace minerals known to be required by man are listed in Table 4, with their tentative dietary allowances. Requirements for only a few—iron, iodine, and zinc—are known with any accuracy. The other allowances are stipulated according to probable content in diets of good quality and with consideration of amounts known to be needed by experimental animals. Other minerals essential to one or more animals but not yet proved to be required by man are aluminum, vanadium, tin, nickel, and silicon. As long as normal foods are used in space diets, the probability is favorable for meeting these uncertain requirements, but these nutrients pose exceptionally difficult problems in regenerative systems. Danger exists from both deficiency and excess of these elements.

OXYGEN REQUIREMENT AND CARBON DIOXIDE PRODUCTION

The total amount of oxygen consumed each day, and the amount of carbon dioxide produced, depend primarily on total energy expenditure and to a lesser extent on composition of the diet. The basal oxygen requirement increases in a nonlinear fashion with body weight [35], but muscular activity which is the chief variable in total energy needs, has the greatest effect on oxygen need [36]. A rough but useful guide is: 5 kcal energy are released for every liter oxygen consumed, under normal metabolic circumstances. The daily requirement for oxygen thus varies from 300 l for a small individual at rest and spending 1500 kcal, to more than 1000 l for a heavy active worker who utilizes 5000 kcal/d [32].

Because of differences in physical activity, the oxygen requirement by weight for a 70-kg individual can vary within 0.5 to 1.0 kg/d [5]. Under nominal in-cabin spaceflight conditions, the oxygen consumption of astronauts is 7.3–7.5 l/kg body weight [35]. Considering the serious consequences of even brief hypoxia, however, it is advisable to base calculations for life-support systems on a standard oxygen consumption of 1 kg/person/d [35].

If normal RQ is assumed, the amount of carbon dioxide produced can be computed from the oxygen consumption. If oxygen uptake is 1000 l/d and the RQ is 0.83, then 830 l carbon dioxide will be formed. More precise calculations can be made with knowledge of the composition of the nutrients absorbed and utilized (see Table 3). For example, 3000 kcal expenditure utilizing 110 g protein, 90 g fat, and 418 g carbohydrate would require 633 l oxygen (882 g) and result in formation of 566 l (1122 g) carbon dioxide; the RQ would be 0.89 [33]. Additional computations for more extreme diets are in a section of this chapter that follows, END PRODUCTS OF METABOLISM.

WATER REQUIREMENTS

Thermal Balance

If body temperature is to be maintained essentially constant, the heat generated metabolically must be dissipated. Radiation is ordinarily the most important channel of heat loss and becomes increasingly important in cold environments. As the environment becomes warmer, however, radiation becomes less important, so that at an ambient temperature of about 30°C and moderate humidity, radiation, conduction and convection, and vaporization are equally important channels of heat loss. At still higher ambient temperatures approaching body temperature, the heat of vaporization becomes the most important channel of heat loss. It becomes the sole channel of heat loss when the ambient air and wall temperatures equal or exceed body temperature.

Water Balance

The amount of water that must be consumed to maintain constant body hydration varies, depending on environmental conditions, total metabolic heat production, and diet composition. For persons engaged in light occupations in the average climates of the USSR and USA, the usual fluid intake and output are about 2.5 l/d [7, 14, 15, 37]. With usual diets, about 1 l water is taken with the food. Approximately 350 ml are formed during oxidation of the energy nutrients, depending on the amount of each present in the diet (Table 3). With ordinary mixtures, about 12 ml water are formed per 100 kcal energy metabolized [15]. The remainder of the water is taken as fluids.

At comfortable temperatures and light work, the amount of water excreted in the urine, about 1200 ml/d, is approximately the same as the amount evaporated from the skin (700 ml) and lungs (400 ml). With harder work and generation of more metabolic heat, the requirement for evaporative water increases. The heat of water vaporization at body temperature is 0.58 kcal/g water. Thus, an additional hour of heavy work (10 kcal/min) would result in loss of an additional liter of water from the body surfaces to dissipate the heat generated. Under these conditions, the urine becomes more concentrated unless fluid intake is increased. The maximum concentrating capacity of the healthy adult kidney is 1400 milliosmols per liter, so the minimal urine volume, i.e., the limit of this water conservation mechanism, depends on the solute load imposed by the diet. The solute load is primarily a function of salt intake and the urea resulting from protein catabolism. A diet that contains 100 g protein, 12 g salt, and normal amounts of other minerals would result in a solute load of roughly 800 milliosmols and require 600 ml water for renal

TABLE 5.—*Moisture Loss by Men through Lungs and Surface of Skin in a Hermetically Sealed Room* [5]

Number of subjects [1]	Observation time, d	Air temperature, °C mean	Air maximum	Relative humidity, %	Airflow rate, m/s	Water vaporized, g/h
3	15	6–15		56–70	0.05	56
11	30–120	20–23		45–75	0.05–1.0	45–64
6	30	20–28		55–80	0.05–1.0	89
6	15–30	25–30	32–40	29–65	0.05–1.0	104–180
6	60	26–28	32–32	35–65	0.06–1.0	85–108

[1] Ages ranged from 19 to 43.

excretion. In practice, it is wise to increase the fluid intake to cover the entire sweat loss, rather than forcing renal function to the maximum.

Heat, and more particularly a combination of work and heat, can greatly increase water requirement. Values from several studies indicate loss of water from the body surface to be 50 g/h at comfortable temperatures (Table 5). Above an air temperature of 25°C, sweating rate begins to increase. Nonworking subjects lose up to 180 g water/h by this route when the average temperature is 25°–30°C and there are periods of more intense heat [5]. For summer work in the open air in Central Asia, the water requirement is 6–6.5 l/d. With high air temperature and intense solar radiation, such as in the desert, depending on the workload, requirement for water can reach 6–11 l/day [10].

Vaporization of water also increases at reduced barometric pressures. Recorded water losses of men at rest at 18° to 23°C, wearing pressurized suits and oxygen masks, are: at sea level, 44 g/h and at 20 000–35 000 m altitude, 100 g/h. Water loss was increased to 211 g/h when the temperature was increased to 37°C. Work carried out at altitude resulted in loss of 183 g water/h at the lower temperature and 300 g/h in the heat [11].

Water Deficit

The body of a well-nourished, fit young man weighing 70 kg contains about 7 kg stored fat and 45 kg body water. Dehydration exhaustion (for example, inability to walk) occurs with a net loss of 4 to 7 l body water, and death from dehydration when the net loss reaches 10 to 15 l. It is clear that daily replacement of body water losses is extremely important.

In cases of total deprivation of water intake in a comfortable thermal environment and with optimal dietary conditions (low protein, low salt, adequate kcal), the urine volume can fall as low as 300 ml/d and the loss through the feces essentially ceases. However, insensible perspiration from body surfaces is diminished only slightly. An obligatory requirement is approximately 1400 ml water/d, some of which is met by continuing production of metabolic water, but about 1 liter water must be supplied if water balance is to be maintained. Without water intake in a cool environment, man can survive for 10 days at most. This is in contrast to survival without food, but with adequate water, which can be in excess of 40 days for the young man with 7 kg stored fat (noted above). Without water intake in a hot environment, death may occur in a day or two.

Water Allowance for Space Missions

A water allowance of 2200 or 2500 ml/d has been recommended for in-cabin space missions of the USSR [33, 35]. With major extravehicular activity carried out in a pressurized suit, for example, a daily 7-h lunar exploration, energy expenditure would be expected to increase 1400 kcal/d over sedentary missions. The water requirement would then be increased according to the latent heat of vaporization and prevailing humidity, air temperature, flow rate, and barometric pressure. At 1 atm and body temperature, the increased water requirement would be 2500 ml, or a total of 5 l/d. It is irrelevant whether the water is provided entirely as such or partially as a constituent of moist or fluid foods and beverages. But, it is important that water losses be replaced promptly; therefore the crew should have free access to fluids during and after work, and periods of heat exposure.

Excessive water intake is of little value, except just before starting hard work under hot conditions, because the pituitary gland and the kidneys regulate the osmotic pressure of the blood with great precision. Excess water taken into the body is excreted through the urine within 2 or 3 hours.

END PRODUCTS OF METABOLISM

Metabolic products are excreted in urine, feces, expired air, and sweat. Specific substances are retained or excreted as required to achieve homeostasis and some potentially useful substances are removed along with true metabolic end products. Small amounts of materials are also lost to the body in the form of flatus, hair, nails, desquamated skin cells, sebum, ear wax, nasal and vaginal mucus, saliva, tears, semen, and menses. Compendia of these losses have been published [5, 13, 31].

Urine

Urine starts out as an ultrafiltrate of the blood plasma. Plasma water and dissolved substances up to the molecular diameter of very small protein molecules are forced through pores in the glomerular capillaries and enter the nephron tubule. As the glomerular filtrate proceeds along the tubule, a number of substances are reabsorbed (glucose, amino acids, water) and others (uric acid, ammonia) are actively secreted by the tubule and added to the urine.

A major result of urine formation is constant removal from the blood of urea and other nitrogenous end products of metabolism. Other equally important functions include the variable net excretion of water and electrolytes to help preserve osmotic and acid-base balance of the body fluids. A great many other compounds such as hormones or their metabolic end products appear in the urine, and measurement of their daily excretion rate can afford extremely important physiologic information on adjustment to conditions in space.

While urine has an exceedingly complex and variable composition, its principal constituents in terms of weight are water (400 ml to several l), urea (30–50 g), and inorganic ions (10–20 g). With normal diets, energy value of urine is 8.6 kcal/g nitrogen.

Feces

Fecal matter consists of undigested and unabsorbed dietary constituents; material excreted into the gut; residues of digestive secretions, bile, and mucosal cells; living and dead microorganisms and products of their metabolism. The weight of fecal dry solids is governed to a small extent by the amount of food eaten but both solids content and wet weight are more noticeably affected by the type of food consumed. Fecal wet weight and volatile fatty acid content are much higher following a natural food diet that is high in carbohydrate than with diets high in fat or protein content [24]. However, this difference is due to the presence of nondigestible carbohydrates of plant origin rather than to carbohydrate per se.

In one study of a fiber-free formula diet, fecal wet weight was 86 ± 25 g/d containing 15 ± 2 g dry solids. With a less digestible diet based largely on dried and processed foods, these values were 138 ± 17 g and 41 ± 5 g/d [8], about the same as reported for normal diets [19]. Nitrogen and minerals in the feces of Gemini 7 astronauts fed this diet [20] were the same as the laboratory-determined values, showing that digestion and absorption of these elements are not affected by space conditions.

When highly absorbable foods are ingested, the fecal matter will consist mainly of water (100 g) with about 1–1.5 g nitrogen, 4–5 g lipid, 2–3 g salts, and very small amounts of vitamins and other organic compounds. Under normal conditions the heat value of fecal dry organic matter is remarkably uniform, averaging 6.2 kcal/g.

Flatus

Another excretion product to be considered is flatus, which derives from four sources: swallowed air, gases diffusing from the blood into the gut, bicarbonate-rich digestive secretions, and gases arising from bacterial action (carbon dioxide, methane, hydrogen). These gases are diffusible through the intestinal mucosa, so that the bulk of them is carried away by the blood and excreted through the lungs. However, if the intestinal bacteria are highly active, a larger fraction is excreted directly as flatus. An average of 7 to 10 l gas enters or is formed in the large intestine per day but usually only about 0.5 l is expelled as flatus.

Body Surface

Integumental growth continues throughout adult life at a fairly regular but individually variable rate. Nearly all these tissues are protein but the sum of losses is minor [6]. Several nitrogen-containing and organic compounds and minerals are lost with insensible perspiration and still more with active sweating. There are brisk oxygen uptake and carbon dioxide production from the sweating skin. Carbon dioxide elimination is related in part to sweating (as opposed only to diffusion from superficial blood cells) but oxygen may be used entirely by the epithelium. These gases are neglected in mea-

TABLE 6.—*Simplified and Approximate Material Balance for Metabolism: Representative Types of Protein, Carbohydrate, and Fat*

Constituent	Amount, g	Elements, g						Energy, kcal
		C	H	O	N	S	P	
	Protein							
Dietary casein	100.00	53.50	7.13	22.14	15.80	.72	.71	565
Protein in feces (10%)[1]	10.00	5.35	0.71	2.21	1.58	.07	.07	56
H_2O added in hydrolysis	11.70		1.31	10.39				
Absorbed	101.70	48.15	7.73	30.32	14.22	.65	.64	
Urea formed	30.48	6.10	2.03	8.13	14.22			77
Sulfate formed	1.95			1.30		.65		
Phosphate formed	1.97			1.33			.64	
H_2O formed	50.94		5.70	45.23				
Net water yield	39.24		4.39	34.85				
CO_2 formed	154.09	42.05		112.04				
O_2 consumed	137.71			137.71				
Metabolizable energy			1.33					432
	Carbohydrate							
Dietary starch	100.00	44.44	6.17	49.38				420
Carbohydrate in feces (2%)[1]	2.00	.89	.12	.99				8
H_2O added in hydrolysis	10.88		1.22	9.66				
Absorbed	108.88	43.55	7.27	58.05				
H_2O formed	64.98		7.27	57.71				
Net water yield	54.10		6.05	48.05				
CO_2 formed	159.58	43.55		116.03				
O_2 consumed	115.69			115.69				
Metabolizable energy								412
	Fat							
Dietary triolein	100.00	77.32	11.84	10.84				945
Fat in feces (5%)[1]	5.00	3.87	.59	.54				47
H_2O added in hydrolysis	1.93		.22	1.71				
Absorbed	96.93	73.45	11.47	12.01				
H_2O formed	102.50		11.47	91.03				
Net water yield	100.57		11.25	89.32				
CO_2 formed	269.15	73.45		195.70				
O_2 consumed	274.72			274.72				
Metabolizable energy								898

[1] Digestibility coefficient plus allowance for nonmeasured losses such as skin, sweat, and flatus.

surement of energy cost of activities by indirect methods.

Several other trace compounds have been identified in atmosphere enclosed about the human body and presumably excreted from the lungs, skin, or intestinal tract. Some are bacterial in origin, but others arise in human metabolism. Excretion rates of these compounds (acetone, butanol, carbon monoxide, ethanol, hydrogen sulfide) are less than 5 mg/d.

Material Balance

Normally, urine and feces contain about 9% ingested energy as measured by oxygen bomb calorimetry. The remaining carbon and hydrogen, except for small amounts (noted above), are metabolized and excreted as carbon dioxide and water. Approximate material balance for diets of varying composition can be computed from values in Table 6. These values are quite crude in that assumptions were made concerning specific nutrient forms fed, excretory routes and products were simplified, and mineral matter is not shown. However, the computed values serve to illustrate that the excretory material in which potential energy is stored will differ according to the composition of the diet fed. This will be an important consideration if an atmospheric regeneration system is used that processes carbon dioxide but not urinary and fecal solids.

Only small amounts of oxygen would be sequestered as waste, provided the diet were low in protein content. However, for each 100 g protein in the diet, using the example given in Table 6, 8% oxygen would be trapped in urine and feces, in contrast with less than 1% from equal amounts of carbohydrate or fat (Figure 1). About 70% oxygen would appear as carbon dioxide in all cases, but with carbohydrate or fat about 30% oxygen would be excreted as easily recoverable net metabolic water, and only 22% with protein. Viewed in another way, dietary carbohydrate can constitute a useful reserve of oxygen because food would supply nearly 30% required oxygen rather than 14% with protein and less than 4% with fat.

It is unlikely that any flight regenerative system would, or could, demand perfect balance of waste materials, but recovery of urinary waste would be particularly important if a closer balance were desired than merely atmosphere-regeneration. With dietary protein, about 11% carbon and 28% hydrogen would be lost as urea in urine and sweat plus roughly 10% of each in feces, skin, and hair. Urine is also the major excretory route for some minerals (sodium, chloride), but many others are apportioned between urine and feces (calcium, phosphorus, magnesium, potassium, zinc), and a few are excreted almost entirely in the feces (iron). Thus, selection of food systems must be coordinated closely with waste management and regeneration.

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Chapter 2

FOOD AND WATER SUPPLY[1]

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Preparations for the first manned space flights included the basic problem of providing the crews with food and water. The difficulties were mainly lack of experience with this type of flight. From flight simulation under terrestrial conditions, only an approximate idea could be obtained of the required quantities of food and water for a man in space, the specifics of food intake technology, and preparation of food and water during flight in weightlessness. Opinions differed on the peculiarities of supplying food and water in space; for example, on the level of energy expenditures and related food requirements under prolonged weightlessness.

A reduction in energy expenditure with needs approximating the basal metabolism level was proposed by some, while others predicted a considerable increase in energy consumption to accomplish body movements and work operations. Finally, a third group considered that food and water requirements may be essentially the same as for moderate human activity on the surface of the Earth. On the first flights, the practical solution to the problem of providing food was simplified by the relatively brief stay of the astronauts in weightlessness. It was assumed that the first short orbital flights would provide both specific experience in the technology of food intake under weightlessness and precise definition of man's food requirements under the unusual conditions of space.

Supplying the astronauts with adequate drinking water was a continuing center of attention of investigators in the USA and USSR. All agreed that, even during brief flights, the development of body dehydration was intolerable. Moreover, water supplies should contain an adequate reserve for unforeseen water losses.

Providing astronauts with food and water has been indisputably successful. Investigators have accumulated a great deal of practical experience and have precisely defined a number of theoretical aspects of food and water supply. Numerous and diverse medical, biologic, and technologic problems had to be solved, a number of which had not been encountered in ground simulation. Special on-board food and water supply systems were created. Still, in the science and practice of food and water supply for astronauts on extended space flights, only the first steps have been made. In particular, human metabolism during prolonged weightlessness and hypoki-

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[1] Translation of, Pitaniye i Vodosnabzheniye, Volume III, Part 1, Chapter 2 of *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*), USSR Academy of Sciences, Commission of Exploration and Use of Outer Space, Moscow, 1973, pp. 1–111.

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nesia has not been studied adequately because of procedural difficulties in research while in flight and lack of experience in such prolonged flights.

Existing and prospective spacecraft food and water supply systems can be arbitrarily divided into three basic types:

1. Systems based on supplies of food and water taken from Earth. In turn, systems based on food stores can be subdivided according to flight duration, into those intended for short flights (several hours to several days), flights of medium duration (several days to months), and for long flights, which may last for a year or more.
2. Mixed-type supply systems, in which the astronauts use food and water supplies taken from Earth and those obtained from regeneration and reprocessing of human metabolic wastes and wastes from the technologic processes of various spacecraft systems.
3. Supply systems based predominantly on food and water produced by reprocessing various wastes through chemical, physical, and biological methods in flight. In this case, supplies from Earth would be only negligible additives such as vitamins, macroelements, and trace elements, which are too complicated to process aboard the spacecraft, store well, take up little space, and are lightweight.

At present, supply systems of the first type have been the most completely investigated and tested in practice. Food and water supply systems in the USSR and in the USA have had individual and specific characteristics, according to the type of spacecraft and tasks to be performed by the crews. Therefore, problems of providing astronauts with food and water should be examined first in terms of the history of man's conquest of space and the experience of increasingly longer flights.

The creation of systems for regenerating food and water from wastes in spacecraft during long flights has proved extremely complicated. Work is being carried out in this direction in both the USSR and USA. Interesting results have been obtained on individual links in the systems for water and food regeneration from various wastes of human metabolism, and on technological processes for diverse spacecraft systems. However, only the first steps have been taken in the creation of a single closed system for production of food and water in flight. Therefore, astronauts' food and water supply by regeneration is still a matter for the future.

FOOD AND WATER ON SHORT FLIGHTS (VOSTOK, MERCURY, AND VOSKHOD)

The food and water supply systems in the Vostok and Voskhod (USSR) and Mercury (USA) projects were created for relatively short orbital flights, from 1.5 hours to several days. The shortness of the flights and sanitary-technical restrictions demanded as much simplification as possible in the astronaut nutrition program. However, even in such brief flights, systems to satisfy a number of specific requirements were necessary.

The basic requirements for the food system in short flights can be formulated briefly:

food ration (daily or per flight) adequate for astronauts' energy expenditures, containing nutrients necessary to insure optimum metabolic processes;
foodstuffs should have acceptable taste qualities;
low unassimilable matter in foodstuffs;
minimal volume and weight of rations;
food should retain quality and safety for duration of flight;
provision of resources and convenience for eating under weightless conditions;
use of only foodstuffs that require no additional preparation, cutting, or, if possible, heating in flight [137].

In view of the shortness of the flights, ready-to-use foodstuffs were provided. This permitted a food system with a minimum number of components: a selection of foodstuffs or a supply of daily food rations; storage containers; devices for facilitating preparation and intake of food (key for unscrewing the caps on tubes, food cabinets, tableware); and a container for collection and storage of leftovers and empty packages.

During preparation for the first USSR and USA spacecraft flights, research was carried out on feeding under conditions simulating the astronaut work and rest schedule in the spacecraft cabin during flight. This permitted the nutritional value of the rations to be determined approximately for each type of flight, with regard to caloric requirement and to chemical composition. Different types of foodstuffs and the means of packaging them, storage, and eating in flight were tested simultaneously.

The food value requirements of the daily rations were determined on the basis of national physiologic nutrition standards. The nutrition standards recommended for ground population groups in occupations not involving physical labor were the most applicable to the living conditions of astronauts in short flights; the daily energy expenditure of this population group is between 3000 and 3200 kcal/d [18]. The recommendations of the Institute of Nutrition, USSR Academy of Medical Sciences (1951) were used in the Soviet Union. The nutrition standards adopted for terrestrial population groups were refined for space flight in the course of experiments with test volunteers and future astronauts in confined spaces, barochambers, and anechoic chambers [137].

The Soviet scientists concluded from such tests that the caloric value of the daily rations could be 2500–2700 kcal/d [137] in the first Vostok flights. In making allowance for leftovers of liquid and pureed foodstuffs in the aluminum tubes, and variability in individual metabolic patterns, the caloric value of the daily rations was increased to 2800 kcal/day, somewhat above the average requirements. A regimen of four meals per day with 4–5 hours between was the most efficient in terms of assimilation of foodstuffs [137].

The ratio of 1 : 1 : 3 for the basic nutrients (proteins, fats, and carbohydrates) in the ration was preserved, and is recommended by the Institute of Nutrition, USSR Academy of Medical Sciences for persons not occupied in physical labor. Accordingly, the daily ration for the first Vostok flights contained about 100 g protein, 118 g fats, and 308 g carbohydrates.

There was no direct evidence indicating possible development of hypovitaminosis in short-term flights, but it was decided to supplement the diet with a multivitamin complex to prevent possible deficiency due to the use of preserved products and enhanced vitamin expenditure under the influence of flight stress factors. The supplement pills included these vitamins: C, 100 mg; P, 50 mg; B_1, 2 mg; B_2, 2 mg; B_6, 2 mg; niacin, 15 mg; pantothenic acid, 10 mg; E (tocopherol), 50 mg [137]. It was recommended that the astronauts take this complex twice a day in flight.

The final preflight physiologic evaluation of the food rations and acceptability of different types of foodstuffs (after preliminary tasting) was carried out during training tests of future astronauts in barochambers and anechoic chambers. By simulating the work-rest schedules in flight, the energy value of the food actually eaten in these experiments was determined to be 2500–2750 kcal/d. The assimilability of the food was about 95%. Palatability of the food and convenience of packaging were evaluated as fully acceptable for flight conditions.

The biochemical indices of protein, fat, and carbohydrate metabolism observed with consumption of the food rations in the experiments differed little from baseline data. Fluid and electrolyte metabolism did not change significantly during the observation period [137].

The necessity for food intake under weightless conditions required clarification of the questions: Does weightlessness cause difficulty in chewing and swallowing? Do the taste sensations remain unchanged? How will digestion, defecation, and other processes take place? The answers to some of these questions were obtained in the USA and USSR through experiments in parabolic flights of aircraft when conditions of brief weightlessness were created. In these experiments, it was determined that swallowing of well-chewed food and liquids under weightlessness can take place without difficulty [157, 171].

The storage and use of food in a spacecraft cabin, without a refrigerator or kitchen equipment, place strict requirements on foodstuffs and their packaging, as well as on the conditions for food intake. Since foodstuffs must retain quality during storage in the spacecraft cabin with an air temperature of 20°–25° C, the assortment of foodstuffs that can be used in flight is sharply restricted. Perishable fresh food and ready-to-serve dishes, which usually have the highest taste qualities, are of little use under these conditions. The orientation must be toward foodstuffs which are stable in storage, primarily those which have been preserved. The choice of foodstuffs and packaging is further limited by the necessity of consuming food directly from the package, without additional preparation. Contamination of the cabin air with food particles or fragments of packaging is inadmissible. Under weightless conditions, particles of food floating freely about the cabin can enter the respiratory passages and eyes, with undesirable consequences.

Vostok 1 and 2

Only pureed and liquid foodstuffs packaged in aluminum tubes and sterilized in autoclaves comprised the rations for flights of Vostok 1 and Vostok 2, based on the restrictions outlined above. The food (160 g) could be eaten directly from such tubes without warming, on the basis of taste qualities. Foodstuffs included: various purees—sorrel with meat, meat and vegetables, meat, meat and groats, and prunes; meat and liver patés; fruit juices—currant, gooseberry, plum, apple; processed cheese; processed chocolate sauce for dessert; and coffee with milk. Solid foodstuffs were provided in addition to the food in tubes, which included bread and smoked sausage, confectionery items, and multivitamin pills, all vacuum packed in synthetic film. This was done to test the possibility of eating solid food under weightlessness in flight.

The day before the launch all the items were stowed in a special metal food container—food rations, the key for unscrewing tube caps, and film packages for collecting the empty packaging and food leftovers. The container opening was closed with a soft textile flap, which could be easily moved aside to remove tubes. The cosmonauts ate preserved foods in tubes similar to the flight-ration foodstuffs for 2 days before the flight to adapt to the new, unique menu and unusual forms of food. Breakfast on the day of the launch was also pureed and liquid foodstuffs in tubes [137]. The food regimen in flight provided four meals—breakfast, lunch, dinner, and supper.

The flight of Yu. A. Gagarin in Vostok 1 lasted 108 minutes (1 orbit around the Earth). At the 30th minute of the flight, he ate, in accordance with the program. His comment, "I ate and drank during weightlessness, and everything went just as at home on Earth" [137], was not only an extremely interesting result of the first test of man taking food in orbital flight under weightless conditions, but it also determined the prospects for the use of various forms of foodstuffs on subsequent space flights.

During the flight of cosmonaut G. S. Titov in Vostok 2, more complete information was obtained on food intake in space. In 25 hours of flight, he completely fulfilled the program for studying the use in weightlessness of foodstuffs of different consistencies and forms. The cosmonaut did not note any difficulties in eating the test samples of food [137], nor any change in taste sensitivity. In general, both cosmonauts evaluated the feeding system favorably. However, determining the adequacy of the food rations to meet cosmonauts' physiologic requirements was not possible because of the relative briefness of the flights, and methodologic difficulties.

Yu. A. Gagarin weighed 69.5 kg before the flight (4 h before launch). His weight loss was practically restored 6 days after the flight. The body weight of G. S. Titov was 62.6 kg before the flight (2.5 h before launch) and 60.8 kg, 9 h 27 min after landing; his weight reached the preflight level only after 9 days [137]. Thus, it was not possible to determine if the weight loss noted in both cosmonauts was due to dehydration or caloric deficit.

Mercury

The approach of US specialists to provide food for the Mercury crews was similar to that of the Soviet workers. The short duration of the first flights simplified the feeding program. Astronauts Shepard (May 5, 1961) and Grissom (July 21, 1961) did not eat at all in the 15-minute suborbital flights of the Mercury spacecraft. Food was eaten on other flights, both to satisfy the appetite and for test purposes. Predominantly liquid and pureed food, with a total energy value of about

2500 kcal/d, was recommended initially in the US for brief flights [41]. Astronaut Glenn tested the eating of pureed foods from elastic tubes. Carpenter, during flight, attempted to eat solid food (cookies in the form of cubes) that crumbled and the crumbs flew around the cabin. It was concluded that an edible film for packaging such foodstuffs was necessary [42, 109].

Observations were carried out on multiple meals and gastrointestinal tract functioning during the flights of Glenn (Feb. 20, 1962), Carpenter (May 24, 1962) and Schirra (Oct. 3, 1962). These observations and the results of tests in 40-second periods of weightlessness created in parabolic flights conclusively removed misgivings about the effect of weightless conditions on chewing and swallowing [43].

During the 34-hour flight of Cooper (May 15 and 16, 1963), eating was more necessary. On this flight, rehydratable food was tested, the type that was adopted later during development of the Gemini program. The energy value of Cooper's ration was 2494 kcal/d and included 16% protein, 41% fat, and 43% carbohydrates [73]. However, because of reduced appetite, he ate only the roasted meat. The food he actually ate had energy value of 690 kcal [23], his energy expenditure was estimated as 2420 kcal; thus, as a result of the flight he lost about 3.4 kg in weight [72].

Pureed foodstuffs in aluminum tubes and samples of solid foodstuffs were included in the ration of the Mercury spacecraft, most of which were samples of foods, changed to acceptable sizes, developed initially for the US Air Force. The sterile foods in aluminum tubes weighing 156 g per portion, used by Glenn, Carpenter, and Schirra, were developed earlier and used successfully by Air Force pilots making high-altitude flights. The selection of foodstuffs packaged in aluminum toothpaste-type tubes included semiliquid meat (beef and vegetables, beef with gravy) and fruits (applesauce and peaches) [73]. The pureed food was squeezed out of the tubes through an 8.75-cm polystyrene tube.

When the facepiece of the helmet was tilted up during normal pressure in the cabin, the food entered the astronaut's mouth directly through the tube. If the facepiece was closed, the tube was inserted through an opening in the helmet. Solid or chewable items were food cubes and compressed dry food mixtures, which included 5-g, 2.5-cm diameter tablets of malted milk, cubes of a cereal mixture, freeze-dried fruits coated with gelatin and containing negligible amounts of moisture, and bread and fruit cakes covered with a pleasant-tasting digestible film.

In the Mercury flights, foodstuffs were placed in the upper part of a ditty bag, since there was no special section for storage. Individual packages of foodstuffs were fastened to the walls and other free surfaces with pieces of Velcro (self-fastening plastic material, Velcro Corp., USA). On astronaut Cooper's flight, the foodstuffs were packed in an MA–9 container that permitted food rehydration. The container was a two-layer pouch of laminated films of polyethylene-polyester-polyethylene (inner layer) and a double strip of carbon fluorohalide with polyethylene (outer layer). A tube of pressed polyethylene was attached to introduce water and remove food. During space flight, there were some packaging failures resulting in leakage of contents during intake of rehydrated food [111].

Carbon fluorohalide-polyethylene materials also were used to make flexible parts for packaging solid foodstuffs; for example, cubes of food were removed from the container by means of a polyethylene pull tab. Water for food reconstitution was stored in a special container and supplied as needed under pressure created by squeezing the bulb of the sphygmomanometer used for measuring blood pressure in flight.

Successful tests of different foodstuffs and feeding systems on the first flights permitted further improvements, mainly by expanding the assortment of foodstuffs in the daily menu through inclusion of a wider array of foods and ready-to-serve dishes of normal solid consistency.

Vostok 3 and 4

Cosmonauts A. G. Nikolayev and P. R. Popovich, who made flights in the Vostok 3 and Vostok 4, had rations with supplements to the pureed and liquid foodstuffs in aluminum tubes. Various meat dishes were included such as hamburger, roast beef, roast veal, chicken fillet, and beef tongue, as well as pirozhki with sprats, pressed and red caviar sandwiches, pieces of fish (Caspian roach back), confectionery and bread items, and fresh oranges, lemons, and apples. To facilitate intake and prevent contaminating the cabin air with food particles, all foodstuffs were prepared in bite-size portions [136]. Vitamins B_{12}, folic acid, and an increased dose of B_6 were added to the multivitamin complex [136].

Perishable foods included in the ration required various measures to prolong good quality of the foodstuffs. Preparation and packaging of the products were carried out with strict aseptic techniques under bacteriologic control. After cooking and preparation, the foodstuffs were packaged in cellophane-polyethylene film and hermetically sealed under vacuum. The selection of foodstuffs for one meal was in a collective package of the same film. The daily food ration was divided into breakfast, lunch, dinner, and supper, with an interval between meals not to exceed 4–5 h, according to the flight program [136].

Repeated ground tests of this ration, in simulation of astronauts' activities in a spacecraft cabin, showed that the selection of foodstuffs was completely acceptable for short flights in regard to taste, variety, sense of satisfaction, and convenient intake. These rations, which differ less from customary foods than pureed and liquid foodstuffs in tubes, were favorably evaluated by the astronauts both on Earth and in actual flight.

During the flights of Vostok 3 and 4, cosmonauts A. G. Nikolayev and P. R. Popovich received food rations for 3 days. The energy value and chemical composition of the food rations are in Table 1. Although it was formerly considered that the energy value of the rations should be about 2800 kcal/d in flight, the energy value of the rations on the first and last days was reduced, taking into account an additional breakfast before launch takeoff and the next meal on Earth after completing the flight [136].

Appetites were normal throughout the flights of cosmonauts A. G. Nikolayev (94 h 22 min), and P. R. Popovich (70 h 57 min). There was no difficulty in chewing and swallowing, and the feeding system was favorably evaluated. The body weight of A. G. Nikolayev, 8 h after completing the flight, was less than preflight by 1.8 kg; 12 days afterward, it still was not completely restored. The body weight of P. R. Popovich, 8 h, 30 min after landing, was reduced by 2.1 kg. However, about 14 h later (the morning of the next day), the weight deficit was about 0.8 kg. Thus, both cosmonauts lost weight during the flight, with a greater loss for P. R. Popovich who flew a day less. On the basis of existing data, it could not be firmly concluded whether the loss in body weight was due to dehydration or to caloric deficit.

The rapid recovery in body weight by P. R. Popovich indicates probable dehydration. Postflight analysis of the atmospheric regenerative and drying agents of the air conditioning system revealed that A. G. Nikolayev gave off an average

TABLE 1.—*Energy Value and Composition of Food Rations of Cosmonauts A. G. Nikolayev and P. R. Popovich during Flights in Vostok 3 and Vostok 4* [136]

Eating schedule	Energy value, kcal	Protein, g	Fat, g	Carbohydrate, g
1st day, flight				
Breakfast	706	44.6	25.1	75.8
Lunch	560	13.1	16.8	85.2
Dinner	707	39.7	26.1	73.8
Supper	507	8.8	10.0	90.7
Total	2480	106.2	78.0	325.5
2nd day, flight				
Breakfast	732	48.5	24.6	73.7
Lunch	592	39.7	20.1	59.5
Dinner	1011	48.0	49.0	87.0
Supper	511	10.7	18.1	72.9
Total	2846	146.9	111.8	293.1
3rd day, flight				
Breakfast	526	19.3	18.4	67.9
Lunch	617	13.5	14.8	102.3
Dinner	701	49.9	14.0	89.2
Supper	411	21.9	17.1	39.6
Total	2255	104.6	64.3	299.0

of 40.0 g/h water and P. R. Popovich an average 47 g/h, through the skin surface and respiratory tract [136]. Data indicated that extrarenal losses of water were normal for the comfort level; consequently, dehydration, if any, resulted from increased diuresis.

Vostok 5 and 6

The cosmonauts' rations in Vostok 5 and Vostok 6 were mainly the same as the solid foodstuffs in film packages and in tubes used on Vostok 3 and 4 flights. Because of the increased lengths of the flights, the rations for the first days included more perishable foodstuffs than those for the later days of the flight. From preparation to storage of the foodstuffs in the on-board food container (several hours before launch), the food was kept in a refrigerator. The selection for the first days of the flight and the eating schedule are presented in Table 2. The cosmonauts were familiarized with the foodstuffs in advance, which permitted taking into account their individual tastes.

The daily food ration of cosmonaut V. F. Bykovskiy (Vostok 5) contained about 2526 kcal, 105 g protein, 78 g fat, and 330 g carbohydrate, on the average. However, the food value of his ration was changed during the flight. The energy value of the ration was 1670 kcal on the first day of the flight, and about 2500 kcal on the last. The reduction in energy value of the ration on the first and last days of the flight was considered acceptable, because of the possibility of eating food before launch and immediately after completing the flight [135]. The daily ration of cosmonaut V. V. Tereshkova (V. V. Nikolayeva-Tereshkova) in the Vostok 6 spacecraft had an average energy value of about 2529 kcal and contained 120 g protein, 85 g fat, and 305 g carbohydrate [135]. Tablets taken twice a day contained 100 mg vitamin C, 50 mg P, 2 mg B_1, 2 mg B_2, 15 mg niacin, 2 mg B_6, 50 mg E (tocopherol), and 10 mg pantothenic acid.

On the morning of launch day, the cosmonauts had a breakfast on Earth similar to breakfast on the second day. During the flight, the cosmonauts generally ate according to the flight program. The appetite of V. F. Bykovskiy remained good, but was reduced in V. V. Tereshkova; therefore, her rations were not completely consumed. She noted a lack of appetite, especially for the sweet dishes, which caused slight nausea. Both cosmonauts favorably evaluated the food rations and convenience of packaging [135].

A day after the flight, which lasted 119 hours, the body weight of V. F. Bykovskiy still remained 2.4 kg less than before launch. A day after the flight (71 hours) the weight deficit of V. V. Tereshkova was 1.9 kg. Thus, longer flight was accompanied by a greater body weight loss, despite complete consumption of the ration. Analysis of the regenerative and drying agents showed that extrarenal elimination of moisture during the flight remained at a low level in the cosmonauts: 33.2 g/h in V. F. Bykovskiy and 23 g/h in V. V. Tereshkova. Data on temperature

TABLE 2.—*Food Selection in Rations and Eating Schedule of the First Day of Vostok 5 and Vostok 6 Flights* [135]

Eating schedule	Foodstuffs included in the ration
	Vostok 5 (Cosmonaut V. F. Bykovskiy)
Breakfast	Red caviar sandwich, coffee with milk (in tube), fresh lemon sections, multivitamin pill
Lunch	Roast beef chunks (in package), wheat bread, fresh apple in sections, mint caramel
Dinner	Roast tongue chunks (in package), wheat bread, peeled fresh orange, multivitamin pill
Supper	Chicken fillet chunks (in package), wheat bread, pirozhki [1] with fruit filling, prune puree (in tube)
	Vostok 6 (Cosmonaut V. V. Tereshkova)
Breakfast	Bite-size hamburger (in package), pressed caviar sandwich, wheat bread, fresh lemon sections, coffee with milk (in tube), multivitamin pill
Lunch	Pirozhki with sprats and eggs, meatloaf chunks (in package), wheat bread, black currant juice (in tube), fresh apple sections
Dinner	Curds (in tube), roast tongue chunks (in package), wheat bread, cherry juice (in tube), peeled fresh orange, multivitamin pill
Supper	Meatloaf chunks (in package), wheat bread, pirozhki with rice and eggs, pirozhki with fruit filling, prune puree (in tube)

[1] Pirozhki is filled pastry.

conditions in the comfort zone during the flight led to the conclusion that dehydration was due to increased diuresis. This was not contradicted by data on reduced elimination of chlorides in the urine by V. F. Bykovskiy from 15.0 g/d (preflight) to 5.0 g/d on the first day and to 4.2 g/d on the second day of the flight, because the preflight ration was considerably richer in chlorides [135].

Voskhod 1 and 2

A flight of about 24 hours was planned for the multiplace spacecraft Voskhod 1. A comparatively large food container in the cabin provided rations that were more than adequate for cosmonauts' energy expenditures. The total energy value of the food eaten during the flight (24 h, 17 min) by each of the cosmonauts (V. M. Komarov, K. P. Feoktistov, B. B. Yegorov) was about 3600 kcal. The flight ration contained about 150 g protein, 130 g fat, and 430 g carbohydrate. Each cosmonaut received a total of 300 mg vitamin C; 150 mg P; 6 mg each B_1, B_2, B_6, and folic acid; 45 mg niacin; 30 mg pantothenic acid; 75 mg E; and 150 μg B_{12} in 3 doses. The ration included foodstuffs of the same types as in the flights of Vostoks 3–6, but the assortment was expanded. The cosmonauts evaluated as adequate the amount of food for each meal and for the entire flight. Appetites remained at a satisfactory level. The cosmonauts experienced almost no thirst during the flight, but immediately after landing, K. Feoktistov and B. Yegorov who drank little, felt a strong thirst and resorted to the spacecraft water supplies. Cosmonauts each drank approximately a total of 0.2–0.6 l of water on the flight; each received 1.2 l of water with food [5].

Between preflight and postflight examinations (33 h, 50 min), all the cosmonauts lost weight: V. M. Komarov lost 1.9 kg, K. P. Feoktistov, 2.9 kg, and B. B. Yegorov 3.0 kg. Analysis of their water balance revealed that water losses during flight were not completely made up. Loss in body weight on this flight apparently was almost exclusively by dehydration, since the high energy value of the ration made weight loss through calorie deficit unlikely. Definite body dehydration after the flight was also confirmed by results of water loading tests, in which elimination of water clearly was retarded. A distinctive characteristic of body dehydration under flight conditions was the absence of pronounced thirst in the cosmonauts.

After the flight, some increase in elimination of products of nitrogen metabolism in the urine was noted in the Soviet cosmonauts [119]. Some authors blame this phenomenon on the stress of flight factors [51, 70]. On the other hand, the role of change in diet cannot be excluded, since, in a number of cases, the cosmonauts received more protein during the flight than before. The level of nitrogen elimination by Voskhod 1 crew members immediately after landing corresponded to the high protein standard in the flight ration [5]. Changes in certain physiologic functions (pulse and respiration rate) recorded during individual flight stages evidence stress phenomena. However, the extent to which this stress influenced metabolism remains unclear. A small increase in blood cholesterol was noted in the cosmonauts after the Voskhod 1 flight; however, at the same time (3 days postflight), no increase was noted in the urine of 17-oxycorticosteroids, 17-ketosteroids, epinephrine, potassium, creatinine, uric acid, chloride or sodium [5].

Some reduction of indicators of the metabolism of vitamins B_1, B_2, B_6, and niacin was noted in the cosmonauts' urine postflight. Hypothetically, the increased B_6 utilization was connected with the effect of weightlessness on the vestibular apparatus. An accelerated metabolism of vitamin B_6 (a decrease in the content of pyridoxine metabolites in the urine) was noted in the laboratory experiments involving vestibular loads. Also, test subjects showed better vestibular tolerance when taking B_6 preparations. However, an evaluation of the effects of vitamins on the cosmonauts' bodies in flight was complicated by the fact that, during the postflight examination period, the cosmonauts did not receive vitamin preparations.

The same food supply system was used during the flight of the Voskhod 2 [5, 119]. The cosmonauts responded favorably to the feeding system. However, because of Voskhod 2 landing in a remote area, an evaluation of the food status of the cosmonauts was not carried out immediately after the flight.

FOOD SUPPLIES DURING FLIGHTS OF MEDIUM DURATION (GEMINI, APOLLO, AND SOYUZ)

Gemini and Apollo

The flights of Gemini-type spacecraft, planned to last 14 days, required an efficient feeding system. Adequate nutrition from the food and its acceptability had to be combined with rigid weight and volume requirements; reliable and convenient packaging was also necessary. Standards had to be developed for the foodstuffs, their preparation, and materials and design of food containers. Mandatory indices were specified for food quality, organoleptic properties, shelf-life, stability of fats, moisture content, physical characteristics, and microbial levels. Optimum combinations of foods were developed. This work was begun upon instruction of NASA in the fall of 1963.

Commercial and experimental formula diets which were evaluated showed that natural products were the most stable and most suitable for space flight, especially if dried for later reconstitution. In tests during the Mercury flights, acceptable recipes were devised for preparing such foods in space and their quality evaluated. Subsequent work was directed toward varying the food ration, within the limits of a nutrient-defined diet [36]. Particular attention was paid to the energy value of foods and the content of water, proteins, and calcium in the ration. Recommendations of the Food and Nutrition Board, National Academy of Sciences-National Research Council (NAS–NRC) [45] were adopted as the baseline, and the research of Sargent and Johnson [121] and others [122] on the physiologic basis of components in emergency rations were used to establish minimum criteria and ratios of proteins, fats, and carbohydrates. Tests with humans were carried out in two different laboratories to define precisely the biologic value and health safety of space rations. Experimental feeding with prototype space foods yielded good results [99, 139]. The US Air Force (USAF) also carried out research with various menus of space food samples as well as with diets constituted according to experimental formulas [152, 165].

A great deal of work on the engineering design of food rehydration systems was carried out in the USA in connection with the prospective use of dehydrated foods requiring reconstitution with water.

A single device for food rehydration and drinking water was to be created. Much work was directed toward developing a valve device in dehydrated food containers to insure safety in rehydration. A valve was installed in a sleeve inserted into the food pouch in one design, which had a reliability index of about 95%, but the necessity for heat bonding of many layers of plastic at one point was a deficiency, and pinhole channeling along the valve insertion decreased the container material's resistance to bursting. In an improved design, the valve was included in the structure of the container, thereby preserving the container's basic dimensions and configuration and allowing its strength to be increased. However, during repeated bursting tests, approximately 50% of the containers failed because the material ruptured.

The astronaut food supply systems in the Gemini and first Apollos were designed to serve two or three men for 14 days, or more if necessary. The menu included freeze-dried and other types of dehydrated or low-water-content foodstuffs, some of which were formed under pressure. Components of the Gemini and Apollo menus are in Table 3. A typical daily ration was composed of approximately 50% rehydratable foodstuffs. The other 50% was solid foods which were rehydrated in the mouth and could be eaten during planned meals (breakfast, dinner, supper) while the rehydratable foods were being prepared, or as a snack between the main meals. The USAF Manned Orbiting Laboratory Program researched the possibility of changing the ratio of rehydratable and solid foods from 50:50 to 33:67 to decrease packaging weight and eating time, and increase variety in the diet [148].

In the Gemini spacecraft and Apollo lunar modules, rehydratable foodstuffs were reconstituted with water at 21.1°–26.7° C, i.e., at the cabin air temperature and without special warming. Reconstitution of the foods took 10 minutes or less. There were both cold water (7.2°–12.8° C) and hot water (45.0°–50.6° C) in the Apollo command module. Rehydratable food was considerably more acceptable than dehydrated foodstuffs, whether cold or hot water was used. A nine-point evaluation scale for food acceptability showed that water increases the evaluation indices by a whole point; the temperature of the water [115] can be set as desired. The existing assortment of foodstuffs permitted planning a 4-day menu cycle of 3–4 meals per day or several combinations of meals and snacks.

For the Gemini flight, the energy value of the menu was set at 2500 kcal/d. For the Apollo lunar landing program, the energy value was increased to 2800–3000 kcal/man·d^{-1}. In a typical menu, 17% of the calories were from proteins, 33% from fats, and 50% from carbohydrates. It should be noted that only the most general conclusions can be drawn as to the adequacy of inorganic substances in the diet, but a deficit still has not been proved.

Multivitamin pills to supplement the daily ration of astronauts were suggested earlier in the USA to provide NAS–NRC recommended daily allowances. However, natural foodstuffs were used in Gemini and Apollo crew rations, flight duration having been limited to 14 days, so that these preparations were not included. On the other hand, Paul A. Lachance considered it necessary to provide multivitamins to the astronauts, since the food status, individual requirements of crewmembers, and the effect of space flight on food requirements had not been studied. There is also likelihood of anorexia and irregular food consumption.

The use of dense, solid foods, usually of high-calorie and low-protein content, permitted regulating the ration energy value, and decreasing or not changing the number of foodstuffs requiring prolonged preparations for rehydration. The

TABLE 3.—*Menu Components for Gemini and Apollo*

Solid freeze-dried briquettes	Other dehydrated foodstuffs			
	Meats [1]	Drinks	Soups	Pressed solid briquettes
Cinnamon toast	Ham with applesauce	Cocoa	Potato	Bacon squares
Toast	Chicken in gravy	Tea	Pea	
Beef	Chicken with vegetables	Orange	Corn chowder	
Chicken	Beef	Grapefruit	Chicken [2]	
Bacon and eggs	Beef with vegetables	Pineapple-grapefruit [1]	Tomato [2]	Cubes
Sausages [2]	Spaghetti with meat sauce	Orange-grapefruit		Apricot
Turkey [2]	Shrimp cocktail	Orange-pineapple [1]		Strawberries
	Beef in gravy			Toast
Sandwiches	Sausage patties		Cereal products	Pineapple
	Veal with barbecue sauce			Peanut
Beef			Toasted oat cereal	Cheesecake [2]
Chicken		Puddings [1]		Graham crackers [2]
Cheese	Vegetables		Cornflakes covered with sugar	Cheese and crackers [2]
		Banana		Cinnamon bread [2]
Salads [1]	Peas	Chocolate		Chocolate [2]
	Corn	Apricot		Coconut
Chicken		Butterscotch	Bakery products	Custard [2]
Potato	Fruits [1]			
Tuna			Pineapple cake	
Salmon	Fruit cocktail		Date cake	
Cottage cheese and peaches [2]	Peaches		Brownies	
	Applesauce		Gingerbread	

[1] Rehydratable food, i.e., requiring addition of water before use.

[2] The product was not in the Gemini ration but was in the Apollo.

Manual on Production of Prototype Foods for Space [87], which gives formulas and procedures for all types of spaceflight foods, is used by industry. Space food technology is also discussed in other works [61, 73, 74, 88, 111].

Typical composition and value of food in the daily menus of Gemini and Apollo crews are in Tables 4 and 5. The main effort was concentrated on production of rations which could serve as a basis for several flights. Changes in the rations were necessitated by continual improvement of products.

The food composition of the astronaut ration obviously cannot be evaluated adequately without systematic study of not only the foods, but also the food status of the astronauts under simulated and actual spaceflight conditions. Thus, in research during Gemini 5 and Gemini 7 flights with ^{51}Cr-labeled erythrocytes, in three of four astronauts the red blood cell lifetime was shortened [44, 141], which indicated a hemolytic condition. During the last three Gemini flights, a considerable reduction in vitamin E content in the plasma of several astronauts prompted increased interest in studying the vitamins and minerals in the astronauts' food.

Spaceflight foodstuffs still lag behind "home cooked" foods in properties and quality, and must be eaten completely during flight. Therefore, the quality of prototype space foods has been given much attention [122]. Astronauts' foodstuffs were subjected to careful organoleptic evaluation in laboratory studies and under simulated manned space flight [110]. In three 12-day experiments, a diet of dehydrated and solid foodstuffs was demonstrated to be prac-

TABLE 4.—*Typical Menus of Gemini and Apollo Crews*

Day 2	Day 4
Meal A	Meal A
Applesauce [1]	Peaches [1]
Sugar frosted flakes [1]	Pastry cubes with strawberries [2]
Bacon squares (8) [2]	Sausage patties [1]
Cinnamon toast (6) [2]	Cinnamon toast (6) [2]
Cocoa [1]	Orange drink [1]
Orange drink [1]	Grapefruit drink [1]
Meal B	Meal B
Beef with vegetables [1]	Potato soup [1]
Spaghetti with meat [1]	Chicken salad [1]
Cheese sandwich (6) [2]	Beef sandwich (6)[2]
Apricot pudding [1]	Butterscotch pudding [1]
Gingerbread (6) [2]	Tea [1]
Meal C	Meal C
Pea soup [1]	Shrimp cocktail [1]
Tuna salad [1]	Beef with gravy [1]
Cinnamon toast (6) [2]	Creamed corn [1]
Fruitcake (4) [2]	Toast cubes (6) [2]
Pineapple-grapefruit drink [1]	Pineapple cake (4) [2]
	Orange-grapefruit drink [1]
Total caloric value = 2514 kcal	Total caloric value = 2533 kcal
Net wt. food = 580.66 g	Net wt. food = 558.50 g

[1] Rehydratable food products.

[2] Solid food, number of pieces in each meal in parentheses.

TABLE 5.—*Food Composition of Daily Menu*

Meal A	Meal B	Meal C
Fruit cocktail	Chicken salad	Beef stew
Bacon squares	Beef with vegetables	Potato salad
Strawberry cubes	Butterscotch pudding	Sweet pastry cubes
Cocoa	Fruitcake	Grapefruit drink
Orange drink	Pineapple-grapefruit drink	

Food values

Constituents	Meal A	Meal B	Meal C	Total
Energy (kcal)	759	1123	911	2793
Protein (g)	28.5	45.2	28.7	102.4
Fat (g)	25.4	42.0	32.4	99.8
Carbohydrate (g)	106.4	140.0	125.7	372.1
Ash (g)	7.0	6.8	7.3	21.1
Ca (mg)	176.0	505.0	486.0	1168.0
P (mg)	342.0	712.0	592.0	1646.0
Fe (mg)	3.3	4.8	4.9	13.0
Na (mg)	1659.0	1526.0	1916.0	5101.0
K (mg)	818.0	863.0	1047.0	2728.0
Mg (mg)	64.3	89.5	95.3	249.1
Cl as NaCl (g)	4.30	3.05	3.94	11.29

tically equal, in organoleptic qualities, to a diet of fresh, preserved, and baked foodstuffs [139].

General NASA standards which were established for all foods to guarantee reliability and quality [64] were stricter than those for commercial foodstuffs. However, it was taken into account that precise engineering design standards could not be unconditionally applicable to such biologic items as foodstuffs. To provide microbiologic limits for astronaut food, overall microbiologic indices of sanitary practice were imposed and directed toward detecting the most important pathogenic food microorganisms [27, 37]. Fungus and virus studies were omitted because water content is controlled in prepared foodstuffs and their ingredients which reduces the risk of fungus infection to a minimum. To control the microorganism growth in rehydrated food leftovers stored as food wastes, 1-g tablets of 8-hydroxyquinoline sulfate were inserted directly into the film containers with the leftovers. Cultures of the contents of containers (film packages) selected at random from the Gemini spacecraft postflight showed that this bacteriostatic agent was highly effective.

Packaging methods were given much attention to meet the requirement that there be no increase in volume of film food containers during exposure to vacuum at a pressure of 25 mm Hg. For this reason, all food products were packed under vacuum at 10±2 mm Hg pressure. After preliminary study, a four-layer plastic material was selected consisting of a 2.2-mm inner and a 1.0-mm outer layer of polyethylene, and middle layers of 2-mm carbon fluorohalide and 0.75-mm polystyrene. The Gemini food was packaged in laminated film with layers of 1-mm polyethylene, 0.34-mm aluminum foil, 1-mm nylon, and 2-mm polyethylene. A transparent film with high inflammability temperature was proposed for Apollo, in place of the foil. The daily rations of packaged food for the astronauts in the Gemini program weighed 725.7 g and had a volume of 2131 cm^3. A daily ration with an energy value of 2800 kcal weighed approximately 850.5 g and had a volume of 2393 cm^3.

Food containers were loaded the night before the proposed flight. To maintain the sequence of menus and make it easier to reach the food, the rations were placed in a definite order, tied with string and tagged with the type of food and menu. On most space flights, the food was packaged in a sequence corresponding to the menu and marked for each crewmember. The individual food containers in Gemini were labeled with black and white Velcro squares, and with red, white, and blue in Apollo. The meal schedule and the time necessary were documented by the crew in the on-board log and radioed to Earth. Unused foodstuffs during flight were taken into account in determining the total quantity of food eaten. Food consumption by the crews of Gemini 4, 5 and 7 is presented in Table 6, calculated from food consumption data and a number of analytic indices of food value [89]. Food leftovers in rehydration containers, which can reach 20% (in the moist state), must be considered in evaluating consumption by the astronauts, and to calculate the amount of foodstuffs actually eaten.

Food consumption was the greatest in Gemini 4 and 7, but clearly inadequate. In the Gemini 4 flight, weight loss of the commander was 2.0

TABLE 6.—*Food Consumption in Gemini 4, 5, and 7*

Flight	Ration, contents and consumption	Composition, amount (24 h)			
		Energy (kcal)	Protein (g)	Ca (mg)	Cl (g)
Gemini 4 3–7 June 1965 4:0:56[1]	Contents	2549	108.9	847	10.35
	White consumed:	2230	89.2	739	7.96
	McDivitt consumed:	2066	90.7	676	8.17
Gemini 5 21–29 Aug. 1965 7:22:55[1]	Contents	2755	96.4	849	10.29
	Cooper consumed:	1075	41.9	373	4.70
	Conrad consumed:	915	35.8	333	4.06
Gemini 7 4–18 Dec. 1965 13:18:35[1]	Contents	2333	90.2	1194	8.70
	Bormann consumed:	1774	67.6	945	6.66
	Lovell consumed:	1804	68.3	922	6.88

[1] Flight duration—days: hours: minutes

kg and of the pilot, 3.9 kg: in Gemini 7, comparable weight losses were 4.5 and 2.9 kg. During the Gemini 5 flight, very little food was consumed, which was attributed to anorexia. A suppression of appetite was noticeable in both crewmembers during the last days of the flight; in 8 days, the commander lost 3.3 kg and the pilot 3.9 kg. Astronauts lost weight on all US and Soviet spacecraft flights. Several authors consider the weight loss unrelated to flight duration and amount of food consumed, but as a consequence of dehydration and increased perspiration [163]. The weight loss possibly is due to an increase in diuresis as a specific result of weightlessness, and there is a basis for assuming that the amounts of water and food consumed cannot be separated from this problem. Astronauts involved in operations requiring physical work lost more weight than the commander. Work while wearing the space suit was accompanied by great losses in body weight.

The calorie deficit during a flight can be calculated from the indices of food consumption and the amounts of CO_2 adsorbed by lithium hydroxide in special canisters. In Gemini 5, the calorie deficit accounted for about half the weight loss of the astronauts. Measurements of body mass must be made during flights to clear up this question. For purposes of prophylaxis of bone demineralization and maintenance of calcium equilibrium, calcium lactate was added to the fruit cocktail in the rations, which increased calcium intake to the required level of about 950 mg/d in Gemini-7 astronauts [98, 166]. The basic assumptions of the food supply systems in the Apollo program were adopted for the feeding systems in the Manned Orbiting Laboratory of the USAF [148].

Soyuz

Water regeneration devices were not provided in Soyuz spacecraft; therefore, it was considered advisable that the rations be composed primarily of preserved, natural, undehydrated foodstuffs. Dehydrated, briquetted foodstuffs were reduced to a minimum. Products which had proved satisfactory in Vostok and Voskhod flights were included in the daily food rations: pureed soups in aluminum tubes (borsch, sorrel, and kharcho soup) as the first dishes at dinner, cream cheese with fruit, and coffee and chocolate. Black currant juice was stored separately in a special container. Beginning with the Soyuz 9 spacecraft, the cosmonauts could consume hot soups and drinks from tubes in a special heater [21].

Meat products were supplied in tin cans to preserve quality, in a fairly broad assortment: steak, meatloaf, chicken, beef tongue, veal, ham, pork hash with eggs, stuffed sausage, liver and meat paté (net weight 100 g). Sterilized Rossiyskiy processed cheese was included in the same package in the ration [21]. Various types of bread adopted in the USSR were included as grain products in the ration, which were baked in small bite-size loaves and packaged in polyethylene film. Confectionery products in the ration were honeycakes, hard chocolate, fruit sweets, and prunes with nuts. As in the first flights, Caspian roach, in boneless back chunks, was included in the ration as a snack. Some of the products were packaged under vacuum. The cosmonauts took a multivitamin pill twice a day; each pill contained: A, 3300 IU; B_1, 2.58 mg; B_2, 2 mg; B_6, 3 mg; B_{12}, 12 μg; C, 75 mg; E, 10 mg; nicotinamide, 20 mg; folic acid, 0.5 mg; calcium pantothenate, 3 mg; and rutin, 10 mg [21]. The ration was a 3-day menu, with four meals per day. The foodstuffs in one of the daily rations were:

Breakfast: 100 g meatloaf (canned), 50 g bread, 50 g chocolate candies with nut praline, 150 g coffee with milk, 128 g prune juice (from container).

Lunch: 100 g beef tongue (canned), 50 g bread, 60 g prunes with nuts.

Dinner: 15 g Caspian roach, 165 g borsch (in tube), 100 g veal (canned), 50 g bread, 40 g rich pastry, 128 g black currant juice (from container).

Supper: 165 g cream cheese with black currant puree (in tube), 50 g candied fruit, 128 g black currant juice (from container).

The daily ration, which weighed about 1460 g without packaging, contained about 2803 kcal, 139 g protein, 88 g fat, 345 g carbohydrate, and 850 g (850 ml) water. The ratio of basic food substances in terms of total energy value of the ration was kept within the limits of 20% protein, 30% fat, and 50% carbohydrate. The ration was balanced in required amino acids and contained minerals in accordance with the general physiologic standards adopted in the USSR. In the course of a day, the total energy value of the ration was distributed by meals: breakfast 26%, lunch 21%, dinner 30% and supper 23% [21]. In ground research, assimilability of the ration was quite high: 90% protein, 97% fat, 96% carbohydrate and 95% energy value. The foodstuffs in the ration were well-rated organolepitically during flight. The ration basically met the requirements of the cosmonauts in energy value and nutritional content [21].

FOOD PRODUCTION IN SPACECRAFT DURING LONG FLIGHTS

On prolonged space flights, as distinguished from short-to-moderate flights, all or nearly all consumables of the crew life-support system, including food, must be regenerated aboard the spacecraft [20, 138, 149, 150]. For this purpose, turnover systems on the spacecraft must decompose human and biocomplex wastes to water, carbon dioxide, and minerals from which nutrients are synthesized or processed in biologic systems that can directly utilize urine and other wastes of complex composition. Food production in flight through creation of a matter cycle has been proposed, based on physicochemical processes or with the aid of biologic methods. An appropriate combination of physicochemical and biologic methods of food production in flight is undoubtedly possible.

Food Production by Physicochemical Methods

A possible method of food regeneration from the final products of human metabolism involves physicochemical methods alone. Under ideal conditions, the products of human metabolism and elimination (carbon dioxide, water vapor, urine, feces, hair, and so forth) would be converted into foodstuffs and substances from which a food ration with adequate nutrition, composition balance, and taste acceptability could be made. Thus, the regeneration process should consist of a completely closed and balanced "food-waste-food" cycle. Since most nutritional substances and foodstuffs have a complicated chemical composition, which makes their synthesis extremely difficult, the main attention of scientists at present is on synthesis of individual, simple food elements. The problem may be solved, for example, by insuring regeneration of the largest possible number of nutritional substances from a minimum number of chemical materials produced from the wastes, simultaneously providing the spacecrew with chemical compounds such as proteins and vitamins, which are indispensable for the body but cannot be synthesized. The final metabolic products of crewmembers, carbon dioxide and water, could serve as initial materials for synthesis of a number of nutritional substances. The final products of metabolism, accounting for more than 90% of the weight of food and fluid consumed, are precisely these two substances. Consequently, conversion of carbon dioxide and water alone into food products should encompass about 90% of the mass of a closed food substance cycle.

The principal advantages of physicochemical methods of food production are: high energy value of the substances formed, with low weight and volume; good assimilability of the substances and ease of preparing food from them; the possibility of automatic regulation and control of the technical process; and the relative independence of physicochemical processes from such significant spaceflight factors as weightlessness and ionizing radiation. However, this method of food production is difficult to fully implement at the present levels of knowledge and technology. Only in the future, when appropriate automatic apparatus for accomplishing all technologic processes and syntheses will have been created, when the necessary equipment weighs less than the food supplies required for a flight, can this method of food production be completely justified and acceptable in terms of most indices [21, 150]. Table 7 outlines a ration, for up to 6 months, proposed by Taylor [145] as a version of food supply with products of physicochemical synthesis.

Synthetic foodstuffs can be given desirable taste and odor by special food additives or by additional processing. Powdered substances can be converted into gelatins, jelly, and fruit jellies, which are more convenient to eat, with starch, agar-agar, and synthetic polymer compounds. Clinical investigations with experimental feeding of liquid foods, a mixture of balanced amino acids, glucose, unsaturated fatty acids, a full selection of vitamins and mineral salts, and a ration energy value of 2700 kcal/d, did not reveal any unfavorable physiologic shifts in the body or any toxic effect.

Carbohydrates, fats, and proteins must be recreated in the synthesis process. Carbohydrates, providing more than 50% of the total energy value of the ration, are the basic component of a normal diet; therefore, the main research at present into physicochemical food synthesis for space flights is directed to this category of nutritional substances [125, 132]. Methods for chemical synthesis of fats and proteins are also being studied. The synthesis of carbohydrate monomers (glucoses), fatty acids, and amino acids should have first priority.

Carbohydrates

The development of methods for carbohydrate synthesis has a relatively long history, for which attention has increased considerably in connection with prospective long flights. Since carbohydrates constitute at least 50% of the total energy value of the astronaut ration, the creation of reliable, low-energy-consuming methods of carbohydrate synthesis in flight obviously will permit considerable reduction in the launch weight of the spacecraft and in the volume of the life-support system. Methods for synthesizing sugar-like substances were proposed by von Butlerow who, as early as 1861, produced a mixture of monosaccharides from formaldehyde (CH_2O), which he also discovered [155]. This mixture contained mostly optically inactive hexoses, which Leow named formose [92]. To this day, the term "formose sugars" is applied to the purified complex mixture of autocondensation products of CH_2O.

TABLE 7.—*One Version of a Food Ration Based on Products of Physicochemical Synthesis (according to* [145])

Synthetic food components	Weight (g)	Number of calories (kcal)		
		Total	Per g	Relative %
Amino acids	131.2	528	4	15
Carbohydrates	455.0	1820	4	52
Fats	138.3	1155	9	33
Total	724.5	3503	–	100

Formose sugars do not have favorable characteristics. A large number of sugars are present in the mixture, the composition of which depends on the reaction conditions. Thus, for example, slow addition of calcium carbonate to a 2% aqueous solution of CH_2O leads to formation of appreciable quantities of pentose and arabinose [40, 93]. DL-fructose, DL-glucose, and dendroketose have been detected in the mixture, and, when the reaction proceeds less energetically, glycolaldehyde, glyceraldehyde, and dihydroxyacetone also have been detected [40, 84, 93, 96].

Paper chromatography has shown that formose sugar is an extremely complex mixture of substances. A mixture of formose sugars was analyzed more fully by Akerlof and Mitchell [3] who determined the quantitative characteristics of the individual components on a chromatogram (see Table 8). Most of the substances detected were hexoses. Separation of the mixture of formose sugars by gas-liquid chromatography has revealed still more complexity. Only about a third of the 30–40 components of the mixture have been identified.

In tests with rats fed unpurified formose sugars in the amount of 30%–50% of the total diet, the animals ate a smaller quantity of food, lost weight, developed diarrhea, and died [3]. By chromatography on cellulose, 3 main fractions of the formose sugar mixture were identified as the toxic components of the mixture. The conclusion was that the toxic properties of the mixture are associated with the presence of CH_2O. However, in special tests, rats fed formose purified of CH_2O showed the same symptoms, although they survived somewhat longer [125]. The toxicity of formose is considered due to specific carbohydrate component(s) of the mixture. The formose mixture contains equimolar quantities of all the stereoisomers, including the nonphysiologic L-isomers of sugars normally found in food, possibly causing the observed toxicity of formose sugars.

Artificial carbohydrates are a syrupy mixture of pentoses, hexoses, lower sugars, formic acid, and other unidentified compounds; the major problem is purification and separation of the monosaccharides useful for human nutrition. Synthetic monosaccharides purified by precipitation, filtration, and adsorption purification on ion exchange resins and activated charcoals have been subjected to biologic evaluation [147]. The absence of a toxic effect with purified synthetic carbohydrates produced from CH_2O in the presence of $Ca(OH)_2$ has been demonstrated. Synthetic carbohydrates also can be used in media for growing cell and tissue cultures of higher plants [19], where it is not necessary to separate the mixture into individual monosaccharides. The cells and tissues of higher plants, grown in synthetic carbohydrates, could be used directly as food by man or animal.

Formose sugars are produced from CH_2O after an initial reaction to form glycolaldehyde and a subsequent series of aldol condensations. A broad group of substances can catalyze this reaction: $Ca(OH)_2$, almost all alkali-earth element oxides and their hydroxides, and the oxides of lead, copper, zinc, and iron [123]. A recent report on the kinetics of this reaction stated that almost 80% of the CH_2O conversion products in a homogeneous system were glycolaldehydes, trioses, and tetroses; each is a catalyst and reagent [164]. A possible ratio of the formation rates can be expressed by the formula:

TABLE 8.—*Composition of Formose Mixture (according to* [3])

Percent by weight in mixture	Probable substance
0.4	Glycolaldehyde
1.1	Glyceraldehyde
1.8	Dihydroxyacetone
3.2	Erythrose, threose, erythrulose
2.5	Xylulose
6.5	Ribose, dendroketose
17.2	Xylose
16.5	Fructose, mannose
17.5	Sorbose, arabinose
16.8	Glucose
8-5	Galactose
4.4	Unidentified sugar
2	α-Heptulose

$$\frac{d(A_2+A_3+A_4)}{dt} = 0.0582 \cdot (A_1+A_2+A_3+A_4) \cdot (A_2+A_3+A_4) \cdot [Ca(OH_2)]$$

where A_m denotes the concentration of substances containing different numbers of carbon atoms expressed in moles (m) and time (t) in minutes.

The basic materials for production of carbohydrates under spaceflight conditions are CO_2, given off by man or formed from breakdown of wastes, and H_2 produced through electrolysis of water regenerated from the condensate of atmospheric moisture or urine. Physicochemical synthesis of sugars directly from the inorganic compounds CO_2 and H_2 (or H_2O) still has not been accomplished despite considerable work. Synthesis is the most promising method of carbohydrate production from the byproducts of human activities, through a series of intermediate reactions, in a continuous process.

A system was developed in which a reagent mixture, 1.5 M CH_2O solution and 0.15 M $Ca(OH)_2$ solution, was passed through a 5-meter spiral at 4 ml/min and 60° C. The mixture flowing out of the spiral was treated with CO_2, filtered, deionized and concentrated by evaporation under low pressure. This apparatus produced about 7.5 g/h of formose sugars [3]. Later improvements in the apparatus and reaction flow permitted increasing formose synthesis to 110 g/h. Basic flow patterns also were developed for physicochemical carbohydrate-monosaccharide production by stages [132]. The basic stages in these schemes are: (1) oxidation of human metabolic products to CO_2; (2) CH_2O production; and (3) condensation of CH_2O into sugar. The most promising schemes for production of monosaccharides [131] are:

1. $$\text{Wastes} \xrightarrow[1\ \text{atm};\ 350^\circ\ \text{C}]{O_2;\ MnO_2;\ CuO}$$

$$CO_2 \xrightarrow[180^\circ\text{–}200^\circ\ \text{C};\ 1\ \text{atm}]{H_2;\ Ni;\ Ru}$$

$$CH_4 \xrightarrow[700^\circ\ \text{C},\ 1\ \text{atm}]{NO;\ O_3}$$

$$CH_2O \xrightarrow[37^\circ\ \text{C};\ 1\ \text{atm}]{Ca(OH)_2} \text{monosaccharides}$$

2. $$\text{Wastes} \rightarrow CO_2 \xrightarrow[\text{or C at } 700^\circ\ \text{C}]{H_2,\ \text{electric discharge}} CO$$

$$\xrightarrow{H_2,\ \text{electric discharge}}$$

$$CH_2O \rightarrow \text{monosaccharides}$$

3. $$\text{Wastes} \rightarrow CO_2 \rightarrow CH_4 \xrightarrow[1\ \text{atm};\ 350^\circ\ \text{C}]{Cl_2;\ Cu_2Cl_2} CH_3Cl$$

$$\xrightarrow[1\ \text{atm};\ 350^\circ\ \text{C}]{Ca(OH)_2} CH_3OH \rightarrow \xrightarrow[1\ \text{atm};\ 700^\circ\ \text{C}]{Ag \cdot Cu}$$

$$CH_2O \rightarrow \text{monosaccharides}$$

4. $$\text{Wastes} \rightarrow CO_2 \xrightarrow[100\ \text{atm};\ 300^\circ\ \text{C}]{H_2,\ ZnO,\ Cr_2O_3}$$

$$CH_3OH \rightarrow CH_2O \rightarrow \text{monosaccharides}$$

Scheme 1 may be accomplished at atmospheric pressure, based on these chemical processes:

(a) oxidation of human metabolic products to produce CO_2;
(b) hydrogenation of the CO_2 to CH_4;
(c) oxidation of CH_4 to CH_2O;
(d) condensation of CH_2O to carbohydrates.

The first stage, oxidation, is accomplished by the oxidation-catalytic method [86, 134], the wet combustion method, or high-temperature oxidation. Obviously, the oxidation-catalytic method is most acceptable, since the oxidation process takes place under comparatively mild conditions: 1 atmosphere pressure at 350°–400° C. Two promising variants of the catalytic method have been proposed [85, 134]. The first is oxidation of the metabolic products supplied directly to the surface of a heterogeneous catalyst. The second method is based on preliminary pyrolysis with subsequent oxidation of volatile gaseous compounds. The CO_2 formed from oxidation of the wastes is easily hydrogenated to CH_4 at atmospheric pressure at 180°–200° C with a nickel or ruthenium catalyst.

Methane can be oxidized to CH_2O by various methods, one of which, already developed, is oxidation of CH_4 in the presence of nitrogen oxides, at atmospheric pressure and 700° C. Nitrogen oxides can be produced from the urea in human urine by its decomposition into NH_3 and CO_2 by urease or the thermal method at 105° C and a pressure of 1 atm. The ammonia formed is oxidized at 600° C, in the presence of catalysts, to nitrogen oxides [9, 147]. The optimum NO concentration in the mixture is 0.01% at a pressure of 1 atm and 680°–700° C [147]. Oxidation of NH_3 and CH_4 are exothermic processes and the heat given off during this reaction is usable.

Condensation of CH_2O into sugar is the greatest difficulty. Several studies have shown that the best catalyst of CH_2O into carbohydrates is $Ca(OH)_2$ [6, 85, 131]. The CH_2O-carbohydrate condensation reaction rate depends on the concentrations of catalyst, CH_2O, and organic cocatalyst; at the optimum ratio 1:2 of $Ca(OH)_2$ to CH_2O, the reaction is autocatalytic. The mixture produced by this scheme consists of various monosaccharide racemates. Chromatographic analysis has shown 10 or more monosaccharides in the mixture, predominantly pentoses and hexoses [147].

The most promising method of conversion, according to US authors, is CO_2 to CH_4 by reaction with H_2 (a byproduct of the atmospheric control system) and subsequent partial oxidation to CH_2O [124]. These methods are selected on the basis of (1) appropriate thermodynamic characteristics; (2) flow of the processes at low pressures; (3) capability of carrying out the reactions in a gaseous environment; and (4) the potential of removing the end product in the form of a precipitate. The first stage of the process, CO_2 reduction with H_2, is well-known and the reaction has been worked out. Partial oxidation of CH_4 is a reaction difficult to control [14, 15]; however, a study of catalysts has shown that gaseous nitrogen oxide in the presence of sodium tetraborate on a porcelain substrate insures better flow and control of the reaction [14, 15]. A cyclic regeneration system with two reactors has been built in which the first produces the CH_4 synthesis reaction, and the second the partial oxidation reaction. In this system, conversion of CO_2 to CH_2O is almost 100%, with very small energy expenditure, and the system can operate in the absence of gravity. The end product is an aqueous solution or a precipitate of paraformaldehyde.

Glycerol, Propylene Glycol, and Ethyl Alcohol

Glycerol occurs normally in food as a component of fats; propylene glycol is a component of food phospholipids, and ethyl alcohol (ethanol) is contained in certain foodstuffs in small amounts and in significant amounts in alcoholic drinks. The human body can metabolize these components in a manner similar to that of carbohydrates and can tolerate their use in considerable quantities. In the well-known research of Johnson and colleagues [68], it was shown that: (1) rats grew normally on a diet containing glycerol as 41% of the total food weight for 40 weeks; (2) harmful physiologic symptoms were not evident in rats and dogs during glycerol use; and (3) 15 human subjects consumed glycerol at the rate of 110 g/d for 50 d without unfavorable symptoms. Later investigations of glycerol as food for man indicated it to be a desirable source of carbohydrates for diabetics [38, 50]. Healthy and sick persons tolerate glycerol up to 300 g/d.

In connection with the use of regenerated products as a basic part of the diet, the maximum amounts of glycerol and triacetin that can be fed to rats without unfavorable effect on their growth was determined. The maximum glycerol and triacetin contents in the diets, at which animals exhibited good growth, were 40% and 30% respectively. With a diet containing 60% of either substance, the rats died in a few weeks. When the diet contained 40% glycerol and 30% triacetin, i.e., 70% of the diet, the rats were in good health [125]. This allowed the interesting conclusion that the metabolism of the two substances proceeded by different pathways. Propylene glycol in significant quantities is tolerated well by animals. However, rats showed degenerative changes in the liver when fed a diet containing 30% propylene glycol for a long period. These, as well as other unfavorable symptoms, were noticeably decreased or completely absent with a propylene glycol content of 20% or less in the diet [54].

Dogs given drinking water containing 5% propylene glycol for 9 months were in good health and gained weight; no pathologic changes were noted in liver or kidneys [153]. The mean daily intake of propylene glycol was 5.1 cm^3/kg body weight. In a human weighing 70 kg, this corresponds to a quantity of food with an energy value of over 2000 kcal/day. Propylene glycol is a normal component of the tissues of animals; its presence in the form of phosphate compounds has been demonstrated in the tissues of brain, liver, and kidneys [94].

The effects of ethanol and its metabolites on the body have been extensively studied; many changes in man under its influence have been recorded in studies on alcoholics or people using amounts of ethanol sufficient to cause an average degree of intoxication. At the same time, under specific conditions, ethanol can produce considerable energy without causing functional or physiologic disturbances. The metabolic rate of ethanol is 10–25 $mg/100\ ml\ blood \cdot h^{-1}$ [65]. For a man weighing 70 kg, an increase in ethanol content in the blood of 15 mg/100 ml blood can be expected after ingesting 7 g of alcohol. This ethanol level is not intoxicating; a man is capable of metabolizing 100–200 $mg/kg \cdot h^{-1}$ [65]. Consequently, for a man weighing 70 kg, the lower limit of ethanol intake which can be completely utilized is 7 g/h. In this manner, by restricting the rate and amount of ethanol intake to the parameters presented, the production of about 50 kcal/h can be insured without metabolic disturbance or undesirable pharmacologic effects.

Fats

Intensive studies on the synthesis of fats for food have been carried out in Germany for 30–40 years. Wittene began production of food fats in

1938. A waxy, high-polymer hydrocarbon was produced by the Fischer-Tropsch process [62, 63]. To produce fat, this substance was oxidized with oxygen of the air to fatty acids, thoroughly purified, and combined with glycerol. Margarine was produced by adding water, salts, aromatic substances, and vitamins [167]; 3 million kg of margarine were produced in 1943 and 1944 [167]. Most of the synthetic fat was used by the army because of increased stability resulting from no unsaturated fatty acids in its composition. Considerable quantities were used by the population and in hospital diets. No disturbances of digestion or other symptoms of illness were noted to develop from consumption of synthetic fat [167].

The achievements in petrochemistry and technology in recent years have been examined toward developing reliable processes of synthesis and storage of food fats aboard spacecraft [48, 49]. The Ziegler method was more promising than the Fischer-Tropsch method, it was concluded. The most feasible sequence of reactions is: (1) synthesis of ethylene from carbon monoxide; (2) polymerization of ethylene into olefins by the Ziegler method; (3) oxidative ozonolysis to monocarboxylic acid; and (4) condensation with glycerol to yield fats which have no branching chains, dicarboxylic acid, or polycyclic compounds. The energy consumption in this synthesis is low; however, the great complexity of automatic systems for carrying out the processes makes the advisability of developing this method further for space flight questionable [48, 49].

The difficulties in synthesis of long-chain fatty acids caused increased interest in possible use of the simplest compounds, with even numbers of carbon atoms in the chains, as foodstuffs. These substances are of the triglycerol and triacetin types. It is tempting to use simple chemical methods of synthesizing acetic acid from carbon monoxide or methane. Triacetin taken perorally is more rapidly absorbed in the small intestine than certain other triglycerides [35]. There is little information on the toxicity of triacetin in the diet. Rats given a diet with 55% triacetin grew half as fast as rats receiving lard [31]. However, when the rats were kept on a diet with a smaller quantity of triacetin, no delay in growth was observed [125].

Before food fats can be produced by synthesis from the wastes of metabolism and other sources, much research still has to be conducted; a diet containing full-value food fats must be created, and economical and acceptable technologic equipment must be developed for spacecraft.

Amino Acids

Protein structures are highly complicated and diverse; therefore, chemical synthesis of proteins for inclusion in food presents immeasureably greater difficulties than synthesis of carbohydrates or fats. Moreover, to insure balanced nutrition, the products must include a full selection of amino acids in specific combinations, whereas carbohydrate requirements can be satisfied by glucose alone.

Controlled synthesis of individual amino acids under spacecraft conditions is extremely difficult. The method of synthesis that permits production of usable complexes from mixtures of amino acids is more feasible. For this purpose, the method is promising of obtaining glycine, alanine, and aspartic acid by passing an electric discharge through a mixture of methane, ammonia, hydrogen, and water [102]. A broad spectrum of amino acids is detected in the reaction of an aqueous solution of ammonia saturated with methane, with quartz, or aluminum catalysts, heated to 900°–1000° C [56]. Under certain conditions, carbon dioxide can replace methane [2]. Of the amino acids which usually are included in the composition of proteins, only the sulfur-containing amino acids, histidine, and tryptophan, were not found in synthesis by this method. Interesting results also were obtained by heating formose sugars with urea; under these conditions, at least 10 different amino acids were formed [47].

Polymerization of mixtures of amino acids to form proteinlike products was also studied [118]; the food properties of some have already been investigated [46]. In tests on the bacterium *Lactobacillus plantarum*, which requires for growth a selection of amino acids close to human requirements, it was shown that growth of the bacteria on a medium containing a proteinlike product from thermal condensation of a mixture of amino acids was 60% of the growth on a peptone medium. In the diet of rats, replacing half the proteins with proteinlike products obtained by thermal condensation, in combination with threonine, did not change the important index of increase in body weight [28, 46].

The current status of research in food production by physicochemical methods shows that, despite its obvious importance not only for space flight, but also for inhabitants of Earth, the results of numerous theoretical investigations indicate at this time only possible pathways for solution of the problem rather than specific procedures for routine practice.

Food Production by Biologic Methods

Food can be produced during space flight by biologic methods based on a partial or completely closed matter cycle. There is a similar matter cycle on Earth. Such a system of food production utilizing the wastes of crewmembers' metabolism and the biocomplex of the spacecraft would be efficient only for prolonged flights, a year or more, or in long-lived planetary stations. Lower autotrophic organisms (one-celled algae), higher autotrophic plants, lower heterotrophic organisms (yeasts, bacteria, zooplankton), higher heterotrophic animals (small animals and birds), man, and a waste transformation system could serve as links in the matter cycle in a spacecraft [20, 138]. Various combinations of biological and physicochemical methods of food production using the products as supplies or as individual food substances also are possible.

Algae

Microscopic algae use light and carbon dioxide more efficiently than higher plants [17], and they are more resistant to extreme concentrations of components in the nutrient medium and to fluctuations in temperature and pressure [97, 129]. The majority of cultures studied for use as food sources are mixtures of various types of algae and bacteria [30, 107]. Young, actively dividing algae cells provide a high content of protein [104] and nucleic acids in the biomass [66]. As the cells age, they continue to accumulate starch, but they may store an excess of fats [103, 104, 105]. The ratio of fats, proteins, and carbohydrates in the cells depends on the quality of the medium and the culture conditions. Cells of *Chlorella*, cultured for 83 days under light in a medium deficient in nitrogen, contain 86% fats, 10% proteins, and 6% carbohydrates. This same alga, grown in a medium with a normal quantity of nitrogen, contained 4% fats, 53% proteins, and 38% carbohydrates [105, 140a]. There are many other quantitative and qualitative differences between algae biomasses. Algae cannot synthesize certain vitamins, such as B_{12}; and they contain little vitamin D or K. Although the amino acid content in several algae is comparable with animal protein, the quality of proteins is decreased because of the low content of sulfur-containing amino acids.

It was established in animal tests that the efficiency coefficient of algal proteins and their biologic value are lower than those of proteins of animal origin, but higher than those of most vegetable proteins [29, 60, 66, 75, 143, 151, 154]. In comparative tests on rats, the biologic value of the proteins in a mixture of algae reached 71%, compared with casein at 79% [39]. The assimilability of algal proteins was estimated at 69%, and of casein, 97%. If the cell membranes are treated by grinding, boiling, and extraction of the fat-soluble fractions, the assimilation of algal proteins increases, because certain amino acids in the membranes become available.

Efforts to introduce large quantities of algae into the human diet have met with variable success [24, 32, 58, 78, 79, 80, 120]. Several investigators concluded that the diet should not contain more than 20 g of algae for normal gastrointestinal tract function. It was shown that 50 g freeze-dried, boiled algae added to a mixed diet did not change protein, fat, or carbohydrate assimilation [77]; however, 100 g caused decreased assimilation of nearly all food substances [77, 78]. Plasma phospholipid [77, 78] and urine corticosteroid [78] content increased in persons eating green and bleached algae.

To enhance assimilation of nutritional substances from the algal biomass, it is necessary to grind the cell membranes, and remove the nucleic acids, chlorophyll, and other substances, including those still unidentified. These substances, the wastes of processing algae for food, should be returned to the bioregenerative system to prevent loss of carbohydrates and other elements [24].

Bacteria

Bacteria can grow autotrophically with carbon dioxide and nitrogen from urine and feces. Bacteria that show promise for space regeneration systems can bind these substances to hydrogen produced by hydrolysis of water. Bacteria utilizing methane could be connected with a chemical system for regeneration of oxygen. Systems using bacteria are attractive because of the relatively small energy requirements.

Bacterial cells contain large amounts of nitrogen during the rapid growth period: however, with a deficit of food components, they enter into a resting state and accumulate lipoid materials. Like algae and fungi, bacteria can store triglycerides and other lipids [33, 128]. The cell membranes of bacteria contain many substances not found in other organisms; the primary structural components usually are complex polymers of rarely encountered carbohydrates, muramic acid, hexosamines and D- and L-amino acids [108, 168]. Most bacteria contain more nitrogen than either algae or fungi in the growth phase of culture, 11%–14% of dry solids. The content of vitamins and inorganic substances in bacterial cells still has not been studied sufficiently. It is known that bacteria can manufacture most of the B-complex vitamins. Vitamins A, D, and E usually are absent, but certain species form vitamin K.

The data from numerous investigations on animals, with bacteria the major portion of the diet, are difficult to interpret, since the material studied frequently was a mixture of bacteria with other microorganisms, such as protozoa and fungi. The quality and assimilability of proteins in the biomass vary greatly and are frequently low. On the other hand, *Escherichia coli* supported the growth of rats and chicks to the same extent as fish meal [69]. Proteins from a washed culture of *E. coli* had assimilability of 81%–87% and approximately the same biologic value (61%–70%) as legumes [69]. In tests on rats, both boiled and ultrasonically disrupted cells of *Hydrogenomonas eutrophae* had proteins equal to casein in biologic value and nearly equal in assimilability [23], while the fats of these bacteria were poorly assimilated. Rats fed acetone-extracted cells of *E. coli* and *H. eutrophae,* in amounts of 11% and 17% of the diet, showed the same growth as those fed an equal amount of casein. However, if the bacteria content in the diet was increased to 72%, the growth of rats was retarded compared with those fed casein. Moreover, the high protein and mineral salt content in the bacteria diet led to an increased water requirement and an increased urine production [126].

Higher Plants

Certain plants, such as sweet potatoes, Chinese cabbage, radish, tampala, and duckweed (family Lemnaceae), with many broad and thin leaves can absorb nutrients and use solar energy more efficiently and therefore, can grow faster than others, such as corn and wheat. Moreover, man is habituated to these plants. These factors have led investigators to recommend precisely these plants for use in space systems.

The leaves of these plants are rich in assimilable food matter, trace elements, carotene, ascorbic acid, calcium, and iron; however, in some plants the inorganic substances are insoluble or poorly assimilable compounds. The leaves also contain other vitamins, inorganic substances, fatty acids, and 30%–40% (of dry weight) protein. However, the large water (90%) and fiber content (20%–30% of dry weight) restrict the amount of fresh leaves that can be eaten by nonruminant animals. Analysis of the biologic value of leaf proteins revealed a methionine deficit; therefore, methionine must be added to improve the protein portion in the rations of experimental animals [112]. Protein from leaf protein concentrate was assimilated better than that from green leaves, but it can vary in different types of plants [8, 112], with methods of processing of the plants, and the size of the stalk mass.

Green-leaved plants are a part of the normal diet of man, but they are rarely eaten in quantities greater than 10–30 g dry weight per day. It has been found that concentrated vegetable protein can replace 50%–74% of milk protein in the diet of children; in this case, the protein deficiency showed up only as a small decrease in absorption and retention of nitrogen [162]. If leaves are to serve as a basic source of astronaut food, the weight, volume, and energy capacity of the bioregenerative system must be increased considerably to provide for preparation of leaf protein concentrates and disposal of large fecal masses, which also entails considerable losses in carbon with the residues. At the same time, hydroponic plant culture in large space stations is considered to be a desirable source of food supply [26].

Fungi

Fungi cannot grow in human waste because they require reduced forms of carbon for growth and development; however, fungi can be part of a system based on higher plants, algae, or bacteria. Fungi can be useful in a bioregenerative system for converting the fibers of higher plants and cell membranes of algae and bacteria into more available forms of food.

Fungi contain different amounts of fat, from 1% to more than 50% of dry weight of the mass, but the percentage varies with the nitrogen content and mineral composition of the medium [100, 127]. Young fungi cultures contain few unassimilable substances and many free amino acids and nucleic acids (from 8% to 14% [142]). Fungi are a good source of vitamins of the B complex, but contain little ascorbic acid or vitamins A, E, and K. Assimilability of fungi varies to a considerable extent, from 44% to 90% [52, 53, 57, 83].

In tests on rats, the biologic value of *Saccharomyces* proteins was 60%–90% [52, 53, 83]. Several fungi contain proteins of low quality: the content of sulfur-containing amino acids (methionine) is limited. Man assimilates about 80%–90% of the proteins of yeast, 94% of the fat, and 99% of the carbohydrates, if the yeast content in the diet is low [161]. The biologic value of *Torula* proteins is 52%, and of *Saccharomyces*, 71% [4, 16]. To insure a positive nitrogen equilibrium, man must receive 8–9 g nitrogen daily (55 g protein) if nourished with the yeast *Torula utilis* [161]. Such a large quantity of yeast (about 100 g dry weight) causes considerable increase in the uric acid content in the blood plasma and urine [161].

Man can digest from 72% to 82% of the proteins in a diet in which *Agaricus campestris, Boletus edulus*, or *Cantharellis cibarus* serve as the sole protein source; 43–62 g protein was required daily for maintenance of the nitrogen equilibrium. No abnormalities were noted in the subjects [95]. The main problem in creating a yeast bioregeneration system is removal of the nucleic acids.

Organisms which can convert human wastes into food biomass theoretically can solve simultaneously the problems of regeneration of the atmosphere in the cabin and removal of wastes. Autotrophic algae and bacteria are considered the most suitable organisms for a total bioregeneration system, in terms of the weight and volume of necessary equipment [140]. Many fungi, heterotrophic algae, and bacteria could be used in a multicomponent system including autotrophic organisms [30] and chemical methods of carbohydrate synthesis [55, 67, 101]. Higher plants can be grown hydroponically in large orbital and planetary stations [13, 76], and animals requiring plant food can serve as an additional link in bioregeneration [1, 24].

If a biomass produced by regeneration of the atmosphere and wastes is to constitute a major portion of the diet, precise and efficient relationships between the food needs of the crew and the elements of the bioregenerative system must be determined. Man needs at least 7 or 8 g nitrogen in food daily; he can tolerate a nitrogen load of up to 48 g/d. About 250–300 g carbon are required daily for energy processes. An acceptable C:N ratio is between 6:1 and 35:1 and should be 15–20:1 in the daily diet; therefore, algae are more suitable than bacteria, in which the C:N ratio is too high. Leafy plants have a C:N ratio much closer to that necessary for man.

The problem of creating an efficient total cycle with microorganisms also is complicated by the fact that certain end products of human metabolism cannot be sufficiently assimilated by them, and a number of microorganisms do not use them at all. For example, not one of the nine species of single-cell algae studied could use creatinine, and five were not able to break down uric acid, i.e., the nitrogen-containing compounds present in the urine [10, 71]. In other experiments it was determined that, in a 17-day stay in space, a system with algae recovers only 50% of the nitrogen [97]. There are other difficulties as well in creating a complete cycle by biologic methods; for example, discharges flowing out of the activating waste reactor, diluted in a 1:2 proportion, were lethal for various higher plants [13].

On the other hand, many microorganisms produce substances which are not used by man, and sometimes not even by the organisms themselves. Extracellular polysaccharides have been found in the media of algae, but only a few algae use these compounds. Polysaccharides of another type, which are part of the capsular coatings of the cells, are not digested by enzymes of animal origin, which leads to losses of carbon in the production of food [113]. Certain bacteria accumulate indigestible intracellular polymerized lipids [159]. Higher plants can have inedible roots and stalks but edible leaves, tubers, and seeds containing carbohydrates of varying assimilability, such as cellulose, hemicellulose, pectin, and lignin. Animal organisms can remove combined food components from the system, including eggshells, scales, feathers, and bones. Moreover, it was shown in a number of investigations that losses of food components from the matter cycle occurred because of unassimilable portions of the biomass. In this case, unassimilable residues facilitated removal of other food substances from the body. Thus, in a man receiving 120 g of algae daily, a decrease in calcium and magnesium assimilation and a large negative balance in these elements were found during the 30 days of the test [117], although the blood content of these macroelements remained normal.

The biomass also can contain pharmacologically active or toxic substances, the type and amount of which can vary according to biomass culture conditions. Thus, all microorganisms used for the bioregenerative system contain large amounts of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). The end product of metabolism of the purine bases of these acids in the human body is uric acid, which dissolves poorly at physiologic pH values and tends to crystallize in the joints and urinary tracts. Intake of 2-4 g of RNA per day leads to an increase of uric acid above the normal level in blood plasma and urine [34, 161]. An astronaut must treat the products of fresh biomass carefully and consume them in small quantities, since the microorganisms normally contain from 4% to 12% nucleic acids, and leaves contain 1%-2% (of the dry weight). Another danger is nitrates; their concentration in the biomass depends on the sources of nitrogen in the substrate and the activity of human intestinal bacteria, which reduce nitrates to nitrites [116, 130].

Pathophysiologic reactions have been noted in the use of microorganism biomasses as food by man. Doses even less than 12 g of dry bacterial mass of *H. eutrophae* and *Aerobacter aerogenes* caused vomiting and diarrhea in healthy men [160]. Two men, who each received 150 g dry green algae per day, developed face and arm edema, petechial hemorrhages, cyanosis of the nail beds, and, later, peeling of arm skin, and itching, pain, and edema of the big toes [79]. The use of yeast as food caused painless peeling of skin of the palms and soles of the feet in 12 of 50 young men who received from 45 to 135 g yeast per day for 3-4 weeks [146].

The food value of edible products produced in a bioregenerative system has been detailed by Carol I. Waslien in an unpublished review of the literature from 1917 to 1968 [158]. Bioregenerative systems for producing food should be supplemented in a spacecraft by a system for processing nutritional plants. Data on the edibility of a biomass and processes necessary for its treatment are in Table 9.

Any of the bioregenerative systems proposed should be capable, above all, of providing sufficient protein to meet human requirements. The proteins must be purified of unnecessary cell components. Undigested components removed in purification should be returned to the system for maintenance of its equilibrium. It is advisable to use the higher plants as an adjunct of the diet, but not as a dominant part of it. There has been progress in solving the problem of bioregeneration of food, which even now, with appropriate technical equipment could at least partially provide crews with food products through bioregeneration of metabolic wastes. The completely closed matter cycle based on bioregeneration is a problem for the future.

PROVISION OF WATER SUPPLIES

Potable water for the astronauts can be supplied, depending on flight duration and spacecraft system technical equipment, from various sources: (1) from stores of potable water brought from Earth or taken to the spacecraft by special shuttle; (2) from stored water during some periods of flight and regenerated water during the major portion of the flight; and (3) by means of water regeneration from astronaut metabolic wastes, as well as wastes produced in links of a closed ecological system, or as a result of technical processes taking place in various spacecraft systems. During the comparatively short flights so far, preference has been for water supply systems based on reserves of potable water from Earth. However, in working out problems of astronaut water supply on prolonged flights, many investigators have concluded that it is advisable to create systems based on the principles of regenerating water from various wastes during flights lasting more than 20 days [12, 51, 133, 156].

Water Supply Systems Based on Reserves

For each type of water supply there are specific criteria, which are complicated by spacecraft design and nature of the flight. However, certain requirements are common to the majority of water supply systems in flight.

First, the system must meet the physiologic need for regular intake of water by the astronauts in amounts adequate to prevent dehydration in flight. Water occupies first place by weight in the material balance of the body, and its daily weight consumption exceeds the total consumption of oxygen and food substances. The physiologic importance of water and water supply standards under various conditions of human metabolism were discussed in detail in Part 1, Chapter 1 of this volume. Under spaceflight conditions, accurate water consumption standards (i.e., determination of the quantities of water necessary for astronauts) are of increasing importance, since weightlessness, acceleration, reduced barometric pressure, hypodynamia, and the unusual conditions of heat exchange and specific nutrition can cause definite changes in the water metabolism of the body [5, 11, 119].

Thus, on the Vostok and Voskhod spacecraft, when sufficient experience had not been gained in providing for prolonged space flights, reserves of potable water were established that allowed the highest possible water consumption standards for the flight conditions. Subsequently, after study of the water balance in the test subjects during ground simulation of flight conditions, and on the basis of experience with water supply to the crews of the Vostok, Voskhod, and Soyuz spacecraft, several authors concluded that a water consumption standard of 2.2 l potable water/man $\cdot$ d^{-1} meets the requirements of the astronauts for water, under normal microclimatic conditions in the cabin and energy expenditures of about 2700 kcal/d [11, 170]. However, after more thorough investigations in this field, a higher water consumption standard of 2.5 l/man $\cdot$ d^{-1} was recommended [106, 133, 170]. Along with other factors, the water content of food products and the form of the products in the food ration also have a definite effect on the amount of potable water that must be supplied daily by the water supply system.

During flights in the Soyuz spacecraft, the cosmonauts were provided with 1.6 l/man $\cdot$ d^{-1} of drinking water; in addition, the cosmonauts should have received up to 0.95 l/d with food, and 0.35 l/d from the metabolic water from oxidized food substances. Thus, the total water consumption was planned to be about 2.9 l/man $\cdot$ d^{-1}. Actually, water consumption was somewhat less, since thirst was reduced [21]. The change to a broad assortment of dehydrated products requiring reconstitution should be accompanied by increased consumption of cold and hot drinking water. If the food includes dehydrated products, the amount of drinking water consumed per day will almost correspond to the daily water consumption standard.

A second important requirement for all types of astronaut water supply systems is the provision of good quality drinking water, with high organoleptic qualities, free of toxic impurities and, if necessary, enriched with minerals to optimum level. A number of studies in the USSR led to the decision that drinking water in systems based on reserves and the regeneration principle must satisfy the specific sanitary-hygenic requirements established for potable tap water by GOST[2] 2761–57 and 2874–54.

To supply astronauts with water on short flights, these problems were solved first:

- development of water supply systems to operate under conditions of weightlessness (storage, supply, and intake of water);
- selection of materials permissible for contact with drinking water and safe for use in the spacecraft cabin;
- determination of the daily water consumption standards;
- selection of a reliable preservative to retain the quality of the water;
- selection of initial sources of sanitary water with satisfactory organoleptic qualities [137].

Water supply system design and materials must withstand all technical parameters of the space flight.

The water supply system on Vostok and Voskhod spacecraft included a rigid metal container, an elastic container for water storage, a water supply line, and a water intake device equipped with a mouthpiece for intake, a cartridge for disinfecting and deodorizing the water, and a water cutoff device [135, 137]. Water was sucked into the mouth through the mouthpiece. The discharge thereby created in the mouth was sufficient for abundant water intake from the water supply system [137]. On the first flights, the cosmonauts determined that there was no difficulty with this system under weightless conditions [135, 137].

During Mercury spacecraft flights, water was stored in a special tank and supplied as needed under a pressure head created by squeezing the air bulb of a sphygmomanometer. Gemini and Apollo spacecraft were equipped with a device which supplied the astronauts with water for both drinking and food rehydration. The device was equipped with a mouthpiece adaptable for water intake with the visor of the spacesuit helmet open or closed.

The working out of water distribution has been given much attention. The first water distributor designs, in Gemini 3–5 spacecraft, did not provide for measurement of water volume. A little training was sufficient for accurately measuring out up to 150 ml. The first flights

TABLE 9.—*Potential Use of Regenerative System Biomass (adapted from* [140])

Usage	Leaves	Algae	Bacteria
Maximum quantity of raw product which can be used for short periods (g/man · d^{-1})	100	100	
Protein yield (g, approximate)	25–30	40–60	
Energy cost (kcal)	260	280	
Factors limiting use	Fibers and various substances (oxalates, nitrates, thiocyanates)	Alcohol-soluble factor: nucleic acids; unassimilable carbohydrates	Toxins, nucleic acids, other substances
Established requirements for improvement of food acceptability	Hydrolysis of "fibers"; solvent extraction; removal of nucleic acids; other extractions	Hydrolysis of carbohydrates; solvent extraction; removal of nucleic acids	Removal of toxins and nucleic acids; other?
Maximum use after all improvement processes:			
Proteins (g)	185	300	300
Energy (kcal)	2800	2200	1360
Economy of food preserved by use of raw biomass products	135	kg (6 men) 500 d 150	
Economy of food preserved by use of all processed biomass products	1500	1170	720

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[2] GOST – All-Union State Standard.

were so short that measurement of the water drunk and its total consumption were only of relative interest. During the 14-day flight of Gemini 7, which included medical research on metabolism, more precise measurement of the volume of water drunk was needed. There was special interest in clarifying the interrelation between the water balance, blood volume, and orthostatic stability.

A device for measuring 15-ml water portions was introduced into the design of the original water distributor. Astronaut Borman devised a log sheet for recording readings of a counter. The same water measurement mechanism was connected to the line supplying water for drinking to the area of the Apollo command module seats. The command module also had a meter installed near its storage place for hot and cold water for food reconstitution. This device, which measured water volume in 30-ml portions, did not have a recording device. The water distributor in the lunar module did not have a device for measuring water and was reminiscent in design of the system used in the first Gemini.

The water storage container on the Gemini spacecraft, with a capacity of 7272 ml, was located inside the cabin between the seats. When the container was emptied, it was refilled from the reserve water stored in the adapter section connecting with the spacecraft. However, the adapter section was separated from the spacecraft before reentry; therefore, after landing, only the water from the container installed in the cabin could be used.

A byproduct of the chemical reaction in the fuel cells (hydrogen fuel and oxygen oxidizer) is water, which could be used for astronaut water supply. In Gemini flights, since the water from the fuel cells (produced after combustion of the fuel), was not suitable for drinking, water reserves were established aboard the spacecraft. The daily water consumption standard amounted to 3000 ml per man. Water formed in fuel cells that was considered suitable for drinking was used in the Apollo spacecraft. The need for using water reserves stored in the cabin arose only after reentry or under unforeseen circumstances. The astronaut water supply in the lunar module was obtained from stored reserves. This same water was used for recharging the portable life-support system used by the astronauts during landing on the surface of the Moon. Parts and units of this water supply system were made and assembled in clean rooms, but not under sterile conditions.

In the Gemini program, standard procedures for washing and disinfection of the water supply system were with solutions of ammonia mixtures, and continued until plate counts met USPHS drinking water standards, and until pathogenic or potentially pathogenic forms (fecal coliforms) were completely absent. The systems sometimes had to be treated also with other substances, in particular, chlorine, to reduce bacterial contamination to a permissible level in samples of the water and dispenser. Contamination of water stored aboard the spacecraft increased continually and substantially as indicated by analysis of samples taken at the end of a flight. In 1968, NASA issued instructions on water suitability. The definition of "acceptable water" for spacecraft supply systems needs further refinement. Even if completely sterile water is supplied to the spacecraft, there is no guarantee that it will retain its sterility in the water supply system.

In designing water supply systems based on water stores, much attention is given to development of reliable storage methods to supply the astronauts with good quality water with high organoleptic properties during the entire flight. This problem is solved, on the one hand, by an appropriate choice of materials for manufacturing both containers and other parts of the water supply system in contact with the water and, on the other, by measures for preliminary treatment of the water and reliably preserving it. Reliable sterilization of tap water under terrestrial conditions presents no great difficulty; the preservation of sterilized water in a spacecraft is considerably more complicated. Studies of physical, biological, and chemical means of preservation of drinking water resulted in Soviet investigators settling on complex silver preparations [81, 137]. This method was used in the water supply systems of Vostok and Voskhod spacecraft. The water was disinfected by boiling before preservation [135].

The organoleptic properties of the water during Vostok 3 and Vostok 4 flights were evaluated as outstanding by the cosmonauts [136]. The storage stability of preserved water was determined from data of physicochemical and sanitary-bacteriologic research. For this purpose, determination was made of the water's organoleptic properties, active reactions, transparency, color index, alkalinity, hardness, oxidizability, ammonia nitrogen, nitrite nitrogen, calcium, magnesium, iron, sulfates, fluorine, and iodine. In addition to solutions of silver salts, an electrolytic method of introducing silver ions into the water is promising for preserving the water supplies for spacecraft [82, 106].

Pure natural water with a low content of organic substances and salts can be stored in a glass-and-polyethylene container and kept in good condition for up to 6 months with silver introduced by the electrolytic method, at concentrations of 0.1, 0.2, and 0.4 mg/l, with silver nitrate at concentrations of 1.5 and 2.0 mg/l, as well as by the preparation Kumanzin[3] in concentrations of 50.0 and 100 mg/l. The dynamics of the physical properties and chemical characteristics of water under these conditions of treatment and storage were independent of the silver treatment method. The recommended doses of silver had a good bactericidal effect and proved nontoxic [169]. Spaceflight experience in the USSR and USA with water reserves used in the water supply system confirms that drinking water has been reliably stored, at least for short- and medium-duration flights.

Water Regeneration in Flight

Effective water supply systems based on regeneration involve several completely new problems in which technological and medical problems are tightly intertwined. These problems are due to both the peculiarities of the technology of various methods of water regeneration and the peculiarities of water sources: water vapors in the atmosphere of manned cabins, urine, wash and other moisture-containing wastes. The water regeneration methods in spacecraft can be arbitrarily divided into two groups. In the first group are the methods for regenerating water from wastes with minimum expenditures of energy. Such methods as sorption, filtration, coagulation, water purification by semipermeable membranes and others require practically no expenditure of energy. However, energy consumption is inescapable for such auxiliary devices as pumps and blowers. Only liquids containing relatively small amounts of impurities can be purified by these methods, such as atmospheric moisture condensate (AMC) and liquid produced by electrochemical generators (ECG).

In the composition of the spacecraft AMC, various substances can be included in addition to components from discharges by the human body, which are products of the functioning of complicated technical systems of the spacecraft and of destruction of diverse materials used in the spacecraft. Besides nitrogen-containing products of human metabolism, a broad spectrum of chemical compounds including aldehydes, ketones, alcohols, esters, organic acids, and others have been separated from spacecraft AMC. Many such organic substances are among the toxic compounds that act strongly on an animal body. Therefore, a basic requirement for AMC purification is sufficient reliability in producing safe drinking water [7].

The ability of cations and anions to adsorb nitrogen-containing compounds and organic acids, which is well-known, suggested the possibility of adsorption of organic compounds in the AMC by ion exchange resins. Numerous studies determined that treatment of AMC by passing it through ion exchange resins and activated charcoal insured adsorption of practically all impurities. With an appropriate selection of sorbents, a mixture can be created which insures purification of AMC to the quality of drinking water [7]. Therefore, those methods of water regeneration requiring minimum energy expenditures are the most promising for primary use during the transition from portable water stores to the systems in spacecraft based on water regeneration.

An increase in flight duration necessitates as nearly as possible total recycling of water in spacecraft. For this purpose, in addition to water regenerated from dilute solutions, such as AMC

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[3] Kumanzin is a patent drug of the German Democratic Republic; its formula was not found in the available literature.

or that formed from the operation of on-board technical systems, devices must be created for repeated use of water from such highly concentrated solutions as human urine and washwater wastes. Both these types of moisture-containing wastes of the metabolic activities and existence of the astronauts will accumulate in considerable quantities on long flights. Water is one of the basic substances required by man and, simultaneously, one of the main products of the metabolic activities of the body. Recycling of water from urine would supply about 50% of the total drinking water requirement of the astronauts.

The creation of systems for regenerating water from high molecular weight solutions requires a second group of methods. One of the most promising is freeze-drying. This method of molecular drying is attracting attention because it could provide water purification by using the vacuum and cold of space without significant expenditures of heat energy from the resources of the spacecraft systems. Studies have been carried out on regeneration of water by freeze-drying from a series of moisture-containing human and biocomplex products, urine, wash water, feces, *Chlorella* reactor effluent, and others. These studies indicated the possibility of efficient removal of water from these products [106]. Therefore, the freeze-drying method is promising both for use in a water supply system based on reprocessing human metabolic and activity wastes and for inclusion in the complicated machinery for operation of an on-board bioregenerative system of food production with plants on long flights. This method may be useful as well for providing water to plants and for mineralization of wastes, with the purpose of producing nutrient media for them.

The vacuum distillation method has been proposed also for regenerating water from urine. However, this method, like the freeze-drying method, while providing water purification of the overwhelming majority of impurities, nevertheless does not bring it to a condition that meets the current GOST requirements for drinking water. The necessity arises for developing an additional system of prepurification of water to remove its remaining organic impurities. The adsorptive properties of a number of ion exchange resins and activated charcoal could accomplish this. The sorbents have now been chosen which provide maximum prepurification of water from organic impurities, ammonium nitrates, and nitrites, as well as other components remaining in the water after vacuum distillation of urine.

The possibility of using the oxidative-catalytic method of regeneration of water from moisture-containing wastes also has been studied. The basis of this method is oxidation of all volatile organic and inorganic compounds that are toxic or biologically active, as well as malodorous, to the simplest oxides or elements. This process requires specific catalysts and high temperatures. A number of authors have used hopcalite as the catalyst, which includes manganese and copper oxides [12, 25].

Several investigators have developed and experimentally tested the basic scheme of a unit based on thermocatalytic oxidation for regeneration of water from moisture-containing wastes [25]. The most effective water purification was achieved by using as catalysts hopcalite, palladium, chromium oxides, and nickel oxides. Hopcalite is preferred, because nickel or chromium can enter the water in quantities harmful for man.

Investigation of temperature conditions in a catalytic furnace led a number of authors to recommend a catalyst temperature of 150° C, which insures mineralization of organic impurities with a relative minimum of energy expenditure. Below 100° C, the degree of oxidation of the organic substances is lower, and above 300° C the process of mineralization of the organic compounds also is less effective because of irregularities in the process itself. Impurities of inorganic origin remaining in the regenerated product can be completely removed by subsequent passage through appropriate sorbents [12, 25]. The positive aspect of this method is that stable organic impurities in the wastes can be oxidized to the simplest compounds and substances such as CO_2, N_2, H_2O, which are easily adsorbed. The catalytic regeneration methods apparently can remove practically any organic impurities from water by their oxidation. Thus, catalytic regeneration is considered one of the most reliable methods of recovering water from urine.

A year-long experiment carried out in the

USSR,[4] during which recycled water from urine was provided for three test subjects by a unit based on the catalytic method, confirmed the reliability of this method of water regeneration from such complex products of human metabolic activity as urine. Unquestionably, the prospects for the use of this method of water regeneration are closely linked to the spacecraft energy resources, since the catalytic method, like freeze-drying and distillation, requires definite expenditures of energy.

In analyzing the prospective use of methods of both groups on long flights, it is assumed that methods of the first group, which do not require large energy expenditures, would be used for regeneration of water from low-concentration liquids in combination with methods of the second group for purification of liquids with a high content of impurities.

The problem of water regeneration in flight also involves conditioning the taste, chemical, and bacteriological characteristics of the regenerated water before it is used for drinking or reconstituting dehydrated foods. However, up to the present there have been no definitive water standards which are actually used in the evaluation of the end products of water regeneration systems, and investigators are occupied with establishing and testing them.

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[4] Refer to Part 2, Chapter 9 of this volume, "Life-Support Systems for Interplanetary Spacecraft and Space Stations for Long-Term Use."

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Chapter 3

AIR REGENERATING AND CONDITIONING[1]

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The selection of a specific system for insuring physiologic well-being of spacecrews in hermetically sealed cabins is determined by the habitation duration. For short-term space flights in both the USSR and in the US, the cabin atmosphere systems were constructed of basic materials which insure air-conditioning and regeneration in flight. Such systems are characterized by an increase in weight and volume directly proportional to the flight duration.

For long flights, it is expedient to make maximum use of the materials eliminated in human life processes. Carbon dioxide and water, the basic oxygen-containing materials eliminated by man, contain approximately 3.5 times the oxygen needed for respiration. The CO_2 eliminated by man in a day contains approximately 650 g oxygen, about 82% of the respiratory requirement. If a water recirculation system is also available, then the additional oxygen required for respiration, approximately 150 g, could be obtained from metabolic water eliminated by a man in a day—approximately 336 g. Systems for obtaining O_2 from CO_2 and H_2O can insure practically complete oxygen circulation (Fig. 1).

The problem may be solved at present by the physicochemical method of regeneration in air-conditioning. A schematic structure of such a system with the basic tasks it accomplishes is shown in Figure 2. The novelty and complexity of this technical problem require comprehensive analyses of possible solutions and use of technologic processes for conditions significantly different from those on Earth.

Various physicochemical means and methods of regenerating and conditioning air for spacecraft are described in this chapter. Flight duration and other conditions affect the efficiency of the system. In this regard, it was considered necessary to give complete descriptions of various air-regeneration methods, with a sufficient number for specific selection.

Various life-support systems intended for use in closed, hermetically sealed environments, (for example, in spacecraft) will be discussed in some detail, with numerous references to actual application in the Soviet Soyuz and Voskhod manned spacecraft.

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[1] Translation of: Regeneratisya i konditsirionirovaniye vozdukha, Volume III, Part 1, Chapter 3, of *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*), 145 pages. Moscow, Academy of Sciences USSR, 1972.

Sincere appreciation is expressed to Dr. W. L. Jones, NASA, for his clear presentations of materials on this problem, which, to a significant degree, allow a more objective statement of the problem's basic aspects. Dr. Jones' assistance also made it possible to present the level and quantity of work in this area carried out in the US [2, 4, 10, 11, 16, 23, 27, 34, 35, 44, 50, 56, 62, 64, 80, 99, 101, 112, 117, 118, 119, 120, 121, 122, 132].

AIR-CONDITIONING FOR TEMPERATURE AND HUMIDITY IN A HERMETICALLY SEALED ENVIRONMENT

Methods of Thermal Regulation

The atmospheric temperature of a hermetically sealed spacecraft cabin is determined by the thermal capacity of the gases making up the atmosphere and the temperature difference between thermal currents flowing into and out of the cabin.

Each crewmember contributes an average 100–150 kcal/h. Part of the heat is transmitted to the cabin air by convection, and part by conduction from equipment in contact with the crewmember. Electrical and radio equipment also emit heat during operation. Practically all electrical energy required by spacecraft equipment in-flight is converted into heat, since the wave-radiation power of radio equipment usually comprises only a small portion of the power required by these devices.

The outer sheathing of spacecraft in-flight absorbs several thermal currents: direct solar radiation, solar radiation reflected by the Earth, and infrared radiation from the Earth. The heat flux from solar radiation strikes the spacecraft sheathing and heats it during flight over the Earth's surface which is illuminated by the Sun. The specific heat flux of direct solar radiation at an altitude greater than 100 km is 1200 kcal/h · m^2; the specific heat flux reflected by the Earth and made up of solar radiation at the same altitude is 400 kcal/h·m^2. The specific heat flux from Earth infrared radiation at an altitude of approximately 100 km is about six times less than the heat flux from direct solar radiation. The heat flux of infrared radiation from Earth enters the cabin during flight over both the illuminated and the dark portions of the Earth. Only a slight change occurs, determined by the temperature of the Earth's surface beneath the spacecraft [83, 122].

The thermal balance of the spacecraft in the established state may be represented as

$$G_{he} = G_c + G_{eo} + G_{ei} + G_{ob} \qquad (1)$$

where G_{he} is the heat emitted by the spacecraft into the surrounding atmosphere; G_c, heat from solar radiation; G_{eo}, heat reflected from Earth; G_{ei}, heat radiated from Earth; and G_{ob}, heat given off by the crew and equipment inside the spacecraft.

The gas atmosphere temperature regulatory system of the hermetically sealed cabin must be capable of removing thermal currents into surrounding space. Removal of heat from the spacecraft cabin may be by:

1. Use of latent heat of fluid evaporation or sublimation of solid coolants during removal of formed vapors into space;
2. Removing heat to space through special radiating heat exchangers [122].

The first method involves loss of a significant mass of coolant and may not be used during relatively long flights.

Direct cooling of the air by blowing it through radiating heat exchangers which vent into space has several significant shortcomings:

danger of air loss into space due to leaks in the exhaust air ducts;

probability of cabin decompression from puncture of heat exchanger surface by a meteor;

large surface area of heat exchanger as the result of small values of coefficients of heat emission from air to wall;

possibility of freezing moisture and ice clogging the convecting ducts.

A system with an intermediate heat carrier is more practical, which may undergo phase conversions (fluid gas) or remain fluid. A schematic with fluid intermediate heat carrier in Figure 3 shows that cabin air is blown by ventilator "1" through air-fluid heat exchanger "2," installed in the cabin. A pump passes fluid (heated during air-cooling) to the external radiating heat exchanger "6" for cooling. The system for maintaining necessary atmospheric temperature in the hermetically sealed cabin was built according to this principle for the Vostok spacecraft.

The system for automatically maintaining the assigned temperature regime in the Vostok spacecraft consists of two circuits: the internal and the external. Air temperature in the Vostok cabin is regulated by a change in the quantity of air entering the air-fluid heat exchanger for cooling by means of increasing and decreasing the area of contact of the air with the cooling surface of the heat exchanger. Accuracy of temperature maintenance by the regulator is ±1.5° C [107]. The effectiveness of the regulator, basically, is determined by the temperature drop between cabin air and the coolant. The greater this drop, the greater the effect of regulation; that is, the amplitude of fluctuation between the extreme values of the cabin air temperature will be less [33, 49, 55, 66, 73, 99, 107, 111, 123].

Air Humidity Conditioning

Assigned air humidity and temperature in the hermetically sealed spacecraft cabin must be maintained for normal activity of the crew and for normal functioning of spacecraft apparatus.

Air in the hermetically sealed cabin is humidified by the presence of a living organism (man) who constantly eliminates various gas and fluid substances, including water vapor, into the surrounding space. The quantity of moisture eliminated by a human is determined by the frequency and depth of respiration, the temperature regulating mechanism under physical stress, and food rations.

With the food rations used at present, a man eliminates in 1 day through lungs and skin, approximately 1100 g water (46 g/h); with urine, 1200 g; and with feces, 200 g. With use of the sanitation system, up to 5% of the moisture in the urine and feces may enter the cabin atmosphere, and up to 2% of the moisture from inaccurate use of water supply systems.

The separate parts of the gas atmosphere regeneration system may be sources of atmospheric humidity. Thus, where lithium hydroxide (LiOH) is used for removing the carbon dioxide, the chemical reaction yields water

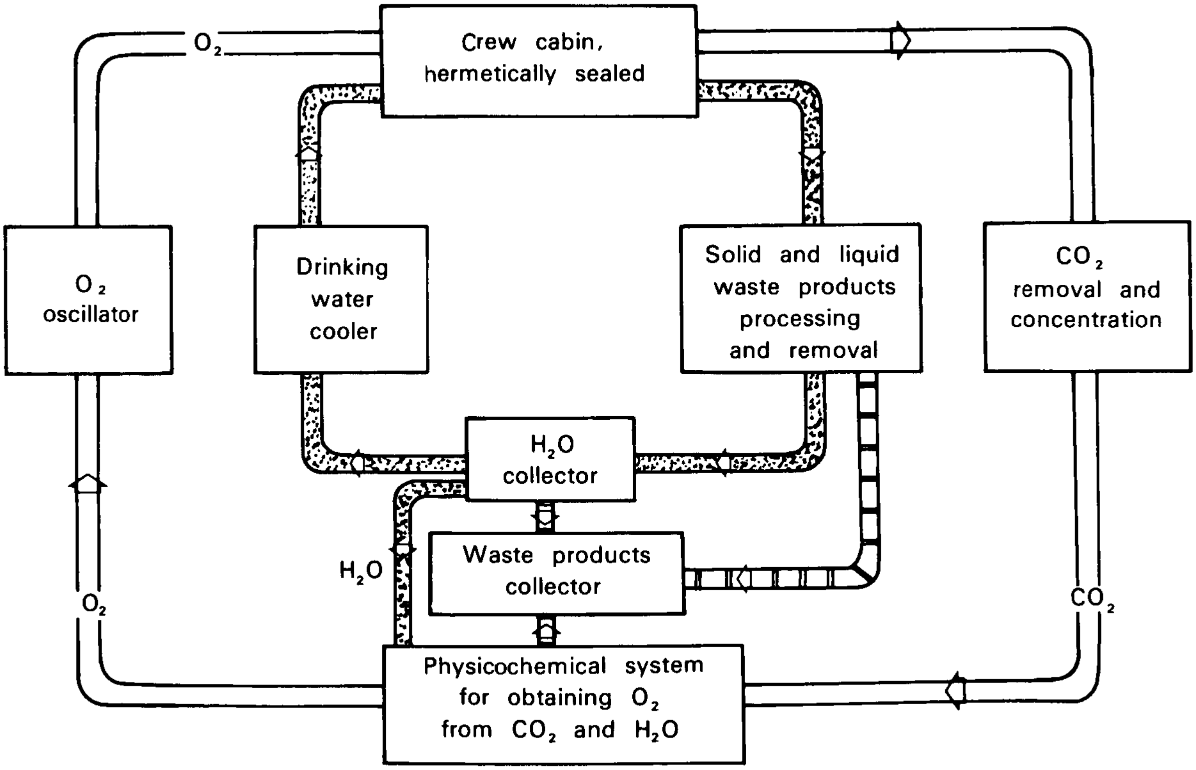

FIGURE 1.—Schematic of a partially closed physicochemical system for air regeneration.

$$2LiOH + CO_2 = Li_2CO_3 + H_2O \qquad (2)$$

With the removal of 25 l/h CO_2, nearly 20 g/h H_2O will be liberated. Part of the water is bound to the absorbent (LiOH), while part of it enters the atmosphere of the hermetically sealed cabin with the air current.

The oxygen supply system may also be a source of water. A measurable amount of water is liberated during decomposition of water in systems involving electrolysis of alkali and saline solutions, and during use of electrolytic devices which form oxygen and hydrogen from water. If the productivity of the electrolyzer is accepted as equivalent to 20 l/h, the water entering the cabin at an oxygen temperature of 20° C will be approximately 0.4 g/h.

Water could enter the atmosphere of the cabin from devices for catalytic hydrogenization of CO_2 gas to water and carbon. This problem may be solved by constructing a gas atmosphere regeneration system which insures closing, and communication of separate apparatuses and devices for gas and liquid communication with continuous mass transfer of the liquid phase from apparatus to apparatus by means of speed synchronization of separate physicochemical and electrochemical processes. In this procedure, the total amount of water entering the atmosphere of the cabin exceeds human water elimination. For conditional calculations, it may be considered equal to approximately 50–60 g/h·man^{-1}.

To maintain a hygienically acceptable amount of humidity in the atmosphere, or to avert condensation of water on surfaces and in the cabin air, and for optimal work regimes of several life-support systems, moisture must be removed continually from the cabin atmosphere. To accomplish this under spaceflight conditions (dynamic weightlessness) requires drying ap-

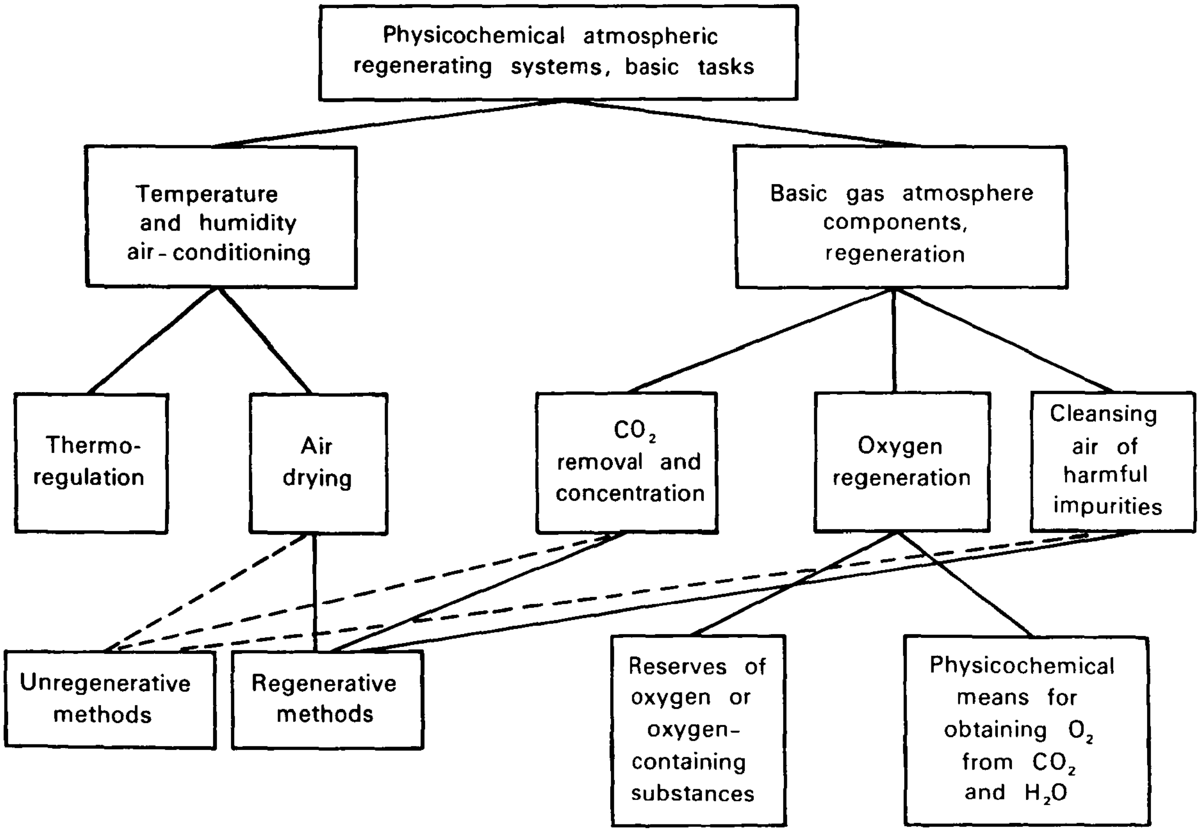

FIGURE 2.—Structure of a physiochemical system for air-conditioning and regeneration.

paratus of new structural design. Dehumidifying devices may be divided into: automatic, to remove water only from the atmosphere of spacecraft living areas; and nonautomatic, for insuring and organizing various physical, chemical, and electrochemical processes with the necessary speeds and mass characteristics, stably and reliably, throughout an extended period.

Nonautomatic dehumidifying devices are necessary with: oxygen-containing substances for gas atmosphere regeneration; hydrophilic absorptional means for removing CO_2 gas from the atmosphere; electrochemical methods of gas atmosphere regeneration; and catalytic methods of CO_2 utilization. For atmospheric regeneration in Vostok and Voskhod spacecraft [44, 107, 120, 121, 122], the oxygen-containing substances used were peroxide compounds of alkali metals.

In the first period of the substance's working, there is a reaction which requires 10–12 g water to liberate 20–25 l oxygen. At the same time, the volume of air needed for absorbing the 20 l CO_2 carries with it a significantly greater amount of water, which in turn leads to a large amount of liberated oxygen, and actually, to oxygenation of the atmosphere of the hermetically sealed environment. To insure liberation of enough oxygen for the spacecraft crew, the humidity of the air entering the device holding the peroxide substance must be regulated. A system for preliminary drying of the gas atmosphere is diagramed in Figure 4.

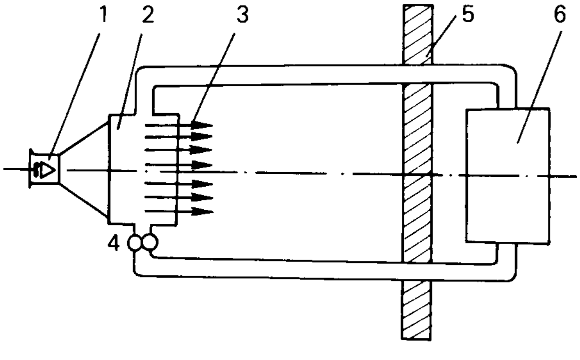

FIGURE 3.—Schematic of cooling system for spacecraft cabins using radiation heat exchanger. 1, ventilator; 2, heat exchanger; 3, air to cabin; 4, pump; 5, cabin wall; 6, radiation heat exchanger.

When hydrophilic absorbents are used (e.g., zeolites for cleansing the atmosphere of CO_2 gas), preliminary drying of the air becomes especially important, since zeolite absorbs water vapor first, thereby significantly lowering the CO_2 gas sorbability. Therefore, in systems for absorbing CO_2 gas based on zeolites, dryers are the first step in regeneration to insure drying of the air to a dew point, 40°–60° C.

The second stage is the absorption of CO_2 gas. Substances which absorb moisture are periodically regenerated by dry-heated air; such a system is shown in Figure 5.

It is also possible to use carbonates of alkali metals, for example, K_2CO_3. Such substances work stably with the molar correlation of sorbed water vapor and CO_2 gas equal to 1. This conforms to the formation of bicarbonate compounds not containing crystal hydrate water. With molar correlation greater than 1, a liquid film of aqueous solutions may form on the surface of the substance, slowing the process of CO_2 sorption. To prevent formation of this film, relative humidity of air entering the regeneration process must not exceed 30%–40%.

Electrochemical methods in physicochemical systems of gas atmosphere regeneration (based on electrolysis of aqueous solutions of alkalis and salts—carbonates, sulfates) are necessary when using special heat exchangers-dehumidifiers.

Chemosorption of CO_2 gas (based on use of liquid absorbents such as monoethanols and alkalis for stabilizing and preserving absorptional capabilities of the absorbent) makes it necessary

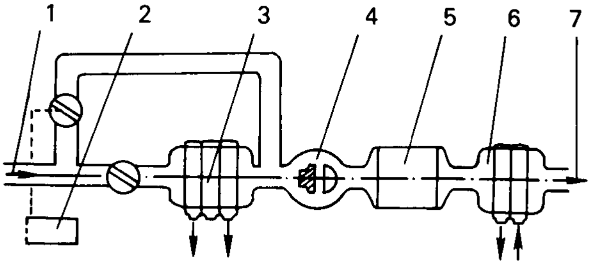

FIGURE 4.—Regeneration system of a gas medium with the use of an oxygen-containing substance KO_2 or NaO_2. 1, air inlet; 2, oxygen monitor; 3, air dryers; 4, ventilator; 5, KO_2 or NaO_2 container; 6, filter for harmful impurities; 7, air outlet.

to constantly maintain gas concentration, since, as with the electrolyzers, changes result from mechanical dispersion when the absorbent is in contact with the air. To preclude this phenomenon, heat exchangers-dehumidifiers are mounted at the exit of the absorbing apparatus, and carry out functions analogous to those of dehumidifiers in electrochemical devices.

For air dryers-heat exchangers-dehumidifiers it is necessary to establish both specific and general requirements. Air dryers in the life-support systems for the spacecraft crew must have little weight, minimal volume, and minimal energy requirements. They must have high work reliability, mechanical durability, and must not break down under the vibration and stresses that act upon the spacecraft. The drying assembly must not produce harmful impurities and must insure absorption of water in the necessary quantities and with sufficient speed so that the remaining moisture corresponds to the normal input of subsequent technologic processes. The dryer must be capable of repeated use of thermal or thermovacuum regeneration without disturbing its characteristics [19, 123].

Methods of Drying the Air

Both nonregenerative and regenerative air dryers are used for short-term space flights, but for those exceeding 30–40 days, only regenerative air dryers have proved practical.

Nonregenerative chemical methods of drying the air are divided into those based on chemical interactions and those based on the formation of crystal hydrates. The interaction process of drying materials of the first group includes the decomposition of the drying substance and water during their interaction and formation of new molecules from their atoms. During interaction of the drying materials of the second group with water, the water molecule does not break down, but enters independently into a new compound. The majority of oxides, peroxides, and hyperoxides of alkali and alkali-earth metals belong to the first group, as do anhydrides of several acids. The hygroscopic salts of several inorganic substances of the type LiCl, $CdCl_2$, $ZnCl_2$, and others belong to the second group of drying substances.

The regenerative means of air-drying are physicochemical and physical. The physicochemical means of air-drying may be divided into sorptional, and sorptional with the formation of crystal hydrates. Sorbents for drying the air may be divided into solid sorbents such as silica gel, alumina gels, activated charcoal, and liquid sorbents, such as sulfuric acid, various solutions of salts, and other hygroscopic liquids. Physical methods for drying the air may be based on condensation or freezing of water vapor. Spaceflight conditions require that physical methods of air-drying as well as those using liquid sorbents be of special design. This is determined by the system itself, which consists of three phases: *gas-liquid-solid.*

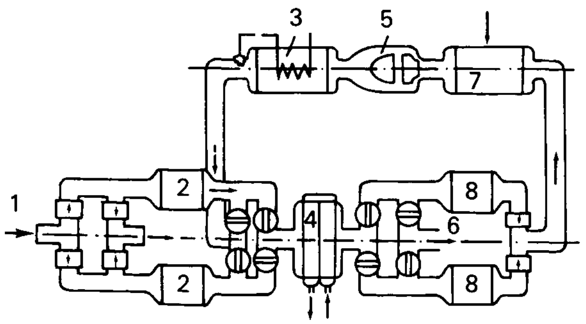

FIGURE 5.—Typical system for removing CO_2 with reduction/regeneration of adsorbents. 1, air intake from cabin; 2, packets with dryer; 3, heater; 4, dehumidifier; 5, compressor; 6, CO_2 exit to vacuum; 7, heat exchanger; 8, packets with CO_2 absorber.

Chemical Methods for Drying the Air

During chemosorption, the absorbing material undergoes chemical changes which determine the character of the surface of the chemical bond with the natural surface of the radicals. The speed of chemosorption depends on: the number of molecular encounters with the absorbing surface; the coefficient of condensation; the energy of activation; and the probability of collision of water vapor molecules with the active centers. Chemosorption always takes place at a temperature corresponding to the determined energy of activation. In most cases, physical adsorption and chemical absorption occur simultaneously. Depending on the approach to the adsorbing surface, the molecule is subject first to the effect of physical forces of adsorption, which act over greater distances than the forces of a chemical bond.

The intensity of the process of chemosorption of water vapor from a water vapor-air mixture, analogous to the rate at which chemical reactions occur, is determined both by chemical kinetics and by flow hydrodynamics, which characterize the mechanism of mass transfer near absorbing surfaces. The heterogenous chemosorption reaction of water vapor takes place in several stages:

emission of regulated molecules to the surface on which the reaction occurs;

its own heterogenous reaction (absorption);

removal of products of the reaction from the zone of reaction.

The kinetic relationships for LiCl, which connect the rate of flow of the air-water vapor mixture and atmospheric humidity with the intensity of its absorption of water vapor, are shown in Figure 6.

The relationships introduced indicate that the interaction of water vapor with LiCl itself is extremely great and does not have an actual effect on the total rate of chemosorption, since the slowest reaction is the diffused supply of water vapor to the absorbing surface; that is, the intensity of the process of chemosorption in the given instance is determined by diffusion kinetics [122].

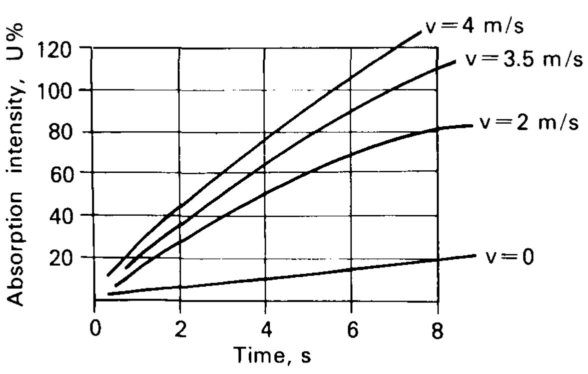

FIGURE 6.—Relation of the intensity of absorption, U, by an absorbent of water vapor to the speed of the air vapor mixture, v, in seconds, s; when v=0,2,3.5, and 4 m/s.

In the process of water absorption by hygroscopic salts of the type LiCl, $CaCl_2$, and others, a crystallizational annexation of the water is observed, while the relative humidity above the salts, with insignificant temperature fluctuations, remains practically constant. During the reaction of such substances, with the current of moist air on their surface, a layer of solution forms which slows the ensuing process of water vapor absorption. This negative factor for hygroscopic salts is a change of its original form while absorbing a large quantity of water. LiCl also corrodes metals and is toxic. The drying capabilities of several of the substances used during chemical drying of the air are presented in Table 1.

The chemical moisture absorbers enumerated are widely used in laboratory practice, but are insignificant factors in space technology, specifically, for crew life-support systems [44, 61, 107, 120, 121, 122].

Physicochemical Methods for Drying the Air

The sorbents of the physicochemical methods for drying the air may be solid or liquid.

Air-drying with solid moisture adsorbers results from physicochemical reaction of water vapor and the sorbent; that is, sorbents of water,

TABLE 1.—*The Drying Capabilities of Several Substances Used During Chemical Air-Drying*

Drying substance	Quantity of water vapor remaining in 1 l air, mg at 25° C
$CaSO_4$	1.4
$ZnBr_2$	1.1
$ZnCl_2$	0.8
$CaCl_2$ (fused)	0.36
$CaCl_2$ (granulated)	0.14–0.25
NaOH (fused)	0.16
MgO	0.008
H_2SO_4 (100%)	0.003
Al_2O_3	0.003
$Mg(ClO_4)_2 \cdot 3H_2O$	0.002
KOH (fused)	0.002
$Mg(ClO_4)_2$ (anhydrous)	0.0005
P_2O_5	0.000025

the formation of hydrates, and solution. Solid sorbents are gels or natural sorbents which have been impregnated with dryers.

Air-drying with gels takes place by sorption and consequent capillarial condensation of water in the porous structure of the dryer. Silica gel, alumina gel, and activated charcoal are solid sorbents.

Silica gel is a solid, glasslike, chemically inert, homogeneous, highly porous substance, composed of 99% silicon dioxide. Depending on the number of pores, silica gel is divided into a finely pored variety with a filled mass of 700 kg/m^3 and a coarsely pored variety with a filled mass of 400–500 kg/m^3 [46].

Alumina gel or activated aluminum consists basically of aluminum dioxide, Al_2O_3, with admixtures of soda and oxides of other metals. Its mean capillarial surface comprises approximately 2.5×10^6 cm^2/g, with a filled mass capacity of 800 kg/m^3, a density (true) of 3.25 g/cm^3 [46].

Activated carbon (charcoal) is specially processed to increase the adsorptional surface and free the pores of resonant substances. Granular activated charcoal is used with various dimensions of from 1 to 7 mm, or in powdered form. The adsorbing properties of activated charcoal depend on the magnitude of its specific active surface and on the number of pores, although only micropores take part in the work; that is, pores with a diameter less than 1×10^{-5} mm.

Adsorption is caused basically by the physical forces of attraction; that is, by nonpolar van der Waals forces, dipole interaction forces, and polarizing forces [122].

For capillaries with a radius $> 10^{-5}$ cm, the vapor saturation pressure above the meniscus is practically equal to the vapor saturation pressure above the plane surface.

Vapor from free space diffuses in the capillary if its tension is greater than the tension of the adsorbed vapor over the concave surface of the meniscus. The walls of the capillary adsorb vapor and lock in water with a film which forms the meniscus. With the appearance of the meniscus, capillarial condensation or vapor sorption occurs. Microcapillaries ($r < 10^{-5}$ cm) fill with water only upon direct contact. Macrocapillaries do not adsorb water and are capable of passing it to an atmosphere saturated with water vapor.

The adsorptional capability of silica gel depends on the temperature of the moist air and on the partial vapor pressure: with an increase of temperature and decrease of partial vapor pressure this capability decreases (Fig. 7). It is obviously inappropriate to use silica gel at a temperature higher than 35° C.

In the process of drying the air with sorbents their adsorptional capability decreases; upon achieving a determined state, the required decrease of atmospheric humidity cannot be assured and the sorbents must be regenerated. The most widespread means of regeneration is to pass air with a temperature +160° to +170° C through the sorbent and dry the sorbent to a dew point temperature not greater than +28° to +30° C.

Dryers with solid adsorbents are two-sectional devices: in one section, water adsorption takes place, while in the other there is regeneration by means of an electric, gas, or vapor heater.

The adsorptional capability of alumina gel is lower, although the degree of air-drying is higher than with silica gel. It is expedient to use alumina gel at an air temperature not greater than 25° C.

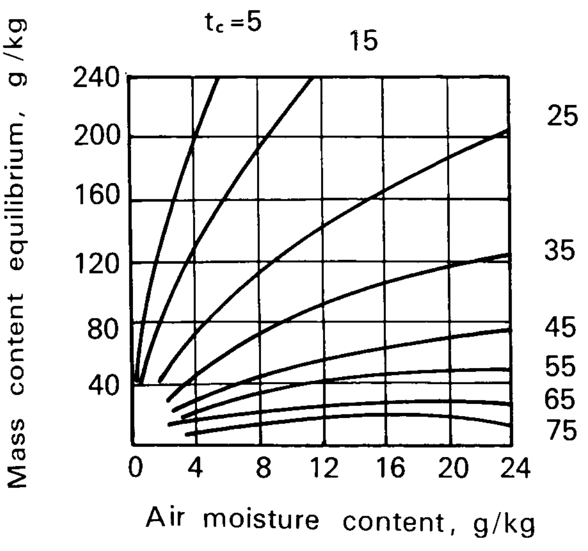

FIGURE 7.—Relation of equilibrium of total mass of silica gel to moisture content and air temperature.

Adsorbents for drying the air must have these properties [38, 43, 115]:

- high adsorptional capabilities under normal conditions;
- chemical stability and resistance;
- mechanical durability;
- capability of regeneration at low temperatures;
- temperature stability during regeneration temperatures used;
- small volumetric weight and no swelling.

Impregnated dryers of porous materials, to whose surfaces hygroscopic substances have been applied, belong to the second group of physicochemical methods for drying the air. Water adsorption is accomplished in these dryers by the layer of hygroscopic materials as well as by capillarial water condensation. The hygroscopic additive changes into crystal hydrate or a solution that absorbs water, although its concentration does not reach equilibrium with the dried air. Silica gel, alumina gel, activated charcoal, and similar substances are used as carriers of the hygroscopic additives.

The volume of the impregnated dryer is determined by the porosity of the carrier and the quantity of hygroscopic additive. In dryers based on coarse-pored silica gel, the quantity of water taken up at 20° C reaches 61% of the mass of the dryer; with those based on fine-pored alumina gel, the amount is 25%; those based on activated charcoal reach 62%. For example, $CaCl_2$ borne on the surface of coarse-pored silica gel increases its water capacity approximately six times [122]. The determining factor in selecting hygroscopic additives is the minimal pressure of water vapor over its solutions in the temperature range of 5°–40° C. The carrier must be well-impregnated with a solution of hygroscopic additive, have low density, and maintain solution stability during inertial stresses [38, 47, 120].

Physical Methods of Drying the Air and Means of Separating Gas-Liquid Phases Under Dynamic Weightlessness

Physical means of drying the air include cooling it to a temperature lower than the dew point or to freezing temperature. Depending upon the final cooling temperature, the water may be in the liquid state, condensate, or the solid state—ice.

Change in the water content of the air in the cooling process, as the result of a 1° decrease of the air temperature in the case of freezing the water, is insignificant; that is, drying the air by freezing is a higher capacity thermal process than the condensation method. Freezing is used where considerable air-drying is required. Drying the air by cooling, which has real advantages over other methods, is therefore widely used in air-conditioning systems of spacecraft cabins. The basic advantages of such systems are:

- relative simplicity and work reliability of the drying device;
- independence of weight and volume on duration of use;
- insuring heat removal from the condensed volume in the process of drying;
- simultaneous removal from the dried air, with the water vapor, of those portions of soluble or easily frozen harmful impurities [47, 61].

The shortcomings of these methods are:

- necessity for sources of cold for lowering the air temperature the required amount;
- necessity for a quantitatively new design for separating gas-liquid mixtures in conditions of actual space flight.

In terrestrial installations, condensation of the liquid phase as the result of the difference in specific gravity between the gas and the liquid flows into special containers through the action of their own weights.

In actual spaceflight conditions (dynamic weightlessness), separation of the liquid phase from the gas requires new technological and structural methods. Technological processes for drying the air (lowering temperatures, moisture condensation, water removal) may be located together in one device, which accomplishes all the processes simultaneously; or, a series of devices may be used which sequentially carry out the functions of decreasing temperature and condensing moisture, when coagulationconsolidation of a dripping liquid and moisture separation is necessary.

A line diagram for the dehumidifier from the English firm, Normaler, is shown in Figure 8; it was used in the air-conditioning system of a hermetically sealed aircraft cabin [122].

In the cyclone-type separator (Fig. 9), moist air passes through a tangentially located nozzle. The resulting centrifugal forces insure transposition of the dripping liquid to the sides of the casing. The air moves along a spiral trajectory in a circular space between the casings and exits the separator through the connecting pipe. Water is removed through the overflow.

In the centrifugal separator with an axial duct (Fig. 10), the moist air passes through the spiral apparatus; the water flows along the sides and is removed through the connecting pipe. Dried air is released through the outlet nozzle.

Dehumidifiers may have recoil valves with the centrifugal effect, or specially constructed vanes. The disadvantages of the systems examined above for separating the liquid and gas phases are the presence of rotating assemblies and parts that require periodic replacement and maintenance, as well as additional expenditure of energy.

The most expedient method for separating the liquid from the gas phase is based on the use of porous capillary elements such as hydrophile and waterproof elements [2, 32, 121]. Condensation dryers, as well as drying the air, simultaneously insure its cooling; i.e., they simultaneously accomplish temperature and atmospheric humidity regulation within the hermetically sealed cabin.

In the spacecraft Vostok and Voskhod. a cooling-drying device maintains temperature and atmospheric humidity in the cabin (Fig. 11) [121]. The work principle of the cooling-drying device includes constant cooling, condensation of moisture from the dried air, and removal of the drop-liquid phase by porous capillary wicks that closely adjoin the cooling surface of the radiator. Removal of the liquid phase in this system is regulated with difficulty.

Air from the cabin at a temperature of 25° C with an absolute water content up to 17.5 g for 1 kg of air is sucked in by ventilator "2" (Fig. 11) through suction air duct "1" and forced into the

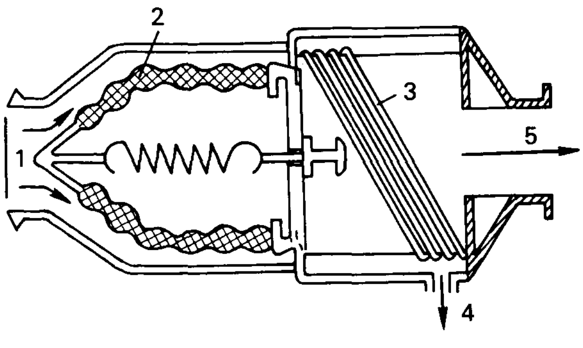

FIGURE 8.—Dehumidifier. 1, gas-vapor mixture inlet; 2, reticulated filter-coagulator; 3, drain pipes; 4, liquid phase exit; 5, gas mixture outlet.

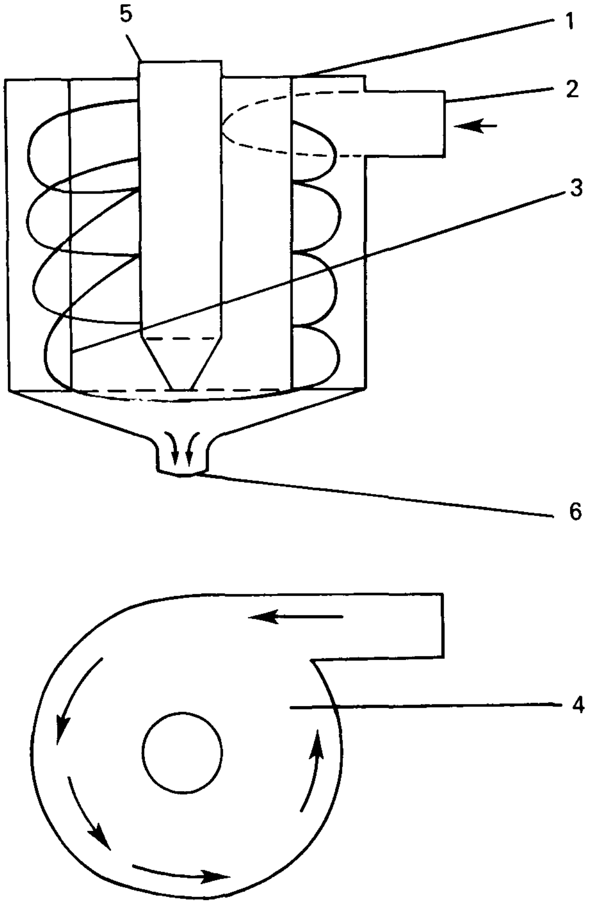

FIGURE 9.—Dehumidifier of the cyclone type. 1, casing; 2, moist air entrance; 3, internal pipe; 4, air path; 5, air exit duct; 6, overflow drain.

intertubular space of the heat exchanger. The liquid-coolant circulates through pipes "4" (Fig. 11) at a temperature of +5° C, and is forced through the duct "6" from the circuit of the radiating heat exchanger. Between the pipes and in contact with them are the hygroscopic wicks "5" which are in contact with the hygroscopic porous material which fills a container (condensate collector) "7." Water vapor from the air, circulating in the interpipe space, is condensed on the pipes, after which the condensate passes along the wicks into the collector. The coolant, at a temperature of +7±10° C, passes through pipe "6" (Fig. 11) into the radiating heat exchanger circuit, where it is cooled and again passes into the feeder pipe "3." The condensate flows through the overflow valve and is pumped into the water regeneration system.

Heat exchanger-separators may also be constructed using hydrophile and waterproof porous elements, in which the speedy removal of the liquid phase is determined by the filtering capacity of the porous elements and the decrease in pressure between the gas-liquid phase and the liquid phase. There is wider use of this type of heat exchanger-separator in the separate devices of the life-support systems and in the gas atmosphere-conditioning systems [5, 50, 61, 115, 121, 131].

Aspects of Systematizing Basic Methods of Air-Drying

In air-conditioning systems for both temperature and humidity, water removal and temperature decrease are highly interrelated. The operating force for air-drying by physicochemical and physical means is the temperature gradient between the air mass and the surface on which water vapor condensation occurs, which leads to a temperature decrease of the air mass in contact with the cooling surface. The characteristic peculiarity of air-drying, the inevitable phase shift from a gaseous to a liquid state, significantly complicates the process of water mass removal and its subsequent transport to the system

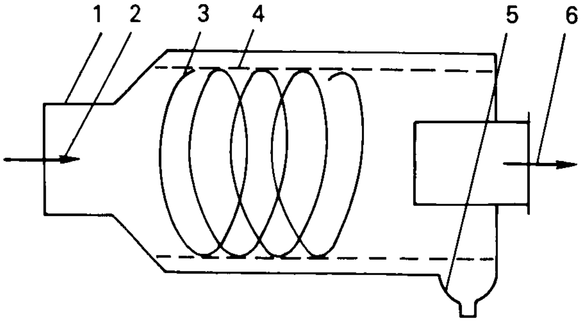

FIGURE 10.—Dehumidifier with an axial duct. 1, main body; 2, moist air entry; 3, moist air path; 4, separator; 5, water drain; 6, dry air outlet.

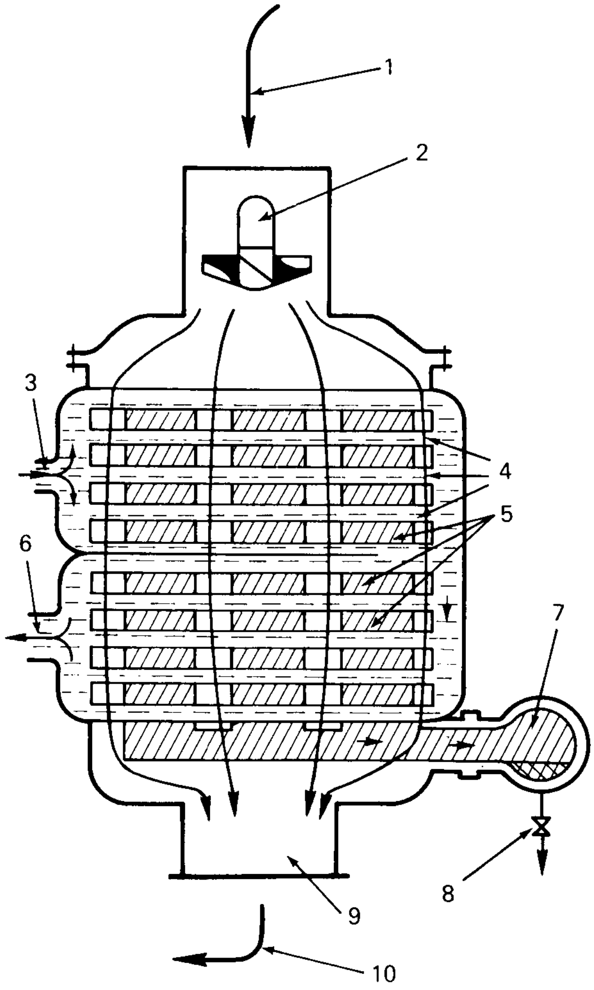

FIGURE 11.—Cooling-drying heat exchanger. 1, moist air input; 2, ventilator; 3, pipeline for carrying coolant to heat exchanger; 4, heat exchanger tubes; 5, wicks; 6, pipeline to radiation heat exchanger; 7, condensate collector; 8, condensate evacuation valve; 9, forced air line; 10, air outlet.

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devices under conditions of weightlessness. Intensification of this process, using porous capillary elements or other hygroscopic materials, is considered effective and is practical during processing and the creation of a practicable working device.

In accordance with the methods of air-drying examined, and separation of the liquid phase from the gas phase, they may be represented in a systematized form (Figs. 12 and 13).

Regenerative methods of air-drying at present have practical use. Of all the methods examined, electrochemical methods, which are interesting because of their possibilities and multipurpose designs, have not been given attention. Electrolysis or electrolytic methods using P_2O_5 or H_2SO_4, as well as a silver-plated cathode with simultaneous absorption of water vapor, insures extraction of suitable quantities of oxygen and hydrogen. Practically all methods have received sufficiently intense attention by scientists in both the USSR and US [2, 50, 55, 61, 101, 103, 104, 105, 122, 123].

CONCENTRATION OF CO_2 GAS AND ITS REMOVAL FROM THE ATMOSPHERE OF HERMETICALLY SEALED ENVIRONMENTS

In life-support systems, removal of CO_2 gas, water vapor, and harmful impurities from the air is as important as the supply of oxygen. Removing CO_2 gas may be divided into nonregenerative and regenerative methods. For short-term flights, nonregenerative methods of CO_2 gas removal are used, since the size and weight of such systems increase proportionally with the duration of flight; but regenerative methods are used for prolonged space flights [44, 55, 61, 107, 120].

Nonregenerative Methods for Removing CO_2

Substances with practical use as nonregenerative sorbents for CO_2 gas removal are:

hydroxides of alkali and alkali earth metals, (LiOH, KOH, NaOH);

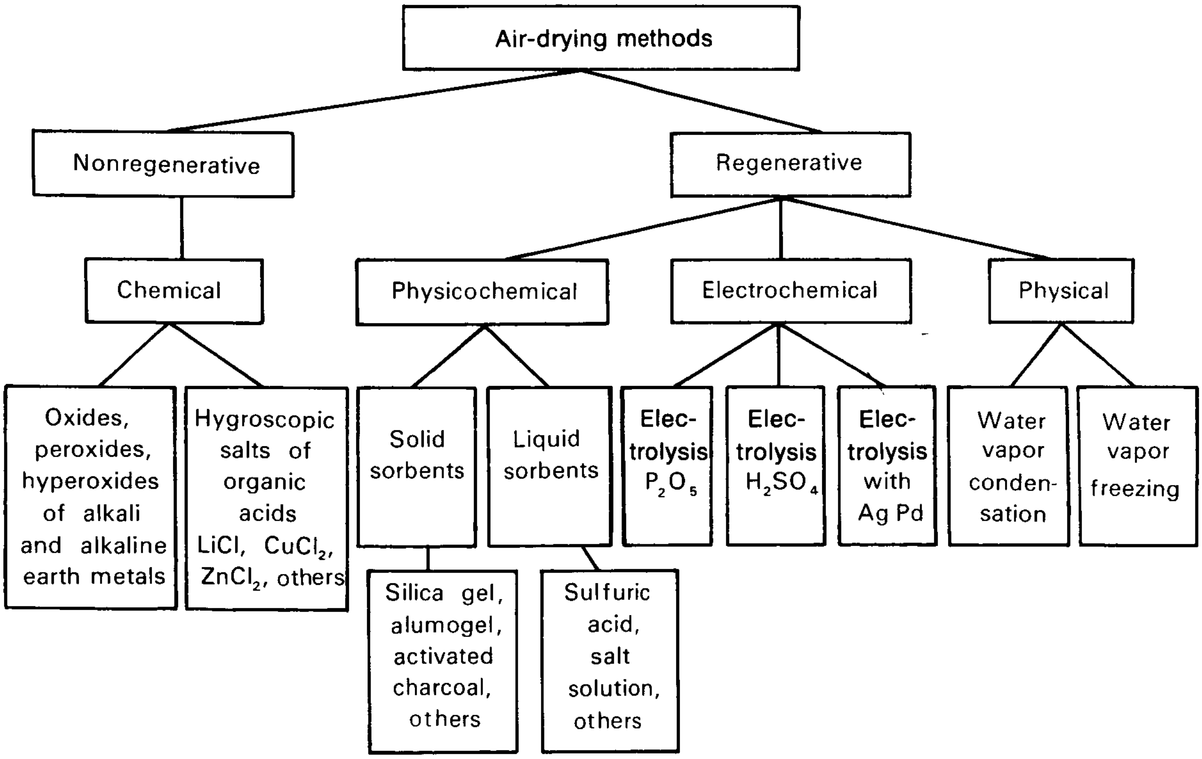

FIGURE 12.—Possible methods of air-drying in life-support systems.

hyperoxides of alkali metals, which at the same time are sources of oxygen;
carbonates of alkali metals (in solutions and solid products);
organic amines (liquid and solid).

The process of CO_2 gas absorption, for example, by lithium hydroxide, is

$$2LiOH+CO_2 \rightarrow Li_2CO_3+H_2O+485 \text{ kcal/kg } CO_2 \quad (3)$$

By this reaction, on the average, 1 kg CO_2, which corresponds to the daily CO_2 elimination by man, requires 1.3–1.5 kg LiOH.

In actual gas atmosphere regeneration systems, on Soviet spacecraft, highly active oxygen-containing substances based on hyperoxides of alkali metals are used. These substances simultaneously release the necessary quantity of oxygen for respiration and absorb from the air CO_2 gas and part of the harmful acid-type impurities as well as water vapor.

The process of reaction of the substances with the moist current of air which contains an increased quantity of CO_2 gas may be represented by equations in the general form

$$MeO_2 + H_2O \rightarrow MeOH + O_2 + Q \quad (4)$$

$$MeOH + CO_2 \rightarrow Me_2CO_3 + H_2O + Q \quad (5)$$

for the final period (in the event of complete processing of the substance)

$$MeO_2 + H_2O \rightarrow MeOH + O_2 + Q \quad (6)$$

$$MeOH + CO_2 \rightarrow Me_2CO_3 + H_2O + Q \quad (7)$$

$$Me_2CO_3 + CO_2 + H_2O \rightarrow MeHCO_3 \quad (8)$$

The capacity of substances for releasing oxygen and absorbing CO_2 gas and water vapor on the average comprises: oxygen, 200–220 nl/kg; carbon dioxide gas, 150–300 nl/kg; water vapor, 80–150 nl/kg. Systems of this type are characterized by simplicity, reliability, and low energy expenditure [8, 50, 107, 120, 121].

Regenerative Methods of Removing Carbon Dioxide Gas

Several means of cleansing the atmosphere of CO_2 used at present in the capacity of regenerative sorbents are distinguished individually by the character of their reactive phases, temperature, necessity of creating an artificial force field, or concentration gradient.

In the *gas-solid body* systems, molecular sieves and synthetic zeolites with a selective adsorbent capability in regard to CO_2 gas are used as adsorbents. The process of adsorption occurs independently of the effect of the Earth's

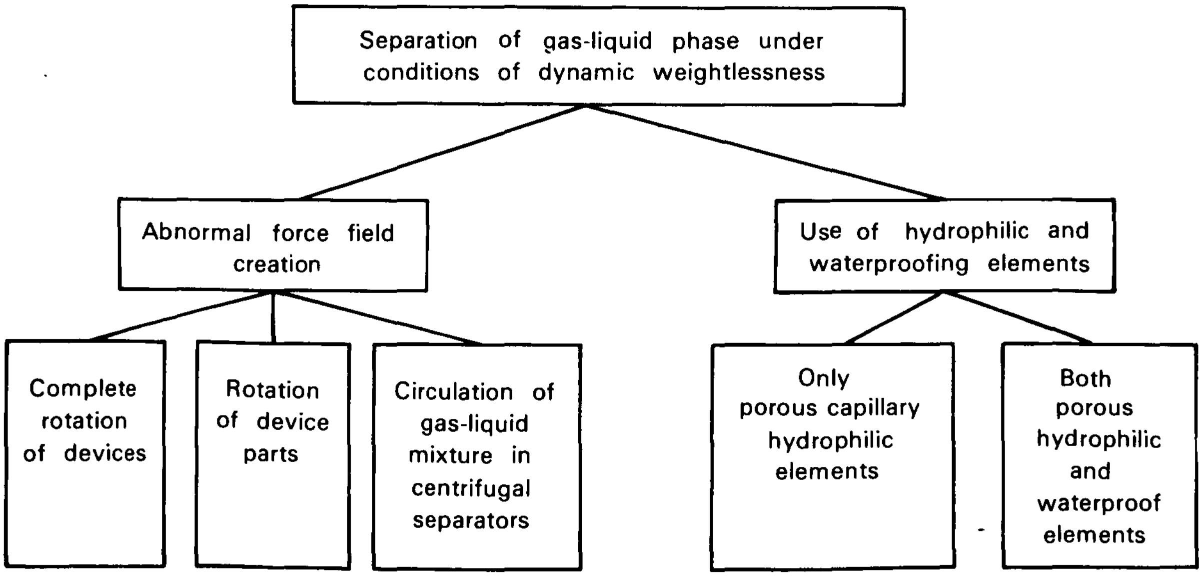

FIGURE 13.—Means of separating gas-fluid phases in dynamic weightlessness.

gravitational force and may take place in realistic spaceflight conditions. Methods of cleansing the atmosphere of CO_2 gas which may have practical use are: adsorption using synthetic zeolites, physical adsorption, and absorption during electrochemical processes.

During the adsorption of CO_2 by synthetic zeolites, desorption may take place by various methods and means: the space vacuum, vacuum and temperatures; within the flow of an inert gas by means of decreasing the partial pressure of CO_2 over the layer of adsorbent, and at vacuum and temperatures with subsequent compression of CO_2 to normal pressure.

The selection from various means of CO_2 desorption is made depending on the means of oxygen regeneration and flight duration. When using oxygen reserves, it is expedient to use the vacuum and temperature desorption of CO_2 in space. Physical methods of removing CO_2 from the atmosphere are freezing, centrifugation, and diffusion.

Purification methods based on freezing and centrifugation are in the theoretical design or research stage. The diffusion method of cleansing the atmosphere of CO_2 requires little energy, is simple, and promising. Absorption of CO_2 during electrochemical processes is differentiated from the continuous process by simultaneous liberation of oxygen from both water and CO_2 gas. Cleansing the atmosphere of CO_2 is achieved by chemosorption—by the final products of electrolysis which form in the cathode space of the electrolyzing devices during the electrolysis of aqueous solutions of carbonates, sulfates, and alloys of alkali metals [50, 107, 109, 126]

Removal and Concentration of CO_2 by Adsorption Using Synthetic Zeolites

The most widespread regenerative sorbents of CO_2 gas at present are the zeolites (molecular sieves), consisting of synthetically hydrogenated aluminosilicate with various alkali metal oxide additives.

Zeolites are porous, granulated substances with granular dimentions of 3–5 mm and pore dimensions of several angstroms. The porous structure of the adsorbents has an important effect on the adsorptiveness of various substances during physical adsorption. In the most finely pored adsorbents, such as the microporous, with dimensions comparable to those of the adsorbing molecules, there is overlapping of the entrance to the pore caused by fields of adsorptional forces, which are created by the reverse sides of the pores. As a result, there are increases of the adsorptional potentials and of differential adsorptive heat which lead to a significant increase in the magnitude of adsorption [31, 38]. This is explained by the exclusive selectivity of forms of zeolites with known structural characteristics for adsorbing from a gaseous mixture, only the components whose molecules approximate the dimensions of the micropores.

For example, type A and KH zeolites have substantial, clearly expressed peculiarities:

(1) strictly constant dimensions of pores for each type of zeolite;

(2) a bidispersant character of the primary porous structure of the zeolite crystals—there are two varieties of pores, coarse and fine cavities, respectively, within the structure of the aluminosilicate skeletons;

(3) the interconnection of pores through narrow apertures, which determines the adsorbed molecules entering the pores;

(4) the surface of the aluminosilicate skeleton (the surface of the pore itself) is formed by oxygen ions; positively charged ions of aluminum and silicon are distributed deep within the aluminosilicate skeleton [31, 38, 129].

Three cavities between the crystal elements and the crystal conglomerates form secondary porosity of the granulated zeolites. The dimensions of these cavities may fluctuate within wide limits and depend on both the dimensions of the crystals and the packaging. According to Dubinin's data [38], the equivalent radii of the secondary pores are from several tenths to hundreds of thousands of angstroms. In such pores, which differ significantly in dimensions, there are, naturally, various coefficients of diffusion and mass transfer of the component gaseous mixture which is under the obstructive effect of adsorptional fields.

The diffusion coefficient in secondary porosity depends on the conditions of extraction and the granulation of the zeolites, as well as on adsorption conditions: in a vacuum or from a flow of carrier gas, with low or high pressure. The general diffusion coefficient in a granule depends on the diffusion coefficients in the crystals, that is, in both the primary and secondary pores [38]. These considerations make it obvious that the nature of adsorptional forces and the adsorptional kinetics in the zeolites depend on many factors and are extremely complex.

Data on adsorption of CO_2 gas by potassium, sodium, and calcium zeolites at 20° C are in Table 2; there is a clear relationship between adsorption and the dimensions of the elementary cavities' apertures in the crystalline structure. In the crystalline structure of zeolites, the apertures of the elementary cavities allow passage of a molecule of water. The critical diameter of a water molecule is commensurate with the dimension of apertures of adsorptional cavities of synthetic crystalline aluminosilicates (Table 3).

The isotherms of adsorption in zeolites with very low concentrations of water vapor are sharply reduced. Synthetic zeolites are adsorbents with extremely thin pores. As a result of the superposition of fields of opposite sides in the thin pores, the effect of adsorptional potential, which leads to high adsorptional capacity with low concentrations of the adsorbent, is sharply expressed. Because of this, synthetic zeolites are good dryers; they significantly exceed silica gels in their drying properties.

Zeolites are regenerated by heating to a predetermined temperature and by evacuation. In this regard, certain brands of zeolite may withstand a significant number of regenerative cycles. The use of zeolites for adsorbing and concentrating CO_2 is considered quite promising. A series of laboratory devices has, at present, successfully used zeolites for adsorbing CO_2 and harmful impurities.

TABLE 2.—*Adsorption of CO_2* (3.2 Å) *in Potassium, Sodium, and Calcium Zeolites at 20° C*

P mm Hg	Adsorption, weight, %		
	KA (3.3 Å)	NaA (4.0 Å)	CaA (5.0 Å)
3	1.32	5.70	7.50
6	1.76	7.05	9.70
15	2.20	8.80	12.70

A system for cleansing the atmosphere of CO_2 gas, based on the use of synthetic zeolites, is shown in Figure 14. Air from the cabin moves through the water adsorber "3" (Fig. 14), where it is freed of surplus moisture, and further moves to the CO_2 adsorber "5"; the air, cleansed of CO_2 gas, is then sent for desorption to the water adsorber "14," which is heated to a set temperature. From the water adsorber the humidified air moves into the cabin "2." During this period, thermovacuum desorption of CO_2 gas takes place in the adsorber "7," followed by its removal into the reservoir "11."

According to the data of several authors [99], two containers filled with zeolites, weighing 2.26 kg and working cyclically in a sorption-desorption regime, insure the removal of CO_2 gas expired by one man. The sorption time of one container is approximately 100 min. The entire system for removing CO_2 weighs 14 kg. The power requirement for regeneration (heating and evacuation) is approximately 700 W, while that for cooling it is approximately 400 W [31, 37, 38, 48, 50, 70, 89, 99, 122, 129, 131].

Removal and Concentration of Co$_2$ by Freezing

Carbon dioxide changes to the solid state at −78° C and absolute pressure of 760 mm Hg. The triple point of CO_2 corresponds to its temperature of −56.6° C and absolute pressure of 5.28 kg/cm^2. Below this pressure and tempera-

TABLE 3.—*Adsorption of Water Vapor* (2.6 Å) *in Potassium, Sodium, and Calcium Zeolites at 20° C*

P[1] mm Hg	P/P$_s$[2]	Adsorption, weight, %		
		KA (3.3 Å)	NaA (4.0 Å)	CaA (5.0 Å)
1	0.050	14.04	22.80	18.00
2	0.110	14.04	24.50	18.70
3	0.170	14.04	25.60	20.70

[1] P—equilibrium pressure.

[2] P$_s$—saturated vapor pressure at temperature T.

ture, CO_2 changes to the solid state, passing through the liquid phase. The partial absolute pressure of CO_2 at a higher pressure in air-separating devices may reach a magnitude of 0.06 kg/cm². Therefore, removing CO_2 from the air, in a cryogenic device is possible only in the solid form.

Carbon dioxide is frozen in regenerators or in special heat exchanger-freezers. Various freezer designs used are: horizontal (Kapitsa's devices), twisted tubular high-pressure pipes with passage of purified air within the pipes, and low-pressure models with straight pipes and passage of purified air in the intertubular space.

To achieve the assigned degree of air purification [45], the CO_2 freezing process must take place with a heat regime which assures crystallization of CO_2 only on a cold wall without the "snow" falling into the airstream. In this case, the quantity of CO_2 in the purified air will be equal, or less than, the CO_2 content of the air at saturation for given temperature and pressure. Variations in temperatures of the air and the cold wall must not exceed 30° C, while the speed of the air current, to avoid breakaway of frost from the walls and removal of CO_2 crystals, must not be greater than 3 m/s. Carbon dioxide freezing begins in that section of the heat exchanger apparatus where the air temperature is equal to the dew point of CO_2 at the design specified partial pressure and air current.

The work duration capability of a freezer up to the clogging point is proportional to its maximal specific loading; i.e., to the quantity of CO_2 in $kg/m \cdot h^{-1}$ precipitated in the highest pressure section. For approximating the maximal specific loading to the mean loading, it is necessary to select a proportion of currents where the difference in temperatures at the warm end of the freezer does not exceed the mean logarithmic difference of temperatures [45].

The method of freezing CO_2 gas may have practical use in spacecraft life-support systems or in planetary stations, due to simplicity of the apparatus design. In actual systems, the freezer consists of two circuits. In one circuit, CO_2 will be separated from air, and in the other, formation of CO_2 in the solid state will occur.

A diagram of a system for cleansing the atmosphere of CO_2 by freezing is shown in Figure 15. Air from the cabin moves into the cooler-heat exchanger "7" (Fig. 15) where water vapor is removed, continuing to the CO_2 cooler-heat exchanger "6" where CO_2 gas is frozen. The air which has been cleansed of CO_2 gas and water vapor proceeds to desorption in the water cooler-heat exchanger "2" and further into the cabin "10." Simultaneously, desorption of

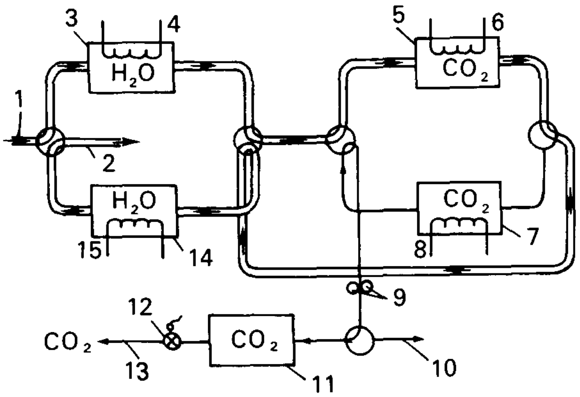

FIGURE 14.—System for removing carbon dioxide gas based on synthetic zeolites. 1, air from cabin (P_{CO_2}=3.8 mm Hg); 2, air to cabin (P_{CO_2}=0); 3, 14, water adsorbers; 4, 15, water adsorber heaters; 5, 7, CO_2 adsorbers; 6, 8, CO_2 adsorber heaters; 9, vacuum pump; 10, air to cabin; 11, CO_2 reservoir; 12, reducer; 13, concentrated CO_2 exit to use block.

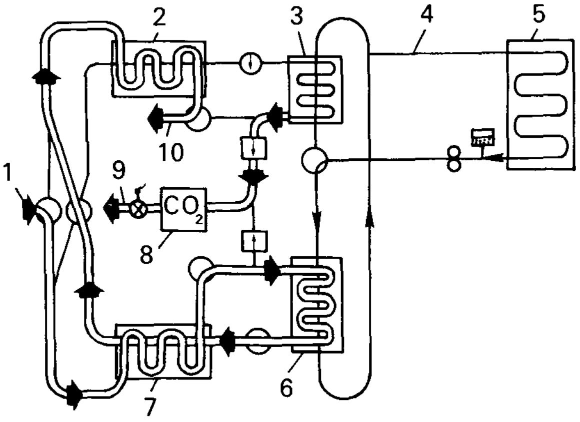

FIGURE 15.—System for removing carbon dioxide gas by freezing. 1, air from cabin (P_{CO_2}=3.8 mm Hg); 2, water-cooler heat exchangers; 3, 6, CO_2 coolers; 4, circulation of liquid coolant carrier; 5, 7, space radiator heat exchanger; 8, CO_2 gas reservoir; 9, CO_2 gas outlet to use block; 10, air to cabin (P_{CO_2}=0).

CO_2 occurs in "3" and is stored in reservoir "8" [45, 50, 122].

Removal and Concentration of CO_2 by Diffusion through Selective Membranes

The process of cleansing the atmosphere of CO_2 with selective membranes is at present a reasonable technologic solution, which is unique in that it is a constant process with small energy requirements. The determinative operating mechanism of the process is the CO_2 concentration gradient; that is, the difference in concentrations of CO_2 in the entering airstream and in the airstream at the other side of the membrane. Effective removal of CO_2 from the cabin air results from using highly selective membranes that are responsible for mass transfer of CO_2, while pressure variations and inert additives (hydrogen, a vapor-gas mixture) in the concentration cavity of the diffusion apparatus, insure the necessary speed of transfer of a CO_2 molecule. A diagram for removing CO_2 from the atmosphere by selective membranes is presented in Figure 16 [50].

The technologic process for cleansing the atmosphere of CO_2 is constructed on the principle of sequential concentration using two diffusion apparatuses "3," "12" (Fig. 16) and a vapor-gas mixture with sequential water removal in heat exchanger-dehumidifiers "6," "9."

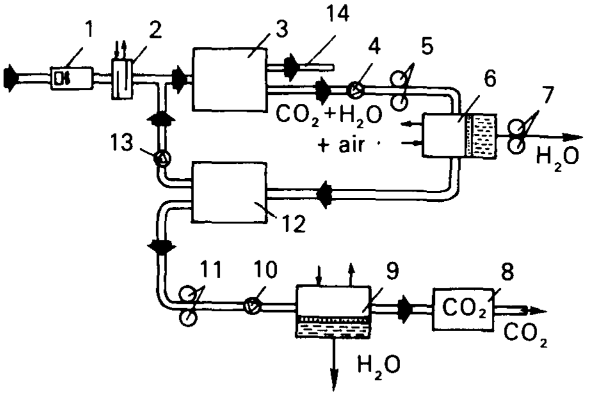

FIGURE 16.—Clearing the air of CO_2, based on use of CO_2 diffusion through selective membranes. 1, air intake; 2, heat exchanger; 3, 12, diffusion devices; 4, 10, 13, reverse valves; 5, 7, 11, compressors; 6, 9, heat exchanger dehumidifier; 8, CO_2 collector; 14, air to cabin.

In the heat exchanger-dehumidifiers "6," "9" (Fig. 16), water removal from the gas vapor mixture is accomplished in conformance with the conditions of dynamic weightlessness using porous capillary elements. The arrangement of reverse valves shown in the diagram "4," "10," "13" (Fig. 16) insures strictly directed circulation of the vapor-gas mixture into the airstream which has been cleansed of CO_2.

This method of removing CO_2 currently is very attractive to researchers, since it has a series of real advantages, and is characterized by simplicity of design and low energy requirements [50, 125].

Separation and Concentration of CO_2 Using Absorption with Electrolysis of Saline Solutions

The chemosorption of CO_2 gas by a hydroxide takes place without the expenditure of any additional energy. The reaction of hydroxides and CO_2 with the formation of carbonates may be represented

$$CO_2+2OH \rightarrow CO_3^{=}+H_2O \qquad (9)$$

According to many authors [88], the reaction described does not take place instantaneously, but with a determinable speed; therefore, the absorption of CO_2 must be viewed as a process taking place in two stages

$$CO_2+OH^- \leftrightarrows HCO_3^- \qquad (10)$$

$$HCO_3^-+OH^- \leftrightarrows CO_3^{=}+H_2O \qquad (11)$$

while the second reaction occurs instantaneously, at the same time as the first occurs with a finite speed.

During electrolysis, the solution of potassium carbonate in the anode space forms potassium bicarbonate, which breaks down upon heating.

$$2KHCO_3 \rightarrow K_2CO_3+CO_2+H_2O \qquad (12)$$

During electrolysis, the solution of sodium sulfate in the vicinity of the anode forms sulfuric acid, which, upon contact with the absorption reaction product sodium carbonate, reacts chemically with it according to the equation formula

$$Na_2CO_3+H_2SO_4 \rightarrow Na_2SO_4+H_2O+CO_2 \qquad (13)$$

Carbon dioxide gas is removed in the concentrated form, while the remaining products of the reaction are sent back into the electrolyzer. The given reaction occurs without heating; therefore, during the electrolysis of sodium sulfate, energy is lost only in the process of electrolysis.

During the absorption of CO_2 gas by NaOH, the CO_2 gas reacts chemically with the active portion of the catholyte. The general speed of the process in the case examined is determined by the rate of CO_2 gas diffusion, by the diffusion rate of the active cation from the basic liquid mass, and by the rate of the chemical reaction. Joint treatment of diffusion and chemical kinetics is necessary only at average reaction rates in which the reaction takes place, basically, in a diffusion layer.

At a very high reaction rate, it may be considered that the reaction occurs in a narrow reaction zone, arranged within the confines of a diffusion layer, while the speed of the process in this case is determined by the diffusion rate of CO_2 gas and by the active portion of the catholyte in the reaction zone. During a high-speed irreversible reaction, in which the reaction may be considered to take place instantaneously, a gas, regulated with a liquid, forms a layer in the liquid film which consists of the products of the reaction. This layer isolates the gaseous phase from the active portion of the catholyte solution, and the further process of sorption occurs on the one hand, in proportion to the diffusion of CO_2 gas through this isolating layer and, on the other hand, in proportion to the diffusion of the active cations from the active mass of liquid. The reaction of carbon dioxide gas with hydroxide (NaOH, KOH) occurs with great speed, in the opinion of a number of researchers [83, 84, 85, 88].

Based on the research by a number of authors [83, 84, 85, 88] about the absorption rate of CO_2 gas and NaOH by diffusion, it may be proposed that the relationships revealed by these studies, without particular distortion, will characterize absorption and our particular conditions. The boundary conditions of absorption with diffusion and the general measurements will be developed as well, with absorption under conditions where the force of gravity is absent. Figure 17 shows the relationship between the rate of change of absorption and the concentration of CO_2 gas and NaOH [66]. These data show that, with an increase in the concentration of CO_2 the rate of absorption increases, while with an increase in the concentration of NaOH the quantity of absorbed CO_2 increases.

Research [66, 83, 84, 85] has shown conclusively that the process of CO_2 gas absorption by solutions of NaOH and KOH is identical and that the corrected rate coefficient of the process is equal in both cases, taking into account the physical properties of the absorbent. The concentration of active absorbent in the liquid is the operating mechanism of the process.

For the desorption process, it is necessary to take into account that the stable state of bicarbonate in solution is characterized by boundary conditions: bicarbonate precipitates at a temperature from 60° to 70° C and a concentration in excess of 30% to 35% [88]. Desorption occurs

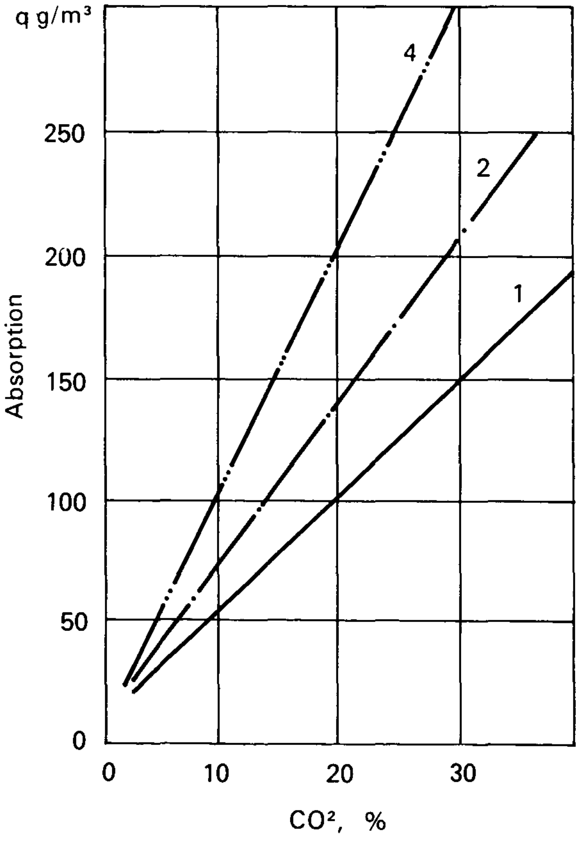

FIGURE 17.—Absorption rate vs concentration of carbon dioxide and NaOH. 1, 2, and 4 g equivalent/liter NaOH.

more intensely at a temperature of 110° C. During the electrolysis of sulfates, there are no boundary conditions for the catholyte and anolyte; i.e., they may be at any concentration, and the temperature will be determined by the temperature at which electrolysis occurs.

In absorptional processes, two phases participate—the liquid and the gaseous—and there is a transference of substances from the gaseous phase to the liquid phase. In reverse absorption (desorption), removal of the dissolved gases from the solution occurs with the transition of substances from the liquid to the gaseous phase. For insuring the stable operation of an absorption-desorption apparatus, certain basic conditions must be created:

contact between liquid and gaseous phases;
supply of catholyte and anolyte electrolytes to reaction apparatus;
removal of reaction products from the reaction apparatus;
separation of gaseous and vapor gaseous phases from liquid phases;
heat supply to the reagents;
removal of heat from the apparatus.

Under terrestrial conditions, absorptional processes take place in special apparatuses which differ from each other according to their method of phase catalysis. In film apparatuses, the liquid flows as a thin film, on the surface of which the contact phase occurs. The flow of the liquid results from the action of the Earth's gravity, and, no doubt, would be disrupted in weightlessness. In apparatuses working by diffusion of liquid in a gaseous mass, the contact phase occurs on the surface of a drop. In weightlessness, the contact phase will occur, but separation of the liquid phase from the gaseous phase will be disrupted due to absence of a difference in specific gravity.

In diffusion apparatuses working on the principle of gaseous diffusion in a liquid mass, contact of the gas with the liquid occurs on the surface of a gas bubble, which is moving through a layer of liquid. In this case the separation of the gaseous from the liquid phase will also be more difficult due to the absence of a difference in specific gravities between contact phases.

Surface-type absorbers accomplish two-phase contact by the passage of gas over the free surface of a motionless or a slowly flowing liquid. In weightlessness, the liquid will tend to flow along the sides of the apparatus; as a result, a gas-liquid mixture will flow along the gas outlet channels.

When using the apparatus described above in weightlessness, the introduction and removal of the liquid phase will be more difficult. This also leads to disruption of absorption statics and kinetics, i.e., of the equilibrium between the liquid and gaseous phases and the rate of the mass exchange process. Consequently, terrestrial absorptional apparatuses may not be used in weightlessness.

In the desorption apparatus (desorbers), in weightlessness, to accomplish the transition process of substances from the liquid to the gaseous phase, as well as in the absorptional apparatus, problems arise with the maintenance of the electrolyte in the reaction apparatus with the introduction and removal of liquid, and with the separation of the liquid and gaseous phases. For this reason, it is also not possible to use terrestrial desorption apparatuses in weightlessness.

Usyskin and Zigel [13] established that heat supply to the desorber and the process of separation of gas from a liquid during diffusion in conditions of a weakened gravitational field or of weightlessness will be different from analogous processes in terrestrial conditions. With a decrease in the intensity of the gravitational field, theoretically, the critical heat current decreases. With diffusion in a weakened gravitational field, the speed of rising bubbles decreases, and there is an increase in their diameter approximately proportional to the intensity of the field of a magnitude of 1/3.5; that is, under weightless conditions the film diffusion and diffusion appear to be identical.

When examining the data of these processes, it is necessary to keep in mind two criteria which affect the processes of diffusion: (1) that the temperature at which the dynamic forces of diffusion predominate and their magnitude are sufficient to insure removal of the bubbles from the heated surface; and (2) that the rate of required convection at which the displacement forces near the heated surface predominate and their magnitudes are sufficient for removing vapor from the heated surface.

On the basis of Usyskin and Zigel's investigations, the actual effect of gravitation on these criteria of the diffusion process was not established; i.e., it may be that supplying heat and diffusion in conditions of weightlessness does not differ from terrestrial conditions.

With electrolysis of salt solutions at present, the organization of absorptional-desorptional processes occurs as the result of creating an artificial circulating electrolyte with subsequent separation of the gas-liquid mixture and special apparatuses, based on the use of porous capillary elements. A line diagram for absorption and desorption of CO_2 using secondary products of electrolysis of salts is in Figure 18. It shows that absorption and desorption of CO_2 take place continuously, and the apparatuses are connected in a unit system closed with regard to gas and liquid communications [50, 81, 116].

CO_2 Removal and Concentration by Absorption During Electrolysis of Salt Solutions Using Ion Exchange Membranes

In the electrochemical processes during the electrolysis of aqueous solutions of alkalis and salts, a phenomenon affects external diffusion kinetics; this phenomenon is related to disproportionation in the interelectrode space portion of ions under the effect of an electrical field. These ions do not directly take part in the electrode processes, which in turn, leads to concentration gradients and diffusion currents, creating a migration of ions in a direction opposite the action of the external electrical field. This phenomenon is extremely undesirable; it increases overall energy expenditure and lowers the capabilities of the system.

During the electrolysis of aqueous solutions of salts it is necessary (already mentioned), simultaneously with the extraction of determined quantities of hydrogen and oxygen, to extract the necessary quantity and a determinable concentration of anolytes and catholytes. This is achieved during the electrolysis of aqueous salt solutions by selecting a specific rate of the electrochemical process (current density) with a rate of electrolyte feeding into the electrolyzer, taking into account the diffusion currents which occur during this process, and which are determined, first of all, by differences in the potentials between the electrodes and the temperature which either hastens or delays this process. The intimate interrelationship of basic electrochemical and mass exchange processes complicates, to a significant degree, the extraction of the anolyte and catholyte in determinable quantities, and in the necessary concentrations. These phenomena may be localized by intensification of external mass exchange currents. Use of selective membranes insures regulation of the movement of charged ions in the interelectrode space, which to a significant degree simplifies the process of extracting the necessary concentration of anions and cations.

The ion exchanger, in a molecular sense, is a heterogeneous system, composed of matrices and liquids in the pores. The rate of the diffusion currents depends on the filling of spaces by the ions of the matrix, and on the porous structure of the membrane itself (porosity, type of pore, size, and distribution of pores by volume).

Ion membranes designated for use in electrochemical devices must have the necessary

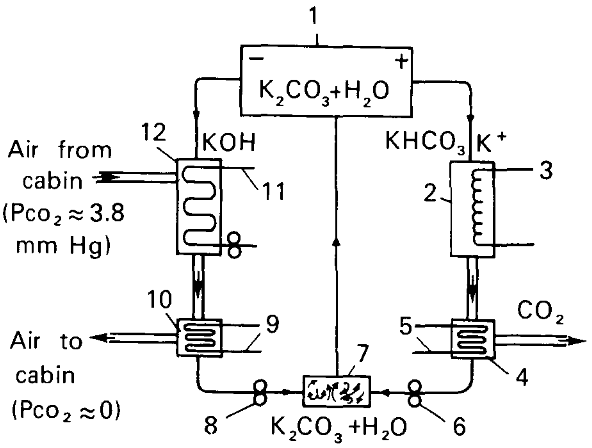

FIGURE 18.—Adsorption of CO_2 by the catalyst (KOH) and resorption of CO_2 electrolyte ($KHCO_3$). 1, electrolyzer; 2, desorber; 3, heating element; 4, 10, heat exchangers-separators; 5, 9, coolant lines; 6, 8, alkali pumps; 7, mixer; 11, coolant line; 12, adsorber.

selectivity, a high degree of electrical conductivity, be stable and resilient over long periods, and not swell.

Ion exchange membranes in electrochemical devices for regeneration of gas atmospheres differ from electrolysis of salt solutions in that they allow the creation of an apparatus which simultaneously carries out several functions: the extraction of oxygen and hydrogen, and clearing the atmosphere of CO_2 with simultaneous extraction of CO_2 in a 100% concentration. In the apparatus with ion exchange membranes, under the effect of an electrical field, directed mass transfer of ions is insured with a determinable charge with the achievement of the necessary concentration in determinable areas and with a physicochemical reaction which leads to intensive chemosorption of CO_2 from the moving air current and to the formation of chemically unstable substances that disintegrate upon the removal of CO_2 gas.

In realistic spaceflight conditions, as with the electrolysis of salt solutions, the organization of electrochemical and physicochemical processes in the electrodialyzer may be accomplished by creating an artificial circulating electrolyte with subsequent separation of gas electrolyte products using a special apparatus, and porous capillary elements.

A line diagram of regeneration of the gas atmosphere in a hermetically sealed cabin, based on the use of an electrochemical device with ion exchange membranes, is shown in Figure 19.

The electrodialyzer "6" (Fig. 19) consists of three ion exchange membranes. The air current from the hermetically sealed cabin flows between ion-exchanging membranes "8," "9" (Fig. 19) where removal of CO_2 takes place through its chemosorportion according to the reaction

$$CO_2+OH^- \rightarrow HCO_3^- \tag{14}$$

$$HCO_3^-+OH^- \rightarrow CO_3^= + H_2O \tag{15}$$

The negatively charged ions HCO_3 and CO_3, under the effect of an electrical field, move between the cation-exchanging and the anion-exchanging membranes, in which the desorption of CO_2 occurs according to the reaction

$$2HCO_3^- \rightarrow CO_3^= + H_2CO_3 \tag{16}$$

$$H_2CO_3 \rightarrow H_2O + CO_2 \uparrow \tag{17}$$

From the electrodialyzer the air current and the gases formed (CO_2, H_2, O_2) move to the corresponding heat exchanger-separators "4," "6," "12," "17" (Fig. 19) in which condensation of water vapor and separation of the liquid phase from the gaseous phase occurs. The liquid phase (an aqueous solution of the electrolyte and water) is forced by a pump "15" (Fig. 19) into the corresponding areas of the electrodialyzer. Purified CO_2 gas is moved into a buffer container "2" (Fig. 19).

Using ion exchange membranes in electrochemical apparatuses allows intensification of the physicochemical processes of absorption and desorption of CO_2 due to creation of optimal conditions for concentrating reacting reagents and significantly lowering diffusion limitations.

However, in this apparatus with ion exchange membranes, in the interelectrode space specific power characteristics are higher than in electrochemical apparatuses with permeable membranes: for 1 l O_2, 16–18 W are required [13, 50, 65, 66, 84, 88, 116].

CO_2 Removal and Concentration by Absorption in an Oxygen-Hydrogen Fuel Element

A system for removal and concentration of cabin atmosphere CO_2 based on oxygen-hydrogen fuel cell technology has the advantage of relatively high chemosorption. This results from decreased limits on diffusion characteristics since, basically, the mass exchange processes depend only on the rate of the fuel cell electrochemical process. A line diagram of the cell of a fuel element is in Figure 20.

The given electrolyzing cell consists of two porous electrodes "2," "5" (Fig. 20) closely abutting a porous interelectrode diaphragm "4." Note that the active portions of the porous diffusion electrode, which is in contact with the liquid electrolyte, is a reaction area of three phases: liquid, gas, and the solid phase of the electrode itself. The air current (O_2, N_2, CO_2) from the hermetically sealed cabin passes through the cathode chamber. On the cathode, an electrochemical reaction occurs which leads to oxygen ionization with the formation of hydroxides, the quantity of which is determined in the process of chemosorption of CO_2. In general, the cathode and anode processes may be presented

On the cathode

$$O_2+2H_2O+4\acute{e}\rightarrow 4OH^- \quad (18)$$

$$2CO_2+4OH^-\rightarrow 2CO_3^{=}+2H_2O \quad (19)$$

On the anode

$$2H_2+4OH^-\rightarrow 4H_2O+4\acute{e} \quad (20)$$

$$2CO_3^{=}+2H_2O\rightarrow 4OH^-+2CO_2 \quad (21)$$

The alternate reaction of the electrochemical concentrator has the form

$$O_2+CO_2+2H_2\rightarrow 2H_2+CO_2+\text{energy} \quad (22)$$

In the given electrochemical apparatus, it is assumed that CO_2 will be extracted not in the pure form, but in a determinable proportion with H_2. This type of gas system (CO_2—H_2) may be successfully utilized up to the necessary final substances (C, CH_4, H_2O). It is necessary to consider the removal of water, one of the problems of organizing the technologic process; this water is formed as a result of the chemical reaction. In principle, the following means of removing H_2O may be used:

- a process with a temperature near 100° C, or a higher temperature with increased pressure;
- a process with lower temperatures and decreased pressure;
- gas circulation to insure a temperature difference between the gas and the electrolyte.

A line diagram for cleansing the atmosphere of CO_2, based on the use of a fuel element, is in Figure 21.

The electrochemical system for removing CO_2 consists of gas air current exciters "1," "4" (Fig. 21), a fuel element "3," and two separate devices "2," "6," which are located at the entrance and exit of the gas air currents of the fuel element, which act as basic conforming and stabilizing elements within the system. The water heat exchanger "2" accomplishes the role of a fuel element temperature stabilizer, as well as an electrolyte concentration stabilizer. The air current which flows through the cathode chamber, as the result of diffusion processes, and purely mechanical reaction with the electrolytes, is saturated with water, which changes to some degree the concentration of the electrolyte, and thus has an effect on the quality of organization of the electrochemical process. To stabilize the process, a component is used in the system "2" (Fig 21) to transfer water which was carried away by the exiting current to the entering

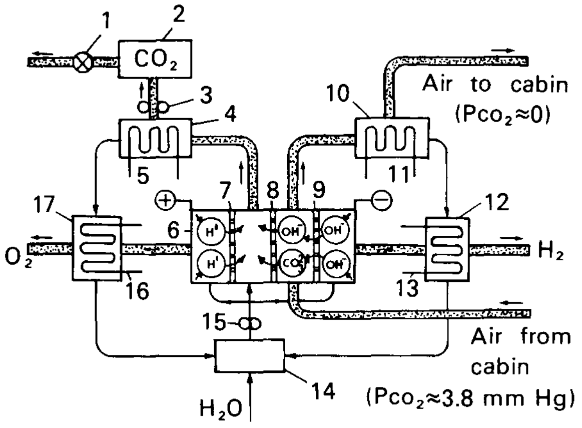

FIGURE 19.—Electrochemical device electrodialyzer with ion exchange membranes. 1, reducer; 2, buffer space with CO_2 gas; 3, compressor; 4, 10, 12, 17, heat exchanger-separators; 5, 11, 13, 16, coolant lines; 6, electrodialyzer; 7, 8, 9, cation and anion membranes; 14 intermediate water container; 15, alkali pump.

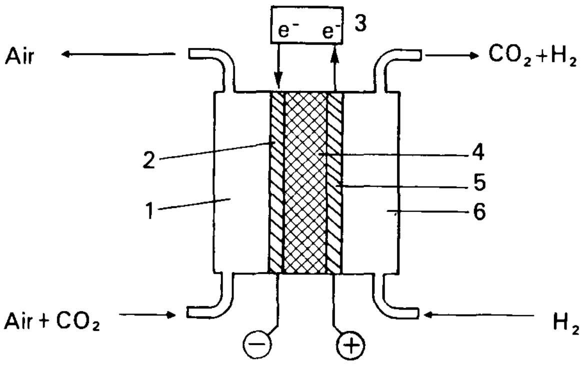

FIGURE 20.—Carbon dioxide concentrator based on use of a fuel element. 1, cathode chamber; 2, cathode; 3, electrical load; 4, porous interelectrode element; 5, anode; 6, anode chamber.

current. The heat exchanger-dehumidifier "6" condenses H_2O from a gaseous mixture of CO_2-H_2O and simultaneously divides the liquid phase thereby formed from the gaseous phase.

The system described has considerable interest because of its determinable simplicity of design and its small energy requirements [9, 32, 50, 128, 130].

Aspects for Systemizing Basic Methods of Separating and Concentrating CO_2 Gas

Systems for removing CO_2 from the atmosphere of the hermetically sealed cabin and for concentrating it, influence the design of oxygen regeneration systems (in systems with oxygen in circulation), with predetermined selection of technologic components for extracting oxygen from CO_2 or H_2O or from CO_2-H_2O.

Methods of removing CO_2 gas from the air may be divided by the phase principle into *gas-solid body* and *gas-liquid-solid body.* The design of adsorptional processes in dynamic weightlessness is simple and does not require new principles, as opposed to absorptional processes. A certain difficulty notwithstanding, absorptional processes are unique because they are compact and because of the continuous nature of their absorptional-desorptional processes.

On the basis of published disclosures at present [13, 27, 56, 99] and work that systematizes systems data [50], the methods of removing CO_2 from the air and concentrating it as described above, may be presented in a single combined form (Figs. 22, 23).

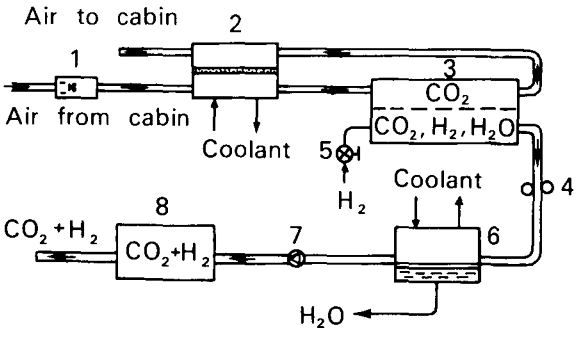

FIGURE 21.—Removal of CO_2 from the air, based on use of a fuel element. 1, air intake; 2, dehumidifier heat exchanger; 3, fuel element; 4, compressor; 5, output regulator; 6, dehumidifier-heat exchanger; 7, reverse valve; 8, adapting buffer element.

The selection of this or that method will be determined, primarily, by the reliability and stability of the technologic processes over a long period of use.

Scientists in the USSR and the US give practically the same attention to all the methods presented above [2, 50, 99], which may explain the objectiveness of the dialectic approach to solving scientific problems, leading to a unity of concepts and principles.

OXYGEN REGENERATION IN HERMETICALLY SEALED ENVIRONMENTS

Methods of Oxygen Supply

The oxygen supply may be from stores of pure oxygen, from oxygen-containing substances obtained from the Earth or intermediate stations, or from oxygen contained in liquid and gaseous products eliminated by man (water, CO_2 gas). The choice of a particular method as a basic source will be determined by the designation and by the length of time the environment is required.

Methods based on oxygen supplies are limited by the increase of weight and volume with flight duration. Methods based on the use of oxygen reclaimed from waste products of human metabolic activities (H_2O, CO_2), without taking into account sources of electrical energy, are not related to the required duration of the environment [50, 56, 94, 97, 99, 120, 121].

Oxygen Supply Based on Stores of Pure Oxygen

Methods of supplying oxygen from stores of pure oxygen may be divided into: supplies of pure oxygen in the gaseous or the liquid state; and supplies of oxygen-containing substances in which oxygen is found in a state chemically combined with other elements.

It is possible to preserve oxygen in the pure state under these conditions:

in the gaseous state under high pressure;
in the liquid form, under pressure, in the single-phase state;

- in the two-phase state (liquid-gas) under pressure;
- in the single-phase state under pressure at super critical temperatures;
- in the solid form at supercool temperatures (−218° C).

At normal temperature and pressure, oxygen is a colorless gas; it is odorless, tasteless, and is somewhat heavier than air. Its density relative to air is 1.1. The mass of 1 m^3 of oxygen at 0° C (273° K) and 760 mm Hg equals 1.43 kg; at 20° C (293° K) and the same pressure it is 1.33 kg.

When oxygen is cooled at atmospheric pressure to −183° C, it becomes a transparent bluish liquid, which quickly evaporates at room temperature. With further cooling to −218.7° C, liquid oxygen changes to the solid state—bluish crystals with a density of 1.46 g/cm^3.

One l liquid oxygen has a mass of 1.1321 kg and upon evaporation forms 850 l of gaseous oxygen (at 20° C and 760 mm Hg); 1 kg of liquid oxygen upon evaporation (20° C and 760 mm Hg) forms 750 l of gaseous oxygen.

It is expedient to have supplies of gases under high pressure primarily for reliability and simplicity of use during real space flight. This method may be considered optimal for oxygen regeneration during comparatively short-term flights. The general approach for planning such an oxygen regeneration system involves optimizing high-pressure cylinders by finding the corresponding relationship between the pressure of the gas and the weight of the cylinders. In this instance, the high-pressure compressibility of oxygen is determinative: at a pressure which exceeds several hundred atmospheres, the compressibility of the gas decreases to the point of causing an unwarranted increase in the weight and volume of the cylinders.

Figure 24 shows the change in the total mass and volume of a spherical oxygen cylinder with respect to pressure [123]. It can be seen from the drawing that the combination of mass and volume will be optimal at a pressure approximately equal to 575 atm. When basic means of oxygen supply are evaluated comparatively, it is expedient to introduce the coefficient which characterizes the degree of structural perfection.

On the basis of conclusions [122], the initial weight of a system may be represented

$$G_l=(G_s+G_a)n \tag{23}$$

where G_l is the initial weight of the system at launch; G_s, the weight of supplies (e.g., oxygen); G_a, the total weight of the entire assembly (weight capacity); and n, number of days of the flight.

Introducing the coefficient

$$\alpha=\frac{G_a}{G_s+G_a} \tag{24}$$

all systems may be represented as

$$G_l=\frac{G_s n}{l-\alpha} \tag{25}$$

It is obvious from Equation 25 that the smaller the coefficient α, the smaller the weight of the system, and the more ideal its design.

When storing oxygen in cylinders (steel or titanium alloys) under high pressure with the most ideal cylinder design, 2–3 kg of cylinder weight is required for each kg of oxygen; that is, the coefficient α is 0.66–0.75. Considering the weight of accessories (stopcocks, reducers, conducting pipes, bracing parts, and controls), the coefficient α reaches a magnitude of approximately 0.8.

During space flights of approximately 20 days, it is preferable to use an oxygen regeneration system based on the use of liquid oxygen, which has several advantages over storing gaseous oxygen [54] under high pressure. Due to the lower storage pressure, the weight and volume of the liquid oxygen container is significantly decreased.

During development and creation of such systems, particular attention must be paid to:

- insuring thermoinsulation of the containers to minimize undesirable evaporation of the liquid oxygen;
- creating conditions for reliable conversion of the oxygen from the liquid to the gas state, and its supply to the spacecrew with necessary speed and in sufficient quantity in weightlessness;
- controlling the state and consumption of liquid oxygen;
- insuring storing conditions for liquid oxygen

and accident-free release of pressure from the formation of gaseous oxygen during the storage period.

When storing liquid oxygen, various materials are used for container insulation: magnesium carbonate, mipor, aerogel, perlite, and others. In the most ideal designs of liquid oxygen containers, 1 kg of oxygen requires not less than 1.2 kg of capacity weight; that is the coefficient α in this case is equal to ~ 0.55 [122].

A line diagram of an oxygen regeneration system based on the use of liquid oxygen is in Figure 25. In the given system, oxygen is supplied from the cryogenic container by means of its replacement by an elastic volume "10" (Fig. 25) in which an inert gas (helium) equal to the necessary quantity enters the container.

Storing liquid oxygen in the pure form is possible only when constant temperature of the entire liquid mass is maintained. With an unequal heat supply in weightless conditions, a localized boiling may occur in the boundary layer; that is, oxygen conversion into the gaseous state, which leads to unstable function of the system.

The system of storing liquid oxygen presented above is quite complex, since it requires two tanks, under pressure, and a system of pressure regulation. The reliability of this system depends, in the first place, on the reliability of the elastic displacement chamber, into which the helium is fed, and on its capability to withstand multiple deformations at low temperature.

Liquid oxygen can be stored in the two-phase state as a mixture of liquid and vapor. In this instance, the total oxygen system is significantly simplified, but a very serious problem arises with regard to separating the gaseous and liquid phases in weightlessness.

A method of storing oxygen at supercritical temperature may be considered vastly simpler and more advantageous. The critical temperature (−118.8° C), above which oxygen is not compressible, corresponds to a critical pressure of 49.7 atm.

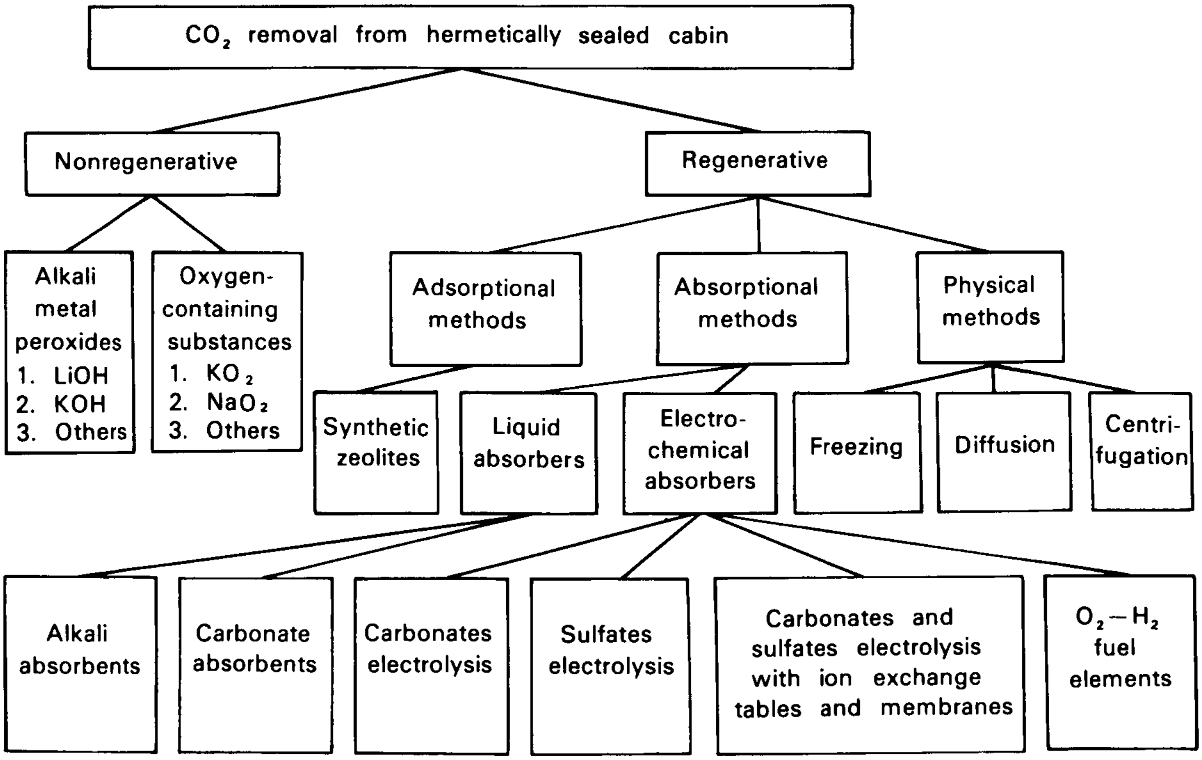

FIGURE 22.—Removal of carbon dioxide from air of closed system.

A diagram for an oxygen supply system based on the use of oxygen maintained under supercritical conditions is in Figure 26. The oxygen displacement from the tank, in this system, is by means of an increase in pressure as a result of internally supplied heat. A phase separation is not required in this system and its use in weightlessness does not cause difficulties.

Of the three methods described for storing oxygen maintained in the fluid and the supercritical states, the latter means is preferable at present as the simplest and most economical. The coefficient α of such systems is approximately 0.52. Such an oxygen supply system was used in the US Gemini spacecraft [122].

Storing oxygen in the solid form at supercool temperatures on the order of −218° C is of interest. However, practical design of a system will require solution of such highly important technical problems as reliability of thermoinsulation of the oxygen, and extremely accurate regulation of the heat supply for converting oxygen into the gaseous state [45, 122].

Oxygen Systems Based on Supplies of Oxygen-Containing Substances

Systems with supplies of oxygen in chemically combined form are more advantageous than systems with pure oxygen supplies, since with the formation of oxygen for respiration, simultaneously they allow absorption of the CO_2 and toxic substances. Compounds used in the life-support systems may be classified as: peroxides, hyperoxides, and ozonides of alkaline metals and alkaline earth metals; hydrogen peroxide, chlorates, and perchlorates of alkali and alkaline earth metals. The basic characteristics of these oxygen-containing substances are shown in Table 4 [99, 122].

The use of oxygen-containing compounds for air regeneration is based on the chemical reaction of these substances with water vapor and CO_2 gas. The use of hyperoxides and ozonides results in the liberation of oxygen from the interaction reactions with water vapor

$$2MeO_{2(s)} + H_2O_{(v)} = 2MeOH_{(s)} + 3/2\,O_{2(g)} \quad (26)$$

$$2MeO_{3(s)} + H_2O_{(v)} = 2MeOH_{(s)} + 5/2\,O_{2(g)} \quad (27)$$

where s is the solid state; v, vapor; g, gas; and Me, alkali metal.

Alkali metal hydroxides, formed during these reactions, absorb carbon dioxide gas from the air and form carbonates and bicarbonates.

$$2MeOH_{(s)} + CO_{2(g)} = Me_2CO_{3(s)} + H_2O_{(l)} \quad (28)$$

$$2MeOH_{(s)} + 2CO_{2(g)} = 2MeHCO_{3(s)} \quad (29)$$

where l = liquid.

Based on these stoichiometric relationships, the theoretical coefficient which characterizes the relationship of CO_2 absorption to the quantity of liberated O_2, $\beta \dfrac{V\,CO_2}{V\,O_2}$, in the system with hyperoxides will change from 0.67 with the formation of carbonate alone, to 1.33 with the for-

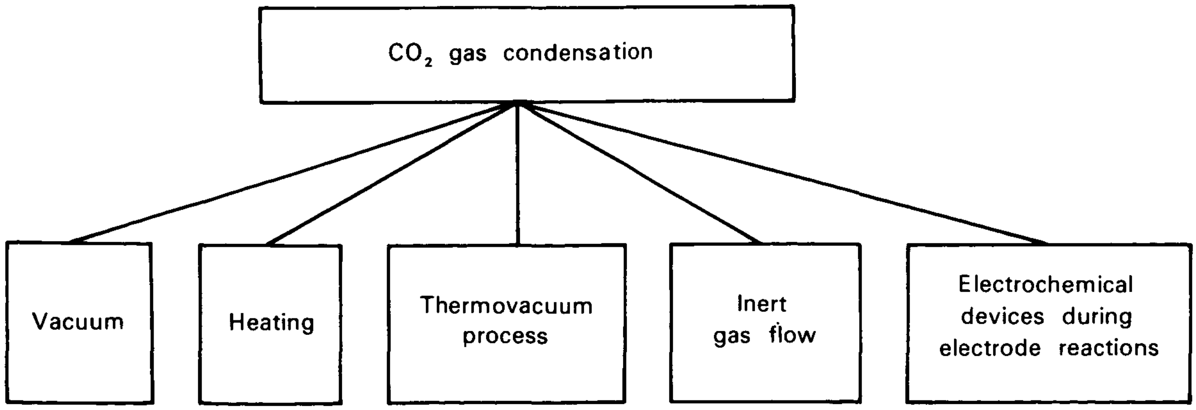

FIGURE 23. — Concentration of carbon dioxide gas.

mation of bicarbonate only, while in the system with ozonides it varies from 0.40 to 0.80 [122].

Lithium peroxide Li_2O_2 has special interest with regard to air regeneration, since at a certain level of atmospheric humidity it reacts directly with carbon dioxide gas and forms oxygen and lithium bicarbonate

$$Li_2O_{2(s)}+CO_{2(g)}=Li_2CO_{3(s)}+\tfrac{1}{2}O_{2(g)} \quad (30)$$

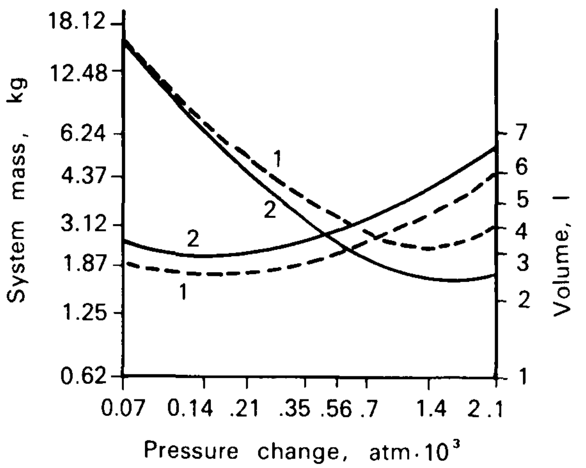

FIGURE 24.—Mass and volume of a spherical oxygen container relative to pressure. 1, steel cylinder; 2, titanium alloy cylinder.

In this case, 1 kg lithium peroxide allows the removal of 0.96 kg carbon dioxide and at the same time returns 0.348 kg oxygen to the system. The coefficient β, using lithium peroxide only, will equal 2.0.

Absorption of carbon dioxide gas and oxygen liberation occur as a result of two separate reactions. Lithium peroxide and water vapor, in reaction, first release the active absorbents LiOH, $LiOH \cdot H_2O$ and hydrogen peroxide

$$Li_2O_{2(s)}+2H_2O_{(v)}=2LiOH_{(s)}+H_2O_{2(l)} \quad (31)$$

$$LiOH_{(s)}+H_2O_{(v)}=LiOH \cdot H_2O_{(s)} \quad (32)$$

after which absorption of carbon dioxide occurs

$$2LiOH_{(s)}+CO_{2(g)}=Li_2CO_{3(s)}+H_2O_{(l)} \quad (33)$$

$$2LiOH \cdot H_2O_{(s)}+CO_{2(g)}=Li_2CO_{3(s)}+H_2O_{(l)} \quad (34)$$

Further, as a result of the liberation of hydrogen peroxide, oxygen is formed

$$H_2O_{2(e)}=H_2O_{(v)}+\tfrac{1}{2}O_{2(g)} \quad (35)$$

Systems with supplies of hydrogen peroxide may be successfully used for providing oxygen to the crew. These systems are more economical with respect to mass and dimensions than systems using gaseous oxygen.

Sodium chlorate ($NaClO_3$) in the form of candles may be used for supplying oxygen to the

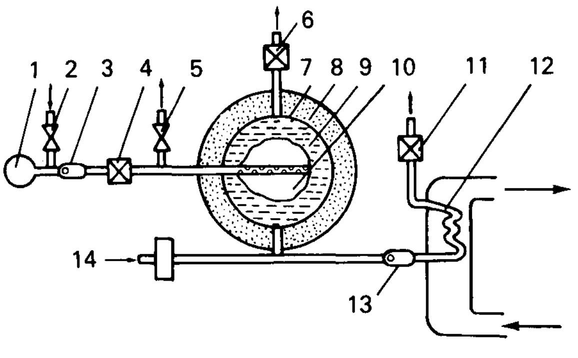

FIGURE 25.—Oxygen regeneration system based on use of liquid oxygen. 1, cylinder with helium under high pressure; 2, control cock for helium cylinder; 3, reverse valve; 4, reducer; 5, surplus pressure release cock; 6, surplus pressure release valve; 7, cryogenic vessel; 8, powder vacuum insulator; 9, liquid oxygen; 10, elastic helium displacement chamber; 11, output regulator; 12, heat exchange device; 13, reverse valve; 14, liquid oxygen input.

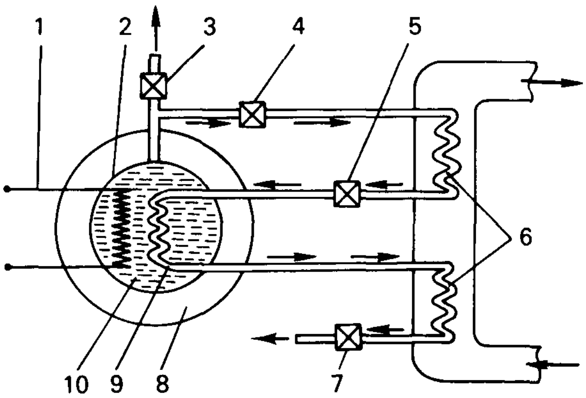

FIGURE 26.—Oxygen regeneration system based on use of oxygen in supercritical conditions. 1, supplementary heat source; 2, container; 3, drain valve for oxygen and surplus pressure; 4, stopcock; 5, heat regulator valve; 6, heat exchanger; 7, pressure reducer; 8, powder vacuum insulator; 9, internal heat exchanger; 10, oxygen in supercritical state.

crew. In this case thermodecomposition of the sodium chlorate is used, the sodium chlorate breaking down at a temperature of 700°–800° C into sodium chloride and oxygen by the reaction

$$2NaClO_3 = 2NaCl + 3O_2 + 232 \text{ kcal/kg} \qquad (36)$$

A massive oxygen yield of 45% is theoretically possible in this instance, but actually equals 40%. Heat, which is necessary to maintain the reaction, is liberated during oxidation of a small quantity of powdered iron which is mixed with chlorate

$$2Fe + O_2 = 2FeO + 885 \text{ kcal/kg} \qquad (37)$$

The candles may be "burned" with a phosphorous match, by electrical firing, or by the use of a timing charge.

The advantages of storing oxygen in the chemically combined state are obvious compared with cryogenic methods of storing. Actually, while the most ideal cryogenic methods of storing oxygen can obtain a coefficient of $\alpha = 0.52$, the method using sodium hyperoxide insures $\alpha = 0.56$ with simultaneous absorption of CO_2. Taking into account the inevitable absorption of CO_2, the coefficient α of the cryogenic method will be equal to 0.73.

In conclusion, the advantages of an air regeneration system using oxygen stored in the chemically combined form are:

a sufficiently wide temperature range (20°±10° C), relative humidity (30%–70%), barometric pressure (760±500 mm Hg), in which the systems effectively operate;

the capability of absorbing gaseous waste products eliminated in the process of human metabolism;

the capability to withstand vibration and a high stress factor without disruptions;

heat explosion-proof;

simplicity of design;

low power requirements compared with other systems;

high operational reliability;

the possibility of process automation for creating the necessary microclimate in the cabin.

TABLE 4.—*Basic Characteristics of Oxygen-Containing Substances*

Oxygen-containing substances	Chemical formula	Kg O_2 in 1 kg	Density kg/dm^3
Lithium ozonide	LiO_3	0.73	
Sodium ozonide	NaO_3	0.563	
Potassium ozonide	KO_3	0.46	
Lithium hyperoxide	LiO_2	0.61	
Sodium hyperoxide	NaO_2	0.436	
Potassium hyperoxide	KO_2	0.338	0.655
Calcium hyperoxide	$Ca(O_2)_2$	0.46	
Lithium peroxide	Li_2O_2	0.348	2.14
Hydrogen peroxide	H_2O_2	0.471	1.42
Lithium perchlorate	$LiClO_4$	0.601	2.43
Sodium chlorate	$NaClO_3$	0.451	2.26

In the Soviet spacecraft Vostok and Voskhod, as well as in the Soyuz series, oxygen-containing substances, specifically potassium hyperoxide, were successfully used as regenerative materials [23, 86, 99, 120, 121, 122, 123].

Physicochemical Methods of Oxygen Supply

Long space flights, a qualitatively new stage, determine the design principles of human life-support systems. Planning and developing systems for such flights make it necessary to strive to create a practically complete circulation of substances by means of maximum utilization of the waste products of human metabolism.

Carbon dioxide gas and water, as the basic oxygen-containing substances eliminated by man, contain 3.5 times greater oxygen than is required for human respiration. The total quantity of CO_2 gas eliminated in a day by man contains approximately 650 g oxygen, which comprises approximately 82% of the required amount.

Because of the need for creating water circulation, it has been suggested that the deficient quantity of oxygen (150 g) be obtained from the 336 g of metabolic water eliminated by man per day.

Selecting means of obtaining oxygen in physicochemical gas atmosphere regeneration systems is determined by the design principle of the total oxygen supply system and, specifically, by the fact that water or CO_2, in the capacity of a terminal substance, is used as a base from which oxygen is obtained.

When oxygen is obtained directly from CO_2 gas, the necessity arises for supplementary extraction of oxygen from water by the same method as from CO_2 gas, or, if necessary, its extraction by some other method. A system of oxygen supply may also be designed, when, in the capacity of a terminal substance containing the necessary amount of oxygen, only water will be used. In this case it is necessary to convert CO_2 gas to water using the available physicochemical methods.

When using water or carbon dioxide gas as terminal oxygen-containing substances, the expediency of their use is determined by their physicochemical properties, and by the possibility of extracting oxygen from them in realistic spaceflight conditions. Carbon dioxide gas is force-fed into the corresponding devices, which may be successfully used under both terrestrial conditions and those significantly different. In this case, in *gas-solid body* systems, during their use under conditions differing from terrestrial, qualitatively new structural designs, with changes in the basic technologic processes are not required.

Water is a fluid whose conditions depend on the magnitude of the gravitational field acting upon it. In terrestrial conditions, under the effect of its own weight, it has determined characteristics in open vessels. It is significantly differentiated with respect to specific gravity from gaseous substances, e.g., oxygen and hydrogen. In conditions of weightlessness, determinants in the behavior of a liquid will be the forces developed by forces which arise during the interaction of the liquid with the surrounding medium, both gaseous and solid bodies.

In *gas-liquid-solid body* systems, in which the physicochemical processes are determined by the effect of gravitational forces, during their use in conditions of decreased gravitation or weightlessness, a quantitatively new process design is necessary.

The following electrochemical methods may be considered possible means of extracting oxygen from water:

electrolysis of aqueous alkali solutions;
electrolysis of aqueous salt solutions;
electrolysis of alkali and salt solutions using ion exchange membranes;
electrolysis of CO_2 and H_2O using solid electrolytes;
electrolysis of an air-vapor mixture based on phosphorus pentoxide.

Methods of gas electrochemistry may have practical use as a means of extracting oxygen from CO_2:

electrolysis with use of solid electrolytes;
electrolysis of alloys of alkali metal salts;
the low temperature of plasma method;
methods of electrical discharges in gases;
method of photocatalysis.

When extracting O_2 from H_2O, H_2 is simultaneously formed, while when extracting O_2 from CO_2, CO is simultaneously formed. Therefore, taking into account the maximum possible utilization of substances eliminated in human metabolic activity, in physicochemical oxygen regeneration systems, the use of intermediate components which are designed for utilizing H_2 and CO is provided for.

Present methods of utilizing CO_2, H_2, and CO by means of catalytic hydrogenation to various terminal products—CH_4, CO, C, H_2O—by the well-known Sabatier, Boudoir, and Bosch reactions have been found to be practical. In this case, physicochemical methods of extracting oxygen from basic oxygen-containing substances (H_2O, CO_2), make possible a quantitative division of reactive phases and significant differences in the physicochemical processes themselves.

The methods of extracting oxygen, enumerated above, are divided into these different physicochemical processes:

electrochemical methods of extracting oxygen from water and carbon dioxide gas;
low temperature of plasma method;
photocatalysis method;
method of electrical discharge in gases;
catalytic methods of utilizing CO_2 gas.

Qualitatively, the reactive phases are necessarily divided into two-phase and three-phase systems; that is *gas-solid body* and *gas-liquid-solid body*.

Of the methods used in oxygen regeneration systems (described above), those systems are interesting where the capacity of working phases are in mutual contact and the gas, liquid, and solid body are used; that is, three-phase systems—*gas-liquid-solid body*—from the point of view of their practical operation under decreased gravitational force or weightlessness. [2, 99, 122].

Supplying Oxygen by Water Decomposition During Electrolysis of Alkali Solutions

Electrolysis is a combination of oxidation and reduction processes, which occur on electrodes during the electrolysis of water in a potassium hydroxide solution

on the cathode

$$2H_2O + 2\bar{e} \rightarrow 2H^+ + 2OH^- \tag{38}$$

$$2H^+ \rightarrow H_2 \tag{39}$$

on the anode

$$2OH^- - 2\bar{e} \rightarrow 2OH \tag{40}$$

$$2OH \rightarrow H_2O + O \tag{41}$$

$$2O \rightarrow O_2 \tag{42}$$

Extracting oxygen from water generally takes place according to the formula

$$2H_2O \rightarrow O_2 + 2H_2$$

Efficiency of the oxidization-reduction electrochemical process depends on the electrode material, means of supplying the reagents to the reaction zone, temperature, concentration of the electrolyte, specific reaction speed-current density, and so forth. Weight, volume, and the electrical energy requirements of the electrolyzing installations depend upon the current density. Electrochemical processes at present occur at a current density of from 100 to 200 mA/cm^2. The temperature of the electrochemical process is determined, basically, by the physicochemical properties of the electrolyte, water, and specifically on their boiling temperatures which are maintained in the range 80°–100° C. Concentration of the electrolyte is selected so that it will insure maximum possible electrical conductivity in the inner electrode space.

More than a half century of experience in the electrolysis of water makes it possible to extract oxygen and hydrogen in practically pure forms (purity higher than 99.9%).

Water-decomposition electrolyte systems used for supplying oxygen to the spacecrew require the solution of quantitatively new problems, not encountered in conducting electrolysis earlier. To insure stability in electrolytic decomposition of water into oxygen and hydrogen, certain basic conditions must be maintained:

good contact between the electrolyte and the electrodes;
a cathode-electrolyte-anode electrical circuit must be present;
forming gases must be removed from the electrodes and electrolytes;
forming gases (H_2 and O_2) must be separated from each other;
a given concentration of electrolyte in the interelectrode space must be maintained;
an uninterrupted supply of water, in necessary amounts, must be fed to the electrolyzer.

When an electrolyzer is used as a device for extracting oxygen in a life-support system, it is necessary to take into account the removal of gases from the electrolyte aerosol, water vapor and hydrogen impurities in the oxygen, as well as returning the aerosol to the electrolyte and the water vapor to the electrolyzer.

In terrestrial electrolysis installations, the organization of electrochemical and physicochemical processes is determined basically by the effect of the Earth's gravity. A detailed examination of the basic physicochemical phenomenon in the electrolyzer shows that it is impossible to use terrestrial electrolysis installations in actual space flight.

The requirements for a good contact between the electrolyte and the electrodes are met as a result of the wettability of the electrodes by the electrolyte. In physics, wettability is characterized by the boundary angle zero, which, for equilibrium conditions, is expressed by the equation

$$\cos \theta = \frac{\sigma 1.3 - \sigma 1.2}{\sigma 2.3} \tag{44}$$

where cos θ is the boundary angle of wettability, radians: $\sigma 1.3$, the surface tension between the solid body and the gas, n/m; σ1.2 equals the surface tension between the solid body and the liquid, n/m; and σ2.3, the surface tension between the liquid and the gas, n/m. Surface tension depends on the nature of the substance and is characterized by the force of intermolecular attraction. In this case, wetting does not depend on the force of the Earth's gravity; therefore the equation is useful in weightlessness.

The presence of an electrical cathode-electrolyte-anode circuit, which is insured in terrestrial conditions, results from a determinable state of the electrolyte in the vessel (under the effect of its own weight) and in which natural separation of the forming electrolytic gases occurs. In conditions of weightlessness, obviously, this will be disrupted.

If no force acts upon a liquid other than the force of molecular attraction in the surface layer, then the liquid will be in equilibrium, in which these forces are normal to its surface; that is, the mass of the liquid under the effect of these forces becomes spherical.

In weightlessness, differences in specific gravity of the gas in the electrolyte will not exist; that is, the force which insures separation of gases from the electrolyte will be absent. The effect of the resulting forces of interphase attraction will be manifest only in the initial moment and will gradually decrease to zero as the result of an inhibiting effect from the electrolyte layer. In a terrestrial electrolyzing device, under weightlessness, in the initial period the process of electrolytic decomposition of water will take place. The bubbles of electrolytic gases forming will accumulate in the interelectrode space, causing pressure in the interelectrode space to increase as the gas electrolyte mixture moves to the gas-removal canal. With an increase of pressure, the electrical resistance of the interelectrode space increases simultaneously.

When using a direct current electrical energy source, which changes within a small range, in accordance with Ohm's law, an increase in resistance leads to a decrease of the current force. A decrease of current force leads to a decrease in the quantity of substances liberated in the electrolysis process. In the confines of the interelectrode element, resistance will incline toward infinity, while the current force will incline toward zero; i.e., there will finally come a moment at which the process of electrolytic decomposition of water stops.

In weightlessness, the effect of the force of attraction may be replaced by creation of an artificial force field. Such a field may be created by rotating the entire electrolysis device, or separate parts of it, as well as by forced injection of the electrolyte through the interelectrode space with subsequent separation of gases from the electrolyte in special centrifugal separators, or in devices with selected elements. In a centrifugal field, a liquid assumes a completely defined state with a completely defined free surface, which will insure an electrical cathode-electrolyte-anode circuit.

In the rotating electrolytic device, bubbles of gas forming under the effect of centrifugal field forces, will move in the direction of the axis of rotation; that is, the direction of the phase interface.

To provide conditions for separating gas bubbles from the electrolyte, it is expedient that acceleration of the centrifugal field at the level of the phase interface be equal to the acceleration of the Earth's gravitational force. Angular rotational speed and radius are selected according to structural considerations.

A diagram of a monopolar rotating electrolytic device is in Figure 27. In this device, an electric motor and drive "26," "25," "7" (Fig. 27) rotate the moving part. The electrolyte "11" (Fig. 27) is distributed in the centrifugal field along the equipotential surface. When the electrical energy source of the electrodes is turned on, bubbles of oxygen and hydrogen begin to be released through the collector coupling on the surface of the electrodes. To separate the electrolyte aerosol from the gases, labyrinth centrifugal separators "13" (Fig. 27) are used which are a collection of membranes of various lengths that rotate together with the drum of the device. The diaphragms are porous elements which are well wetted with electrolyte. Hydrogen impurities are removed from the oxygen in the burning columns; hydrogen in the oxygen is removed by catalytic combustion using a palladium catalyzer. The electrolyzer water supply is maintained constantly

C-2

(in doses) from a reservoir under pressure, and dependent upon the work regime.

The rotating electrolyzing device has a series of elements that must be changed during operation. The moving gasket couplings, brushes, collector, bearings, reduction gears, and motor require periodic checking, cleaning, and replacement. The reliability of such assemblies decreases with time, and the rotation process requires additional energy.

A diagram of an electrolyzing installation with rotating diaphragms is in Figure 28, which shows that a centrifugal force field is created as a result of the diaphragm's rotation. A centrifugal force field may also be created from the electrodes' rotating, but in that instance with respect to the energy requirements, the design is less advantageous.

The advantage of this system compared with the completely rotating electrolyzing device is that the body of the electrolyzer is motionless, which significantly decreases the number of moving gasket couplings. In the device with the moving diaphragms, the collector supply of electrical energy is absent. But, as in the former schematic, devices of this type require periodic replacement of certain rotating parts.

A monopolar electrolyzing device with rotating diaphragms and electrodes is diagramed in Figure 29. The centrifugal force field is created from the rotation of diaphragms and electrodes. The distinguishing feature of this device is its use of reticulated electrodes, which closely abut the diaphragms.

Electrolytic decomposition of water is accomplished in weightlessness by creation of a directed artificial electrolyte circulation in the interelectrode space, with subsequent separation of gas electrolyte mixtures in the centrifugal separators or in the devices with selective elements, closely approximating conditions for electrolysis on Earth. Centrifugal separators in this plan must simultaneously serve as a device which pushes the electrolyte through the interelectrode space. The work principle of this

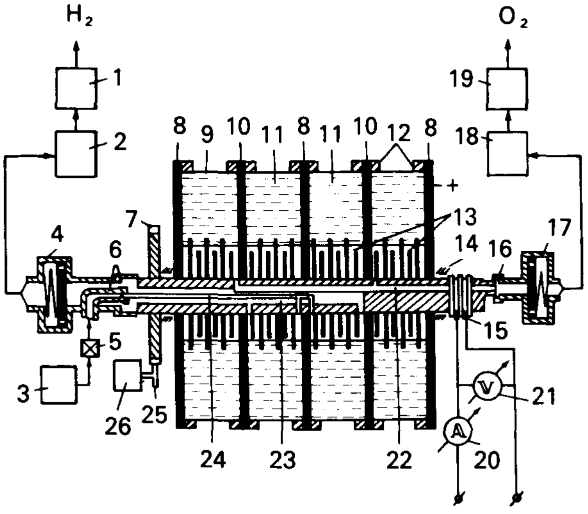

FIGURE 27.—Rotary electrolyte installation. 1, 19, burning columns for oxygen in hydrogen and hydrogen in oxygen mixtures; 2, 18, fine cleaning filters; 3, water reservoir; 4, 17, reverse spring valves; 5, solenoid valve; 6, 16, moving gasket joints for gas and water mains; 7, rotation shaft of electrolysis device with primary geared reducer to engine; 8, electrodes; 9, main body of electrolysis device; 10, diaphragms; 11, electrolyte; 12, cover gaskets; 13, labyrinth separators; 14, shaft bearings; 15, collector electrical connections; 20, ammeter; 21, voltmeter; 22, oxygen canal; 23, hydrogen canal; 24, drinking water inlet; 25, output reducing gear; 26, reducer with motor.

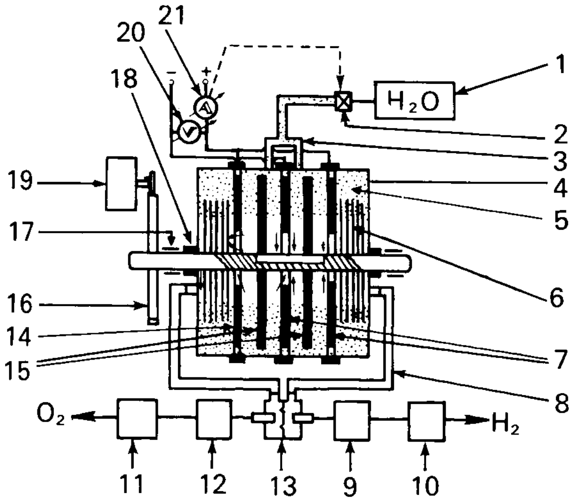

FIGURE 28.—Installation with the rotary diaphragm. 1, water reservoir; 2, solenoid valve; 3, input water pipes; 4, main electrolyzer body; 5, electrolyte; 6, centrifugal labyrinth separators; 7, 15, electrodes; 8, output gas pipes; 9, 12, fine cleaning filters; 10, 11, burning columns; 13, regulator membrane; 14, diaphragm; 16, shaft for the rotating diaphragm and labyrinth disks with primary reducing gears; 17, shaft bearings; 18, gasket filler rings; 19, reducer with motor; 20, voltmeter; 21, ammeter.

electrolysis device is based on forced removal of formed gas bubbles by the electrolyte current, which is cleansed of gas and which flows with a determined speed from the centrifugal separators. Artificial circulation of the electrolyte with greater effectiveness than in terrestrial devices will decrease the unequal electrolyte concentration in the interelectrode space.

A diagram of a monopolar electrolyzing device with an artificially circulating electrolyte and with separation of the gas electrolyte mixture in centrifugal separators is in Figure 30. In this device, centrifugal separators separate the gas from the electrolyte, which takes place in a centrifugal field created by rotation of blades. The separated gas then passes through a thin cleaning filter and combustion columns. In this diagram, the centrifugal separators simultaneously accomplish the role of pumps, which feed the electrolyte into the interelectrode space. To insure a better supply of the gas electrolyte mixture, and with the objective of better separation of gas from the electrolyte, the feeder pipe is located at a tangent to the axis of rotation of the blades. The drawoff pipe for feeding the electrolyte into the interelectrode space is also located tangentially. The membrane pressure regulator is designed to maintain identical pressure in the gas electrolyte mixture in both the oxygen and hydrogen portions of the cell.

The basic advantage of this design is its greater simplicity of construction compared with those previously described. The electrolysis device in the given system is completely stationary, which simplifies considerably the supply of electrical current, and eliminates the need for connections to the electrical circuit in the moving gasket couplings of the collectors.

The electrolytic decomposition of water in weightlessness, accomplished by creating an artificial force field from rotation of the entire device, or rotation of its separate parts, necessitates periodic replacing of moving assemblies and parts, plus an additional expenditure of electrical energy.

The most expedient means of organizing the electrochemical process in the physicochemical processes accompanying it, in weightlessness, must be those methods based on use of the

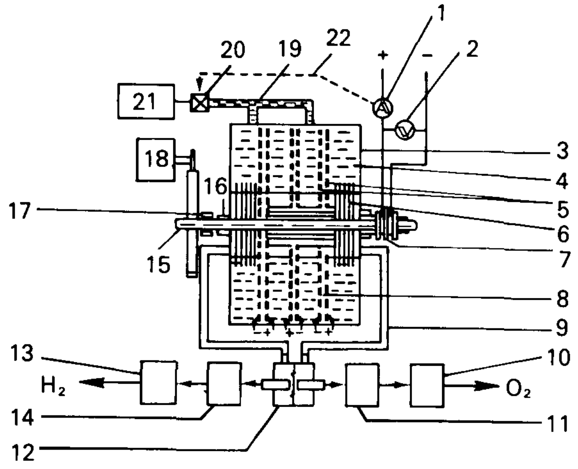

FIGURE 29.—Electrolytic installation with the rotating diaphragm and electrodes. 1, ammeter; 2, voltmeter; 3, main body of installation; 4, electrolyte; 5, reticulated electrodes; 6, centrifugal laybrinth separators; 7, commutator; 8, diaphragms; 9, gas pipe exits; 10, 13, burning columns; 11, 14, fine cleaning filters; 12, pressure regulator membrane; 15, rotation shaft of the electrode diaphragms and the labyrinth disks with a primary geared reducer; 16, gasket filler rings; 17, shaft bearings; 18, motor; 19, water exit pipe; 20, solenoid valve; 21, water reservoir; 22, electrical connection between ammeter and electrocock.

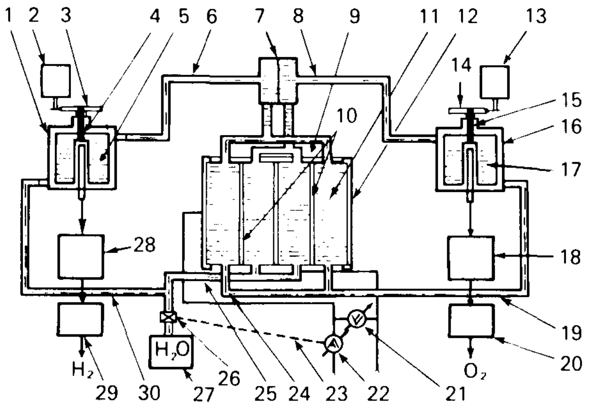

FIGURE 30.—Electrolytic installation with an artificial circulating electrolyte and separation of gas electrolytic mixture by centrifugal separators. 1, 16, main body of the centrifugal separator; 2, 13, drive motors; 3, 14, reduction gear; 4, 15, gasket filler rings; 5, 17, vanes of the centrifugal separators; 6, 8, input centrifugal separator pipes; 7, pressure regulator membrane; 9, output pipes for gas-electrolyte mixture; 10, diaphragms; 11, electrolyte; 12, electrodes; 18, 28, fine cleaning filters; 19, 24, 25, 30, input pipes for the electrolyte; 20, 29, burning columns; 21, voltmeter; 22, ammeter; 23, ammeter-solenoid valve electrical connection; 26, solenoid valve; 27, water reservoir.

physicochemical properties of separated components, and on the electrode and diaphragm materials; that is, the use of porous capillary elements. Devices of this type differ in compactness; they are comparatively light in weight, simple in design, and reliable. In devices of this type, electrolytic gases are separated from the electrolyte by using perforated, reticulated, or porous electrodes, which closely abut the porous interelectrode element. Electrolytic gases are formed where the electrode comes in contact with the porous element, the gas-electrolyte phase interface. The gases formed pass through pores in the electrodes, along the path of least resistance. Reticulated electrodes insure a directed removal of gases. Porous electrodes insure not only a direct removal of gases, but also return the electrolyte aerosol, which is mechanically carried back to the interelectrode space by gases. Therefore, the electrolytic devices with reticulated electrodes are considered the simplest modification of porous electrodes.

Porous materials are extremely effective for intensifying various chemical and electrochemical processes. An internal surface of porous electrodes allows sufficiently high intensity processes to occur in them, with small active speed. Their permeability to currents of liquid and gas allows an actual decrease of limitations, related to the low-diffusion speed of reagent supply by creating a force-directed current from capillarial potentials. In systems with porous electrodes, this is comparatively simple without using special selective membranes and diaphragms, and may be used to separate electrode products. All of this creates favorable conditions for intensive mass exchange. In the systems under examination, it is necessary to move the fluid and gas through porous bodies as the result of a force effect, or the presence of capillarial potential for the liquid phase.

The properties of porous bodies depend largely on their structure. In turn, the structure of porous elements depends on the means of manufacture and the materials used. The state of capillarial equilibrium between two phases, one of which wets and the other which does not wet the solid surface, is determined by the probability of the presence of pores of a determined radius at a determined point of the porous medium.

An electrolytic cell with porous electrodes and interelectrode elements is in Figure 31. The electrolytic cell consists of porous electrodes "2," "6," (Fig. 31) in a porous interelectrode element "3." The electrodes and the porous element are pressed closely together. The interelectrode element of uniform structure consists only of fine pores. The porous electrodes include both coarse and fine pores.

Questions concerning the flow design and the movement of water to the reacting surfaces of the electrodes have exceptional significance for insuring the stability of the electrochemical process with porous capillary elements. Supplying water for decomposition may be accomplished:

- along the periphery of the porous interelectrode element;
- along channels located in the interelectrode element by means of capillarial saturation or by creating an artificially circulating electrolyte;
- through a porous capillary element with a

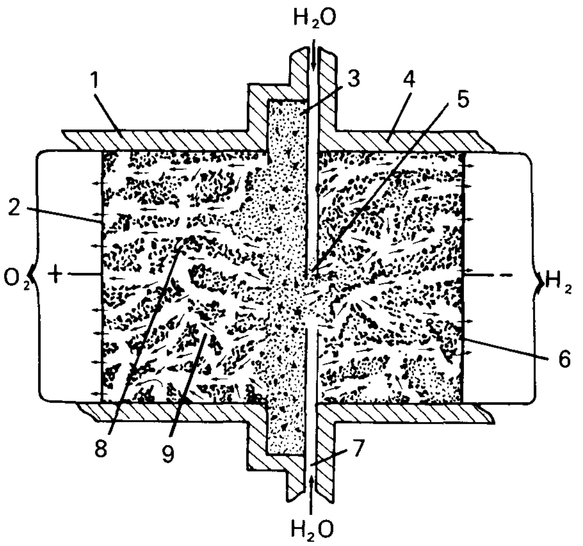

FIGURE 31.—Electrolytic cell with porous electrodes in interelectrode elements. 1, main body of oxygen electrode; 2, porous oxygen electrode; 3, porous interelectrode element; 4, main body of hydrogen electrode; 5, feeder canal for drinking water; 6, porous hydrogen electrode; 7, water feeder; 8, fine pores; 9, coarse pores [51].

monodispersed structure from the rear side of the hydrogen electrode;

- by water vapor diffusion through the hydrogen cavity of the cathode to the area with a higher electrolyte concentration.

Selecting a method of water supply for decomposition is determined by three requirements:

- reliability of the water supply to the reaction surface with regard to the speed of the electrochemical process;
- maximum possible decrease of concentration phenomena naturally occurring in the interelectrode space as the result of discharges of one type of ion (OH^-);
- excluding the formation of gas-air cushions (vapor locks) in the liquid main lines for supplying water for decomposition.

In accordance with these requirements, and taking into account possible methods of transporting water, important factors to consider include means which are based on artificially circulating electrolytes with water supply or water vapor supply coming from the rear side of the hydrogen electrode.

The electrolytic cell in Figure 31 has no moving parts or devices for force-feeding water under pressure and has the smallest space between electrodes. This space is equivalent to the thickness of the diaphragm (the porous interelectrode element) [49].

Constant conditions for accomplishing electrolytic decomposition of water may be achieved by using supplementary assemblies and adapter components to regulate and stablize elements in the total mass exchange system for gas and liquid main lines. A system for the electrolytic decomposition of water is in Figure 32.

According to present data [49, 60], practical electrolytic devices may be constructed which use not only asbestos matrices as interelectrode elements, but also those which use ion exchange membranes. Obviously, using ion exchange membranes to a significant degree must decrease limitations caused by redistribution of the electrolyte concentration in the interelectrode space. Electrolysis devices usually require considerable energy, and on the average it may be considered that 10–12 W are required for 1 liter of oxygen [60]. In this case, optimal conditions for accomplishing the electrolytic decomposition of water are a current density of 100–200 mA/cm^2, and a temperature for the process of 80°–90° C [1, 3, 7, 13, 14, 29, 49, 50, 55, 60, 63, 68, 71, 102, 105, 110, 115, 126, 133].

Supplying Oxygen by Decomposition of Water With Electrolysis of Salt Solution

An atmospheric regeneration system designed to use salt electrolysis is one of the most promising methods. The salt electrolysis method allows, in a single closed technologic process, oxygen extraction, and cleansing the atmosphere of CO_2 as well as securing a 100% concentration of CO_2. The chief drawback of this system is the necessity for creating quantitatively new electrochemical and physicochemical processes in actual space flight.

Reliability of the given method will be determined by the degree of success in developing the physicochemical processes in conditions of dynamic weightlessness and solving phase separation problems.

The most promising systems at present are based on the electrolysis of carbonates and sulfates.

In the electrolysis of a solution of K_2CO_3, this process occurs on the electrodes

on the anode

$$CO_3^- + H_2O \rightarrow HCO_3^- + OH^- \qquad (45)$$

$$HCO_3^- + H_2O \rightarrow H_2CO_3 + OH^- \qquad (46)$$

$$20H^- - 2e \rightarrow H_2O + \tfrac{1}{2}O_2 \qquad (47)$$

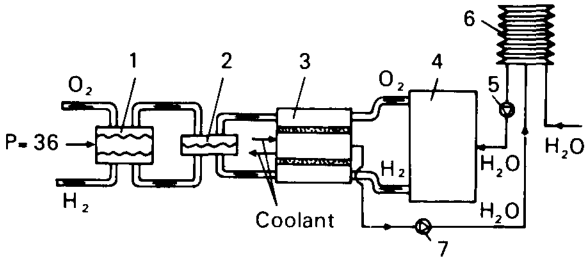

FIGURE 32.—System of electrolytic decomposition of water. 1, pressure bleeder; 2, pressure equalizer; 3, heat exchanger-dehumidifier; 4, electrolysis block; 5, 7, reverse valves; 6, elastic container.

on the cathode

$$2H_2O + 2e \rightarrow 2OH^- + H_2 \qquad (48)$$

The arrow formula for the electrochemical process is

$$4K_2CO_3 + 6H_2O \rightarrow 4KHCO_3 + 4KOH + O_2 + 2H_2 \qquad (49)$$

The solution of K_2CO_3 + KOH goes in the absorber, where CO_2 is absorbed from the air in the active portion of the absorbant (KOH).

From the anode chamber of the electrolyzer, the solution K_2CO_3 + $KHCO_3$ goes to the desorber, where at a boiling temperature (~110° C) desorption of CO_2 takes place.

During the electrolysis of sulfate solutions, the basic electrode reactions are

on the anode

$$H_2O - 2e \rightarrow 2H^+ + \tfrac{1}{2}O_2 \qquad (50)$$

on the cathode

$$2H_2O + 2e \rightarrow 2OH^- + H_2 \qquad (51)$$

The general formula of the electrochemical process is

$$4K_2SO_4 + 6H_2O \rightarrow 4KHSO_2 + KOH + O_2 + 2H_2 \qquad (52)$$

CO_2 is also absorbed during the electrolysis of carbonates; desorption of CO_2 is during the chemical reaction of the products of electrolysis from the anode chamber ($K_2SO_4 + H_2SO_4$) with the solution which is subsequently yielded to the absorber (K_2CO_3).

The primary difference between salt solution electrolyzers and the electrolysis of aqueous alkali solutions concerns the inevitability of extracting not only oxygen and hydrogen, but also the catholyte and anolyte. Of all possible designs for the electrochemical processes for the electrolytic decomposition of salt solutions in dynamic weightlessness the most advantageous is the method based on an artificially circulating electrolyte with subsequent separation from a gas catholyte and a gas anolyte mixture in special gas liquid separators.

A diagram of a system for the electrolytic decomposition of salt solutions is in Figure 33. The electrolyte goes to the central chamber of electrolyzer "1" (Fig. 33), through the porous diaphragms "2," and is distributed to the anode and cathode chambers, achieving a directed removal of gas from the electrodes. The electrolyte communication between electrodes is insured by a close attachment of the reticulated electrodes to the porous diaphragms. The electrolyte concentration may be regulated by changing the flow rate of the electrolyte through the electrolyzing chamber.

An alternate system of eletrolysis of salt solutions is shown in Figure 34. According to this design, the catholyte and anolyte formed in the electrolyzer with hydrogen and oxygen move to the heat exchanger-separators "15" and "3," in which water vapor condensation and separation of the liquid phase from the gaseous phase occurs. The catholyte goes to the absorber "13," where chemosorption of CO_2 from the cabin air occurs. The gas-liquid mixture from the absorber is directed to the heat exchanger-separator "11," from which air, which has been cleansed of CO_2, is directed into the cabin, while potassium carbonate is pumped through a mixer "9" by alkali pump "16" to the electrolyzer. After passing through the heat exchanger-separator "3" the anolyte goes to the desorber "5," where thermodesorption of CO_2 from calcium bicarbonate takes place. Carbon dioxide gas in a 100% concentration is directed from the heat exchanger-separator "7" to a container "17." Potassium carbonate, formed in the desorber, is pumped through the heat exchanger-separator "7" and mixer "9" by a pump "16" to the electrolyzer "2."

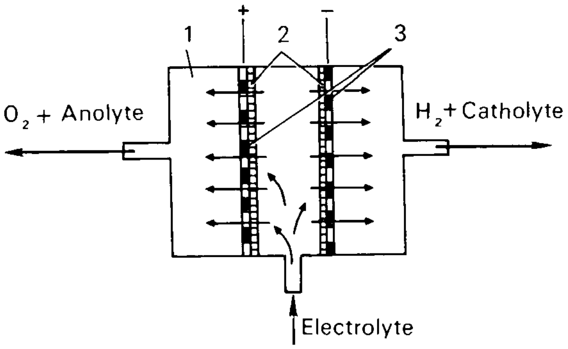

FIGURE 33.—System for electrolysis of saline solution. 1, main body of electrolytic cells; 2, porous diaphragms; 3, reticulated electrodes.

When carrying out the electrochemical processes, the temperature must be maintained within certain limits:

in the electrolysis units, 70°–80° C;
the absorbers, 18°–30° C;
the desorbers K_2CO_3, 100°–110° C;
K_2SO_4, 60°–80° C.

It is expedient to maintain the current density in the electrolysis units within the limits of 100–200 mA/cm^2.

The specific power of this system during the extraction of 1 liter of O_2 will fluctuate within the range of 13–15 W [13, 50, 55, 81, 133].

Supplying Oxygen by H_2O and CO_2 Decomposition During Electrolysis Using Solid Electrolytes

Electrochemical methods based on the use of solid electrolytes are one of the possible means of extracting oxygen from water and CO_2 gas.

Solid electrolytes have a practical use in devices for directly converting chemical energy of the fuel into electrical energy; these devices are used for obtaining the high temperature for thermodynamic characteristics of several oxides, partial pressures of oxygen in various systems, and so forth. The electrolysis cells with solid electrolytes have been used in recent times in human life-support systems, and in their basic component—the gas atmosphere regeneration part.

Solid electrolytes in gas atmosphere regeneration systems have real advantages, such as: a constant electrolyte composition during work, insignificant amount of corrosion of electrode and structural materials, absence of electrode wetting, and others. Such a method of extracting oxygen is sufficiently simple, and is free of the necessity of separating gas and liquid, which allows stable work in weightlessness, and the extracted oxygen does not require additional purification. Decomposition of water vapor and CO_2 gas may be carried out in the electrolyzing cell.

An electrolysis cell with a solid electrolyte is shown in Figure 35. Carbon dioxide gas or water vapor is located in the cathode space. The solid electrolyte separates the gaseous phases CO_2, CO, and O_2, which are located in the cathode and anode spaces. When using platinum electrodes, and ZrO_2–CaO for a solid electrolyte, the model of this system may be presented in the form

$$A(PCO_2), \qquad Pt(Zr_{0.85}Ca_{0.15}O_{1.85})Pt \qquad B(PO_2) \tag{53}$$

where $A(PCO_2)$ is the quantity of CO_2, expressed as partial pressure; Pt—the platinum electrode;

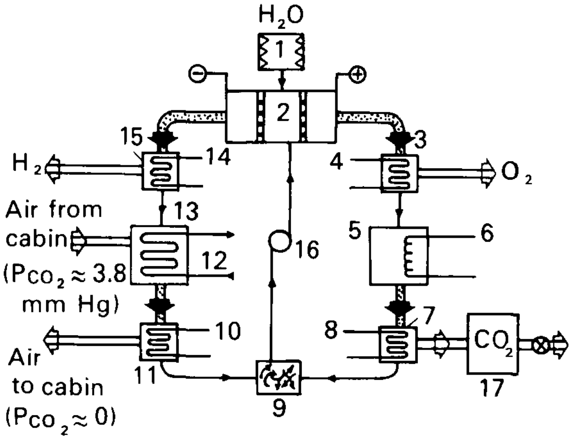

FIGURE 34.—Alternate system for electrolysis of saline solution. 1, elastic water reservoir; 2, electrolyzer; 3, 7, 11, 15, heat exchangers-dehumidifiers; 4, 8, 10, 14, coolant lines; 5, desorber; 6, heating element; 9, mixer; 12, coolant line for the absorber; 13, absorber; 16, alkali pump; 17, CO_2 container.

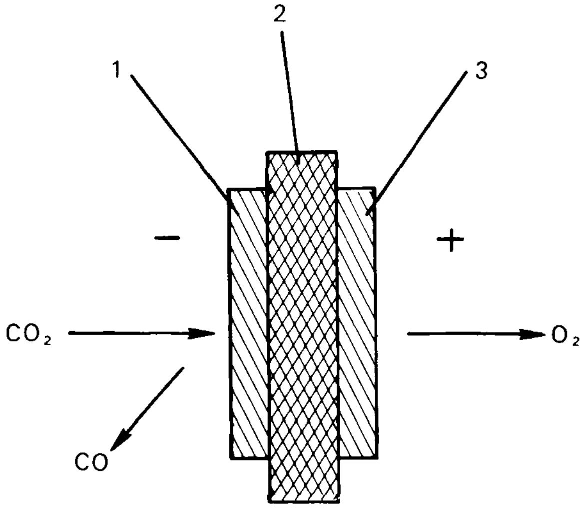

FIGURE 35.—Electrolysis cell with a solid electrolyte. 1, electrode-cathode; 2, solid electrolyte; 3, electrode-anode.

$Zr_{0.85}Ca_{0.15}O_{1.85}$, the solid electrolyte of determined content (in mole units) in each of the elements; $B(PO_2)$, the quantity of O_2, expressed as partial pressure.

The electrode reaction when using platinum electrodes and the removal of ions in the electrolyte with oxygen ionic conductivity may be written

$$CO(g)+O^{2-(\sigma)}|O^{2-}(H)|O^{2-(\sigma)} -2e \rightarrow O_o^{\cdot\cdot}+{}^1/_2O_2 \quad (54)$$

where $CO_2(g)+O_0^{\cdot\cdot}+2e$ is the system of elements participating in the first stage of the total reaction; $CO_2(g)$, carbon dioxide in a gaseous phase; $O_0^{\cdot\cdot}$, the location in the lattice of the solid electrolyte which is free of oxygen ions; $CO(g)+O^{2-(\sigma)}$, the system of elements forming as the result of the occurrence of the first stage of the general reaction; $CO(g)$, carbon monoxide in the gaseous phase in the boundary layer of cathode contact with the solid electrolyte; $O^{2-(\sigma)}$, an ion of oxygen which is located in the ion sorptive layer; $O^{2-}(H)$, an ion of oxygen, which is shifting within the solid electrolyte; $O_0^{\cdot\cdot}+1/2\ O_2$, the system of elements, formed as a result of a transfer of electrons from the inner ion oxygen envelope to the anode.

The element system "$CO_2(g)+O_o^{\cdot\cdot}+2e$" and "$O_0^{\cdot\cdot}-2e-1/2\ O_2$" is necessary and determines the prevailing conditions of the general reaction and characterizes the statistical state of the electrolytic cell with regard to the cathode and anode.

A schematic for extracting oxygen may be represented as

$$CO_2(g) \rightarrow CO_2^{2-(\sigma)} \quad (55)$$

$$CO_2^{2-(\sigma)} \rightarrow CO(g)+O^{2-(\sigma)} \quad (56)$$

$$O^{2-(\sigma)} \rightarrow 1/2\ O_2 \quad (57)$$

The first two stages are characteristic for the cathode space of electrolysis cells with the solid electrolyte, proceeding with the electron requirements. The last stage characterizes the anode space, in which the transfer of electrons of the anode occurs.

Decomposition of carbon dioxide gas (water) to carbon monoxide (hydrogen) and oxygen in the electrolytic cell with a solid electrolyte consists of six stages:

(1) supply (diffusion) of CO_2 on the adsorptional surface (the cathode);
(2) adsorption of CO_2 gas on the surface of the electrode-cathode;
(3) ionization of a molecule of CO_2-transfer of an electron from the cathode to a molecule of CO_2;
(4) diffusion of an ionized CO_2 molecule to the electrode-electrolyte interface;
(5) ion adsorption of a CO_2 molecule by the surface of the solid electrolyte with simultaneous disruption of an ion-absorbing atom of oxygen and carbon monoxide;
(6) desorption of carbon monoxide from the surface of the solid electrolyte.

The reaction of carbon dioxide gas decomposition of a solid surface is analogous to the process of heterogeneous catalysis, in which CO_2 gas is used in the capacity of an original substance, while the products of the reaction are carbon monoxide and oxygen. The process of decomposition of a molecule of CO_2 gas on the electrode (cathode) includes the most important stage of heterogeneous catalysis, which is the adsorption of a gas on the surface of an electrode-cathode, the simplest event of the heterogeneous reaction.

Reactors are usually constructed so that the diffusion processes occurring in them take place rapidly, which eliminates stages 1 and 5.

The catalyzer has a high degree of porosity diffusion to the inner surface of the interelectrode-catalyzer and plays a determining role.

The area of diffusion kinetics for a given reaction decomposition will be determined by the conditions of gas supply (diffusion) to the surface of the electrode, by the rate of diffusion of a molecule of gas to the inner surface of the electrode (the electrode-electrolyte boundary), and by the rate of transfer of a molecule of CO_2 to the surface of the solid electrolyte. Chemical kinetics will depend on the rate of chemical reaction of a molecule of gas with the surface of a solid electrolyte. The slowest of these processes will be determined by the general rate of the reaction.

In this case, the electrode in the electrochemical gas decomposition is also a catalyzer, insuring the necessary stage of the reaction-adsorption of gas and its supply to the reaction zone; therefore it must be an element with a developed surface; that is, it must be made of extremely porous material. A molecule of gas penetrates a pore, chiefly by diffusion; its further penetration into the boundary will be determined by its collisions with the sides of the pores, and also with other molecules. In each separate case, the rate of diffusion will be determined by the dimensions of the pore, the presence or absence of other gases, and the rate of diffusion of these other gases. In equilibrium, when formation of oxygen occurs simultaneously with the desorption of carbon monoxide, the diffusion rate of the reaction molecules will be equal to the diffusion rate of the reacted molecules and determined by the electrochemical reaction rate on the surface of the electrode.

Of the systems for electrochemical decomposition of H_2O and CO_2 which are based on the use of solid electrolytes, only those systems have interest which have ion conductivity; that is, systems which form cubic solutions of the fluoride type. The level of ion conductivity in this type system is determined by the quantity and type of added oxide. Thus, for systems based on ZrO_2, a significant oxygen ion conductivity is observed, which increases in conformity with this series of stable oxides: Nd_2O_3, Y_2O_3, Sc_2O_3, MgO. Systems designed to use solid electrolytes must meet two conditions: high electrical conductivity and a 100% level of oxygen ion conductivity, which, in turn, is determined by the completeness of formation of solid solutions and by their stability. Systems based on zirconium dioxide more completely fulfill the requirements, since they have nearly a 100% level of oxygen ion conductivity with a sufficiently high degree of electrical conductivity.

A diagram for supplying oxygen based on the use of an electrolyzer with a solid electrolyte is in Figure 36. The system consists of an electrolyzer with a solid electrolyte "1" (Fig. 36) and two catalytic reactors for utilizing carbon dioxide "5," "8," alternately working in disproportionation regimes of carbon dioxide according to the reaction: $2CO = C + CO_2$ and extracting the solid carbon.

Carbon dioxide enters the electrolyzer "1" (Fig. 36), in which, at a temperature of 1000° C, decomposition of CO_2 into O_2 and CO occurs. The process begins with minimal energy requirements. Carbon monoxide in a part of the unreacted CO_2 passes through the heat exchanger "3" (Fig. 36) to the catalytic reactor "5" converting CO to C and CO_2. The carbon dioxide, recirculating by pump, returns to the electrolyzer. Simultaneously, carbon is extracted from the catalytic reactor "8" (Fig. 36) and stored in a special container "11."

Using this system, oxygen may only be partially regenerated; the deficient quantity of oxygen must be obtained from H_2O. As previously stated, oxygen may be obtained from water by the electrolytic decomposition of water using hydroxides, carbonates, and sulfates as electrolytes; this process may also occur in electrolyzers with a solid electrolyte. Electrolysis installations with solid electrolytes not only permit the extraction of oxygen separately from H_2O and CO_2, but also from a gaseous $CO_2 - H_2O$ mixture. In conformity with the material balance, a gaseous mixture consisting of 70% CO_2 and 30% H_2O must be considered optimal at the time of entry into the electrolyzer. During work of the gaseous mixture $CO_2 - H_2O$, and in a case of a recirculation system, generally with a gaseous mixture $CO_2 - CO - H_2O - H_2$ the oxygen regeneration system, based on the use of solid electrolytes, must also have two devices: an H_2O evaporator and a regenerating adsorber of H_2.

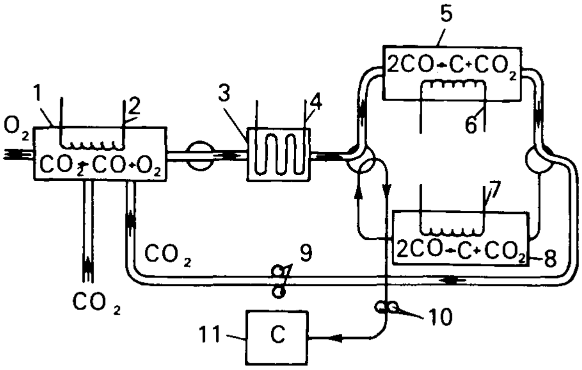

FIGURE 36. — Oxygen regeneration based on use of electrolyzer with solid electrolyte. 1, electrolyzer with solid electrolyte; 2, 6, 7, heating elements; 3, heat exchanger; 4, coolant line; 5, 8, catalytic CO_2 reactors; 9, recirculating pump; 10, vacuum pump; 11, container for stored carbon.

Obviously, for an evaporator, a device with a porous capillary element with a built-in heater may be used, while a palladium membrane can serve as an H_2-adsorber. There are many other possible electrochemical devices that may also be used.

In accordance with the experimental data, during the extraction of oxygen from a gaseous mixture $CO_2-CO-H_2O-H_2$ for the extraction of 1 liter of oxygen, there is a power requirement of 6–8 W [18, 20, 24, 25, 26, 28, 42, 50, 52, 53, 57, 59, 61, 69, 75, 100, 113, 124].

Supplying Oxygen by H_2O Decomposition During Electrolysis Using Phosphorus Pentoxide for an Electrolyte (P_2O_5)

This method is based on the use of two insulated electrodes, between which an absorbing membrane consists of a layer of phosphorus anhydride which actively absorbs water from the air. With the passage of an electric current through the membrane on the anode and cathode, respectively, oxygen and hydrogen are extracted; P_2O_5 is regenerated.

The process occurs according to:

$$P_2O_5 + H_2O \rightarrow 2HPO_3 \qquad (58)$$

$$2HPO_3 \rightarrow H_2 + \tfrac{1}{2}O_2 + P_2O_5 \qquad (59)$$

This method is comparatively simple; however, it requires a large quantity of electrical energy, and the series of problems related to using it in a closed system must be solved [12, 60, 99, 105, 122].

Supplying Oxygen by CO_2 Decomposition During Electrolysis of Salt Alloys

The electrolysis of salt alloys, specifically carbonates, may be used for obtaining O_2 from CO_2. When using the alloy Li_2CO_3 at a temperature from 540° to 1070° C, the oxygen yield approaches 100%. However, simultaneously with the formation of O_2, CO or CO_2 may be formed.

To insure stable operation, the gas entering the electrolyzer must be dried to a dew point of approximately −26.11° C.

During the electrolysis of carbonates, the reactions characterizing the given process may be presented in the form

$$Li_2O + CO_2 \rightarrow Li_2CO_3 \qquad (60)$$

$$Li_2CO_3 \xrightarrow{\text{electrolysis}} Li_2O + O_2 + C \qquad (61)$$

Summary reaction

$$CO_2 \rightarrow C + O_2 \qquad (62)$$

Lithium chloride is added to the carbonate system to decrease the temperature of the electrochemical process, which lowers the system's melting point.

When designing such a system for conditions of dynamic weightlessness, it is necessary to adopt a qualitatively new approach, as well as to pay particular attention to the problem of continuous removal of carbon, which forms on the cathode during electrolysis [13, 50].

Methods of Utilizing Carbon Dioxide Gas. In the gas system CO_2–H_2 in the temperature interval 200°–1000° C, three basic reactions are thermodynamically possible

$$CO_2 + H_2 \leftrightarrows CO + H_2O \qquad (63)$$

$$CO_2 + 2H_2 \leftrightarrows C + H_2O \qquad (64)$$

$$CO_2 + 4H_2 \leftrightarrows CH_4 + 2H_2O \qquad (65)$$

The first reaction occurs at a temperature higher than 700° C with a significant yield, the second and third reactions at lower temperatures. The gases formed, CO, H_2O, and CH_4 may participate in other reactions. Reactions reducing carbon dioxide gas to methane and water and reducing CO_2 to carbon and water are of practical interest at present.

Catalytic Reduction of CO_2 by Hydrogen to Methane (CH_4) and Water with Methane Cracking

The first reactions for reducing carbon dioxide gas by hydrogen were studied by Sabatier and Senderens in 1902.

During this reaction, secondary reactions are possible, including

$$CO_2 + H_2 \leftrightarrows CO + H_2O \qquad (66)$$

$$CH_4 + H_2O \leftrightarrows CO + 3H_2 \qquad (67)$$

$$CH_4+CO_2 \leftrightarrows 2C+2H_2O \quad (68)$$

$$CO+H_2 \leftrightarrows C+H_2O \quad (69)$$

$$2CO \leftrightarrows C+CO_2 \quad (70)$$

$$CO_2+2H_2 \leftrightarrows C+2H_2O \quad (71)$$

$$C+2H_2 \leftrightarrows CH_4 \quad (72)$$

These reactions may lead not only to a decreased yield of water, but also to the formation of carbonaceous substances, which, with time, may block the active centers of the catalyzer.

With appropriate selection of catalyzers and conditions for the process (e.g., temperature, rate of supply of the base gas mixture), it is possible to insure reliable and stable accomplishment of the necessary reactions.

Thermodynamic calculation shows that the optimal temperature for Sabatier's reaction is approximately 310° C. Lowering the temperature below 280° C decreases the degree of conversion. Raising the temperature (higher than 400° C) may lead to irreversible changes in the catalyzer, and also to the possibility of secondary reactions. It is necessary to bear in mind that Sabatier's reaction is exothermal (a thermal effect equal to 39.4 to 40.6; −41.8; −42.8 kcal/m with temperatures of 0°; 127°; 227°; and 327° C respectively); i.e., the process, according to the temperature, becomes self-sustaining.

Research has shown it is necessary to create a stoichiometric ratio of H_2 to CO_2 = 4:1 [50].

Various metals are used in the capacity of a catalyzer for Sabatier's reaction. The most active at 300° C is nickel [30, 96, 108]. Cobalt catalyzers are less active and work at higher temperatures (400° C) [50]. With copper and platinum catalyzers the reaction occurs only above 430° C; at this temperature, using copper, chiefly carbon monoxide is obtained [50]. Paladium and iron oxides allow the reaction to occur at a temperature not lower than 500° C. For a nickel catalyzer carrier, diatomaceous earth and pumice may be used [74].

A heating element must be provided for the beginning of the reaction in the device for the hydrogenation of CO_2. To insure stable conduct of the reaction in the established regime, correctly selected thermal insulation for the reactor and maintenance of an optimal ratio of the mixture of CO_2 and H_2 will be determinative [15].

Exclusive use of the device for hydrogenating the CO_2 to methane and water in the oxygen regeneration system is not expedient, since in this event it is necessary to have supplies of pure oxygen or oxygen-containing substances onboard the spacecraft. It is therefore necessary to consider a device that insures the decomposition of methane to carbon and water as an inherent component of the total system for utilizing CO_2, based on the use of Sabatier's reaction.

Methane may be decomposed by chlorination according to the reaction

$$CH_4+2Cl_2=C+4HCl \quad (73)$$

$$2HCl \rightarrow H_2+Cl_2 \quad (74)$$

Hydrogen may also be liberated from methane by means of pyrolysis and thermocatalytic decomposition.

Methods of utilizing methane by combining it with carbon dioxide gas are also possible

$$CH_4+CO_2=2C+2H_2O \quad (75)$$

A diagram for using CO_2 gas, based on the use of Sabatier's reaction and on methane pyrolysis, is in Figure 37. Carbon dioxide gas and hydrogen pass through mixer "1" (Fig. 37) to the catalytic reactor "2;" the gas-liquid mixture goes from reactor "2" to the heat exchanger-separator "4," at which condensation of water vapor and separation of the liquid phase from the methane occur. The methane goes to reactor "6" for pyrolysis. The hydrogen which was formed is delivered by the recirculating pump to mixer "1." Simultaneously, carbon is removed from reactor "9" (Fig. 37) and stored in container "12."

The advantages of the methane reaction are:

- the possibility of conducting it with a degree of conversion approaching one for a prolonged period without catalyzer regeneration;
- an exothermic nature which allows energy expenditure on reactor heating to be kept to a minimum;
- low reaction temperature (300° C);
- a small quantity of impurities in the water formed [62].

Catalytic Reduction of CO_2 to Carbon and Water

This process is described by the reaction

$$CO_2 + 2H_2 \leftrightarrows C + 2H_2O \qquad (76)$$

Actually, reversible reactions occur

$$CO_2 + H_2 \leftrightarrows CO + H_2O \qquad (77)$$

$$CO + H_2 \leftrightarrows C + H_2O \qquad (78)$$

$$2CO \leftrightarrows C + CO_2 \qquad (79)$$

$$CO_2 + 2H_2 \leftrightarrows C + 2H_2O \qquad (80)$$

With the goal of intensifying the process, Fostér and McNulty consider it necessary to conduct reactions for obtaining CO and C separately in different catalyzers and at different temperatures, although in the same reactor [40, 62].

Besides the basic reactions, secondary reactions are also possible

$$CO_2 + 4H_2 \leftrightarrows CH_4 + 2H_2O \qquad (81)$$

$$CO + 3H_2 \leftrightarrows CH_4 + H_2O \qquad (82)$$

$$C + 2H_2 \leftrightarrows CH_4 \qquad (83)$$

$$CO + CH_4 \leftrightarrows 2C + 2H_2O \qquad (84)$$

The basic products of these reactions are methane and water. The formation of methane is undesirable, since it leads to a lowering of the general conversion percentage to carbon and water. For decreasing methane formation, they recommend carrying out a reaction to reduce CO_2 to CO in that portion of the reactor in which there is a high partial pressure of water vapor.

The temperature 750° C is the limit of the metallic reactor [40]. Increasing the temperature enables carrying out the reduction reaction of CO_2 to CO [40, 62], but makes the carbon formation reaction more difficult. For this they recommend conducting carbon formation [40, 62] in a colder part of the reactor.

Varying the proportion of H_2 to CO_2 has a strong effect on the rate of the process and the yield of certain products [40]. Decreasing the quantity of H_2 in the reacting mixture leads to a decrease in the rate of the process, while an increase in its content is marked by an increase in CH_4 liberation.

Reducing CO_2 in carbon and water usually requires iron catalyzers in the form of wadding,

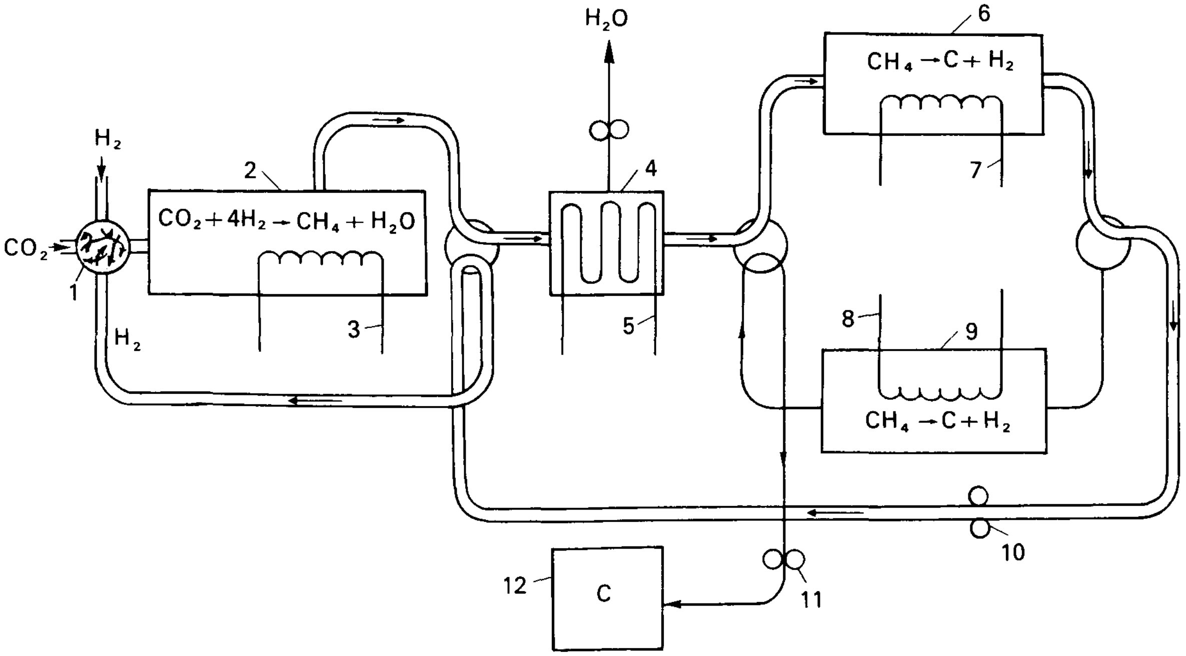

FIGURE 37.—Catalytic hydrogenation of CO_2 and pyrolysis of methane. 1, mixer; 2, catalytic CO_2 hydrogenation reactor; 3, heating element; 4, heat exchanger separator; 5, coolant line; 6, 9, methane pyrolysis reactor; 7, 8, heating elements; 10, recirculating pump; 11, vacuum pump; 12, container for storing carbon.

netting, pellets, flakes, or porous granules [40, 62]. Iron chromate is an effective catalyzer for the reaction [17, 62, 98].

Since the carbon formed in the reaction does not have the required catalytic properties, the activity of the catalyzer (Fe) decreases with time. This necessitates removing carbon and prolonging the life of the catalyzer. Obviously, porous catalyzers with a developed interior surface are not appropriate for this process. Appropriate forms of catalyzers are those in which the active centers are located at the exits of spiral dislocations, since in this case the carbon is in the form of dendrites that are not securely attached to the surface. This type, obviously, is appropriate during the use of iron wadding. In this system, the use of steel wool or iron mesh catalyzers is avoided, and iron flakes are used instead, which rotate after a determined interval of time, or constantly, at a low rate, and scrapers remove the accumulated carbon.

Iron pellets, kept in place in weightlessness by a screen, may be the solution to the problem of constantly removing carbon. The carbon may be removed from the surface of the pellets by mechanical means, or by applying a magnetic field either constantly or periodically.

A system for using carbon dioxide gas, based on the use of Bosch's reaction, is in Figure 38. Carbon dioxide gas and hydrogen enter mixer "1" (Fig. 38) and catalytic reactor "2," in which the hydrogenation reaction of CO_2 by hydrogen to carbon and water occurs in stages. The gas vapor mixture enters the heat exchanger-separator "4," in which water vapor condensation and removal to a liquid storage container occur. Simultaneously, carbon is removed from the reactor "7" and stored in container "6."

The chief advantage of the reaction reducing carbon dioxide to carbon and water is that, theoretically, it is possible to create a completely closed regeneration system, since in this case

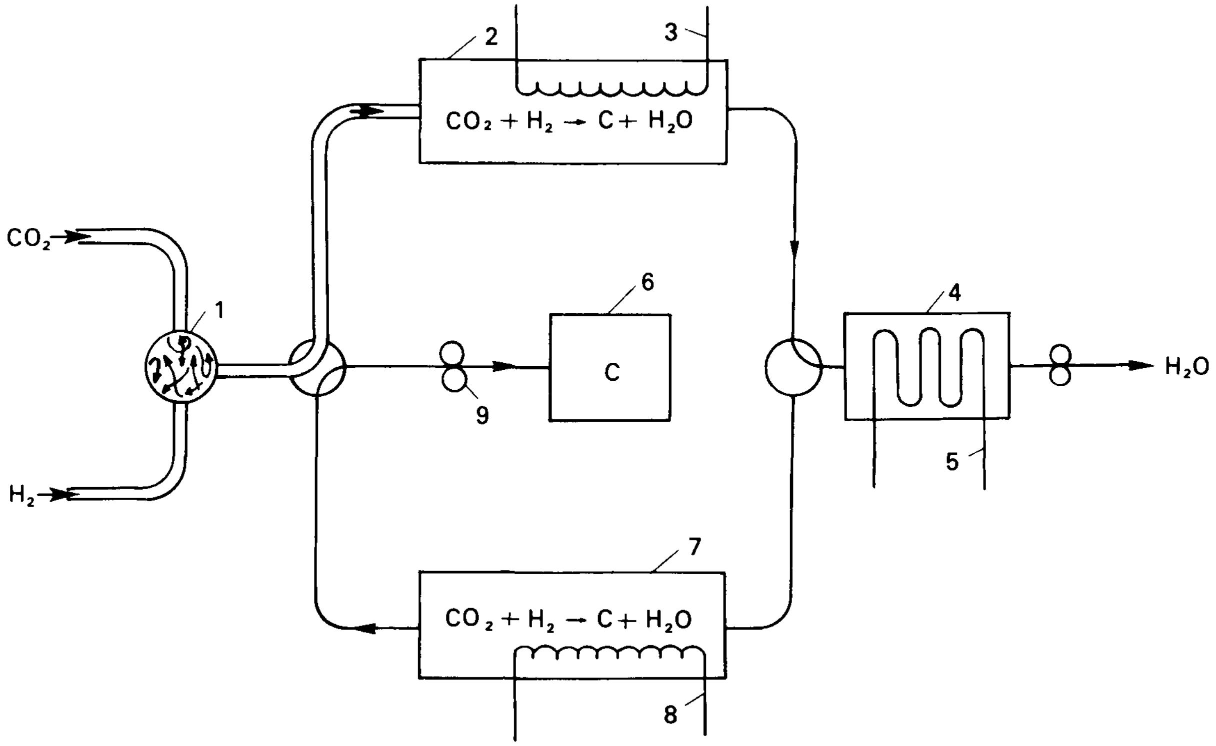

FIGURE 38. – Catalytic hydrogenation of CO_2 to carbon and water. 1, mixer; 2, 8, catalytic CO_2 hydrogenation reactors; 3, 7, heating elements; 4, heat exchanger-separator; 5, coolant line; 6, container for storing carbon; 9, vacuum pump.

hydrogen returns to the cycle. The disadvantages of this reaction are:

- short catalyzer lifetime and the necessity of frequency regeneration (cleaning carbon from the catalyzer);
- comparatively (with the methane reaction) large energy expenditure on heating the reactor (T = 700° to 750° C);
- the possibility of a large number of secondary reactions occurring [6, 34, 41, 50, 51, 60, 74, 76, 77, 78, 79, 91, 92, 93, 95].

The Low-Temperature Plasma Method

Low-temperature plasma is the state of a gas at a temperature of 10 000° to 16 000°K, in which a significant part of the atoms or molecules are ionized. The plasma state is the normal form of existence for substances at temperatures of 10 000° K and higher.

Low-temperature plasma in which discharge and ionization of gases occur may be considered more optimal means of obtaining oxygen from CO_2 gas and water. The flow of an electric current in the system maintains a degree of gas ionization at a constant level. The electrons and ions formed during ionization are the carriers of this current.

Conditions that shift equilibrium in the system and insure subsequent separation of the components of the original gas are necessary when obtaining oxygen from CO_2 gas and methane decomposition. The low-temperature plasma method may have practical use in gas atmosphere regeneration systems of hermetically sealed environments.

Electrical Discharges in Gases

A chemical process to be accomplished by discharging depends largely on the character of the discharge, and the phenomena occurring upon discharge depend on the properties of the gas, its pressure, the material making up the gas, the geometry of the electrodes, and the character of gas currents.

Of the possible types of discharges — silent, glow, and arc discharges — the glow discharge method has practical use in systems for the decomposition of CO_2 gas or its hydrogenation.

Systematizing Basic Methods of Oxygen Regeneration

The methods of oxygen regeneration already examined can be presented diagramatically in a single systemized form, divided according to their physicochemical capabilities, design complexity, performance under conditions of dynamic weightlessness, and proposed duration of use. In Figures 39, 40, and 41 the basic methods of oxygen regeneration and of using CO_2 gas, as well as hydrogen and CO, are presented in a generalized form.

According to a great deal of the research data at present, which has been published in the past decade [2, 27, 43, 50, 56, 99, 103, 104], scientists in both the USSR and the US have given significant attention to practically all the methods of oxygen regeneration presented above. An objective analysis of the existing information permits confirmation concerning the uniformity of selecting means for accomplishing and intensifying basic technologic processes. Basic attention has been given to problems of reliability, instability, weight, size, and the energy requirement characteristics of these systems.

REMOVING HARMFUL IMPURITIES FROM HERMETICALLY SEALED ENVIRONMENTS

Man excretes not only carbon dioxide gas into his environment, but also a large number of harmful impurities in microquantities, which, accumulating with time, have an adverse affect on his work capability, and which at increased concentrations, may even be toxic.

Besides man, the spacecraft equipment, as well as the physicochemical processes in the life-support system and in other devices which may influence the ion content of the air may be sources of harmful impurities. Man himself, the equipment, or insufficiently careful sterilization of the cabin before flight may be sources of bacteria and viruses in the hermetically sealed cabin.

It may be maintained with certainty today that man eliminates these harmful impurities in microquantities [117]:

- carbon monoxide
- ketones (acetone)
- aldehydes (acetyldehydes)
- aliphatic acids (glacial acetic acid)
- methane and its products
- unsaturated hydrocarbons
- aromatic series hydrocarbons
- hydrogen sulfide and mercaptan (methylmercaptan)
- indole
- skatole
- sulfur anhydride
- nitric oxides
- phenol.

The intensity of excretion of these impurities may fluctuate within significant limits relative to the individual particularities of the organism, the type of work done, the quantity and quality of food, and microclimatic conditions in the cabin. Quantitative characteristics of the harmful impurities listed above are presented elsewhere [99].

In view of the complete solubility in water of hydrogen sulfide with mercaptan, and of aliphatic acids and ammonia, carbon monoxide, hydrocarbons, ammonia, ketones, and aliphatic acids are constantly present in the air of the hermetically sealed environment.

The greatest danger to the spacecrew, without means of cleansing the air of harmful impurities, is carbon monoxide and hydrocarbons. A man eliminates approximately 34–108 mg CO in 1 day. Removing hydrocarbons is based on the use of activated charcoal as an adsorbent.

The greatest difficulties are encountered when cleansing the air of carbon monoxide, since the usual adsorptional methods are ineffective. The air may be cleansed of CO by catalytic oxidation of CO in CO_2. According to the data [131], these oxidizing catalyzers of carbon monoxide may be used:

- metals and alloys (Pt, Pd);
- miscellaneous chemical compounds;
- manganates and chromates;
- salts and oxides (or mixtures of them) of metals with changeable valence;
- ordinary or activated refractory materials.

Catalyzers may be divided into low-temperature ($t < 50°$ C) and high-temperature catalyzers ($t > 50°$ C), depending on the temperatures at which the most intense oxidation occurs. Hopcalite catalyzers, the most widely used, usually consist of four components; 30% CrO, 50% MnO_2, 15% Cu_2O_3, 5% Ag_2O or 60% MnO_2, and 40% CuO. The active component is manganese peroxide; other components fulfill the role of substances which increase the catalytic capability.

The hopcalite mass is prepared as granules or grains with dimensions of 2.5–3.5 mm. The density of the hopcalite is approximately equal to 1.1 kg/dm^3. The normal temperature interval of catalytic activity is 50°–200° C. When oil vapors and water are present in the air, the effectiveness of hopcalite is significantly decreased; hence, it is usually placed in filters between two layers of drying substances. The shortcoming of the hopcalite catalyzer is an increase of its temperature during the work process which may sometimes lead to an explosion of the filter. The explosion results from momentary contact on the surface of the hopcalite of burning components formed in the process of catalytic oxidation.

Several authors [129] evaluate the catalytic activity of various metal oxides in various combinations of these oxides, beginning with mechanical mixtures and ending with binary compounds, basically, of the spinel composition. Khauffe and Shlosser [60] explain the particular catalytic properties of the spinels by the unique form of their lattice structure, in which the crystallographic equivalence areas are occupied partly by bivalent and partly by trivalent ions. On the basis of their investigations [60], catalyzers made of Pt, Pd, have considerable interest.

The mechanism of the process for oxidizing CO, according to the data of a series of authors [73, 95], most probably occurs according to

$$O_2 + 2e \leftrightarrows 20^-_{ads} \tag{85}$$

$$CO + 20^-_{ads} \leftrightarrows CO_{3\ ads} \tag{86}$$

$$CO^=_{3\ ads} \leftrightarrows CO_2 + O^-_{ads} + e \tag{87}$$

Cleansing the air of mechanical impurities (e.g., dust, aerosol, and partly of bacteria), may be accomplished by (1) trapping in filters,

(2) hydraulic precipitation, and (3) precipitation and electrostatic field.

The first method is the most widely used for on-board air-conditioning systems. Filters for cleansing the air of mechanical impurities may be divided into volumetric-action, surface-action, and combined filters (a combination of the first two types).

Dust-precipitating filters belong to the first type, the elements of which are paper tissues and other materials which trap the dust in their structural skeleton. The dust capacity of such filters is insignificant, but their degree of purification is high. Filters composed, e.g., of metal screens or coils, are surface-action filters which are simple in design and have a high degree of

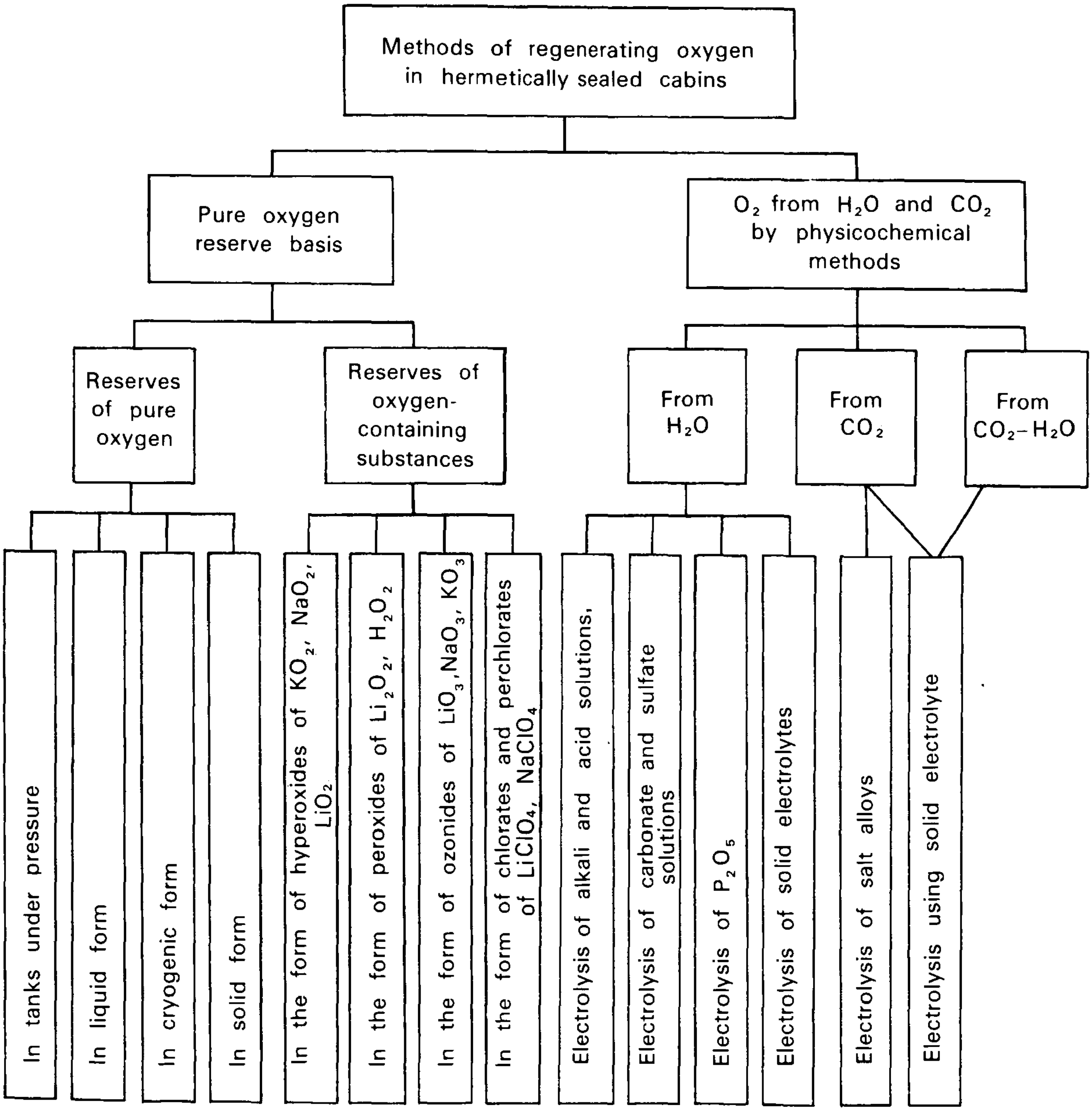

FIGURE 39.—Basic oxygen regeneration insuring the creation of both automatic and partially closed physicochemical systems of gas medium regeneration.

purification. The combined filters are the most effective.

The high working quality of a filter is determined by certain indicators: low and time-stable hydraulic resistance; high dust capacity; and long work duration. Filters must be explosion-proof, lightweight, and small in volume. Special bacterial filters are used in the life-support system (LSS) for cleansing the air of bacteria and viruses.

When designing an artificial atmosphere for spacecraft cabins, it is necessary also to keep in mind the atmospheric ion (aerion) content. The cleaner the air, the more aerions will be contained in it. Aerions, unlike other physical factors, affect the human organism, basically through the lungs. The character of the effect of aerions on the organism is determined first by its electrical charge. Aerions with a negative charge generally have a favorable effect on the organism; these ions improve the reduction-oxidation processes in a living organism. The hygienic criterion of the gas atmosphere is the so-called coefficient of unipolarity, which is determined by the proportion of positive to negative aerions. The coefficient of unipolarity of gas atmospheres, which determines the high life activity of the organisms, must not be greater than one.

When designing a gas atmosphere for spacecraft cabins, hygienic requirements with regard to aerion content which must be met are:

> total concentration of light aerions must be maintained at a level of $2 \cdot 10^3 - 5 \cdot 10^3/cm^3$; the coefficient of unipolarity must be 0.7–0.8.

The achievement of these parameters in LSS, in all likelihood may be insured by using special dephlegmators, which usually neutralize the superfluous quantity of positive ions [22, 30, 36, 39, 50, 73, 75, 87, 96, 108, 123, 132].

CONTROLLING CONTENTS OF AN ARTIFICIAL ATMOSPHERE OF A HERMETICALLY SEALED ENVIRONMENT

The artificial atmosphere created in a hermetically sealed environment is of a comparatively small volume and strongly reflects its dependence on the crew and equipment located there. Dependent upon the duration of the flight, a small or large volume of information is selected to define the composition of the artificial atmosphere according to the basic indicators (O_2, CO_2, humidity) or with a calculation of microimpurities. For short-term flights, a determination of O_2, CO_2, and humidity is sufficient. For extended space flights, there is also the direct

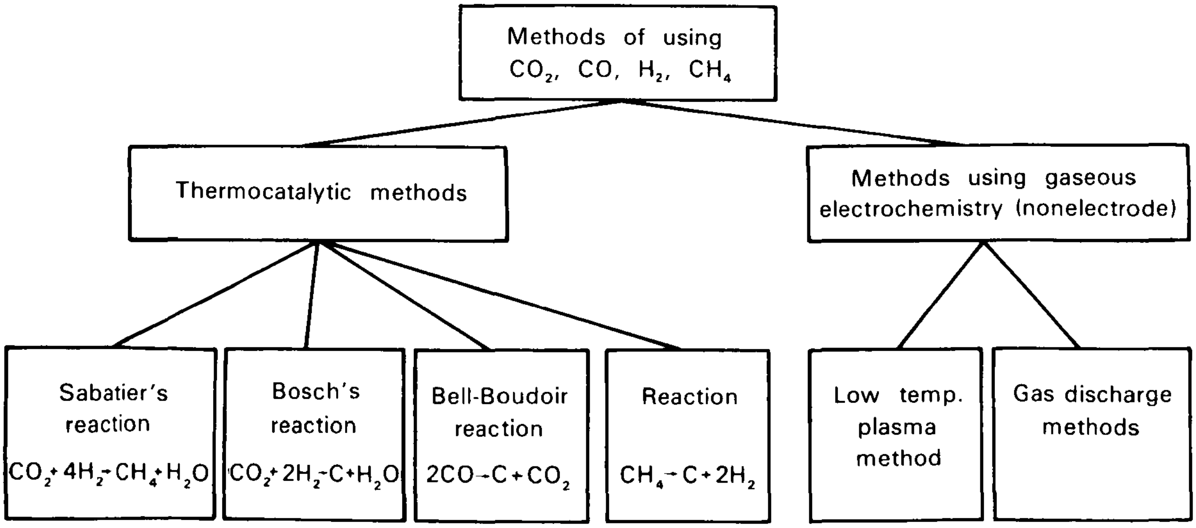

FIGURE 40.—Basic utilization of CO_2, CO, H, and CH_4.

necessity for determining microimpurities, basically toxic microimpurities, which are eliminated both in the process of human metabolism and by the equipment.

Controlling the content of microimpurities is necessary for maintaining comfortable living conditions, as well as for evaluating the functional activity of the crew, for assuring the regeneration and conditioning of the artificial atmosphere, and for efficient operation of systems and devices located within the living quarters of the spacecraft.

When there is slow periodic growth or a rapid accumulation of microimpurities, it is expedient to have systems for both constant or periodic control and emergency signals to warn the crew so that they can make decisions and take measures for eliminating malfunctions or maintaining impurities at a level within allowable concentrations. Under conditions of a closed volume and the effect of spaceflight factors, the problem becomes extremely complex, requiring original means of solution, taking into account high reliability requirements for safety during its use.

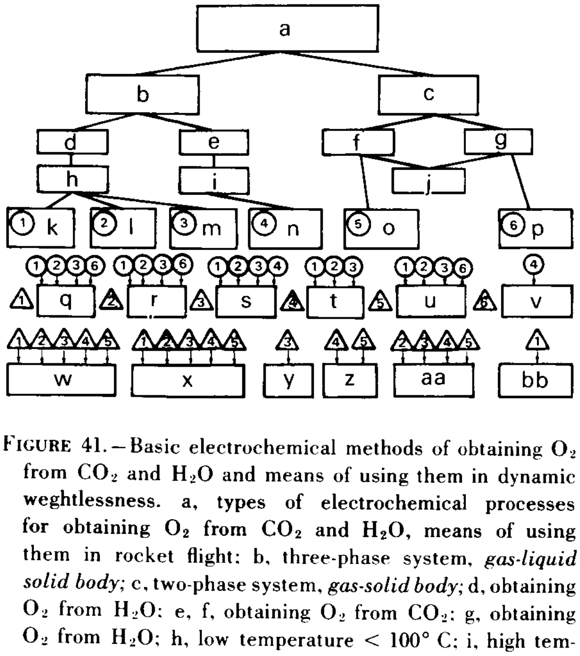

FIGURE 41.—Basic electrochemical methods of obtaining O_2 from CO_2 and H_2O and means of using them in dynamic weghtlessness. a, types of electrochemical processes for obtaining O_2 from CO_2 and H_2O, means of using them in rocket flight: b, three-phase system, *gas-liquid solid body*; c, two-phase system, *gas-solid body*; d, obtaining O_2 from H_2O: e, f, obtaining O_2 from CO_2: g, obtaining O_2 from H_2O; h, low temperature < 100° C: i, high temperature ≥700° C; j, high temperature ≥1000° C; k, electrolysis of aqueous alkali solution: l, electrolysis of aqueous salt solutions: m, electrodialysis: n, electrolysis of salt alloys: o, electrolysis with a solid electrolyte: p, electrolysis with a solid electrolyte; q, saving H_2O; r, eliminating H_2O; s, constant electrical circuits K–E–A; t, separating H_2 and O_2 from the electrolyte; u, condensation of separated vapor H_2O from H_2O_2; v, CO_2 supply; w, creating an artificial gravity; x, creating an artificial gravity by rotating the equipment or its parts; y, creating artificial electrolyte circulation; z, silphon (elastic) containers; aa, centrifugal separators; bb, porous capillary elements.

The most practical devices apparently are multipurpose monitors capable of analyzing small volumes of gas and giving complete response concerning the contents, such as the basic components of the gas atmosphere as well as microimpurities. The most appropriate methods for these purposes may prove to be those based on gas chromatography, mass spectrometry, and so forth.

An example is the mass spectrometer designed for controlling and regulating the gaseous components of an artificial atmosphere, developed by the Perkin-Elmer Corp. in 1970. This device is a specially adapted electronic tube through which samples of gases pass whose parameters are subject to measurement. The mixture of gases enters an ionization chamber, the gases are ionized, and subsequently accelerated in a focusing device. The ionized beam enters the mass separator, in which, under the influence of a magnetic field, there is formation into bands; the radii of these depend on the mass and charge of the components of the gas atmosphere. In the associated components, fixed fluxes of ions are amplified to allow a signal to be obtained, which acts on secondary instruments enabling direct transmittal of information in parts, percentages, or partial pressures. A device of this type is capable at present of working in realistic spaceflight conditions [50] and may simultaneously control the parameters of the gas atmosphere, which consists of five components (hydrogen, water vapor, nitrogen, oxygen, and carbon dioxide) and which may dispense the basic components of the artificial gas atmosphere—oxygen and nitrogen. The authors maintain [50] that, with slight modification of the device, it may be also adapted for determining microimpurities.

The most suitable analytic methods for work in space must therefore be considered: gas chromatography, mass spectrometry, and infrared analysis.

The problem, it must be emphasized, is current and important, and safety and reliability in carrying out space flights depend to a great extent on its solution [21, 82, 87, 106, 114, 127, 132].

Possible Physicochemical Methods of Regenerating the Atmosphere of a Hermetically Sealed Cabin

The degree of development at present of basic components of systems for regenerating the atmosphere makes it possible that several variants of closed physicochemical systems (with respect to oxygen) for regenerating the atmosphere may be realized, including [50, 99]:

- cleansing the atmosphere of CO_2 using synthetic zeolites or aluminosilica gels with subsequent regeneration;
- catalytic hydrogenation of CO_2 to methane and water with subsequent methane cracking;
- obtaining oxygen from water using electrolysis of aqueous solutions of alkali salts.

First variant:

- cleansing the atmosphere of CO_2 using synthetic zeolites or aluminosilica gels with subsequent thermovacuum regeneration and compression of CO_2; catalytic hydrogenation of CO_2, methane, and water with subsequent methane cracking;
- obtaining oxygen from water using electrolysis of aqueous alkali solutions.

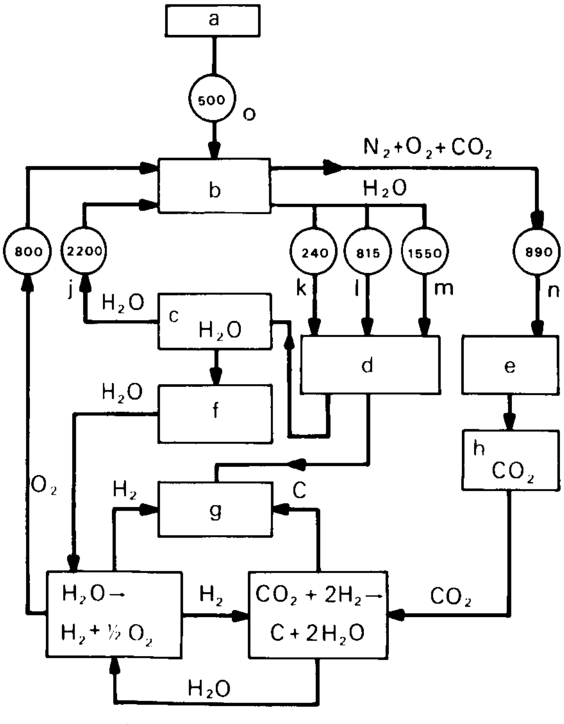

FIGURE 42.—System for regeneration of a gas medium, variant 1. a, food supplies; b, living quarters; c, H_2O collector; d, system for regenerating life-support waste products; e, system for removing CO_2 and harmful impurities; f, metabolic H_2O collector; g, waste products collector; h, CO_2 concentrator; i, oxygen, g/man · d^{-1}; j, water, g/man · d^{-1}; k, fecal water, g/man · d^{-1}; l, urine water, g/man · d^{-1}; m, expired and perspired water, g/man · d^{-1}; n, CO_2 exhaled, g/man · d^{-1}; o, dry food, g/man · d^{-1}.

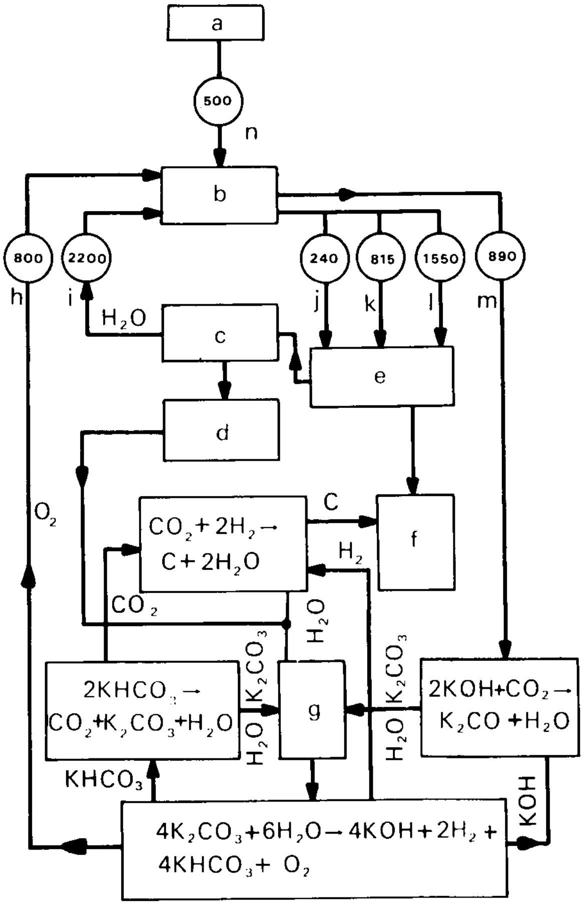

FIGURE 43.—System for regeneration of gas medium, variant 2. a, food supplies; b, living quarters; c, H_2O collector; d, metabolic H_2O collector; e, system for regenerating life-support waste products; f, waste products collector; g, mixer; h, oxygen, g/man · d^{-1}; i, water, g/man · d^{-1}; j, fecal water, g/man · d^{-1}; k, urine water, g/man · d^{-1}; l, expired and perspired water, g/man · d^{-1}; m, CO_2 exhaled, g/man · d^{-1}; n, dry food, g/man · d^{-1}.

Second variant:

cleansing the atmosphere of CO_2, concentrating CO_2, obtaining oxygen by electrolysis of aqueous carbonate solutions;
catalytic hydrogenation of CO_2 to C and H_2O.

The second variant of the system differs from the other two because of the possibility of combining the processes of cleansing the atmosphere of CO_2, concentrating CO_2, and obtaining oxygen by the electrolysis of water, practically, in one device.

To obtain oxygen by the method of direct decomposition of CO_2 to O_2 and CO, an electrolyzer with a solid electrolyte may be used. Carbon monoxide must, in this instance, be directed into a catalytic reactor with the objective of converting it to C and CO_2.

These variants of the systems are in Figures 42–45. There is a great interest in atmospheric regeneration systems both with CO_2 ejection and with subsequent use of CO_2; the diffusion method of atmospheric purification uses both. When using this method in a closed (with regard to oxygen) physicochemical system of atmospheric regeneration for removing the CO_2 from the cabin atmosphere, an intermediate gas carrier may be used. Even hydrogen may be used directly, which is necessary for the subsequent utilization of CO_2.

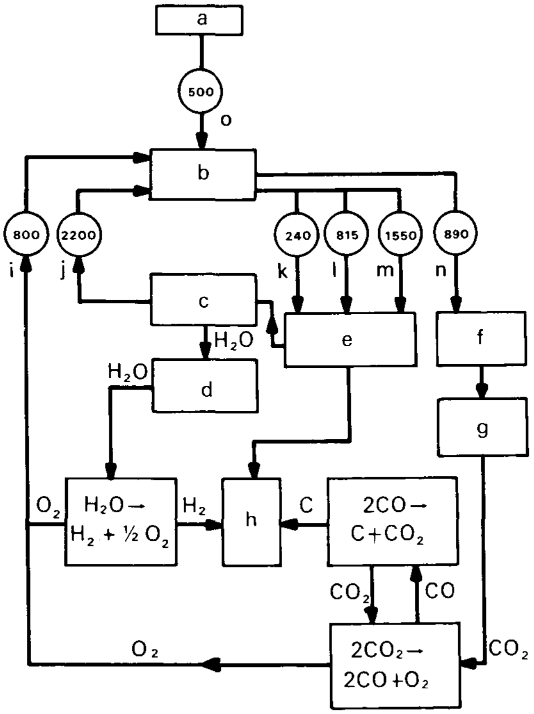

FIGURE 44.—System for regeneration of gas medium, variant 3. a, food supplies; b, living quarters; c, H_2O collector; d, metabolic water collector; e, system for regenerating life-support waste products; f, system for removing CO_2 and harmful impurities; g, CO_2 concentrator; h, waste products collector; i, oxygen, g/man · d^{-1}; j, water, g/man · d^{-1}; k, fecal water, g/man · d^{-1}; l, urine water, g/man · d^{-1}; m, expired and perspired water, g/man · d^{-1}; n, CO_2 exhaled, g/man · d^{-1}; o, dry food, g/man · d^{-1}.

We have examined only a few of the design variants of physicochemical systems for oxygen regeneration which have a high degree of development of basic technologic processes and considerable design development.

The further development of several methods for purifying the air and regenerating oxygen may introduce other variants of physicochemical systems of gas atmosphere regeneration for the hermetically sealed spacecraft cabins [2, 50, 56, 62, 64, 99, 120].

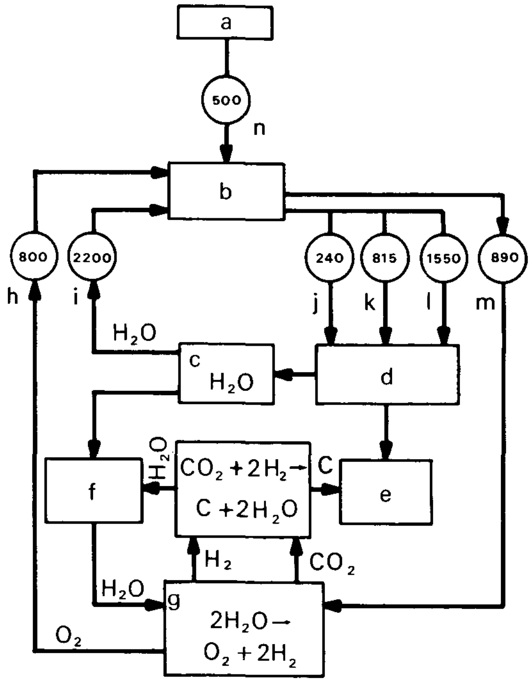

FIGURE 45.—System for regeneration of gas medium, variant 4. a, food supplies; b, living quarters; c, H_2O collector; d, system for regenerating life-support waste products; e, waste products collector; f, metabolic H_2O collector; g, electrodialysis; h, oxygen, g/man · d^{-1}; i, water, g/man · d^{-1}; j, fecal water, g/man · d^{-1}; k, urine water, g/man · d^{-1}; l, expired and perspired water, g/man · d^{-1}; m, CO_2 exhaled, g/man · d^{-1}; n, dry food, g/man · d^{-1}.

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Chapter 4

CLOTHING AND PERSONAL HYGIENE[1]

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One of the main objectives of biomedical maintenance of space pilots, which is the personal hygiene of cosmonauts and their clothing, is discussed in this chapter. It presents the principal characteristics and general requirements which must be followed in perfecting a system of hygienic practices and in devising means to maintain personal hygiene, flight clothing, underwear, bedding, and medical-domestic equipment for manned space flights of varying durations.

The problems associated with flight clothing and underwear are elucidated only in the hygienic sense; the details and particular features in the use and function of compensating suits and pressure suits, which are component parts of the flight clothing systems of the cosmonauts, are described in Part 1, Chapter 7, of this volume.

CLOTHING

In considering the problems associated with cosmonaut clothing, it should be noted that the most important roles of clothing in everyday life are reduction of body heat losses and maintenance of optimal conditions for supporting body temperature at a constant level. Another factor is protection of the body from unfavorable effects of external media—high and low temperatures, rain, snow, wind, dust, external contamination and so on. Thus, the functions of clothing are somewhat different in a spacecraft cabin, where the factors indicated are either absent or reduced to a minimum.

The widely practiced separation of cosmonaut apparel into clothing and pressure suits is arbitrary. Pressure suits provide, under the specific conditions of cosmonaut activity (including emergence into outer space or onto the surface of a planet), all the functions of clothing suitable to a practical activity.

The clothing of cosmonauts, like terrestrial clothing, should be convenient for work and relaxation and not hinder or restrict movements. The well-known concept that the best clothing is that which is not felt is applicable. To continue the analogy, a set of cosmonaut clothing consists of several layers: underwear; the flight suit which cosmonauts wear in the spacecraft corresponding to our everyday clothing; and a heat-protective suit. The underwear and flight suits, intended for everyday wear, can be for one-time or repeated use.

Clothing for one-time use is worn during a specified time, after which it is placed in the waste disposal system or, if provided for by the

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[1] Translation of: Odezhda kosmonavtov i lichnaya gigiyena, Material for Volume III, Part 2, Chapter 4 of *Osnovy Kosmicheskoy Biologii i Meditsiny (Foundations of Space Biology and Medicine)*, Moscow, Academy of Sciences USSR, 1972, 66 pp.

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program protocol, packed into hermetic containers (bags) and stored until the end of the flight. It is understood that the cosmonaut puts on a new set of clothing after removing the one-time set he had worn. Repeated-use clothing is worn during the same or somewhat shorter time than clothing for one-time use; however, it is cleaned to be worn again rather than disposed of.

Different kinds of clothing use have advantages and disadvantages. Clothing for single-time use, which does not require special cleaning equipment, simplifies construction of "household" equipment in the spacecraft. However, the volume and weight of replaceable clothing can reach such proportions with a large crew and a long flight that the space flight becomes almost impossible.

According to data from United Aircraft [18], the weight of single-time use clothing will significantly exceed all permissible weight limits for flights of more than 200 days with a three-man crew for whom clothing is to be changed once every 10 days. At the same time, repeated-use clothing with all its apparent advantages is not the ideal solution because, so far, we lack suitable washing and drying equipment.

A preliminary study [18] shows that suitable equipment will not be produced in the near future. Thus, it can be assumed that cosmonauts will use one-time clothing in the majority of space flights planned at present.

Disregarding the short-duration and special characteristics of single-time garments, heat-protective suits should be classified with single-time use clothing. These suits are intended to be used when landing in an uninhabited locality with unfavorable climatic conditions. In addition, they are applicable in emergency situations associated with disruption of air-conditioning systems on-board the spacecraft. Spacecrew clothing will be discussed in greater detail in the subsections that follow.

Underwear

The first and main requirement of underwear, which is in direct contact with the skin, is that it be nonirritating. The fabric should be light, elastic, and not hinder heat exchange by convection and radiation nor evaporation of moisture from the body's surface. The fabric should be durable enough for extended wear and for the attachment of physiological instrumentation sensors. Washing and various kinds of sterilization should not alter the fabric's properties.

The hygienic properties of natural linen and cotton fabrics first attracted the attention of spacecrew clothing makers. Underwear was made of a porous knitted cotton fabric for the Apollo crews. Preliminary investigations have shown its high permeability to air, moisture capacity, and ability to absorb chlorides and organic substances from the skin. Furthermore, it was found advisable not to use linen and cotton fibers in pure form, but combined with other more durable components to increase the wearability. This factor is of particular significance for underwear worn under pressure suits.

The fabric structure plays an important role in the production of underwear. The necessity for providing maximum compatibility of the underwear with the next layer of clothing (flight suit or pressure suit), for excluding the possibility of developing wrinkles, and for reducing the number of seams to a minimum, has led to the use of knitted fabric. Underwear of knitted fabric provides uniform relief to the body without excessive wrinkles.

Detailed physiologic-hygienic and physicochemical investigations of various knitted fibers [34] resulted in recommending cotton-rayon knitted fabric for cosmonauts' underwear. It possesses high permeability to air (not less than 400–600 $l/m^2\ s^{-1}$ at a pressure of 5 mm water), and high permeability to water vapor (with a resistance of about 1 mm of an air layer). The hygroscopicity of the fabric is not less than 7% when air has a relative humidity of 60%; the durability is sufficiently high; and the tensile strength is not less than 20 kg for a strip 5-cm wide. The thickness of a fiber under a load of 10 g is 0.73 mm.

The experiments cited showed that underwear of such knitted fabric does not complicate wearing the pressure suit and is not uncomfortable when worn under a pressure suit for up to 10 days. The material is well-ventilated and provides sufficient aeration of skin surface during operation of the pressure suit's ventilation system. The design developed for the underwear included: a jersey sweater, undershorts, and seamless socks [34]. A special valve in the crotch of the undershorts permitted the cosmonauts to use a sanitation device.

Successful use of the underclothing by cosmonauts of the Vostok-type spacecraft has confirmed the conclusions drawn and permits recommending that cotton-rayon knitted underclothing with cotton socks be worn under pressure suits [34].

The limited possibilities for hygienic practices (cleansing the body) under conditions of space flight have led to utilizing the absorbency of the underclothing fabrics for such purposes. It is known that if the underclothing fabric is absorbent enough, it can take up a definite amount of skin excretions. As the duration of man's space flights increases, this absorbability of the underclothing fabric will acquire greater significance.

The sorption possibilities of underclothing entail another important aspect of this problem: the transfer of a portion of the microflora from the body surface to the underclothing. In subsequent sections, the dependence between volume and frequency of hygienic treatment of the skin and the amount and forms of microflora will be considered in detail. However, it can be assumed that, as the duration of space flights increases, the problem of lowering the number of microorganisms on the skin will acquire more and more significance. One promising method of decreasing skin and underclothing microflora is the use of antimicrobial textile materials [5]; the development of such materials has been given increasing attention in recent years.

Impregnation of fabrics with various bactericidal and bacteriostatic preparations has been used for this purpose. However, the instability of these preparations during washing and using these fabrics [6] has required further work. The possibility of combining bactericidal preparations directly with the macromolecules of the fiber-forming polymers was explored; the greatest success was achieved with polyvinyl alcohols and cellulose fibers. Underclothing manufactured from the fabric "Letilan" with the introduction of a 5-nitrofuran-type preparation, possesses the desired antimicrobial property for the microflora usually vegetating on skin surfaces. Another method of obtaining antimicrobial chemical fibers is by mixing solutions, which are insoluble or poorly soluble in water, into a spinning solution of polymers when forming the fiber [49].

Experimental wearing of antimicrobial underclothing for 10–15 days under conditions of normal life did not reveal any detrimental effects on the functional condition of the skin [49]. The complexity of producing antimicrobial underclothing results from the difficulties of selecting combinations of bactericidal or bacteriostatic preparations and the corresponding chemical fibers, as well as the need to avoid a different kind of dysbacteriosis arising from the use of such underclothing.

We are witnessing the first phase in the creation of antimicrobial underclothing, but the available data provide an optimistic outlook for the use of such underclothing during extended space flights with limited sanitation and domestic equipment.

Flight Suit

The cosmonauts wear regular clothes over their underclothing, the same as on Earth. Depending on the program and the specific conditions of the flight, this regular clothing can be either a flight suit or a pressure suit.

Construction of the flight suit should provide convenience in its use; not hinder the freedom and range of movements or, in other words, should not affect working ability; be easy and simple to put on and take off; and provide for the possibility of using a sanitation device. The suit should fit well with the underclothing and the heat-protective suit. The intrinsic heat-protective properties of the flight suit should be optimal for the specified temperature conditions of the spacecraft cabin.

The design of the flight suit must provide for the attachment of physiological instrumentation sensors and include several pockets for small personal objects. The fabric should be light, soft, elastic, long-wearing, and flameproof. It should not contribute to the buildup of electrostatic charges. If repeated use of the flight suit is planned, its fabric should maintain its properties after washing and various kinds of sterilization.

In all cases, the fabric and design of the suit should not hinder heat exchange by convection, radiation, and by evaporation of moisture from the body surface. Both the color and coloration intensity of the fabrics of the outer clothing take on definite meaning in extended space flights. Hygiene and engineering aesthetics give preference to clothing of bright, quiet tones. Consideration should also be given to the individual preferences of the crew in the selection of suit colors.

When designing flight suits, fabrics with great wear-resistance and strength must be selected. Investigators were obliged to turn to synthetic fabrics similar to the course followed in designing the underclothing. The majority of synthetic fabrics are characterized by great strength, elasticity, nonwrinkling, and ease of mechanical cleaning. Currently, several flame-resistant and fireproof synthetic fibers have been developed which will not burn at high temperatures.

The use of polymer synthetic materials conceals the potential possibility of volatile injurious materials permeating the ambient air. This can be caused by the presence, in these materials, of a residual amount of free (not entering into the reaction of polymerization or polycondensation) monomers which, as a rule, possess toxic properties. The liberation of monomers and particles with low molecular weight can also be the result of destructive processes [4].

The presence of electrostatic charges in products made of synthetic materials must be pointed out. Heavy charges have been detected in products made of chlorine and acetate silk and in footwear made of polymer materials. In a number of cases, the long-duration intensity of the electrostatic field reaches 6–8 kV/cm^2 and causes unpleasant and even painful sensations to the individual who is wearing such clothing. Such phenomena are detected only when the intensity of the electrostatic field exceeds 200–400 V/cm^2. It should also be noted that the presence of an electrostatic field contributes to more rapid soiling of clothing.

The principal inadequacy of synthetic fabrics in comparison with natural fabrics is their lower hygroscopicity, vapor permeability, and heat-resistance. Investigations have shown that the hygroscopicity of Lavsan is 16 times less, and Nitron 4 times less than that of the pure wool fabric, "Boston" [20].

It was also shown that:

> as the synthetic fibers in a fabric increase, its hygienic properties worsen, and these changes are of a linear nature;
>
> a decrease in the hygienic properties of the fabric containing synthetic fiber (50%) does not greatly affect the general physiologic and hygienic properties of clothing made from it;
>
> clothing made of mixed fabric can be recommended for use in the +18° to +50° C range of ambient air temperature [19].

The polyester fiber of Lavsan is the advisable selection for a synthetic fiber of composite yarn intended for cosmonaut clothing. It possesses a high thermal-protective capability (similar to wool), high durability (almost 3 times more durable than wool), elasticity, thermal and chemical stability, resistance to wear, stability from the effects of solar radiation, chemical agents, and bacteria, and is nonwrinkling [26].

In making flight clothing, one problem is preservation of the cosmonaut's thermal balance, i.e., prevention of both excessive heat exchange and the accumulation of excess heat. According to Vitte [45], a person clothed in the usual two-layer clothing maintains his thermal balance during specific combinations of heat production and ambient air temperatures (Table 1).

The data of Winslow et al [46] may be used to make a tentative determination of the thermal protective characteristics of clothing under relatively quiet conditions, with a small air velocity (see Table 2).

The existing microclimate regime in spacecraft cabins corresponds to comfortable limits: air temperature is 18°–23° C, air motion velocity is 0.05–0.5 m/s, and relative humidity is 40%–65%.

Taking into account that under flight conditions, cosmonauts are generally in a quiescent state or carry out light physical work, their everyday clothing should have a thermal resistance of the order of 1–1.2 clo.

With an increase in cabin air temperature above values calculated for cosmonauts to maintain thermal comfort, it is recommended that they remove the flight suit jacket or remain only in their underclothing. If the air temperature decreases below 18° C, comfort can be achieved by wearing a thermal-protective suit over the flight suit, woolen socks, and a woolen cap or helmet.

TABLE 1.—*Nature of the Physical Effort Necessary to Maintain Heat Balance by a Person Clothed in Two-Layer Clothing for Different Ambient Air Temperatures* [20]

Air temperature, °C	Physical work	Body heat production kcal/min
10	Average	3.5
18	Light	2.5
22–25	At rest	1.5

TABLE 2.—*Thermal-Protective Properties of Clothing for Various Ambient Air Temperatures* [46].

Air temperature, °C	Heat insulation of the clothing, clo[1]
30	0
21	1
12	2
3	3
−6	4

[1] clo: The amount of insulation which will maintain normal skin temperature when heat production is 50 kcal/m^{2}h^{-1}, air temperature 21° C (70° F) in still air. One clo is roughly equal to the amount of insulation provided by a business suit in a temperate climate.

The Thermal-Protective Suit

The main purpose of the thermal-protective suit is to provide comfort for cosmonauts upon a decrease in cabin temperature (in an emergency situation), also when abandoning the spacecraft after touchdown on land or water. The thermal-protective suit, which is not everyday clothing for cosmonauts, should be stowed where it is quickly available when needed. The general requirements for construction of the suit and composition of its fabrics are the same as for flight suits.

Efficient use of separate layers of material is important in making thermal-protective clothing. When designing thermal-protective clothing, it is advisable to rigorously specialize the function of each individual layer. Winter clothing usually consists of an outer fabric, wind-protective lining, warming layer, and backing.

The outer fabrics take the wear and tear during use and determine the external appearance. The main requirements for outer fabrics are wear-resistance, durability, nonwrinkling, and stability against climatic factors (light and precipitation).

The wind-protective lining acts as a windbreaker maintaining a high level of the clothing's thermal properties. The wind-protective linings should satisfy these main requirements: impermeability to air (depending on meteorological conditions) within the range of 7–40 dm^3/m^2 s^{-1}, minimum weight and stiffness, with sufficient durability and vapor permeability.

The warming layers provide the thermal-protective properties of the clothing, the main requirements of which are: stability of the layer and resistance to mechanical phenomena during use; low specific weight; and sufficiently high air and vapor permeability. The interlining should be light, durable, and wear-resistant, with a smooth surface. The vapor permeability of these materials should be not less than 25 g/m^2 h^{-1}.

The design of a thermal-protective suit can, of course, vary. For example, the outer fabric can serve simultaneously as the warming linings. However, it is essential that the thermal-protective suit possess the necessary thermal insulation.

Evidently, the thermal-resistance of thermal-protective suits should be no less than 2 clo, which corresponds to the thermal insulation of clothing worn during the transition seasons (Table 3). This table indicates that thermal insulation on the order of 3.0 to 6.0 clo is necessary for winter and arctic types of clothing.

However, as the thermal insulation increases, the clothing's thickness increases. Clothing with a thickness of 3–4 cm or higher significantly hinders motion. Therefore, it is advisable to create a flight thermal-protective suit with thermal insulation not exceeding 3–4 clo [43]. Thermal-protective clothing that is properly constructed can provide maximum thermal protection of 1.6 clo/cm of its thickness [7]. Two factors prevent achieving the value cited. One is the effect of curvature which is expressed as a decrease in the effective thermal insulation (especially at the extremities); the other is the presence of air layers between layers of the clothing. It is possible to increase significantly the thermal-protective properties of clothing by making use of the insulation properties of "inert air." The thermal-protective properties of clothing can be varied by a maximum of 16% by variation in the fabric material [7].

TABLE 3.—*Thermal Insulation of the Main Types of Clothing* (According to data of [7, 41])

Type of clothing	Thermal insulation, clo
Light summer	0.5
Man's woolen suit	1.0
Clothing for transition seasons	2.0–2.5
Winter overcoat (moderately cold winter)	3.0
Winter overcoat (cold winter)	3.5
Arctic	4.0–5.0
Extreme arctic	5.5–6.0

In designing such suits, it is also necessary to take into account the effect of physical work and air motion on the clothing's thermal-protective properties. The thermal-protective properties of clothing decrease less due to an individual's motion, than the heat generation in the organism increases due to heat production (Table 4). For air motion, it is necessary to take into account the wind "decrement" [7].

Footwear and Headgear

Footwear and headgear are essential components of the flight and thermal-protective suits. Caps can be of the same fabrics as the flight suits. The cap should be constructed of sufficiently light, soft, and elastic fabric and not cause irritations of the scalp. The design of the cap should make its use convenient and not hinder heat exchange by convection, radiation, and moisture evaporation from the surface of the head. A sports-type cap with brim and folding side piece is most convenient.

Helmets are practical which can be worn on top of the cap, attached to it by special devices. The helmets can be an integral part of the suit or removable. The removable helmet can convert into a cape to warm the chest, back, and shoulders. The helmet should fit the head well and should have sufficient thermal insulation; its construction must make it possible to attach physiological sensors and communication devices.

A cosmonaut's footwear should be light and durable with adequate thermal insulating properties, and be usable under conditions of weightlessness. These properties should be provided by the appropriate selection of materials and designs [39].

PERSONAL HYGIENE

At first glance, the unpretentious problems of personal hygiene on-board spacecraft for an extended time have remained in the background

TABLE 4.—*Dependence of Clothing Thermal Insulation on the Level of Physical Work (for Air Motion Velocity of 0.5 m/s and Total Radiation of 0.5 cal/cm² min)* [23]

Air temperature, °C	Thermal insulation of clothing, clo		
	At rest	Work of little difficulty	Work of average difficulty
+ 10.4	2.1	1.2	0.5
− 0.4	3.6	2.2	1.1
− 1.7	4.4	2.8	1.5
− 8.8	4.8	3.0	1.6
− 14.8	6.4	4.1	2.2
− 17.4	6.8	4.4	2.4
− 21.3	7.3	4.8	2.6
− 43.7	10.4	6.7	3.7
− 55.0	11.9	7.6	4.3

of those biomedical investigations accomplished during the first decade of the conquest of outer space. This may be explained by investigators having been faced with more important problems associated with establishing the basic possibility of man living under the influence of extreme factors in space flight.

Although personal hygiene includes important rules for maintaining and strengthening health, the short-term nature of the first space flights permitted, and the complexity of hygienic procedures compelled, the crews of the first spacecraft to neglect standards of personal hygiene customary for terrestrial conditions.

The main requirements of personal hygiene, based on cleansing the skin, hair, mouth, teeth, clothing, footwear, bedding, and other domestic items, could be carried out only in part in the short-term flights. Such restrictions are known to cosmonauts. One of their most urgent desires upon return to Earth is a "hot bath" after the completion of the flight.

The significance of personal hygiene in the medicobiologic protocol of space flight grows immeasurably as duration of flights increases and as long-operating orbital and planetary stations are created. More specifically, because of the special nature of conditions on-board spacecraft, hygienic procedures acquire a breadth and scale far exceeding the level peculiar to terrestrial existence [21].

The distinctive features of the external medium in spacecraft cabins and the flight factors which are strange to humans can result in changes in the physiological indicators of an individual's vital activity. These changes appear as disruptions of metabolic processes, lowering of the level of the body's protective mechanisms, and change in many other indicators. If we assume that these phenomena will occur against the background of changes in the quantitative and species makeup of the microbial flora surrounding the individual [24], personal hygiene measures take on multifaceted significance. It should be added that the small volume of the cabin with its artificial air medium, and the extended contact among the cosmonauts aggravate the situation and impart a new aspect to hygienic procedures [21].

Concurrently, it is not possible to neglect taking into account that personal hygiene procedures, usually carried out easily on Earth, will necessitate solution of numerous complicated technical problems under spaceflight conditions. Difficulties in equipping spacecraft compartments with everyday sanitary devices, providing crewmembers with adequate water, washing agents (detergents), and other items of personal hygiene, as well as the necessity for collecting, conserving, or regenerating water used for washing and household purposes during weightlessness, significantly affect engineering solutions for personal hygiene problems [36].

Our ideas of the necessary volume and frequency of personal hygiene measures (based on terrestrial conditions) require revision, considering the peculiarities of sanitary and hygienic conditions in closed spacecraft compartments.

In quantitative and qualitative respects, it is evident that contaminants in the spacecraft must have certain unusual features because of the distinctive conditions for skin physiology. Pertinent factors are: limited mobility of the individual, unusual condition of the autonomic nervous system and endocrine system, high nervous-psychological stress, and unique water and food rations.

These peculiarities of the physiologic and hygienic conditions in spacecraft cabins, aggravated by engineering complexities in producing sanitary and domestic devices, result in the necessity for devising new recommendations for a rational hygienic regime, perhaps different from the terrestrial regime. It is also necessary to determine measures for carrying out personal hygiene. The problems posed can be successfully solved only by investigating all aspects of the effects that these unusual spaceflight factors have on the body as a whole, and on the skin in particular.

There are certain areas of particular interest for personal hygiene. These include studies of sanitary and hygienic conditions in spacecraft cabins and of clinical, physiological, and biochemical indicators of the skin and oral cavity; and determination of the nature and degree of soiling skin and clothing by metabolic products, as well as the microflora.

SANITARY AND HYGIENIC CONDITIONS IN SPACECRAFT CABINS; CHARACTERISTICS AND SOURCES OF CONTAMINANTS

Emphasis is placed on the formation of sanitary and hygienic conditions in spacecraft cabins, since these compartments completely exclude the possibility of contaminants entering from outside.

In small, isolated, carefully precleaned and disinfected compartments supplied with conditioned air, the external soiling of cosmonauts' skin and clothing will be determined by dust forming from the clothing, footwear, bedding, materials of equipment coverings; microbe aerosols; food residues; and particles of excrement or urine released accidentally during use of the sanitation devices. It is difficult to anticipate that these so-called external contaminants will be of a decisive nature, similar to ordinary terrestrial experience. The main contaminants of the skin, clothing, and surrounding medium under these conditions will, most likely, be endogenic contaminants whose sources are the individual—his skin. Products liberated by the sudoriferous and sebaceous glands, particles of epithelium torn away, and small pieces of hair, comprise the significant, if not major contaminants of the surrounding medium, skin, and clothing of cosmonauts [36].

Data from an investigation to determine the amount of endogenic contamination in the spacecraft cabin [27] are cited in Table 5.

Such materials as ammonia, oxygen, carbon dioxide; saturated, unsaturated, and aromatic hydrocarbons; various aldehydes, ketones, lower fatty acids, alcohols, and ethers; up to 21 compounds in all have been detected among the gaseous products emitted by man [8, 10, 15]. Many of the materials may have toxic significance, since they enter the atmosphere in sufficiently large amounts. Separate authors [8, 22] emphasize that a significant part of the harmful impurities appears from destruction of products contained in perspiration and sebum, and call attention to the significance of hygienic procedures.

Investigations to determine microbial propagation of the nutritive medium in spacecraft cabins and simulators [2, 14a, 33, 44] have shown that the individual is the main source of microbial aerosols. An increase in the number of airborne microorganisms occurs mainly because of the coccus microflora (*Staphylococcus aureus*, β-hemolytic streptococcus, and cutaneous staphylococcus).

It was found during the flights of Apollo 7 and 8 that changes occur in the bacterial and fungal flora related to exchange of microorganisms between crewmembers and enhancement of the growth of Gram positive microorganisms (*Staphyloccus aureus* and β-hemolytic streptococcus), with some depression

TABLE 5.—*Total Weight and Volume of Waste Products from Sources of Contamination in the Closed Cabin of a Highly Maneuverable Manned Spacecraft (1 Person/Day)* [27]

Composition	Mass (g)	Volume (ml)
Miscellaneous cabin compounds	0.700	0.720
Food fragments	0.700	0.700
Desquamated epithelium	8.000	2.800
Hair—depilation losses	0.030	0.030
Hair—facial shaving losses	0.300	0.280
Nails	0.010	0.010
Solids in sweat	3.000	3.000
Sebaceous excretion—residue	4.000	4.200
Solid residue of saliva	0.010	0.010
Mucus	0.400	0.400
Residue of seminal fluid	0.003	0.003
Urine spillage	0.025	0.025
Fecal particles	0.025	0.023
Intestinal gases	— —	2000.0
Microorganisms	0.160	0.140
Solids in feces	20.0	19.0
Water in feces	100.0	100.0
Solid urine residue	70.0	66.0
Water of the urine	1400.0	1400.0
Insensible water	1200.0	1200.0
Total	2802.363	2807.341
Total weight, excluding urine, feces, intestinal gases, and insensible water	12.363	12.341
Total solid residue	102.363	97.341
Total water	3700.0	3700.0
Total gas	— —	2000.0

in growth of anaerobic microflora [2]. These data indicate that the conditions of space flight may result in predomination of microbes whose growth is suppressed under ordinary conditions. The customary airborne bacteria contained in dust, on skin, and in metabolic products were detected prior to launch in the atmosphere of the Gemini 10 spacecraft cabin. After the flight, only microorganisms in dust and on interior surfaces were detected [14a].

One effective method of disinfecting ambient air of a spacecraft cabin is filtration through bacterial filters mounted in the atmospheric regeneration system. However, decreases in airborne microbial propagation can evidently be obtained by selecting correct hygienic procedures, i.e., by opportune removal of microorganisms from the skin's surface.

CONDITION OF THE SKIN AND ITS CONTAMINATION

Investigations conducted at various scientific centers in the Soviet Union and the United States [9, 21, 27, 28, 33, 36, 38, 40, 42, 44, 48] have demonstrated the scientific need for hygienic procedures in the biomedical protocols for space flight. These investigations have permitted evaluating the condition of the skin and oral cavity after extended deprivation of customary hygiene.

The first experiments confirmed that depriving a civilized individual of the opportunity to observe elementary rules of personal hygiene, even for a short period of time, results in an undesirable neuropsychologic stress, although no deviations were noted in the objective indicators of skin condition. Almost all participants expressed a great desire, after 10–12 h of the experiment, to take a bath and change underclothes—to wash up "like new" [36, 42]. This desire usually haunts the participants during the entire experiment when lasting more than 2 weeks. It appears at 7–10 days when participants begin to notice a disturbing itch of the scalp and an unpleasant odor from underclothes and body [42]. The participants complained that they felt "steamed," "contaminated," and "smelly" [9]. When returning to Earth after real flights, the cosmonauts indicated that one of their strongest desires was to take a hot shower or bath immediately after the flight.

In evaluating living conditions in an experimental chamber, the "absence of water for washing" indicator is rated by participants as one of the four most irritating factors of life in small restricted space. In contrast, contamination and unpleasant odor are rated 15th and 16th, respectively, of 19 irritating factors evaluated in experiments permitting the use of washing supplies and a change of clothing [28].

Clinical observations of the skin condition show that significant skin reactions are noticed only in isolated cases [9, 36]. The sedentary lifestyle causes a sharp decrease in eliminating epidermis horny scales on the sole of the foot, resulting in a visible deposition of horny materials on these surfaces [36].

Individual participants incur skin diseases, among which folliculitis is the main problem. Folliculitis is localized mainly in the region of the buttocks and thighs, i.e., in areas of greatest pressure, friction, and moistening of the skin. Folliculitis is noticed on the skin of face and neck on participants who wear helmets for several days. Dermatitis is observed only where electrodes of physiologic monitoring instruments are attached. Isolated cases of furuncles are due to a complication of pimple rash and folliculitis. It is noted that skin diseases cannot be attributed only to restrictions on hygienic practices [36].

In other investigations [9, 22, 42], depriving participants from carrying out hygienic procedures for an extended period did not result in serious complications of skin condition. It was also noticed that individual participants had significant dryness of skin, especially a dryness and peeling of the scalp, and irritation of skin regions where electrodes were constantly worn. Increased itchiness of the entire body was observed only where ambient air was at high temperature [9, 42].

Only insignificant disturbances in the condition of the astronaut's skin, expressed as seborrheal changes on scalp and face, were noticed in the flights of Apollo 7 and 8 as well as during Gemini flights [2].

The condition of mouth and teeth causes some anxiety. The absence of customary oral hygienic care usually results in abrupt deterioration of the teeth and mucous lining. An unpleasant odor arises from the mouth, the thin coating on the teeth accumulates, coloration occurs, and gingivitis of different degrees develops [12, 42].

Investigations of physiologic and biochemical indicators of participants' skin condition [21, 22, 36, 49] do not reveal any significant variations. Sebaceous gland function of the skin is not disrupted. The level of the lipid saturation layer of the skin's surface and its rate of renewal during experiments vary little [22, 36].

The shift toward acidity detected in individual measurements of skin surface pH does not indicate biochemical changes in the skin, but is due to the appearance of low molecular weight, free fatty acid contaminants resulting from destruction of sebaceous gland secretions [22, 36].

Extended investigation of the bactericidal activity of skin indicates a gradual decrease in its amount. The index of the bactericidal state of forearm skin, at a level of 90–95 units in its original condition, decreases to 60–70 units after 30 days [36]. According to data of other investigators [48], the bactericidal properties of skin remain at the original level, and a tendency for some decrease is observed only during the period that follows. Even though sufficiently convincing data concerning decrease of the skin's bactericidal function have not been obtained, there is every reason to expect that this negative phenomenon may be encountered in actual flights of long duration.

The effect of such extreme spaceflight factors as fatigue [11], traumatic shock [29], extensive irradiation of the body [13], hypersecretion and hyposecretion of hormones [37], is to decrease the body's resistance to infection and its immunity, possibly including the skin's bactericidal function.

An investigation of the nature and extent of skin and underclothing contamination [22, 36] showed that the contaminants consist of metabolic products, mainly secretions of sebaceous and perspiration glands, fragments of epidermis, hair which has fallen out, microbial cells, and dust from clothing.

The average daily total contamination of skin and clothing by chlorides (shown by a separate experiment) varied from 117 mg/d to 403 mg/d, and from 335 mg O_2/d to 886 mg O_2/d for organic materials. The amount of skin surface lipids (saturation layer) at separate places on the back and chest exceeded only slightly the level for these regions in ordinary life [36]. This indicates sufficient absorbent properties of underwear, its effective cleaning action, and the normal condition of sebaceous glands.

About 90% of the chlorides and up to 80% of the organic materials are absorbed by the fabric of underwear and clothing. The great capability of clothing to cleanse the skin of its metabolic products depends upon both the kind of fabric and design features of the underwear.

The data showing changes in the chemical composition of contaminants found on the skin over an extended time demonstrate the effects of personal hygiene procedures [22, 36].

Skin surface lipids (secretion of the sebaceous glands), which are the main constituents of the contaminants, undergo significant changes due to the effect of oxygen as well as the moisture and enzymes given off by the skin and microorganisms. The acid number of the lipids increases; the saponification number and iodine number decrease. The complex esters of the higher fatty acids and unsaturated compounds included with the composition of the contaminants decompose with the formation of lower and higher fatty acids. This in turn results in a pH shift of the contaminated skin surface toward acidity, particularly in regions with an enhanced sebaceous gland secretion [36]. From the hygienic point of view, this factor can be evaluated as positive, since an unfavorable medium for the growth of microbial flora is produced upon an increase in acidity of the skin surface [22].

Studies on the dynamics of microbial contamination of the skin surface using models of spacecraft cabins [22, 30, 31, 32, 33, 36, 38, 40, 42, 44, 47, 48, 49] show that infestation of the skin usually increases only for the first 2–3 weeks of the experiment. During the succeeding period, the growth and number of microorganisms on most parts of the skin are curtailed, and the level stabilized. Stabilization on the skin of the chest, back, and head starts when microflora exceed the original value by a factor of 2.0–3.5. An increase is detected on the skin of the soles of the feet, in the inguinal region, and on the buttocks; in these areas the original level has been exceeded by a factor of 7–12 [36, 38]. No clearly expressed increase of microbial infestation was noted in the forearm region during the course of the experiment [33]. In investigations on the effect of factors simulating flight (involving eight participants in a training apparatus for 28 days), the formation of mutants was not noticed and differences in the types of organisms being studied were not observed. All participants remained healthy, and decreases in resistance to infection did not occur during the entire period of observation [47].

During a 14-day Gemini flight, no noticeable shifts were detected in the microbial environment of the skin [3]. The crewmembers of Gemini 7 bathed daily with hexachlorophene during the 2-week prelaunch period. Bacterial cultures from certain regions of the skin and mouth before and after the flight revealed an increase in the number of fecal flora in the perineum region and a decrease in numbers of microbes in mucus of the pharynx. Results of an investigation to determine fungi were negative. No significant differences in species of microorganisms were revealed, and no exchange of microflora between crewmembers was observed [3].

Significant growth of cutaneous populations during an extended experiment was noted only in individual cases [44], due to random factors and peculiarities of methodology.

The species makeup of the microbial flora on the skin and in underwear is characterized primarily by saprophytic forms: *Staphylococcus aureus*, diphtheria bacilli, cutaneous staphylococci, and *Sarcina* [33, 36, 38]. Hemolytic forms of staphylococci are noted in individual cases [44].

An increase of yeastlike fungi of the *Candida* genus, having some indications of pathogenicity, have been detected in the mouth [38, 40]. Streptococci (*Streptococcus fecalis*, *Streptococcus salivarius*, *Streptococcus mitis*) are shed from the mouth and throat in individual cases, and anaerobes of a different kind are shed from the throat and anus [38].

The necessity must be stressed for regarding the level of microbial infestation not only as a function of immunity, but also as a function of the environment of the skin and in underwear resulting from changes in chemical composition of skin surface lipids [22, 38]. Under the most unfavorable conditions, there appear to be regions of the body with increased perspiration but small production of lipids: axilla, inguinal region, and feet, where the highest levels of microbial flora are recorded [36].

The level of microflora and species makeup on the face, ears, nose, forearm, chest, back, and navel indicate that these body parts are not critical from the hygienic point of view. Favorable growth conditions for skin microbes in underclothing are produced only when perspiring after washing and changing underclothes [38].

The positive role of the environment formed on skin surface contaminated by lipids (a pH shift in the direction of acidity, the appearance of free lower fatty acids) leads to the paradoxical conclusion that unlimited washing of the skin, removing all products of the sebaceous glands, is not a rational practice and makes no difference to the skin's protective function. It is better to avoid a single doctrine of hygienic principles, such as — the more often one washes, the better — when applied to the conditions of an individual's stay in a spacecraft cabin [22]. Moreover, taking into account the positive role of symbiotic microflora in the formation of protective mechanisms [24], the necessity for actively influencing the saprophytic flora in carrying out hygienic procedures becomes doubtful. Disruption of this microflora equilibrium may cause bacterial disease and actually result in decrease of host resistance. With this situation in mind, hygienic practices, which are normal and habitual under terrestrial conditions, should be approached differently for spacecrews.

The necessity for providing crewmembers with fully adequate hygienic procedures is established regardless of the relatively favorable clinical and functional condition of the skin and its low contamination level under a restricted hygiene regime. However, the versatility of personal hygiene practices under specific conditions of spaceflight shifts the emphasis somewhat on these practices and broadens their motivation. The necessity for hygienic procedures is dictated primarily by psychoaesthetic, epidemiologic, and, possibly, toxicologic considerations as well as by hygienic and physiologic factors.

The distinctive tenor of the cosmonaut's life requires that important habits and activities of terrestrial life, such as observance of personal hygiene rules and procedures, should be unconditionally included. Acceptable conditions of habitability and comfort in a spacecraft cabin cannot be created without observing this factor.

When formulating general requirements for hygienic procedures and personal hygiene under spaceflight conditions, these basic needs should not be neglected:

> Hygienic procedures to maintain crewmembers' cleanliness of body and mouth should be conducive to normal functioning of skin, mucous membrane of mouth, and teeth. Refreshing and cleansing the skin of endogenic and exogenic contaminants should involve personal hygiene methods to maintain biochemical and physiological constants of the skin and its appendages at an optimal level. Such means should possess bacteriostatic activity with respect to indigenous skin flora.
>
> The systematic continuing use of these methods should not cause unhealthy conditions, unpleasant subjective feelings, change in skin coloring, or appearance of pigmentary spots and hyperkeratosis. The methods should not sensitize the skin to ultraviolet and ionizing radiations.
>
> Compounds for personal hygiene should not contain toxic, strong-acting materials and allergens. They should not have an odor nor produce gaseous products capable of creating explosive or flammable concentrations in the cabin.
>
> It should be possible to use these methods under conditions of weightlessness and when life-support systems on-board the spacecraft are operating.

In particular cases, obviously, these requirements may be formulated only for a specific mission, based on purpose, length of flight, conditions in the cabin, and technical equipment.

EXTENT OF HYGIENIC PROCEDURES, THEIR CLASSIFICATION, AND PERSONAL HYGIENE METHODS

In selecting a hygienic regime, the main criteria are flight duration and technical equipment. The extent of hygienic procedures and completeness of their implementation on-board will differ significantly with flight duration. Procedures which should be carried out regardless of spaceflight duration are hygienic care of skin and oral cavity.

For short-term flights (up to 10 d), these procedures may be limited to cleansing exposed regions of the skin and deodorization of mouth. For flights of 2 to 4 weeks, hygienic treatment should include changing underclothing, shaving, and extra care of the mouth. When flights last more than 4–5 weeks, it is necessary to trim fingernails, toenails, and hair.

Personal hygiene can be divided tentatively into everyday and periodic procedures. The first category should include procedures of normal daily grooming: morning and evening washings, hand washing before eating and after use of the toilet, hygienic cleansing of exposed portions of skin, shaving, and cleaning and deodorizing the mouth.

The procedures in the second category should replace the terrestrial shower, and visit to the barber. A complete sanitary-hygienic cleansing of the body and a haircut should be included. Although each procedure is simple to carry out on Earth, an acceptable alternative under spaceflight conditions requires the solution of complex engineering problems.

The four basic hygienic practices can be classified according to purpose: complete sanitary-hygienic care of the body; hygienic care of individual regions of the skin; hygiene of the mouth; combing hair, shaving, and care of the nails. Each procedure will be discussed in greater detail for a clearer delineation of each step.

Complete Sanitary-Hygienic Treatment of the Body

The main requirement for sanitary-hygienic treatment of the body is removal from the skin of the natural products of biologic metabolism as well as small particles of dirt, food residue, and microbes. After treatment, the skin should be dry and clean. Its biochemical and physiologic constants should remain at the normal level.

The methods being discussed provide for use of various napkins, towels, and sponges moistened with special washing or cleansing solutions.

In flights of 3–5 weeks, the periodic (at least once every 5–6 d) use of these procedures (including change of underclothes) has the hygienic effect theoretically equivalent to a shower. However, application of such procedures leaves much to be desired psychologically. Treatment of the body in lieu of the accepted and refreshing practice of showering becomes the tedious task of "rubbing" the body.

A more promising method of creating psychologic comfort and simulating terrestrial conditions on-board the spacecraft is sanitary-hygienic treatment with the use of automatic sponges and special shower installations. For complete hygienic treatment, the shower is the most convenient, effective, and acceptable method; it is necessary and habitual in terrestrial life. A regular shower during extended space flight will help maintain psychologic comfort and remove considerable unnecessary emotional tension. Engineering difficulties and the necessity for great weight and energy reserves on spacecraft and stations make such installations possible only for flights of long duration. A complete sanitary-hygienic treatment that uses an automatic sponge is shown in Figure 1.

The sponge device moves against the skin and consists of an applicator with a handle which provides a regulated solution of water and detergent through pores in the sponge. The applicator sponge is mounted in a surrounding ring designed to pump off the solution from the skin surface. The complete sanitary-hygienic treatment, with minimum washing efficiency, was carried out for 22 min [28]. Even though this device had a weight advantage, compared with the shower device, of a factor of almost 2.8, it did not satisfy psychologic requirements.

A promising method for complete treatment with a shower assembly is presented in Figure 2.

The shower assembly has a diameter of approximately 76 cm (30 in) and a length of 204 cm (80 in). The naked individual enters the unit and uses straps to keep a fixed position while bathing. Warm water enters through the shower head of a device which the cosmonaut holds in his hands. The water is removed from the artificial atmosphere of the cabin by a separator. The shower assembly provides a detergent solution through the shower head. The individual's body can be dried using a blowing ventilator with subsequent toweling. The drying procedure, which draws off water droplets with a sponge, is also applicable. A warm air stream, used after the rest of the water is removed, accelerates the drying-off process. It is expected that the shower assembly will require about 1.89 l water/min for each 4 min of washing under conditions of weightlessness.

This shower unit was developed for the American orbital station, Skylab. It is composed of two cylindrical flanges and transparent housing made of Beta fabric with rings for rigidity.

One flange (ring) is permanently attached to the floor in the living compartment and the second is attached to the ceiling, when in use, by means of easily detachable fasteners. The ceiling flange contains a spraying jet, a sucking attachment, and elastic hoses with easily detachable couplings.

The shower receives water from the on-board water supply system. This water is stored and supplied from a special water unit having a capacity of 2.72 kg; it normally operates at a pressure of 517–1292 mm Hg. The unit receives 1.81 kg hot water (60° C) from a heater and additional cold water, and supplies a flow of water of 200–800 ml/min in a minimum of 3 min.

Used water is collected and returned by a sucking attachment to a collector having exchangeable plastic bags. These bags can be removed through a sluice in a vacuum without danger of destroying them.

The Skylab shower unit makes it possible for each cosmonaut to wash at least once a week during the entire flight.

If the shower method of complete sanitary-hygienic treatment is not satisfactory, for any reasons, damp napkins and towels for single-time or repeated use may be alternatives. Devices should be provided for reliable storage of used napkins or for jettisoning them from the spacecraft.

Hygienic Treatment of Individual Sections of the Skin

The type of hygienic procedure discussed in this section replaces everyday washings which an individual carries out under terrestrial conditions. Procedures of this type include cleansing facial skin and hands after sleeping, before going to bed, after use of the toilet, before eating, and the periodic (once every 2–3 d) drying of such hygienically critical body regions as armpits, inguinal region, and soles of the feet.

There are many commonly used sanitary-hygienic methods for treatment of specific skin sections, among which are drying the skin with various colognes, lotions, and creams; treatments with disinfectant solutions and with ultraviolet radiation. However, a unique, practical solution to this problem under spaceflight conditions is drying the skin with specially moistened towels for repeated or one-time use. Such towels have been applied quite successfully during extended investigations under terrestrial conditions [36, 38, 42, 49], along with cloth towels for wiping dry during flights of the Gemini and Apollo programs. Small towels, 8.9×10 cm in size (3.5×6 in), were moistened with an antiseptic solution, Hyamine 1622, and packed with the astronaut's single ration. A similar method of caring for exposed portions of the skin was applied during flights in the Vostok and Soyuz programs.

The use of towels to carry out hygienic pro-

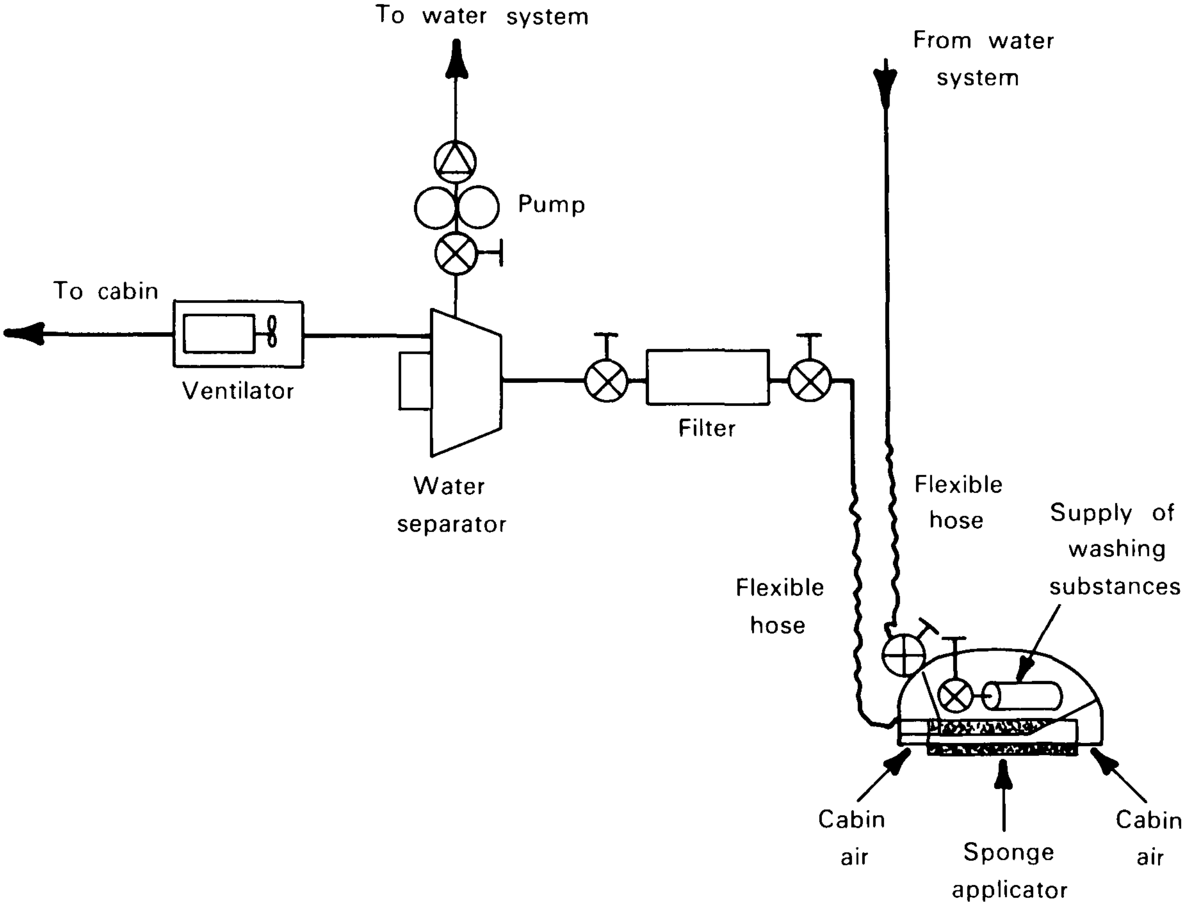

FIGURE 1. – Layout of the automatic sponge [28].

cedures proved to be the most acceptable method. Towels cleanse and refresh the skin adequately and maintain it in a satisfactory hygienic condition. In addition, the used towels can be utilized for wiping various surfaces of the cabin's equipment.

Mouth Hygiene

Hygiene of the mouth is one of the central concerns in an individual's hygienic procedures. This is no accident, since the main problem of oral hygiene is removal of local factors which favor caries, periodontosis, diseases of the mucous membrane, and halitosis. An individual's feeling of well-being depends mainly on a normal condition of the mouth because such important functions as ingestion, pulverization, and in part, digestion of food occur in the mouth.

The mouth is a reservoir for an enormous number of microorganisms. Mouth microflora are subdivided into normal and random varieties. The optionally anaerobic α- and γ-streptococci, strictly anaerobic bacteria, actinomycetes, and spirochaeta predominate. The specific makeup of normal oral microflora is maintained by symbiosis and antagonism between the microbial species and the body's protective mechanisms. Some pathologic processes in the mouth are accompanied by changes in the makeup of normal microflora. Thus, in the case of aphthous ulcers of the oral mucous membranes, the strict anaerobes (fusiform bacteria, spirochaeta, vibrios) multiply intensely, and anaerobes and

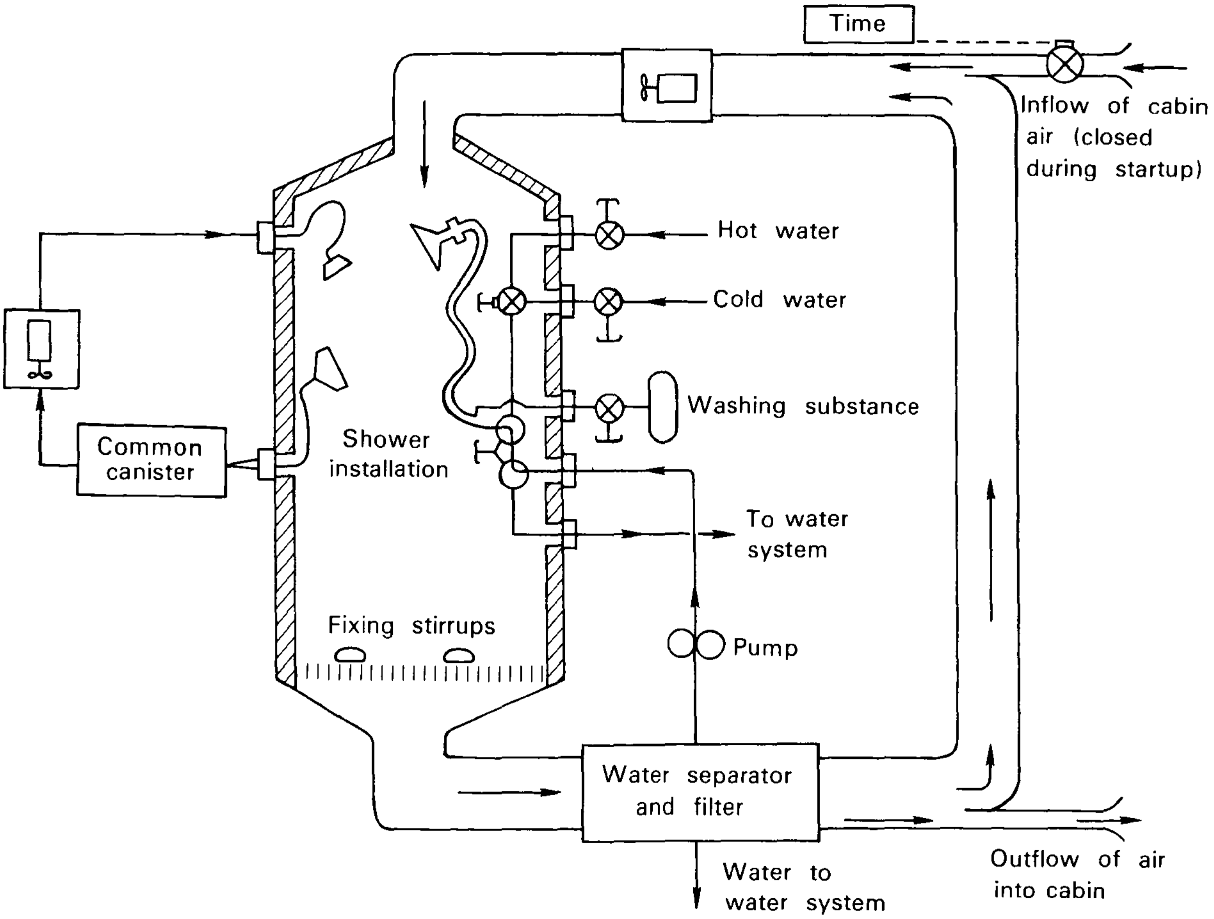

FIGURE 2.—Layout of the shower installation [17].

lactic acid bacteria are possible where there are dental caries.

Microorganisms of the other mucous membranes and skin, saprophytes of the external medium, and pathogenic microbes belong to the random category of microflora.

Streptococci of group D (enterococci), β-hemolytic streptococci of groups A, C, F, and G, pathogenic staphylococci, corynebacteria, the yeasts (*Candida*) and actinomycetes (*Nocardia*), the viruses of herpes, epidemic parotitis (mumps), and measles possess the ability to adapt to the greatest extent to the environment in the oral cavity.

The normal flora of the mouth serve as a biologic barrier because of their antagonistic effect on many kinds of microbes which penetrate from outside. The destruction of this barrier by certain influences (for example, application of antibiotics and strong bactericides) results in the intense multiplication of random forms of flora which are stable against these influences. "Medicinal" infections of the mucous membrane are caused most often by the *Candida* yeasts, the enterococci, and the Gram negative bacteria of the intestines.

As resistance of the oral tissue decreases and the reactivity of the body as a whole alters, pathogenic forms of certain symbiotic microflora can appear [25]. Chronic inflammation in the mouth, which arises most often as chronic intoxication, causes an allergic reaction and may be conducive to focal infection. All these conditions are especially significant when developing oral hygienic practices under spaceflight conditions.

Common oral hygiene includes regular cleaning of the teeth and rinsing of the mouth. For this purpose, various toothbrushes, pastes, powders, cleaners, elixirs, and rinses are usually used.

Extended investigations [17, 39, 42] in spacecraft simulators have shown that the condition of the mouth causes special concern, and the greatest clinical changes have been observed in the condition of the teeth [42].

Data in Table 6 indicate the effectiveness of various oral hygienic procedures under a series of experimental conditions.

The use of toothbrush and toothpaste produced the greatest effect, which is shown in Table 6. Partial hygienic procedures usually resulted in some degree of gingivitis in all participants. Gum bleeding in a number of participants, which developed 3 weeks after the start of the experiment, continued during the entire experiment.

In space flights of the Gemini program, cleaning the mouth was accomplished with a toothbrush and chewing gum. In the Apollo flights, crewmembers were provided with toothbrushes and small tubes of toothpaste. Cleaning the teeth was part of the daily routine, performed after each meal to prevent formation of film on oral mucous membrane and the development of gingivitis.

The most effective procedures specify use of a toothbrush and toothpaste and can be recommended for space flights of long duration. Electric toothbrushes, which have a forced supply of liquid cleaning paste and provide for the re-

TABLE 6.—*Estimate of the Effectiveness of Oral Hygienic Procedures* [42]

Procedure	Experiment	Results
1. Toothbrush and toothpaste (without hexachlorophene)	II	Satisfactory hygiene of the mouth
2. Chewing gum and an interdental stimulator	III	Not effective; gingivitis, discoloration of teeth, and bad breath appear in all participants
3. Electric toothbrush and interdental stimulator	IV	Improvement in the condition of all participants' teeth
4. Interdental stimulator only	V[1]	Not effective—gingivitis, discoloration of teeth, and halitosis appear
5. Toothpaste and water only	VI[1] VII, X	Various degrees of gingivitis, discoloration of teeth, and mild halitosis appear
6. Toothbrush and edible paste (USAF SAM)	VIII	Satisfactory oral hygiene
7. Toothbrush, water, and dental floss	IX	Improvement in dental health of all participants

[1] An electric toothbrush was used only during the first week; all other procedures were tried for 6 weeks.

moval of expectorate, can be used. Expectorate is removed through a special nozzle with a mouthpiece attached to the processed water collection system.

Combing Hair, Shaving, and Nail Care

Hygienic procedures for care of the hair during space flight consist of periodic hair combing or trimming and shaving.

The life of hair varies from several months (for bushy hair) up to 2–6 years (for long hair) and may depend on the time of year, age and sex of the individual. An adult scalp may lose 25–100 hairs in the telogenic phase every day.

The growth cycle of human hair (anagenic phase) is 2–6 years. On the average, hair located on the upper part of the head grows 0.35 mm/d, hair on the chin 0.38 mm, in the armpits 0.3 mm, and in the region of the eyebrows, 0.16 mm [1]. Women's hair grows more rapidly on the upper part of the head, while men's hair grows more rapidly in the armpits. Hair grows more rapidly in summer than in winter.

The growth of a beard and hair on the head is determined by both cultural habits and professional considerations [14]. At times a long hairstyle causes discomfort and can result in a difficulty of normal vision.

Investigations have established [28, 42] that after a 5–6 week interval under conditions of artificial living, participants express a wish to shave and trim their beards [28, 42]. Growing a beard did not cause particular complications during terrestrial experiments which provided for use of hygienic procedures [9]. At the same time, it is scarcely possible to consider a long haircut and beard as positive features from the hygienic point of view. Considering the difficulties of carrying out hygienic procedures as well as the specific character of sanitary-hygienic conditions in spacecraft during extended flights, hygienists will recommend that a short haircut and shaving be required for cosmonauts.

The main problem in hygienic care of the hair during space flight is preventing particles of cut or shaved hair from entering the cabin's atmosphere.

Special electric razors have been developed which are equipped with suction for the removal of cut hair. However, the ordinary safety razor and shaving cream turned out to be the most acceptable. Crewmembers in the space flights of the Soyuz and Apollo programs used ordinary safety razors and shaving cream applied with the fingers. After shaving, the equipment was wiped dry with napkins, and the hair particles were left in the fixing cream instead of entering the cabin's atmosphere.

Cutting the hair on the head during extended flights can be accomplished with electric or pneumatic shears equipped with suction and a flange for discharging cut hair into the waste collection system.

The hygienic care of the nails consists of simultaneous trimming of exceedingly long fingernails and toenails. Nail material is composed of flat, polygonal, horny scales. The growth rate varies with the individual and depends on the person's age, condition, and profession. There is complete renewal of the fingernails in 95–115 d; a nail grows 0.1–0.2 mm during a single day.

Investigations [42] showed that the fingernails of half the participants grew so long during the 4-week experiment that they began to interfere with work operations and writing. Trimming fingernails was usually necessary 6–7 weeks after the initiation of the experiment.

Provision must be made for trimming fingernails and collecting the trimmed scales (particles) in spacecraft and manned space stations when flight duration is longer than 4–5 weeks. Special hermetic boxes can be used for these purposes, and should be equipped with a suction air system connected to a collector of solid wastes. The boxes should be equipped with apertures having cuffs which tighten around the hand or foot to permit trimming nails inside the box. The box can be devised as a collapsible system for saving space.

Shortening nails with manicuring files is one possible method of nail care, but it will be necessary to do this every 2–3 d, i.e., significantly more often than trimming the nails. It will be necessary to carry out this procedure near the intake of the air-conditioning system, which is equipped with filters to collect and store nail scales.

In concluding this discussion of flight clothing and personal hygiene for cosmonauts, it should be emphasized that examination of these problems was based on data from terrestrial experiments with a duration no longer than 90 d and in short-term space flights. However, it can be assumed, with a sufficiently high degree of validity, that the solution to these problems will undergo no radical changes for flights of significantly longer duration (100-500 d and more). It can be stated with firm conviction that successful accomplishment of extended flights is possible only when living and working compartments of spacecraft offer optimal habitation conditions for necessary comfort and convenience. In this respect, the problems of providing cosmonauts with flight clothing and the means for personal hygiene do not play a secondary role.

Spacecraft engineering designs for extended flights should provide for carrying out the complete set of personal hygiene procedures, laundering underclothing, body washing, changing clothes, as well as maintaining personal hygiene materials and sets of flight clothing.

It is reasonable to assume that optimal conditions of habitability will exert a positive effect on the general working ability of cosmonaut-operators and permit them to carry out flight tasks successfully.

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Chapter 5

ISOLATION AND REMOVAL OF WASTE PRODUCTS[1]

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The concept of waste products encompasses a variety of substances formed during the vital activity of man and animals. Properly organized isolation and removal of waste products is one of the principal requirements for normal existence and high work capacity of spacecraft crewmembers and personnel of stations and bases. However, technical accomplishment of the indicated operations under specific flight conditions presents a number of difficulties determined both by rigid operating requirements and physiologic and psychologic peculiarities of the cosmonauts.

As the duration of space flights and number of crewmembers increase, and as the activity becomes more complex, waste products increase both in the overall amount and in the number and variety of individual components; this necessitates strict compliance with on-board sanitary regulations. This chapter describes methods of isolation and elimination of waste products in spacecraft cabins.

ROLE OF WASTE PRODUCTS IN THE ENVIRONMENT

Waste products, regardless of their chemical and bacterial composition and their physical or other properties, have a basic feature in common: they are a source of contamination for working and living quarters by harmful or undesirable agents and they promote the development of microflora, including types that may cause illness among crewmembers or damage to equipment.

Many kinds of waste products undergo definite changes in time. For example, during aerobic and anaerobic decomposition of organic substances due to the effect of microorganisms and physicochemical factors, protein products break up and are converted to ammonia, peptones, amino acids, and so forth. The breakup of carbohydrate compounds is accompanied by the formation of lactic, carbonic, and acetic acids, alcohols, and other substances, which enter the surrounding environment.

A significant part of the solid, liquid, and gaseous substances which substantially affect the environment is formed from a variety of products of vital activity such as discharges from man and animals. The chemical and bacterial composition of these products as well as the gas discharges from them have been long known [73]. However, a quantitative analysis of the components of these substances applicable to conditions of space flight has received attention only in the last 10–15 years.

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[1] Translation of, Izolyatsiya i udaleniye otbrosov, Volume III, Part 2, Chapter 5 of *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*), Academy of Sciences USSR, Moscow, 1972.

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Airborne Toxic Substances from Stored Wastes

Intensive studies designed to ascertain the qualitative and quantitative characteristics of gas composition and microflora of feces during storage have been carried out by Kustov et al [54]. In the first series of tests, in a gas analysis of the air effluent from a desiccator which contained fresh feces at 18°–20° C, certain toxic agents were detected. The amount of toxic substances detected in each of the two tests fluctuated widely (shown in Table 1), which was probably related to the nature of food ingested and composition of the intestinal bacterial flora of the various test subjects.

The data obtained also show that large quantities of hydrocarbons, volatile organic acids, nitrogen oxides, ammonia, carbon oxides, and phenols were released from the fresh feces during the first 2 h of storage. Mercaptans and hydrogen sulfide were detected in trace amounts. Indole and skatole were detected occasionally. This variety of substances can substantially affect human work capacity by causing vomiting and other adverse reactions within a short time.

Sanitary, chemical, and bacteriologic investigations were carried out [69] in view of the possibility of greater toxic action from increased length of exposure to discharges in a closed compartment, and to examine the dynamics of gas emission from discharges in relation to the state of the microflora. Fresh feces were placed in desiccators and stored for 5 days. Then the air of the desiccator was analyzed to determine the amount of gaseous substances and, at the beginning and end of each test, the total amount of aerobic and anaerobic microorganisms, including *Escherichia coli* and *Proteus*, in the feces.

The number of anaerobic microorganisms in the fecal masses remains approximately the same or increases slightly, while in the same storage period, the number of aerobic bacterial flora increases 8–10 times (which is basically due to the *E. coli* coccal and spore forms).

Analysis of the gas in the desiccator shows that significant amounts of hydrocarbons, ammonia and its compounds, phenol, organic volatile fatty acids, nitrogen oxides and carbon oxides were discharged from the feces during 5 days. Sulfur dioxide, ketones, indole, and skatole were detected in lesser amounts. Only trace amounts of aldehydes and mercaptans were detected in some tests; however, it should be noted that under specific conditions these substances may accumulate in concentrations incompatible with human beings.

To establish the role of discharges in the makeup of the environment, the gas composition and microflora were studied in the air of a chamber about 24 m³ into which animal urine

TABLE 1.—*Quantity of Gaseous Toxic Substances (mg) Discharged from Fresh Feces (100 g)* [1]

Test no.	Ammonia and aliphatic amines	Mercaptans and hydrogen sulfide	Phenols	Indole and skatole	Fatty acids	Nitrogen oxides on conversion to N_2O_5	Hydrocarbons on conversion to CH_4	Carbon oxides
1	0.052	traces	0.011	0	traces	0.007	0.120	—
2	0.035	—	0.009	0	—	0.005	0.248	0.023
3	—	0	0.007	0	0.079	0.042	1.780	0.081
4	—	0	0.006	0	0.138	0.008	0.696	0
5	0.008	traces	0.013	0	0.111	0.009	0.173	0
6	0.062	traces	0.010	0	0.155	traces	0.696	0
7	0	traces	—	0	0	0.078	—	0.170
8	0	0	—	0	0.203	0.094	—	0.494
9	0.011	0	0.011	0.007	0.310	0.236	1.230	0.330
10	0	traces	0.006	0.008	0.846	0.123	1.480	0
11	0	0.013	—	0.013	0.500	0.007	—	—
Average	0.019	—	0.009	0.002	0.259	0.061	0.802	0.122

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[1] Data from Kustov et al [54].

and feces were placed daily. Air temperature in the chamber varied between 20°–24° C; relative humidity did not exceed 60%. Material was collected from two mongrel dogs which weighed 6–8 kg. From 60 to 120 g feces and from 110 to 800 ml urine were put into the chamber daily. The gas composition and microflora of the air were examined daily, and near the end of the test, the composition of the urine and feces was examined daily.

Concentrations of ammonia and amino compounds increased constantly and by the 15th day comprised 12 mg/m^3, i.e., increased by 120 times, while dimethylamine comprised 0.09 mg/m^3. In the first 5–7 days, an insignificant increase was observed in concentrations of aldehydes, ketones, mercaptans, and hydrogen sulfide, but then the content of these substances stabilized, and they ceased to accumulate in the air of the chamber. Alcohols, fatty acids, indole, and sulfur dioxide were not detected. Concentrations of carbon monoxide and oxidizable organic substances were at the level of the baseline period in the majority of tests [13, 17, 75].

Thus, under conditions of the test described, the discharge of volatile products from animal excrement is intense. It exceeds, by one order of magnitude, similar data obtained during the passage of air, at a rate of 0.5 l/min, through a sealed container having a significantly smaller volume and containing urine and feces. However, even with such a concentration of toxic gases in the chamber, appreciable increases were observed in blood levels of acetylcholine and cholinesterase in the test animals [53].

Shifts in the acetylcholine-cholinesterase system, which were observed during the action of gas discharges from fresh and stored excrement, indicate certain disorders in the neurohumoral equilibrium of the organism. The onset of such disorders indicates both an irritating and generally toxic action.

Microflora in Stored Wastes

An investigation before and during the first few days of the test revealed no growth of microorganisms during seeding on a meat-peptone agar. In subsequent days, bacteria were observed in the amount of 40–160/m^3 air, but not in each sample probe. Even during seeding onto an Endo medium no growth was noted. Thus, air-medium seeding, despite the intensive breakdown of metabolic products, was practically unchanged. This is probably related to the insufficient mixing of air in unmanned enclosures.

Throughout the 15 days, bacterial seeding of the discharges increased significantly (for urine 170 000 times, for feces 15.4 times). During this period, the putrid odor of urine sharply increased, and it acquired a murky outer appearance which cleared up after standing. As the putrid forms of microorganisms increased, mold appeared on the surface of the feces and inside them. The data presented convincingly demonstrate the necessity of careful isolation of excrement.

Distinct changes in the composition of the microflora of the feces were revealed during the action of certain factors on man which are characteristic of space flight. Thus, the amount of microbial bodies in 1 g fecal mass decreased 100 times in connection with a change of metabolism due to the effect of hypodynamia and various food rations [5, 22, 28, 66, 77, 85, 86, 94].

Long-term human confinement under conditions of relative biologic isolation, as a rule, leads to unfavorable shifts in the composition of intestinal microflora, which are characterized by a sharp reduction of various groups of microorganisms and even by complete disappearance of individual types of intestinal flora. These changes show the tendency toward simplification of microflora of fecal masses (a reduction in a number of its species).

Mutual exchange of microbes among persons under conditions of confinement in a hermetically sealed cabin has been demonstrated by the method of phagotyping discharged strains of staphylococci [7, 56]. In the *Staphylococcus* strains of the same phagotype which were discharged from test subjects during an experiment, an increase of toxin titer and the appearance of additional pathogenic signs were detected which had not been detected in the test subjects earlier. This was expressed by an increase in the number of strains which produce β-hemolysin and fibrinolysin.

In tests on mice, an increase of virulence was established in *Staphylococcus* strains which were discharged from test subjects at the end of a year-long experiment [21]. When the microclimatic and sanitary living conditions in the experiment were made more severe, the presence of antagonistic and hemolytic *Escherichia* showed the exchange of intestinal microflora.

A careful study of the fecal flora of four persons in isolation showed a shift in both anaerobic and aerobic flora [29]. *Shigellae* and enteropathogenic types of *E. coli* appeared frequently. Species of *Candida* have the greatest distribution. Unusual microorganisms also were discharged. A decrease in the number of enterococci somehow supplemented the increase in the growth of coliform microbes. Seven new species of cultures of anaerobic bacteria were found. Similar data were obtained by other investigators [36, 44, 56, 82].

Thus, a good estimate has been formed at present of the substantial change in automicroflora of astronauts during prolonged space flights. However, not all specialists agree. The majority of investigators think that the number of species of microbes in the intestine can be reduced, but that the overall number will remain almost unchanged. They suppose that for 1 g excrement, approximately 10^9 microorganisms will be produced. Any species of bacteria that inhabit the intestine may become predominant. If, however, the dominant microorganism does not adapt well to the temperature, diet, and anaerobic conditions in the gastrointestinal tract, the overall amount of bacteria may reach up to 1 000 000/g fecal mass.

The composition of gaseous products which are discharged from feces reflects changes of their microflora. For example, when there is prevalence of lactic acid flora, lactic acid and its esters can easily be found. An odor of indole and skatole is an unmistakable sign of the prevalence of *E. coli*. Consequently, the atmosphere of the manned compartments is directly affected by peculiarities in the bacterial flora of feces and is subjected to undesirable changes even during normal functioning of the system that is employed for regeneration and conditioning of the gas environment, which was designed for a specific ratio of toxic and foul-smelling substances.

Toxic Materials From Stored Urine

Urine, which is stored in special containers aboard the spacecraft, is also a potential source of contamination of the cabin atmosphere by certain toxic or malodorous substances. Results of tests conducted to determine the amount of toxic substances discharged from urine showed that significant amounts of phenols, ammonia, and aliphatic amines, oxides of carbon, and hydrocarbons are separated even from fresh urine when it is purged with clean air [52]. Mercaptans and hydrogen sulfide were detected in trace amounts only in 5 of 11 tests performed.

In addition to those substances found in fresh urine, after it was stored for 3 days, nitrogen oxides were detected. The average amount of ammonia and aliphatic amines in both fresh and stored urine was practically the same. Substantially less phenols and acetone were discharged during storage of urine in comparison to the amount discharged when clean air was bubbled through the fresh urine. It was noted that significantly greater amounts of fatty acids were discharged from urine stored for 3 days than from fresh urine.

In a study of urine stored for 10 days, it was established that diethyl ether, methane, methanol, ethanol, propanol, benzene, acetaldehyde, and acetone were the principal volatile ingredients. The presence of these gaseous products depended upon the septic and fermentation processes related to the metabolism of microorganisms. When the latter reached the urine from the mucous membranes of the urogenital tract, the ambient air and surfaces, and the materials of devices in the discharge collection and transport systems, favorable conditions were provided and microorganisms multiplied quickly.

Hydrolysis of urea into ammonia and carbon dioxide is one of the most important reactions for the conditions examined. Because of the buildup of ammonia, the urine reaction during storage becomes more alkaline, which creates an additional load on certain parts of the life-support system. Urea breakdown is accomplished not only by typical urobacteria, but also by many species of aerobic septic bacteria. Among these are *Proteus vulgaris*, *Escherichia coli*, fluorescent

Pseudomonas, fungoid bacillus, and other microorganisms which are almost always found in inhabited enclosures.

Studies [50, 53, 92] have shown that the group of gaseous substances emitted by fecal masses and urine are injurious to the human organism, acting not only as irritants but also as toxic agents. These substances also have a negative psychologic effect.

Waste Materials From Skin and Appendages

A substantial portion of waste products is composed of substances which are formed by human skin and its appendages. Among these are the desquamative epidermis, secretions of sweat and sebaceous glands, and nails and hair which have been clipped off.

The desquamative scales of the epidermis contain principally keratin and certain fatty substances (cholesterol, phospholipids, and others), which are formed during keratogenesis. The latter have a noticeable effect on the chemical composition of a group of substances formed from secretion of the sweat and sebaceous glands on the body surface. Their decomposition is accompanied by gaseous emissions, some of which have an unpleasant odor and, under certain conditions, toxic properties [58]. Both organic and mineral components of this group are absorbed by textile clothing materials.

In experiments which simulate sanitary and living conditions of space flight, the average daily total contamination of human skin and its clothing ranges as: chlorides, 117 to 403 mg; and organic substances, 335 to 886 mg (by oxygen in a permanganate study). Due to the action of oxygen from the air, humidity, perspiration components, enzymes, and other factors, the chemical composition of organic substances, and in particular, of lipids on the surface of the skin underwent definite changes. Thus, by eliminating body grooming and change of underclothing from the personal hygiene procedure, one of the basic indices of the chemical characteristics of lipids, the acid number, increased on the average by 21% in 30 days, and the ester, iodine, and saponification numbers decreased [13, 17, 65]. Along with change in chemical composition of substances, the reaction of the medium also changed. The concentration of hydrogen ions on the surface of the skin during the 30–60-day experiment became more acidic and, by the end of this period, reached a pH of 5.2–5.68.

Microbe seeding of the skin of test subjects varied according to these conditions. In the first 2–3 weeks, the quantity of microorganisms on most sections of the skin continuously increased, and by the end of this period had exceeded the initial baseline values by 3–3.5 times (on freshly washed skin, 4–5 colonies were detected per cm^2). Then the level of microbe seeding stabilized and showed no tendency to increase. At the same time, microflora grew rapidly on the skin of the soles of the feet and on the perineum and the buttocks; near the end of the experiment this exceeded the initial values by 7–12 times. After 30 days, 68 colonies were detected per cm^2 in the area of the buttocks, and 82 colonies on the feet. After 60 days, there were 180–200 colonies per cm^2 on the arch of the foot. As the test continued, the importance of forms with individual features of pathogenicity increased.

Under the restricted sanitary and living conditions, a significant portion of organic and mineral substances, also microorganisms are absorbed from the surface of the human skin by textile materials of clothing, which absorb up to 80%–95% of chlorides and oxidizing organic substances and which retain this capacity for 30 days and longer [64].

Many microorganisms find favorable conditions for vital activity in contaminated clothing, especially when it is wet. Among forms with a higher survival rate under these conditions are species of the staphyloccocci flora, including microbes that have pathogenic features. Under conditions of biologic isolation, potentially pathogenic forms [7, 17] appear after only 2–3 weeks. In addition, certain bacteria during the metabolic process produce gaseous substances with an unpleasant odor, which affects the psychologic state of the crew.

Thus, products of metabolism of an organism determine the gas composition of hermetically sealed manned capsules to a significant degree. More than 400 chemical compounds are known at present to be in the composition of metabolic discharges into the surrounding environment; 183 come from urine, 196 from feces, and 271 from the surface of the skin [92]. However, the toxicologic significance of these products is not the same. The most important in the atmosphere of closed systems are ammonia, phenols, methane, hydrogen, indole, skatole, amines, organic acids, carbon monoxide, acetone, mercaptans, hydrogen sulfide, and ethyl and methyl alcohols [48, 55, 61]. Even in trace amounts, these compounds have an unfavorable effect on human work capacity and health, an effect which becomes much more serious as the exposure time increases.

In addition to the products of vital activity, the manned compartments are contaminated by certain forms of waste products with an exogenic origin. These include food particles, packaging materials, degradation products formed during the use of clothing, equipment, personal hygiene and everyday living articles, various kinds of equipment, also instruments and materials used in operating and repair work. The volume of such waste products can increase as the functioning time and the number of crewmembers increase and as the work requirements and equipment maintenance become more complex, despite a portion of the substances being utilized aboard. They may also serve as a source for gas formation due to the physicochemical and biochemical processes, especially in maintaining humidity at a level adequate for the growth of microorganisms. However, the concentration of volatile substances is determined by the specific composition of the varieties of waste products and their percentage ratio in a given time. The dust level of the inhabitated environment is also determined by exogenous waste products.

COMPOSITION AND DAILY AMOUNT OF WASTE PRODUCTS

Types of waste products and their quantitative ratios vary widely because in addition to the varied metabolic products of vital activity of men and animals, included are items used for sanitary support of the crew, substances and objects formed during functioning of the life-support systems and other equipment which are not used up. The type and amount of waste products depend on the program, tasks, and duration of the flight, the number and nature of the activity of the crew, and design of the life-support system.

In open (unsealed), partially sealed (by gas medium or water exchange), and completely sealed life-support systems for the crew (based on physicochemical, biologic-technologic or composite methods), the composition and ratio of the types of waste products differ substantially. These variations are especially great when the ecological system includes such components as an on-board greenhouse for cultivating higher plants, a vivarium for experimental or production animals, and the unrecoverable intermediate products which can never be completely eliminated [23, 49, 79]. Until the present, these problems were slightly studied and require experimental confirmation under conditions which maximally approximate actual flight conditions.

The physicochemical composition of urine, feces, excretion of sweat and sebaceous glands of the skin, and other metabolic products of man under conditions of ordinary life have been quite well-studied [73]. Quantitative ratios of the component parts of metabolites during relatively brief intervals vary within a wide range depending on the nature of the activity, the food ration and schedule, water consumption, microclimatic conditions of the surrounding environment, and individual and other peculiarities [65, 75, 77].

Under the effective factors inherent in space flight, there is a noticeable change in the nature of metabolism and in the average daily amount of certain metabolic products. In hermetically sealed chamber experiments, substantial changes have been found in the daily amount of feces and their percentage composition of water, proteins, fats, carbohydrates, and cellular tissues in relation to the food ration, the degree of motor activity, and other factors [77, 82]. During hypokinesia, an increase has been noted in the excretion of calcium as well as certain protein and other substances in urine and feces [12, 66]. Under conditions of hypodynamia, disruption of normal ratios between the excretion of sodium, calcium, and other ions in the urine has been observed in combination with a high environmental temperature when there was a significant elimination of salt from the human body [5, 6]. Disturbances were noted in protein metabolism during the action of ionizing radiation in doses which are quite likely for space flight [90]. A definite decrease was detected in the elimination of hydrogen sulfide, acetone, phenol, ammonia, and amines and an increase in aldehydes in test subjects who had been given the experimental ration intended for cosmonauts. This ration consisted of sublimated and natural products which completely excluded foods rich in cellulose (e.g., vegetables and fruits).

The above data indicate a substantial change in the physicochemical and bacterial composition of human metabolic products under conditions characteristic of space flight. This disrupts the normal ratios between the component parts of waste products found in a solid, liquid, and gaseous state, and in certain cases causes a noticeable deviation in average daily amounts by weight and volume. The composition and amounts for the average daily accumulation of various types of waste products will become more precise as experimental data accumulate. However, there is at present sufficiently established information on which researchers and designers can base life-support systems. Table 2 presents one of many design variants, as an example.

A typical composition and nominal amounts of the principal types of waste products computed for one crewmember/day, which are presented in Table 2, show quite irregular ratios between various phases of the aggregate state. Solid substances comprise only an insignificant portion according to weight and volume. The predominant amount of the varieties of waste products is found in the liquid and gaseous states. Furthermore, the collection and transport of specifically such substances present the greatest technical difficulties under conditions of altered gravitation. The humid medium also creates favorable conditions for the active growth of many microorganisms, which inevitably leads to additional emission of gaseous products, and in certain cases facilitates an imbalance in the bacterial flora of the manned compartments. All this may reduce the degree of functional reliability of sanitary and other on-board equipment if timely steps are not taken to prevent these unfavorable influences.

COLLECTION AND TRANSPORT OF WASTE PRODUCTS

One of the important operations for isolation and elimination of waste products is their collection and transport to storage containers, to devices for evacuation from the inhabited compartments, or to recovery systems. Under conditions of weightlessness, vacuum is the most efficient means of liquid collection. However, this necessitates separating the liquid and gaseous phases in the tubing and branches of the transport apparatus. Otherwise, it is difficult to avoid exceeding the permissible dimensions of the containers for liquid waste products, and also the escape of gaseous products [93].

The importance of separating the liquid and gaseous phases of the waste products is obvious if it is considered that mixing these components in pipelines intended for movement of liquid can cause obstruction by gas pockets, an increase in pump load, and an increase in the probability of the entire system malfunctioning. This is furthered by continuous gas formation that takes place during fermentation and putrefaction of the majority of moisture-containing substrates of biologic origin.

The collection and transport of solid waste products under weightlessness are accompanied by fewer technical difficulties. Food containers, used articles of personal hygiene and residues of their contents, and other similar types of waste products can easily be gathered and placed into appropriate devices or containers, which do not require the aid of special units. However, in so doing, the psychologic acceptability of one or another kind of operation must be considered.

Handling fecal or vomitus masses under conditions of space flight is accompanied by a number of complications determined not only by their consistency but also by psychologic and esthetic considerations. The significance of these obstacles increases along with an increase in functioning time and crew size when normal interrelationships between crewmembers are especially important for smooth operation in carrying out the program of investigations, tests, and control of systems [2, 84].

Devices for Collection, Transport, and Storage

The variety of waste products and the differences in their physicochemical and bacteriologic properties complicate the designing of devices intended for collection and transport of metabolic wastes, as well as the accompanying wrapping and packaging materials, and articles for carrying out physiologic functions, personal grooming, and so forth. Special difficulties arise during use of component parts of certain types of waste products as starting products for regeneration of substances useful to man.

Because devices for collection and transport of waste products are a part of the crew life-support systems and are closely connected with other forms of equipment, it would hardly be expedient to study the problem of creating general purpose types of such units. The assembly and design of the receptacle devices and the means for transporting waste products may change depending on the purpose of a spacecraft or station, its design features, and the nature of the activity of the crew and the flight program.

TABLE 2.—*Composition and Average Daily Amount of Principal Types of Waste Products from Metabolites of One Person*

Waste product, type	Without containers		In containers	
	Weight, g	Volume, ml	Weight, g	Volume, ml
Solid bodies				
Various cabin materials	0.70	0.72		
Food particles (including vomitus)	0.70	0.70		
Desquamated epithelium	3.00	2.80		
Hairs—fallen off	0.03	0.03		
after shaving	0.05	0.05	0.25	0.23
Nails			0.01	0.01
Sweat	3.00	3.00		
Fatty substances	4.00	4.00		
Saliva	0.01	0.01		
Mucus	0.40	0.40		
Semen	0.01	0.01		
Feces particles	0.02	0.02		
Microorganisms	0.16	0.14		
Excrement			20.00	19.00
Solid substances from urine	0.03	0.02	69.98	65.98
Total	12.11	11.90	90.24	85.22
Liquids				
Water from excrement			100	100
Water from urine			1300	1330
Total			1430	1430
Gases				
Intestinal gases		2000		
Sweat water		1200		
Total		3200		

However, in all cases, the devices must completely fulfill the requirement dictated by the needs of personal hygiene, applicable to a specific set of biologic and technologic conditions [20].

Waste products must be gathered and transported so as to prevent contamination of crewmembers, internal surfaces of the manned compartments, and equipment located in them. In the majority of cases, waste products must be processed during collection to prevent formation of harmful gaseous substances and growth of microorganisms in collectors, branches of the transport system, and storage containers. This is especially important for variations of life-support systems which are intended for prolonged onboard storage of all or certain types of waste products when there is an increased probability of contamination of the living area by bacteria which enter it because of damaged hermetic sealing on the devices [19].

One of the important criteria for evaluation of design criteria of the sanitary equipment is its reliability and efficiency under weightlessness. The latter nearly completely eliminates the possibility of using normal methods for collection and transport of waste products which depend on gravity. The application of pressure, traction, or manual force is most acceptable. In order to insure convenience in the use of such devices under conditions of weightlessness, restraint belts for securing the feet and body or other similar arrangement might also be required.

The peculiarities and specific operating requirements for on-board systems significantly complicate the design of units for collection and transport of waste products. Several types of such devices have been suggested and tested.

For the crew to maintain normal vital activity and high work capacity during a flight of up to 1 year or more, the craft should be equipped not only with devices permitting collection, transport, and isolation of urine and feces, but also with water for washing, showering, preparing food, washing undergarments, and so forth. Systems designed for relatively short-duration flights with few crewmembers may prove basically inexpedient under these conditions due to the substantial increase in weight and size and the lack of compatibility with the units processing wastes.

Under conditions of weightlessness, collection and transport of liquid, with rare exceptions, cannot be performed by the means used under conditions of gravity. When there is no gravity, the behavior of a liquid and its distribution in receptacles are determined primarily by surface tension and wetting forces. It has been demonstrated theoretically and verified in practice [95] that if, under conditions of weightlessness, a liquid is not in contact with the receptacle walls or they are not wettable, the liquid tends to assume a globular shape, which has the minimum surface for a given volume. If, however, the walls of the receptacle are well wet, the liquid—due to the wetting force—adheres to its inner surface and tends to assume its shape. On the basis of this, hygroscopic materials (e.g., moss, activated charcoal) were used on the first biosatellites for the collection and transport of liquid wastes. Such is shown in Figure 1 [33, 35]. Methods of collection and transport of wastes were constantly being improved for the Vostok, Voskhod, Soyuz, Mercury, Gemini, and Apollo spacecraft as well as aboard the Salyut and Skylab space stations. Figure 2 is a general diagram of the positioning of the component parts of a sanitation system.

The pneumatic method for transport of a liquid by means of rapid airflow was first used aboard the Vostok manned craft. Figure 3 is a diagram

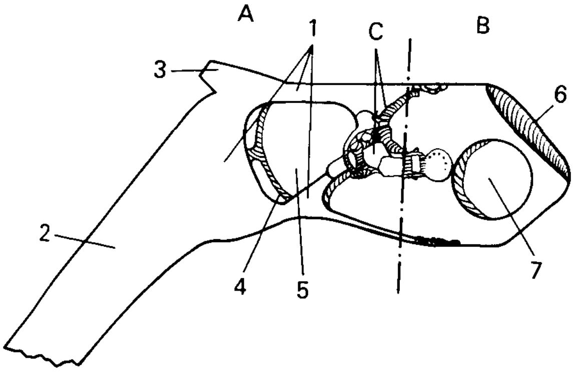

FIGURE 1.—Sanitation device for experimental animals (dogs) during short-duration space flights (adapted from [31]). A, urine and feces receiver; B, "brassiere"; C, Bundles; 1, sheath; 2, tube; 3, opening for tail; 4, obturator seal; 5, opening for hind legs; 6, opening for head; 7, opening for forelegs.

of the system for pneumatic transport of liquid. Liquid from receiver "1" was moved through hose "3" into container "6" by means of an airflow produced by fan device "8." Within the container, there was a special moisture-absorbing material (polyvinyl formol). For the moisture-absorbing material to offer minimal resistance to the flow of moving air, it was used in the form of a charge, cut into cubes with sides of 7–10 mm, as a result of which, labyrinthine channels of the necessary length were produced. The charge was placed inside the container between two walls, which were perforated and of sufficient area. In passing through the layer of charge, the transporting air was completely cleared of liquid and encountered adsorptive filter "7." In the filter, the air was cleaned of harmful gaseous admixtures and returned to the craft's atmosphere by the fan.

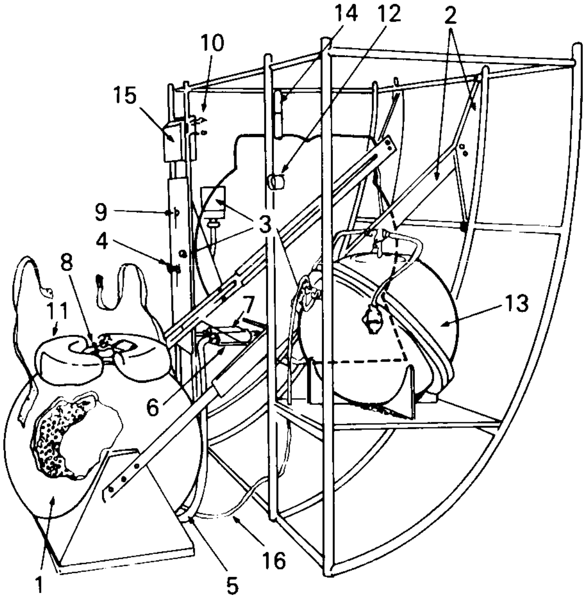

FIGURE 2.—Device for individual collection of human urine and feces during 14- to 30-day flight (adapted from [27]). 1, spherical collector for feces; 2, spherical collector frame; 3, cabin air fan; 4, separation path valves; 5, flexible hose; 6, holder with bacterial filter; 7, holder with activated charcoal; 8, latex urine receiver; 9, valve for connection with space vacuum; 10, high-speed shutoff; 11, removable lid; 12, urine receiver line; 13, urine storage sphere; 14, sterilization tablet container; 15, toilet tissue holder; 16, urine tubing.

Flight Duration Requirements

The method described has distinct advantages during flights lasting up to 14 d, due to its simplicity, reliability, and low power requirements. It offers the crew fully satisfactory hygienic conditions. Results of sanitary-bacteriologic and sanitary-chemical investigations have substantiated the positive data of a subjective evaluation of this technologic process and the devices constructed on its basis. However, for longer flights, collection of liquids in containers filled with a charge becomes inexpedient due to the substantial weight and volume of the collectors as well as the great difficulties involved in achieving the "forced" movement of the collected liquid into the water-regeneration system (when there is such a system). To support a flight lasting 1 year with a three-man crew, when there is no possibility of ejecting wastes from the craft, containers would be required weighing approximately 500 kg and having a total volume of more than 3300 l.

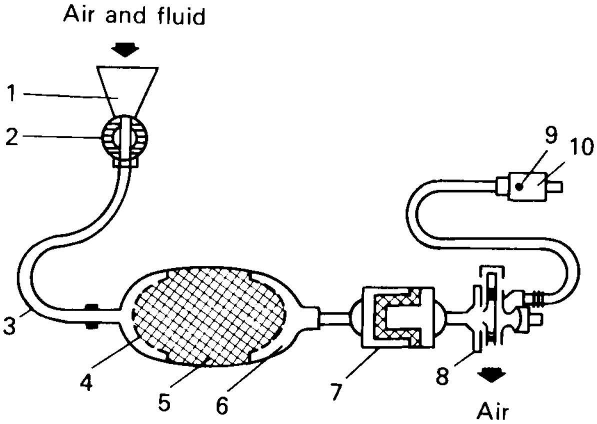

FIGURE 3.—System with pneumatic transport of liquid and phase-separation of moisture-absorbing material. 1, urine receiver; 2, shutoff valve; 3, feed tubing; 4, perforated wall; 5, moisture-absorbing material; 6, collector; 7, adsorptive filter; 8, fan device; 9, signal lamp; 10, switch-on panel.

During flights of the Gemini and Apollo spacecraft, in addition to the pneumatic transport, urine was collected by means of elastic receptacles in the form of special bags. After filling, the inner cavity of such receivers was connected with the overboard vacuum through the corresponding aperture, and the liquid was removed outward. Urine intended for subsequent biomedical investigations was retained in the bag.

Such a system for collection and transport of liquid is insufficiently reliable in operation, because the ejection opening is constantly in danger of freezing or clogging with the dry remains of urine after the water has evaporated. The introduction of a special warming device was required aboard the Apollo spacecraft to prevent the opening from freezing. Furthermore, ejecting liquid or urine overboard is unreasonable in designing closed ecological systems.

Water regeneration presents further demands on the system for transport of wash water and of liquid wastes of the crew's metabolic activity. The system must have a special separator to separate the liquid from the moving air and to pump collected liquid into the receiving devices of the water-recovery system. In this case, it is possible to use separators with periodic or continuous action.

Figure 4a shows one possible variant of a periodic action separator. The principle of its operation is analogous to the collector with a charge. In contrast to the latter, the separator is equipped with an elastic membrane and shutoff devices at the input and output connecting branches. The liquid entering is absorbed by the charge. After the charge is saturated the shutoff devices close, and compressed air is fed into the cavity over the membrane and forces the liquid out into the collectors. The advantage of this method is its simplicity, reliability, and minimum power requirements. However, in forcing the liquid from the separator, the air filling spaces between the charge cubes also escapes. The amount of air constitutes up to 40% by volume, as tests have shown [51].

A liquid-transport system with subsequent forcing out of the moisture-containing charge can find application on long-duration space flights for the preliminary separation of liquid from moving air, while in the case of water-regeneration systems capable of functioning at elevated air content in the recovered liquid, it can be used as an independent system.

The method of separating liquid from gas by hydrophilic membranes has found broad application in recent years in processes of boiling and condensing under conditions of weightlessness. The separator shown in figure 4b is an example of the application of such a method in a liquid-waste transport system. Liquid entering the separator is first absorbed by a layer of moisture-absorbing material and then pumped through a hydrophilic membrane into the collector by a pump which creates a specific pressure drop at the membrane.

Practically complete separation of the liquid from the air is attained in separators with hydrophilic membranes. However, as tests of separators designed on this principle have shown, use of membranes in liquid-waste transport systems during prolonged flights is inexpedient. Their use is restricted both from the standpoint of length of operation and amount of liquid passed through them, due to capillary pore obstruction by particles contained in the moving liquid. Figure 4c shows a unit for separating liquid from gas in which the phase-separation process occurs by squeezing out liquid into the expanding part of the wedge-shaped aperture, and air into the compressing part. Such a unit can be used in systems for supplying water for various purposes.

Other methods, such as wicks, can also be used to move liquid under conditions of weightlessness. Figure 4d shows one device based on this method. The entering liquid is first accumulated in the intermediate volume by the moisture-absorber and then, under the action of the wicks' capillary forces, flows over into the general collector, which is also filled with a moisture-absorbing material. This is not a high-performance means of transporting liquid and its transfer is slow. However, because this method reduces the need for energy expenditure, it has been widely used aboard biosatellites with dogs and other animals to remove their liquid excretions [31]. In certain systems, separators are based on centrifugal force.

Application of any specific method of liquid transport depends on both flight duration and the specific purpose of the system itself. In complex systems intended for servicing the crew of future interplanetary spacecraft, a combination of several methods will be expedient that allows for the features of the devices used, communications, and aggregate units located in the various compartments [1]. Experimental complexes of sanitary equipment designed so far have allowed for both stationary and portable human excretion receivers with individual and combined collection and transport of urine and feces. When they are used, urine—due to its natural pressure head—falls into a funnel and is taken away by the airflow created by the centrifugal separator and fan. The mixture which enters the separator is separated into liquid and air. After separation, liquid—due to the action of a head of 0.25 atm produced by the centrifugal separator—is transported through tubing into the hydroaccumulators. When there is an increase of hydraulic resistance in the main tubing over the value indicated above, the liquid's pressure head is automatically increased by means of the receiving compressing device. Contaminated air passes into the moisture remover and is transferred into the gas medium purification system. After each use, urine receivers are washed from metering devices by a portion of water (75 cm^3) containing a preservative, for improved hygienic conditions.

Used wash water from the washbowls, shower device, washing machine, and other units is transported similarly. The role of preservatives is fulfilled by the corresponding components of the cleansing agents.

When eliminations are performed simultaneously, a combined receiving device is used. The urine receiver, shown in Figure 5, is mounted together with the body of the receiver "1" and lid "7" attached to the seat panel "10." The urine receiver consists of a funnel "6" connected to a filter "13." In the lower portion of the funnel there is an annular mark joined to a connecting branch "12," to which water is fed to wash the filter after use. The urine receiver is joined to the outlet of the receiver body.

The receiver body is cylindrical in shape. At the forward wall of the body, an outlet joins vessel "1" with the urine receiver. Joined to the outlet is a tube with a connecting branch "4" (the connecting branch is designed for attachment of additional urine receivers) and switching valve "15," through which air and urine are drawn off. A replaceable lining is used in the receiver body to collect feces. The lining is attached to the extensions of a ring "5" above which a hinged seat "3" is attached.

The lid "7" is intended to isolate the compartment from emission of noxious gases which is possible when the assembly unit is not in

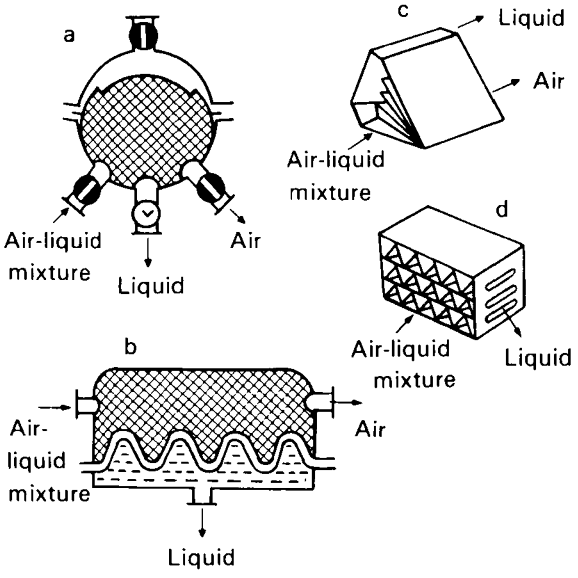

FIGURE 4.—Waste mixture separators into liquid and gaseous phases using capillary forces (adapted from [95]). a, intermittent action separator with moisture absorber; b, divider with hydrophilic membrane; c, slotted wedge-shaped separator; d, wick separator.

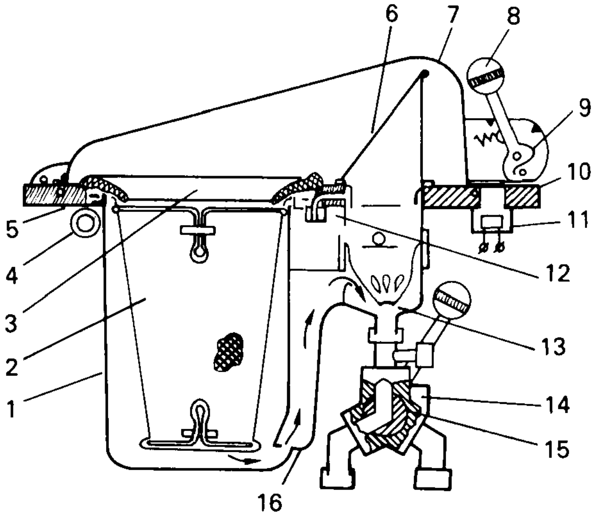

FIGURE 5.—Combined receiver device. 1, body; 2, lining; 3, seat; 4, connecting tube; 5, ring; 6, funnel; 7, lid; 8, handle; 9, lock; 10, panel; 11, microswitch; 12, connecting tube; 13, filter; 14, microswitch; 15, switching valve; 16, connecting pipe.

operation. The lid is joined to the seat panel by a hinge. On the lid there is a lock "9," which makes it possible to clamp it closely to the sealing gasket. The lock is opened and closed by a handle "8." Closing the lid actuates the end switch and opens the electric circuit, which stops the pump and fan devices.

The switching valve "15" is connected by transporting hoses to two separators (one of which is a backup) located in the assembly unit. In the valve body there is mounted a microswitch "14," intended to switch on the main or backup separator, depending on the position of the valve handle.

The lining "2" is a sleeve made of polyethylene film or another water- and airtight material. In the inner part of the sleeve a webbed net is embedded to facilitate drawing the air through and retaining the feces. Laces (timber hitches) run through the upper and lower portions of the lining and are manually drawn tight after use. The lining, useful volume approximately 600 cm^3, is attached to the receiver device by loops set on the wide part of the sleeve. The lining is used once, after which it is placed in the respective hermetic container.

Investigations of the hygienic evaluation of this equipment during tests in a manned spacecraft simulator have shown that it is acceptable physiologically and psychologically. No excess concentrations of noxious gaseous substances above permissible levels were observed. In particular, in the atmosphere of the manned compartments, hydrogen sulfide did not exceed 0.011 mg/l; hydrocarbons, 0.02 mg/l; and ammonia, 0.02 mg/l. Skatole, indole, and mercaptans were not detected.

The chemical and bacteriologic indices of urine and used wash water increased constantly throughout the experiment [1]. The microorganisms found were primarily coccal forms and Gram-positive bacilli, rarely Gram-negative bacilli. *Proteus vulgaris* was observed to increase repeatedly. These data indicate the need to use effective means to prevent putrefaction and fermentation of moisture-containing wastes.

The separate collection of urine and feces has many advantages over the combined collection. In particular, it makes possible the use of metabolites for various experiments. Sanitation devices based on this principle can be used both in manned vehicles and on craft with animals aboard. The acceptability of such a type of device was shown during the 22-day flight of the Cosmos–110 Earth biosatellite with the dogs Veterok and Ugolek [62, 81].

The system for removal of liquid and solid wastes aboard the Cosmos–110 satellite functioned jointly with the air-conditioning and regeneration systems in the individual animal cabins and the cabin ventilation systems. Figure 6 is a diagram of the system for collecting discharges in the animals' cabins and of the related devices. The cabin is an airtight container. The dog can assume several positions in the container and wears a special corset for attaching the waste removal system in the cabin and for attaching various sensors and devices for scientific investigations and food supply. A liquid waste collector "1" is on the floor under the dog's abdomen. It is cuboid and filled with moisture-retaining material (polyvinyl formol). The top of the container facing the dog's abdomen is made of a metal net to allow passage of urine during micturition. A p-nitrophenol urine pre-

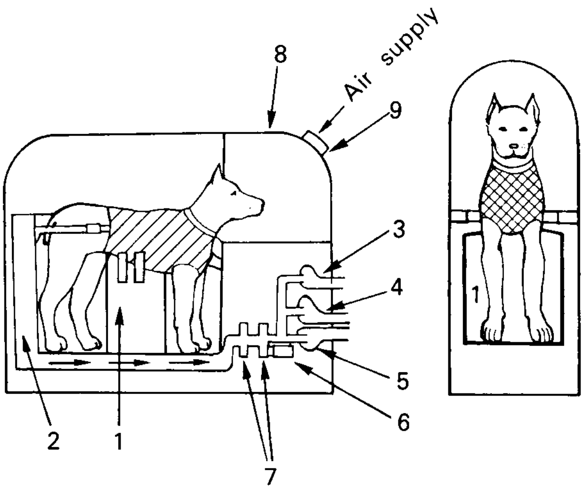

FIGURE 6.—System for individual collection of solid and liquid wastes in animal's (dog's) cabin for flights lasting up to 30 days (Cosmos–110 biosatellite). 1, liquid waste container; 2, solid waste collector; 3, main air fan; 4, backup fan; 5, high-power fan for periodic cleaning; 6, device for automatic activation of fans; 7, filters; 8, transparent dome; 9, air sampler.

servative to deodorize and inhibit growth of microbial seeding was added to the polyvinyl formol prior to flight. Behind the dog there was an open-type solid waste collector "2." The solid phase of the animal's discharges was carried away by a flow of fan air, thus decreasing the degree of moisturization of the fecal masses, which facilitated preservation of the dried matter.

The conditioned air was fed into the animals' container through air sampler "9" of transparent cover "8." The main air fan "3," driven by an electric motor, sucked the air away from the container through a solid waste collector "2" and filters "7," which served to purify the air from moisture droplets and noxious admixtures. The pressure drop in the animal's container resulting from the fan's operation brought fresh air into the container through the air sampler "9."

To increase the system's operational reliability, in the event of failure of the main air fan "3," a special electronic device "6" automatically activated a backup fan "4." Because suspended solid and liquid waste particles can accumulate in the air within the animal's container under conditions of weightlessness, a special programed device activated an auxiliary high-power fan "5" for 30 s every 2 h of flight in order to remove them.

In preparing for the flight, the method described of removing and preserving wastes was evaluated for hygienic indices during ground tests in mockups of the animals' cabins. Gas composition and microbial seeding of the cabin air as well as the quantitative content of the sanitary indicative species of bacteria in urine and feces were studied while the animals were kept in the cabin throughout a period up to 30 d. Limiting permissible values were not exceeded, according to the indices investigated. A positive evaluation of this method was substantiated by testing under flight conditions.

PRESERVATION OF WASTE PRODUCTS

The expediency of combined collection and transport of waste products with their processing (according to data in the previous section), is intended to reduce the vital activity of microorganisms and eliminate substances that have harmful properties or an unpleasant odor for man and experimental animals. Such processing is usually called preservation of waste products. It can be carried out by physicochemical or bioelectric methods, or their combination. These methods must be acceptable to spaceflight conditions and compatible with technology of subsequent processing or methodology of laboratory investigations of waste products [11, 71, 72, 73, 74].

The methods studied for regulation of the decomposition of waste products include freezing, heating, desiccation, ionizing radiation, and chemical processing. Each of these methods has advantages and disadvantages.

The decomposition of metabolic products can be stabilized by freezing and storage at −10° C. The principal shortcoming of the method is the necessity of keeping the products frozen throughout the entire storage period, which in many cases is unacceptable for technical reasons.

Effectiveness of the thermal method with short exposure makes it promising for objects when a large amount of heat is available. Proper heating can prevent decomposition of food and waste products. Sterilization with moist heat requires steam with a minimal 121° C for 15 min; sterilization with dry heat requires minimal 160° C for 1 h [76]. None of the above methods assures sterile waste products after processing (if they are not hermetically sealed under aseptic conditions in special packaging). Consequently, they will be stable only during the time they are maintained in an aseptic state.

Organic products can be stabilized by drying, because moisture is needed for growth of microorganisms. Space vacuum can be used as a drying means, but this causes certain air losses in the cabin of the vehicle during each ventilation of the drying chamber. The use of on-board air-conditioning systems or similar units for these purposes, however, is advantageous only within narrow limits. In the case under consideration, there would be only a small amount of waste products, with little water in its composition.

Burning of organic compounds with the formation of carbon dioxide and water is a tempting method for destroying products of vital activities. But the amount of oxygen absorbed in this way and the amount of carbon dioxide, carbon monoxide, and harmful contaminating admixtures which are formed add a serious additional load to the air regeneration and conditioning systems which in many cases is unacceptable.

The principle of biologic oxidation which has been studied for certain units proposes use of organic waste products in aqueous solutions as a nutrient medium for bacteria. Part of this medium gives off energy during the oxidation process, while another part is changed into a bacterial cellular substance. Biologic oxidation is widely used for processing waste products only in sanitary technology; therefore, the use of this method under spaceflight conditions requires careful development. For instance, treatment of different urban waste products occurs under a normal force of gravity and the nutrient medium of bacteria consists of almost 99% water and 1% solid substances. The method of treating organic products by γ-irradiation also calls for further study.

Antibacterial Chemical Substances

Treatment of waste products with antibacterial chemical substances has many advantages: the treated products do not form harmful gases, do not require storage under aseptic conditions, and the remaining disinfectant compounds destroy microorganisms that might get into the products of vital activity even after initial processing. The method of disinfection by chemical agents is being examined in more detail in connection with the method described.

The preservation of food remains is examined in Chapter 2 of this volume, "Food and Water Supply." One of the most practical means is 8-hydroxyquinoline tablets, intended for disinfection of food remains in packages during storage aboard the spacecraft [57].

Preservation of feces under spaceflight conditions is one of the most complex problems in providing normal conditions for crew activity. A search for chemical preparations for this purpose has generated a number of investigations [47, 59, 68, 70].

Effective preservatives (according to investigations) are silver fluoride, silver nitrate, silver sulfate, silver oxide, copper bromide, copper sulfate, crystalline iodine, catamines, and other substances. Preservation by compounds of silver (fluoride, nitrate, and sulfate) and copper is achieved by a dosage of 5–8 g/100 g feces. Copper sulfate acts more weakly only with a dosage of 30 g. The effect of preservation did not become weaker throughout a 1-year period. A specific odor of feces quickly weakened, which was evidence of the pronounced deodorizing action. However, it was possible to eliminate unpleasant odors completely only by combining these preparations with desiccation.

In comparison of the effectiveness and cost of preparation, preference must be given to copper bromide. Tests using copper bromide showed a sharp decrease in the amount of microorganisms; in the majority of cases, anaerobes were not detected, and 99.99% of aerobes perished. As a result of preservation, the liberation of ammonia and nitric oxides decreased sharply (by 4 and 10 times, respectively), which confirmed the suppression of putrefaction and fermentation [52].

Amounts of phenols, indole and skatole, fatty acids, sulfur dioxide, and ketones remain at approximately the same level as in control experiments. The significant increase (by approximately 10 times) should be noted in the amount of carbon monoxide formed during storage of excrements containing preservative.

Compounds similar to copper bromide cause energetic oxidation of organic substances which are constituents of feces. Carbon monoxide is probably a product of such reactions. Thus, liberation of toxic substances during storage of fecal masses with a preservative can be significantly reduced not only by suppressing aerobic and anaerobic microflora but also by inhibiting oxidation of organic substances.

Attempts to find chemical urine preservatives that are acceptable for different variants of ecological systems present great difficulties. However, the necessity of such searches is evident, considering the almost complete exclusion of physical and biologic methods for preservation of the liquid phase of discharges of man and animals. Many preparations from different classes of compounds have been suggested as urine preservatives for different conditions [67].

The phenol-containing compounds that have been studied are: p-benzylphenol, 2-benzyl-4-chlorophenol, phenyltrichloroacetate, hexachlorophene, resorcinol, p-nitrophenol, and other substances. All have a weak odor, do not yield residues in urine, and do not form additional aromatic gases when entering a chemical reaction with urine components. They are also good deodorants, do not corrode metal, and are barely toxic for warm-blooded creatures.

Compounds added to urine in a 1% concentration prevented it from becoming contaminated for 100 d. Urine to which p-nitrophenol was added was the most transparent. The nitro compound at a concentration of 0.05% was quite soluble in urine, had a strong antimicrobial action, and inhibited multiplication of microorganisms in urine during its storage. The phenyltrichloroacetate had a comparatively low effectiveness.

In working with urine that has been artificially infected by strains of *Escherichia coli* which are resistant to phenol and *Staphylococcus aureus* (1000 microbial bodies/ml), the smallest dose of p-nitrophenol which would support preservation for 100 d was 0.2 g/100 ml urine [16].

Preparations of benzylchlorophenol, benzylphenol, and resorcinol were also effective, but a slight odor was retained during long-term storage of urine with these substances. As a result, use of the latter in hermetically sealed manned enclosures can be recommended only after careful study of the gas composition of the volatile substances and their absorption properties.

Since the majority of gaseous toxic substances are formed during microbial decomposition of organic products contained in urine, the intensity of gas production of the liquid phase of human discharges treated by p-nitrophenol was studied. Adding the preservative decreased the amount of ammonia and aliphatic amines, acetone, volatile organic acids, nitrogen oxides, and phenols liberated into the air above the stored urine, and it did not have any substantial effect on the elimination of carbon monoxide and organic substances which were determined in total by the carbon method [63].

Calculations indicate that in comparison with two control tests, the preservative which was studied reduced the liberation into the air of substances of the ammonia group by an average of 47 times, of acetone by approximately 1.4 times, and of fatty acids by more than 9 times. Nitrogen oxides were generally present in the air above the urine in trace amounts, while in the control tests their content in five of eight samples fluctuated from 0.004 to 0.036 mg/l.

If these data are combined with the bacteriostatic action of the preservative, it can be concluded that production of the above-enumerated gaseous chemical substances depends basically on microbial decomposition of urea and other organic compounds found in urine. The liberation of carbon monoxide from stored urine is apparently not related to vital functioning of microorganisms, since adding preservative had no substantial effect on its production.

Thus, the tests performed showed that the preservative significantly decreased the discharge of certain toxic substances from stored urine, thereby reducing the potential danger of gas discharges.

The next problem in the study of p-nitrophenol was determination of the degree of acceptability, under conditions of weightlessness, by the design features of certain types of sanitation devices using hygroscopic materials for absorption of the liquid phase of biologic wastes. Study of the physical-mechanical properties of cotton, gauze, polyvinyl formol, and other moisture-retaining materials, which are promising for use in sanitary equipment, showed that processing them with the preservative under question slightly reduced the actual humidity (by up to 0.9%). However, the amount of this deviation is so small that it has no practical significance. Also, no substantial difference was noted in readings of the capillary rise of liquid between samples of moisture-retaining materials treated by this antiseptic and the control materials. These properties of p-nitrophenol allowed it to be recommended as a preservative for urine when it is not to be used for extraction of drinking water. The final solution of the possible use of p-nitrophenol must await toxicologic and other investigations.

Quaternary ammonia compounds have been recommended as preservatives [27, 47, 88] for urine and other types of waste products. Alkyldimethyl-3,4 dichlorobenzylammonium chloride (known under trade names as Zephirol, Rokkal, Centaphlon, Desidone, C–4, Benzaconium chloride, and others) is one of the most effective disinfectants from this group of compounds. It is produced under more than 20 names in the US and is the primary component in a series of compounds of one homologous series in which alkyl radicals have varying numbers of carbon atoms from 8 to 10. Quaternary compounds are cationic C active substances because the organic portion of the molecule carries a positive charge.

Quaternary ammonium compounds are quite soluble in water. Their aqueous solutions have a low surface tension, which accounts for foam-forming and emulsifying properties. These compounds are slightly toxic for warm-blooded animals, and, like detergents, having wetting and bactericidal properties. Thus, the antimicrobial action of benzylalkylammonium chloride with respect to vegetative forms of bacteria appears in cultures at the ratio of 1:12 000–20 000. It is effective in a pH range of 3–10 units, and has a high activity in the alkaline zones.

A number of homologs of alkyldimethylbenzylammonium chloride (catamines) and cationic active compounds made from pyridine derivatives (catapines) have been synthesized in the USSR. For the preservation of urine which has been artificially infected by a culture of *Staphylococcus aureus* and *Escherichia coli* to a count of 1000 microbial bodies/ml, a 0.1% concentration of catapine "K" is sufficient [88]. However, for definitive recommendation of the above preservatives, tests under conditions of a specific ecological system are necessary, especially in cases when urine or other metabolic products are used to produce potable water.

A simplified bacteriologic analysis is difficult under spaceflight conditions, so that the technology for regeneration of water must include elements that guarantee its decontamination. During vacuum distillation of urine, a large quantity of bacteria is contained in the distillate, so it has been suggested that the distillate be processed through a bactericidal filter [27, 51].

Water Regeneration

In studying the urine distillation process with high-temperature catalytic oxidation of volatile substances, the decontaminating role of a catalytic furnace has been noted. Investigations with a multifilter regeneration system turned up a large quantity of microflora in the water that had been condensed from the manned cabin atmosphere, which necessitates means of preventing this phenomenon. The amount of microorganisms in the regenerated water depends on two factors: the seeding capacity of the initial products (urine and atmospheric moisture), and the action of physical processes, chemical reagents, and materials to which these initial products have been subjected during the process of extraction and purification of water.

Vaporization is the most promising method for regeneration of water from urine. It is carried out technologically in various ways: distillation at atmospheric pressure, vacuum distillation, evaporation in an airstream, with subsequent preliminary purification of the water condensate by sorbents. Water distilled above 100° C is accompanied by sterilization. During vacuum distillation and during evaporation in an airstream, there is generally vaporization of water from urine at or near room temperature. In this case, it is unavoidable that microorganisms will get into the condensing water. The microflora enter the condenser from the vaporizer with the airstream or from water vapor in aerosols. Under conditions of weightlessness, the probability that bacteria will get into the condenser increases.

Water condensed from the atmosphere of manned compartments is contaminated by microorganisms which enter it with dust and aerosols from the stream of cooled air. The degree of condensate contamination in the atmospheric moisture is directly related to the number of bacteria found in the air, and is determined by many factors; the most important are: effectiveness of purifying the air of microflora during regeneration of air, overall sanitary condition of the manned compartments, underclothing, and crew provisions. *Staphylococcus aureus* and *Staphylococcus albus*, yellow *Sarcina*, various kinds of mold, and other microorganisms are constantly detected in the condensate. There are fewer hemolytic strains in condensates than in air, which can be explained by the more pronounced antagonism of bacteria in a liquid medium.

Part of the waste products enters the atmospheric condensate of manned compartments, which creates favorable conditions for growth of microflora, so that it is expedient to adopt this set of measures:

- preservation of freshly eliminated urine by chemical reagents;
- use of ion exchange resins and activated charcoal to reduce microbial seeding of condensed water;
- use in certain parts of the system of copper or other materials which have antimicrobial properties in an aqueous medium, in order to suppress development of microflora during water regeneration.

The system for water regeneration from urine entails unavoidable urine storage for some time before entering the technological process. During this time, urine undergoes decomposition, which necessitates preservation for:

- reduction in the total microbial seeding capacity and halting of vital activity of microorganisms, and decontamination in case flora enters;
- cleaning urine of mechanical contaminants (mucus, protein, and certain other inclusions);
- binding of certain components of urine into stable chemical compounds (urea, ammonia, and others);
- maintenance of a specific pH value of the preserved urine.

In selecting a preservative suitable for a system for regenerating potable water from urine, the preparation or the combination must:

- have a sufficiently high effectiveness in relation to vegetative microorganisms (*Escherichia coli* and *Staphylococcus aureus*), and inhibit vital activity of microflora during storage of urine for up to 2 weeks and longer at room temperature;
- not have an odor and not form volatile substances in a reaction with urine components;
- not lose antibacterial properties during contact with materials used in a system for regeneration of water from urine, and not cause changes in the physicochemical properties of materials in the system;
- have minimum weight, volume, and convenient physical shape for use under weightlessness.

Prescriptions that completely satisfy the requirements listed, in one way or another are: copper sulfate with hydrogen peroxide; a mixture of chromium anhydride with concentrated sulfuric acid; concentrated sulfuric acid with hydrogen peroxide; p-nitrophenol, formalin, and caustic soda; and certain other substances and their combinations [47, 70].

Chemical Reagents

The preservative action of chemical reagents was examined on a unit intended for study of the moisture-extracting process from the surface of materials into an airstream in a closed-circuit distillation system with subsequent condensation. Before feeding urine into the unit, it was treated with one of the selected preservatives, then passed through this apparatus for 6–7 h.

When any of the following were used: copper sulfate with hydrogen peroxide, mixtures of chromium anhydride with sulfuric acid, concentrated sulfuric acid with hydrogen peroxide, p-nitrophenol, formalin, and caustic soda in the system for regenerating water from urine, there was observed in the condensate a reduction in the amount of ammonia, and total content of organic substances, and a disappearance of odor and murkiness as compared with the condensate obtained from evaporation of nonpreserved urine.

The preservatives enumerated had a bactericidal action on species of normal microflora in urine when given in the prescribed doses. Better results were obtained with sulfuric acid with hydrogen peroxide, and with a solution of chromium anhydride in sulfuric acid. When these preservatives were used, the oxidizing ability of the condensate was reduced to 6.1–7.9 mg O_2/l, and the amount of ammonia was reduced to 5.9-6.6 mg/l, which is substantially less than the corresponding amounts found during a study of a similar product obtained by distillation of nonpreserved urine. The hydrogen ion concentration in the solution ranged from 5.0–5.5 (average 5.2). Optimal amounts of sulfuric acid (2 ml/l) and hydrogen peroxide (2 ml/l), and of chromium anhydride in sulfuric acid (2.49 ml/l), used for preservation of urine are completely acceptable for the types of water-regeneration systems investigated.

The condensate obtained in the vaporization unit with the use of copper sulfate and hydrogen peroxide, sulfuric acid and hydrogen peroxide, chromium anhydride and sulfuric acid, p-nitrophenol, and formalin and caustic soda corresponds to the requirements of accepted standards for potable water based on the content of microorganisms, transparency, and odor. However, it slightly exceeds the established permissible amounts of ammonia, which necessitates prepurification based on ion exchange resins. When favorable conditions for such purification are not present, using water in the indicated condition is possible for certain sanitary needs.

A mixture of sulfuric acid, chromium trioxide, copper sulfate and other compounds is recommended in the US which insure reliable preservation [27, 46]. Preference has been given to chromium oxide because, in addition to bactericidal properties, in a mixture with sulfuric acid it prevents formation of a precipitate that can clog tubing in the water-regeneration system.

Therefore, a number of compounds which have bactericidal properties have been suggested as preservatives for urine from which water can be extracted, among which are acids, heavy metal ions (e.g., copper, iron, silver, cobalt, mercury), and oxidants (e.g., chromium trioxide, hydrogen peroxide, hypochlorite, sodium hypochloride, and potassium hypomanganate). However, many have certain negative in addition to positive properties. For example, chlorine-containing preparations, in the majority of cases, are toxic, have a sharp odor, corrode metals, precipitate, and lose bactericidal activity during storage. Ions of silver and copper are characterized by a bactericidal action in relation to vegetative forms of microbes in aqueous solutions at a concentration of 1:1000. However, at a significant initial bacterial seeding capacity their use is hardly expedient because the salts and organic substances contained in urine are antagonists of the oligodynamic action of silver. In addition, a number of silver compounds form precipitates.

Antibiotics show a selective action in relation to microbes and may cause the development of antibiotic-resistant forms, and may promote decomposition of molds in tubing of the system, which almost completely excludes their use as preservatives.

Hydrogen peroxide and other substances capable of giving off active oxygen in closed systems have limited use because of high reactive capability in the presence of an excess of organic substances. The formation of gases should also be considered a shortcoming of oxidants because separation of phases is required, which complicates the design, reduces operation reliability, and increases the weight of the system. These data indicate the lack of a general-purpose preservative and show the need for similar means applicable to specific conditions.

To increase the effectiveness of preservation means, it is expedient to combine them with other components of a set of measures to reduce the initial microbial seeding capacity of various elements in an ecologically closed system. This relates essentially to air and the surfaces of manned compartments, skin, mucous membranes, clothing, and provisions of the crewmembers [13, 16, 17, 87]. One possible way is to incorporate antimicrobial properties in materials from which underclothing, personal hygiene articles, and other items are manufactured.

Imparting antimicrobial properties to fibrous materials is accomplished most expediently by addition of bactericidal preparations to macromolecules of the fiber-producing polymer by forming a chemical bond. In the last decade, a number of materials have been produced which contain biologically active substances. A multifaceted evaluation has been made of cellulose fabrics to which these compounds provide antimicrobial properties: salts of heavy metals, antibiotics, quaternary ammonium derivatives, and members of the phenol series.

Cellulose and synthetic textile materials that contain these preparations have a sufficiently high antimicrobial activity in relation to certain common microflora of manned enclosures. The seeding capacity for *Staphylococcus aureus* and *Escherichia coli* decreases by 82%–100%, and the capacity for growth of spores of certain microorganisms decreases.

Reaction of compounds with textile materials to form a chemical bond has an advantage over impregnation: the antimicrobial activity of such fabrics, for all practical purposes, does not decrease after 20–50 washings and exposure to other influences during periods of prolonged use. These materials are not toxic for warm-blooded animals.

Clothing worn next to the skin, bed linen, and certain personal hygiene articles made from textile materials which contained hexachlorophene (up to 6% by weight of fabric) and 5-nitrofurfuryl-2-acrolein (up to 20%) were tested in long-term experiments with human test subjects. Their bacterial seeding capacity during tests was far less (from 2 to 130 times) than the control samples. Tissues containing hexachlorophene have more pronounced antimicrobial properties relative to *Staphylococcus*—one of the most probable infectious agents under conditions of manned hermetic enclosures. No harmful or undesirable influences on the human skin and organism as a whole [13, 15, 18, 57] were observed.

Antimicrobial treatment is recommended for emetic masses and waste products that arise during sanitary-hygienic procedures, by means of a device designed primarily for desiccation of feces [37, 96]. Basic components include: mechanical vacuum valve, receiving chamber, a suspended motor with a rotor and exhaust line, and bacterial and wood-charcoal filters. The emetic masses are dried in the same way as the fecal masses. The individual hygienic apparatus and the vacuum cleaner can be attached to the control air-conducting circuit. This unit must gather hairs, nail clippings, waste products from shaving, and so forth. Collector pouches can be used for drying and storing such types of waste products.

A similar device was successfully tested with a human subject in the simulator of a space vehicle cabin at the McDonnel-Douglas laboratory at Santa Monica, California. The system performed faultlessly for 60 days. The wood-charcoal filters eliminated odors well, and the crew had no complaints in this connection.

Thus, results of studies so far in the search for methods and means to preserve waste products enable the conclusion that a varied approach to the solution of this problem is expedient. Types of waste products that contain no more than 75%–80% water can more profitably undergo processing intended to reduce the moisture content up to values which insure inactivation of microflora and inhibition of chemical processes (30%–40% and lower). For preservation of urine and wash water, treatment by antiseptic preparations is more acceptable. For long-duration flights, the electrochemical method is preferable, which has the substantial advantage of minimal weight of expended substances [76].

STORAGE AND REMOVAL OF WASTE PRODUCTS

Waste products collected during flight must be disposed of in a form that is sanitary and esthetically acceptable, or they must be ejected from the vehicle or station. Methods of carrying out these operations depend on the specific peculiarities of the flight program and the kind of sanitary and other equipment available. For example, waste products may be used as fuel for rocket engines; containers emptied of oxygen, water, and so forth, reused as depositories of urine and feces [59].

Waste products can be stored by simply sealing them in containers. However, if waste products contain microorganisms, water, and food or other organic products, biologic activity can begin, which forms harmful or undesirable gaseous substances. As a rule, the longer the storage time, the more intense the gas formation. The equilibrium pressure depends on many variables: degree of container tightness, amount of water, food, and other organic products present, type of bacteria, composition of surrounding gas, and storage temperature. Under ideal conditions, each gram of waste products can produce as much as 0.28 m^3 (10 ft^3) of gas [47].

Simply placing waste products into containers without the corresponding preliminary processing can hardly be recommended for prolonged storage of urine, feces, vomitus, unused food, and other residues. Their biologic activity should be eliminated or reduced to a minimum. Otherwise, the volume of the storage containers should be calculated to allow for potential gas formation at threshold values of pressure, or there should be a periodic dumping of all or part of the contents.

Dumping waste products from the vehicle or station has certain negative as well as positive aspects. Among the negative aspects that should be pointed out are: above all, loss of gas medium from manned compartments, damage to optical instruments, fuel consumption for stabilization of the craft (dumping may be accompanied by a pulsating movement caused by the force of streaming escaping gases), and possible contamination of cosmic space and planets [42]. Furthermore, part of the metabolites are used for biomedical investigations both at various flight stages and afterward.

Further studies will demonstrate the significance of factors and phenomena which serve as bases for selection of one variant or another for storage and removal of waste products. However, it is possible even now to consider removing waste products overboard the vehicle as acceptable for certain types of space programs. Hence, it is necessary to consider the composition of various waste products which are removed, the periodicity and order of carrying out this operation with respect to preventing contamination of cosmic space and planets, and other undesirable consequences.

As the duration of independent existence of spacecraft, stations, and bases increases, undoubtedly the amount of waste products involved in the circulation of substances of more closed ecological systems will increase to a lesser or greater degree. But during the functioning of crew life-support systems based on both physicochemical as well as biotechnological methods, the necessity of storing, destroying, or removing a number of unusable products overboard cannot be completely eliminated. Some unusable products would be tops of root-bearing plants (when there is an on-board greenhouse), cellular tissue, fragments of nails and hairs, used personal hygiene articles, products of destruction of clothing, provisions, and equipment [23, 28, 47, 49, 79, 80]. The collection and amount of such substances will change substantially depending on specific conditions, and this causes corresponding variations of methods and means for isolation and removal of waste products.

In summary, the importance should be emphasized of problems related to isolation and removal of waste products within a set of measures for the biomedical support of flights. Sanitary equipment in space vehicles used until now is basically adequate for operating conditions, but in certain cases it approaches the acceptability limit from psychologic or other points of view. Evidently, the position taken by Genin and other authors [3, 33] that the specifics of a space flight require a certain compromise between trying to create comfortable conditions for the crew and the technical possibilities of accomplishing this, may be taken as a basis for solving problems dealing with health and work efficiency of personnel engaged in such unusual endeavors.

Requirements for various aspects of the psychological and physical work capacity of crewmembers increase and become more specific as the duration of independent existence increases and program and flight tasks become more complex [4, 34, 40].

The importance of preventing autoinfectious and other diseases of man increases substantially. One of the ways of achieving this important goal is constant improvement of methods for isolation and removal of waste products and the equipment for carrying them out. Effectiveness in the creation of such systems will be determined largely by the amount of cooperative contact among workers in medicine, technology, and allied areas [1].

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Chapter 6

HABITABILITY OF SPACECRAFT[1]

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Extended space flight requires the solution of a broad range of problems in organizing the life and activity of the cosmonaut aboard the spacecraft. In formulating and solving these problems it must be borne in mind that there are two interdependent roles of the operator in space flight. On the one hand, the cosmonaut is a complex biologic system that must be protected against various stressful inputs and, on the other, he is an operator—an active, and to considerable degree, defining element in the complex spacecraft control loop. Both roles have direct influence on the reliability of the spacecraft-man system and therefore require particular attention in scheduling the work regime, organizing the cosmonauts' environment and rest, and working out the human engineering and technical-aesthetic aspects of arrangement of the working, eating, service, resting, and sleeping areas. The social and psychologic problems are of considerable importance in extended space flights where Earth analogs are not always applicable because of complete and long-term separation of the crew from the Earth.

It is difficult to combine this range of problems into an integrated whole without resorting to the very complex and inadequately defined concept of habitability. The vagueness of the habitability concept was noted by Barnes:

> The concept of habitability in a given space can only be defined acceptably as the requirement for the arrangement of man within the limits of this space. It represents the relationship between the customary human requirements and the characteristics of the given space which insure definite living conditions [6].

Fraser [22] attempts a more explicit definition of the habitability concept . . . that habitability is the quality of the ambient conditions, evaluated from the standpoint of acceptability of these conditions for man. Thus, man becomes the measure of habitability.

Johnson [33] approaches the definition of habitability differently. Rather than seeking some generalized formulation, he lists the components, the total of which could be considered a thorough definition of the habitability concept:

1. Ambient conditions, temperature, and creation of the atmospheric medium required for breathing, acoustics, lighting, and radiation protection.
2. Architectural and systematic design of the crew cabin, working area, passageways,

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[1] Translation of, Fiziologo-gigiyenicheskiye i psikhologicheskiye aspekty organizatsii zhizni v kabine kosmicheskogo korably. Volume III. Part 1. Chapter 6 of *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*). Moscow, Academy of Sciences USSR, 1972, 97 pp.
The author wishes to thank W. L. Jones, V. V. Zefel'd, B. S. Alyakrinskiy, and V. A. Tishler, for their original materials which were used in preparing this chapter.

provision storage area, and equipment storage area.

3. Movement of crewmembers, crew restraint under weightless conditions and when operating equipment, kinematics of movement and restraint, servicing equipment, and a normal work regime.
4. Foodstuffs, their storage, preparation, and serving; servicing equipment and facilities; water for drinking and for restoring dehydrated foodstuffs.
5. Special garments and personal equipment, conventional garments, personal articles, and notions.
6. Personal hygiene—collection of body wastes, care of the body, and clothing.
7. Housekeeping—tidying the area, collecting refuse, removing wastes, washing underwear, renewing supplies, and maintaining order.
8. Internal communications.
9. Relaxation—pleasant ambient conditions, internal quiet, equipment for physical exercise and entertainment where possible.

In comparing the ideas of scientists concerning habitability, it is clear that this concept implies elements of work psychology, engineering psychology, aesthetics, nutrition, housekeeping hygiene, social psychology, and sociology. However, it would be erroneous to consider that spacecraft habitability is just the sum of these areas of knowledge. This concept can be clarified by using as an example the relationship between cosmonaut nutritional hygiene and spacecraft habitability.

Rational nutrition is an important factor in man's existence under extended spaceflight conditions. To find the boundary between questions of nutritional hygiene and habitability of a particular vehicle, nutritional hygiene must be defined in accordance with the crew work regime, calorie content, amount of proteins, fats, carbohydrates, water, vitamins, salts, and other components of the daily ration. Nutritional hygiene involves the time intervals for eating and the basic outlines of menus for breakfast, lunch, and dinner. However, in the final analysis, nutritional hygiene is not concerned with whether food is served on handsome plates or in an ugly pot; the operator eats at his work station or in the comfortable conditions of the dining area; the spacecraft has fine tableware; or the food is swallowed directly from the opening of the corresponding tube.

ELEMENTS OF HABITABILITY

In evaluating habitability, the factors listed along with taste characteristics of the food are of primary importance, and form an organic part of the overall habitability of a given vehicle. Thus, composition of the meal is only of secondary importance in regard to habitability.

A similar relationship between the elements of habitability and the solution of engineering psychology problems is apparent in the arrangement of the operator's cabin in the spacecraft. Engineering psychology is vitally concerned with rational determination of types, sizes, and location of spacecraft indicators in order to eliminate possible confusion among scales of different instruments, assure accuracy of information readout from various types of instruments, and locate controls within the operator's reach zone.

Other elements are also important for habitability. First, there are the aesthetics of the general cabin layout and design of individual parts of the instrument panels and control consoles. For example, the cabin equipment should not present annoying highlights, nor should there be disorderly bunching of data displays or levers, handles, and knobs on the control console. The operator's couch should be comfortable for normal operations and for brief relaxation during work breaks. Rational color schemes and lighting are important.

Even if these factors are close to the actual situation, they cannot be considered a definition of habitability, which must be a generalization of the most important aspects of the essence of habitability. For this reason, it is advisable to define habitability as the *degree of comfort and aesthetics necessary for the living, working, and resting conditions of the human operator.* Other factors, collectively, while often termed components of habitability, actually form part of the spacecraft's complex ecologic system.

In evaluating the habitability of a particular spacecraft, it is important to know its mission, flight duration, dimensions, and layout of the living and working areas. Conditions that were acceptable for the first space flights, lasting about 1 day in orbits near Earth, are completely unacceptable for extended interplanetary flights[8].

The concept of quantitative evaluation of habitability is of particular interest. Celentano suggested a method termed *habitability index;* his integral habitability model would include regulation of the environment, nutrition, personal hygiene, gravitation, living space, crew fitness, and work-rest regime. This habitability model is meaningful if the factors are maintained within quantitatively acceptable limits [22].

Variational statistics calculation of the weighted mean are used to evaluate the habitability index. The relative value (RV) is calculated for each element of the system. For each element examined, the RV is the ratio in percent of the existing value to the optimal level for this system. The RV value can vary from 0 to 100. The minimal or maximal tolerable value is taken as zero and the optimal level is taken as 100.

Carbon dioxide, one of the environmental gas components, is an example. The maximal tolerable pressure level for long flights is 20 mm Hg, while the optimal pressure level is less than 5 mm Hg. If the CO_2 level in the system is 8 mm Hg, the calculation is made using the formula

$$RV = \frac{(P_g - P_n) \times 100}{P_o - P_n}$$

where P_g is the actual level; P_o is the optimal level; P_n is the tolerable level (minimal value). Thus

$$\frac{(8-20) \times 100}{(5-20)} = 80\%$$

After individual RV values have been obtained, they are divided into four groups, each with its own index by which the resulting average values of each group are multiplied. Thus, regulation of environmental parameters is multiplied by 4, nutrition and personal hygiene are multiplied by 2, gravitation is multiplied by 1, living space by 2, and work-rest regimes together with crew fitness by 1.

The sum of the weighted averages is then divided by 10. The result is the habitability index, which, ideally, equals 100.

$$HI = \frac{\epsilon(R\bar{V} \times q)}{\epsilon q}$$

where q is the importance of the factor; $R\bar{V}$ is the average RV value for each group.

Fraser considers this method quite simple and effective. However, its application is limited to cases where all parameters of the factors being analyzed have been thoroughly studied and measured, and the optimal and limiting acceptable values of these factors defined.

COMMAND MODULE HABITABILITY

Crewmembers of an interplanetary spacecraft will spend a considerable part of their time in the command modules, systematically performing very complex and responsible operations. Therefore, proper planning of the work areas and rational design of the instrument panels, control consoles, and cosmonaut couches are important factors to insure high work capacity during their alternating duty periods and throughout the flight.

When designing interplanetary spacecraft, it will be difficult to develop rational balance between limited vehicle space suitable for location of control stations, and living areas and psychophysiologic requirements to increase reliability of the human element in the complex control loop. A general standard cannot yet be established for allocating useful space with respect to particular types and sizes of the areas. These problems will be solved in each specific design as functions of spacecraft missions and production capabilities.

Classifications proposed by various authors for functional areas inside the spacecraft and distribution of the areas and spaces must be considered very preliminary. However, they can become a basis for critical analysis of arrangement of the internal compartments and correspond, to some degree, to the actual relations which may be realized in future spacecraft.

Fraser [22] proposed this classification for four basic spacecraft areas assigned to the crew:

> Work, where the cosmonauts perform their duties to control the spacecraft and the life-support systems—40% of total space;

General, for preparing food, eating, exercising, and spending free time—25% of total space;
Personal, for sleeping and storing personal articles—20% of total space;
Service, for common storage of clothing and toilet activities—15% of total space.

In general, this classification is quite obvious and includes established crew requirements in various areas. It seems reasonable, although there may be considerable variation in the areas for general and personal use, depending upon the spacecraft's mission and size.

Barnes expands the list to six possible areas aboard the spacecraft [6], indicating that the crew be provided with these space designations:

Command-control center
Living, with space for sleeping
Food preparation, rest, and relaxation
Toilet, with necessary equipment
Repair operations
Internal passageways

Barnes also presents recommendations on the layout and interrelationships between the areas in the spacecraft—that the crew's living quarters be located alongside the command station, all sleeping areas alongside toilet areas, and so on.

The planning and arrangement of equipment as well as other details of the interior of the spacecraft work area can be examined in greater detail. Existing publications on engineering psychology and related subjects contain detailed analyses of the problem of operator work area organization, notably in studies by Zimkin, Dobrotvorskiy, Rozenberg, Fitts, Woodson, Chapanis, McCormick, Lomov, Zinchenko, Sidorov, and others [11, 14, 16, 20, 21, 48, 49, 51, 52, 66, 70, 77, 78, 85, 86].

Two primary aspects of spacecraft command module design and layout are: functions of spacecraft control and on-board systems; and anthropological data defining the minimum required cabin volumes and distance of controls from cosmonauts' couches.

Figure 1 shows the basic dimensions of the human body in the sitting and standing positions [78]. Measured dimensions of the human body are in Table 1. The anthropometric characteristics recommended by Woodson, Sidorov, and others allow designers to construct a geometric layout of the operator work area. Relative positioning of the operator, his couch, and the consoles containing indicators and controls is determined, with attention to the general and specific operator tasks of receiving information and transmitting various commands, the variety and form of equipment, and the overall available space in the vehicle. It is recommended that the designer plan the work area from the whole to the parts, from the ideal to the actual version. The final version will be a compromise to some degree.

Zefel'd [81, 84] recommended the use of sensomotor field geometry, obtained experimentally with the aid of a specially constructed stand, as the starting point in designing spacecraft cabins.

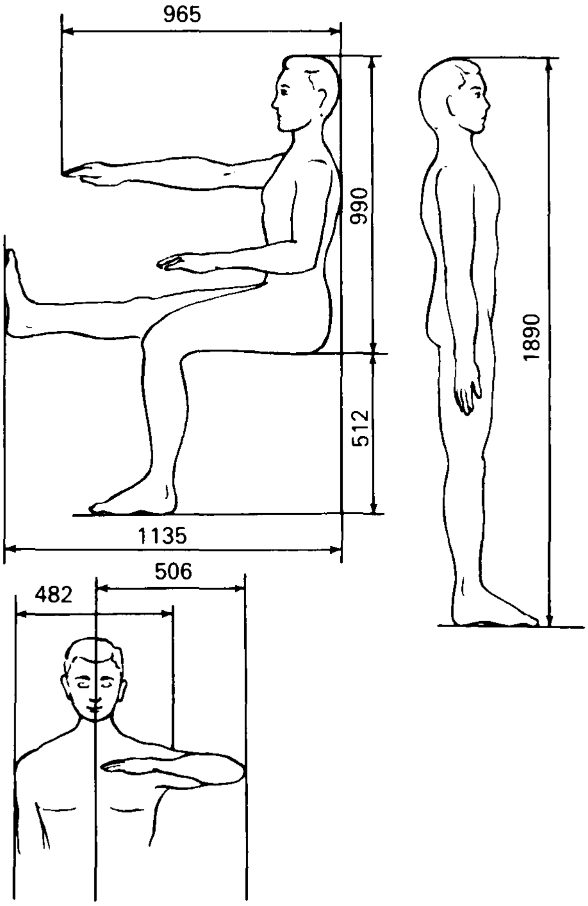

FIGURE 1.—Basic human dimensions (mm).

The author goes beyond the limits of formal anthropometry and approaches the maximal motor field which can be used effectively by the operator in one of the possible postures—sitting, standing, or lying (Fig. 2).

Zefel'd [82, 83] analyzes the concept of functional space by associating it with the nature of the productive and housekeeping operations. The organization of the object-space surroundings should be accomplished as follows:

1. Analysis of the nature of the crewmember motor activity to determine the total number and types of working positions as well as the time each crewmember remains in a particular working position.
2. The maximum motor working space is reduced to the required size and geometric shape corresponding to the given form of activity for the specific work area based on the data in (1).
3. The functional spaces are combined into functional zones (work, rest, lavatory, and so on), spatially arranged on the basis of optimal types of interactions between personnel and equipment. These interrelationships can be control links (man-equipment, equipment-equipment) or links of any other type, for example, visual, vocal, tactile, and so on. The link types are usually selected on the basis of usage frequency, or importance of objects.
4. On the grid formed by these links, individual functional spaces and zones are "threaded in." The functional spaces of personnel working alongside one another may overlap only within a strictly limited range.

The author concludes that in this way, the volume of spaces can be considerably reduced, creating more optimal operator movement trajectories. This approach complements the data accumulated from many years of study in anthropometry. However, excessive streamlining in the command module volume is not acceptable for long space flights. The operator must not continuously feel *pressure* from equipment closely surrounding him. The rational arrangement of equipment in the established cabin "geometry" is a very complex and critical stage in the organization of the cosmonaut working area.

Sidorov lists several requirements of equipment design. The most essential are [70]:

operational reliability under given conditions
convenience and safety of operation
minimal size and weight
maximal use of standard parts
convenient access to parts, components, and instruments for replacement.

According to McCormick [51], the operator should work sitting down. The seat height, dimensions of the table, instrument panel, controls, and pedals must be selected on the basis of anthropometric data. It is recommended that the instrument panel tilt be 30°, pedal inclination 45°, and distance from panel to operator's eye about 70 cm. Control levers should be located at the level of the arm bent at the elbow, and switches should be just below the hand. The instrument panel should be divided into sections, rows, and groups, but these divisions should generally remain in the background and not distract the operator's attention.

Signaling Devices and Controls

McCormick also formulated five principles for the arrangement of signaling devices and controls.

Functional organization. Instruments and controls are grouped on the basis of their function; instruments with related functions are combined into common groups.

Significance. Indicators are grouped on the basis of roles in performing control functions; those having the greatest importance are located in the "best" area, for example, in the center of the panel. The importance of the instrument is established by analysis of operator activity.

Optimal arrangement. Instruments are arranged so as to obtain the optimal position for each instrument. The optimal position is determined by the characteristics required in use of the instrument (precision with which it must be read, speed of perception, frequency of use, convenience, and so on).

Usage sequence. Equipment elements must be arranged in accordance with the sequence in which the operations are performed.

Usage frequency. Instruments and controls should be arranged according to the frequency of their utilization. Those used most often are located in the center, those used infrequently are located around the periphery.

The arguments by Shackel concerning organization of instrument panel elements deserve attention [68]:

> Numerals, divisions, markings, pointers, and other details of the instrument face should contrast clearly in tone and color with the general surface of the instrument face. This contrast must be combined with good illumination, elimination of glare, location of the dial or scale at eye level, and so on.
>
> Counters rather than dials should be used to display exact digital information.
>
> Moving pointers, in contrast with moving scales, make it possible to determine the rate of change of the indications and determine approximately the subsequent position of the pointer.
>
> Scales should be numbered clockwise from left to right or from bottom to top.
>
> The zero position should be located so that the pointer position, which is normal or

TABLE 1.—*Dimensions of the Male Body* (*after* [78])

Measured quantity	Limiting dimensions, mm: Smallest (excluding lowest 5%)	Limiting dimensions, mm: Largest (excluding upper 5%)
Weight, kg	61	92
Vertical reach	1950	2260
Stature	1650	1850
Eye to floor	1550	1750
Side arm reach (from CL of body)	740	865
Crotch to floor	760	915
Forward arm reach	710	840
Chest circumference	890	1090
Waist circumference	710	965
Hip circumference	865	1065
Thigh circumference	510	635
Calf circumference	330	405
Ankle circumference	204	250
Foot length	250	283
Elbow to floor	1040	1170
Head width	145	163
Interpupillary distance	57.7	70
Head length	185	208
Head height		260
Chin to eye		127
Head circumference	550	600
Hand length	175	204
Hand width	94	112
Hand thickness	26.8	32.6
Fist circumference	265	310
Wrist circumference	160	190

Measured quantity	Limiting dimensions, mm: Smallest (excluding lowest 5%)	Limiting dimensions, mm: Largest (excluding upper 5%)
Weight, kg	61	92
Arm swing, aft, in horizontal plane	40°	40°
Foot width	89	102
Shoulder width	430	480
Sitting height (head to floor)	1320	1420
Eye to floor in sitting position	1200	1310
Height of standard chair	460	460
Hip breadth	330	380
Width between elbows	380	510
Arm reach, forward	760	890
Vertical reach	1150	1350
Sitting height (head to seat)	860	965
Eye to seat	750	850
Shoulder to seat	535	635
Elbow rest	180	280
Thigh clearance	120	165
Forearm length	344	410
Lower leg height	510	585
Seat length	400	460
Buttock-knee length	376	545

most frequently encountered, falls in the upper quadrants.

The initial and final points of the scale must be clearly differentiated.

The divisions should be distributed uniformly over the entire scale. Logarithmic and nonlinear scales are not recommended.

The optimal dial size is 5–7 cm diam. Instruments for particularly precise indications must be 1.5–2 times larger.

The numerical progressions on the scale should be rational.

The interval between scale divisions should be chosen with attention to the magnitude of the instrument technical error.

The fewer divisions, the more easily the scale is read.

While instruments provide the operator with the required qualitative and quantitative information, at the same time there are serious drawbacks associated with the absence or weak manifestation of the attention-attracting action of the instrument pointers [68].

The accuracy with which the operator perceives and evaluates signaling devices is considerably better than his accuracy in the perception and evaluation of instrumentation indications. This is explained, first, by the signaling device basically yielding a qualitative characterization of the corresponding regime being monitored. The informational aspect of its indication is simpler than the indication of an instrument. Most often the signaling device provides single-valued information, less frequently it provides dual- or triple-valued information. On the other hand, an instrument often contains more than a thousand measurement units on the scale.

In selecting the specific form of the signaling device, consideration must be given to the total number of such devices and the probability of simultaneous information input for the attention of the cosmonaut during flight. For practical reasons, several analyzers (taste, smell, motor, pain) are not suitable as bases for the construction of signaling devices.

Visual signaling devices have several advantages over all others, including the audible. If three or more signals light up at the same time, the operator can evaluate their importance in rational sequence. However, the cosmonaut's reaction to several audio inputs does not permit

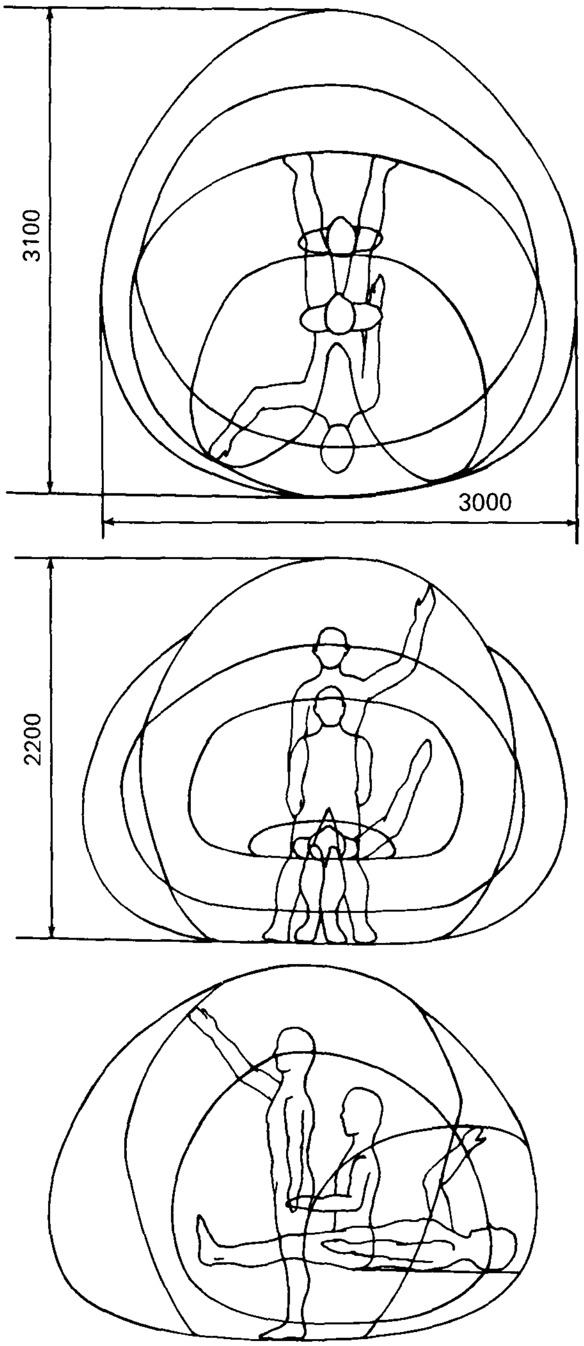

FIGURE 2.—Boundaries and configurations of maximal "motor field" of operator sitting, standing, and lying (after [83]).

him to differentiate the content of the signals; therefore, signals from important secondary factors are converted into noise. A guide for selecting visual displays is in Table 2.

The arrangement should be based on the functional principle of grouping signals which are related in importance, making it possible for the cosmonaut to draw preliminary conclusions about the nature of an event which has taken place on the basis of the location of the signal. Usually, it is sufficient for the cosmonaut to perceive the signal by peripheral vision. Afterwards, the operator can establish precisely the flight regime deviation or operation of an on-board engine beyond acceptable limits by turning his eyes to the illuminated visual signal.

The question of the external form of the signal arises when the cosmonaut perceives signals which indicate a hazardous event. The design of the signal system must insure that the signals do not have a blinding effect, particularly under conditions of low-illumination level. Otherwise, the signal which indicates one hazard may become noise in perceiving and evaluating another signal. In this connection, it is desirable that the signal be given a verbal-meaning quality, along with the graphic nature of the signal (light, form). Specifically, this is achieved by the use of labels alongside the signal light or the provision of luminous annunciator panels.

The period of no signal input, when no light impulses reach the eye, requires particular attention. Special experiments have shown that during flight, such periods may sometimes last tens of seconds, at which time stimuli directed to the other senses may be useful. While the ear is most suitable for this purpose, the use of hearing must take into account the deficiencies of auditory stimuli. The possibility of simultaneous action of several audible stimuli must be eliminated. If several signals do pass through the audio signaling device, an automatic device must be provided for sequential transmission of these signals to the cosmonaut in order of importance. This eliminates the possibility of the extremely undesirable mixing of audio signals.

A rational compromise between numerous and often contradictory requirements [60] must be sought in designing a specific warning system. When selecting and locating the controls in the spacecraft command module, factors to be considered are those which have significant influence on the overall effectiveness of their use by the cosmonauts, rate and precision of performance of the control operations, and on retaining high work capacity over a long period.

The size and shape of the controls must be properly selected in accordance with the control tasks. Then the control locations are established with regard to the position of the operator's body and peculiarities of his clothing. It is important to select the amplitude and direction of the control movements, required resistance (artificial "feel"), and relation between magnitude of the control deviation and magnitude of the corresponding instrument pointer displacement.

Woodson and Conover [78] summarize data relating the functional characteristics of controls with their shape and certain geometric and ergonomic considerations (Table 3). An example of the design layout of the Apollo spacecraft command module is shown in Figure 3 and the layout of equipment on the Soyuz spacecraft control console in Figure 4 [55].

Control Automation

Those functions of the human operator not yet performed successfully by automatic devices [10, 69, 78, 86] must be considered in order to evaluate properly the importance of control automation to astronautics, the future promise for its development, and to identify the areas where automation replaces man with the greatest effectiveness.

The "thinking" machine can surpass man in the speed of certain judgments and deductive reasonings (Table 4). However, man does not yet encounter any competition from automatic devices in the formulation of new concepts required for understanding events and phenomena occurring during space travel and in construction of inductive conclusions. A particularly important characteristic of the cognitive processes is man's capability for correct perception under conditions of interference or, as usually expressed in engineering, "noise." This is essential in carrying out super-long-distance communications through radio and television channels and in perceiving an object under conditions in which it is vibrating or the intermediate medium is oscillating. Other advantages of man over machine are: his capability for detecting weak audio and visual signals, ability to store a tremendous volume of information and use this information adequately at the required instant, capability for learning, and the possibility of proper action under complex unforeseen situations.

TABLE 2.—*Guide for Visual Display Selection* [78]

Display	Selection	Reason
Go, no-go, start, stop, on, off	Lights	Usually easy to tell if on or off
Identification	Lights	Easily detected (can use coding by spacing, color, position, or flashing rate; when used on instrument panel they may also have labels)
Warning, caution	Lights	Attract attention, if bright enough they can be seen at great distance (may flash for greater conspicuity)
Verbal instruction (operating sequence)	Annunciator light	Precise and clear "action instruction" reduces decisionmaking time
Exact quantity	Digital counter	Only one numeral is visible, which reduces the chance of readout error
Approximate quantity	Instrument with moving pointer against fixed scale	Pointer position permits quick determination of quantity and relative rate of change
Set-in quantity	Instrument with moving pointer against fixed scale	Natural relationship between motion of control and instrument pointer
Data pickoff	Electronic or electromechanical tracker with parameter indication on CRT. Coordinates are transferred to digital counter automatically	Simple means for indicating position without need for interpreting or calculating actual value of the parameter
Tracking	Instrument with single pointer or cross-pointer against fixed scale	Yields information on error and facilitates its elimination
Vehicle attitude	Mechanical or electronic instrument indicating position of vehicle relative to established reference (instrument pointer may be graphical or pictorial)	Permits direct comparison of vehicle's "own position" with known reference or baseline.
Geographic position	Plan-position analog	Shows position directly relative to natural geographic features
Guidance	Device reflecting presumed vehicle position or path	Permits observer to predict what will occur in the future
Equipment performance analysis	Meter	Single parameter is easily interpreted
" " "	CRT	Shows relationship among many parameters
" " "	Pen recording	Provides permanent record for later analysis.

TABLE 3.—*Choosing Operating Controls* [78]

Function	Application	Type of control
Selection between two alternatives	To start and stop equipment Sequence of starts and stops To insert momentary signal	Toggle switch Bat-handle switch Push button Foot switch Push-pull control Trigger Sliding rotary switch
Selection among three (or more) alternatives	To choose equipment operating modes Channel selection Range selection	Switch with detents Toggle switch, bat-handle switch
Precise adjustment	Continuous adjustment of parameter Fine adjustment or calibration	Round knob
Gross adjustment	Continuous adjustment (for example, throttle or accelerator) Metering valve Faucet	Round knob Control lever Pedal Wheel
Rapid adjustment of parameter	For example, slewing electronic cursor	Hand crank Toggle or bat-handle switch (operating an electric drive)
Selection between two alternatives	Snap action Visible, easily differentiable control positions	Compatible direction of movement Equitable force requirements Proper location Adequate grip configuration
Selection among three (or more) alternatives	Positive detented positioning	Same as above
Precise adjustment	Smoothness of operation Low friction	Same as above (plus compatibility of control motion with display motion)
Gross adjustment	Smoothness of operation Moderate friction	Same as above
Rapid adjustment of parameter	Smoothness of operation Friction low to moderate, depending on size of control (when using hand-crank)	Same as above (plus optimal instrument pointer speed)
Large force application	Braking Steering	Control lever Wheel Pedal Rudder bar
Multistep (continuous) positioning	Vehicle position and attitude Electronic instrument pickoff	Joystick Combination wheel and joystick Pantograph Pressure stick
Large force application	Optimal dimensions	Same as above

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TABLE 3. — *Choosing Operating Controls*, [78] — Continued

Function	Application	Type of control
Multistep (continuous) positioning	Smoothness of operation Low to moderate friction Optimal dimensions Optimal control displacement	Same as above (plus compatibility of control motion with indicator motion, self-centering, and absence of cross-talk between motions)

The automatic system has clear-cut advantages under spaceflight conditions when there are emergency disruptions of the thermal regulation system, regeneration equipment, or explosive depressurization of the cabin. In these situations, the condition of crewmembers may not permit them to perform certain tasks which present no difficulty under normal flight conditions. Regulation of the microatmospheric parameters obviously must be accomplished by automatic devices. The machine also has advantages over man in speed of reaction to a signal, performance of repeated stereotyped actions, storing information, speed of complex calculations, the capability to simultaneously perform smoothly and precisely several functions which differ in nature.

The machine may surpass man in physical characteristics and operating reliability when performing repeated operations, and is not influenced by the subjective qualities of man. According to Grodskiy [10, 27], human operator errors in rocket systems account for 20% to 53% of the unreliability of the systems as a whole.

Broadbent [12, 13] found that when performing an observational task, the probability of rapid and correct action decreases as a function of working time. He considers that under favorable conditions an operator can carry out accurate observations for up to 30 min. After this time, because of increased operator tension, the use of auxiliary signals to attract his attention to the parameter being monitored is required.

Thus, the cosmonauts' command module must be designed and organized with emphasis on the following requirements: the operators must have a comfortable position on the couches, which maintain their attitude, the instrument panels and consoles must provide for quick input of the required information in a form convenient for its perception and evaluation, and provision must be made for command transmission with the aid of various controls (handles, levers, wheels, knobs, and so on).

ORGANIZATION OF COSMONAUT WORK REGIME

Today's spacecraft is equipped with complex and varied equipment (already noted) to provide for monitoring the flight parameters and conditions, operation of the power supply systems installed aboard the spacecraft, and the life-support systems. The on-board equipment will increase in volume and complexity with the design of interplanetary spacecraft of the future.

The restricted nature of the crew, with regard to number and type of specialists, as well as the complexity of the problems being solved by them, will impose increased loads on each of the crewmembers. In many cases, the operators will have to carry out around-the-clock watchkeeping while at the on-board control consoles. In this connection, the problem arises of rational allocation of functions between man and the automatic controlling devices.

The rational allocation of functions in organizing crew activity is one of the most critical tasks of spacecraft control. The problem of function allocation as a whole can be classified:

1. Splitting of functions between the "ground" (a complex system including large teams of individuals, computer complexes, observation and communications equipment) and the spacecraft.
2. Allocation of functions between the automatic on-board systems and the spacecraft crew.
3. Allocation of functions among individual crewmembers.

In allocating the functions and organizing the working regime of the cosmonauts, the flight mission, command module dimensions, the possibility of installing automatic control devices, crew composition and characteristics, and other factors must be considered.

A preliminary schedule for crew work in an Earth-Venus-Mars-Earth trajectory is worked out in one US publication [17] (Table 5). The schedule provides 844 working h/crewmember for one of the Earth-Venus flight segments; in the Venus-Mars and Mars-Earth segments, there are 1457 and 1150 working h, respectively. The size of various research efforts is notable. A possible time allotment for crewmembers' activities in flights to Mars [17] is given in Table 6.

One of the complex and urgent problems in cosmonaut work organization is justification and selection of the space day-duration for a given spacecraft. Man's development and existence under Earth conditions over millions of years have led to complex and stable stereotypes of the physiologic and psychic functions. Man has developed life-activity rhythms associated with variations of certain environmental factors, which are arbitrarily called *time sensors*. Along with the purely physical phenomena (sunrise, dawn, twilight, nighttime sky), the time sensors of a social nature (breakfast, lunch, dinner, productive work, recreational activity, and rest) are of tremendous importance.

If there is a difference between metabolic rhythms and time sensors, a complex pattern of psychophysiologic adjustments arises, leading to desynchronization phenomena.

Alyakrinskiy [2] classifies desynchronization as:

1. Desynchronization of the time sensors and body rhythms—a phase shift of the entire hierarchy of circadian rhythms with respect to a stable time reference point—
    a. during change of time zones (transmeridional flights, travels over large distances with crossing of time zones using other forms of transport);
    b. during change of the sleep-waking rhythm within the limits of the local time sensor system;
    c. when the sleep-waking rhythm is based on the migrating day principle (impulsive or continuous change of the daily period, duration or phasing).
2. Partial or complete exclusion of geographic time sensors (conditions in the Arctic, Antarctic, orbital, and interplanetary space flights).
3. Illnesses of varied etiology.

Yaroslavtsev [79] studied disruption of the daily physiological function rhythm during travel to distant places by observing effects on 90 inhabitants of Irkutsk after traveling to Moscow, Leningrad, and other cities in the European part of the USSR. Most of the subjects of the study were athletes.

During the first days at the new location, most of the subjects showed some reduction of blood pressure and heart rate. Shortening of atrioventricular conduction with slowing of rhythm was observed on the electrocardiogram. There was a reduction of pulmonary vital capacity, hand strength, and muscle force, and the daily temperature curve changed. Sleep deteriorated and the subjects woke frequently. They complained of sluggishness, absence or reduction of appetite, headaches, and noise in their ears. The observed shifts disappeared after 7–14 d.

Work-Rest Regimes

Gambashidze [25] observed workers in a bakery on a three-shift schedule. Pulse rate, blood pressure, muscle force and endurance, and visual-motor reaction latent period showed negative shifts in the night crew compared with those of the morning and afternoon crews.

Solov'yev and Gambashidze [25] studied subway workers, recording body temperature, pulse rate, pulmonary vital capacity, muscle endurance, and higher neural activity indices. They concluded that the daily rhythms of these functions did not change, and explained this inertia of the rhythms by the stability of certain environmental factors.

Fukalova [23] studied the work-rest regime of operators in radio stations operating around the clock, using the muscle strength of the right hand as a test. Maximum reduction of muscle endurance was found to occur at 3 o'clock in the morning.

The influence of change of the normal daily regime on the condition of subjects was studied [32]. An individual regime was worked out for each of two subjects in a pressure chamber with usable volume of 5 m^3. Regime No. 1 was nearly normal. The subject slept from 03:00 to 09:00 at night and from 15:00 to 17:00 in the day. In regime No. 2, the subject slept from 20:30 to 02:30 at night and from 12:00 to 14:00 in the day. The subjects exchanged regimes in repeat studies. The experimenters recorded: electrocardiogram, respiration, electroencephalogram, arterial pressure, body temperature, reaction of the cardiovascular and respiratory systems to controlled physical activity, and energy consumption. The experiments lasted from 10 to 30 d and showed that in regime No. 1 daily variations of the pulse rate, respiration, and arterial pressure were close to the norm. Regime No. 2, which was unfavorable for maintaining normal functions, either smoothed out variations of the functions studied or led to distortion of their periodicity. The pulse and respiration rates and body temperature were lower in the waking period than in the sleeping period.

In an interesting study by Litsov [41, 45, 46], healthy young males were observed under isolation in a soundproof chamber. Conventional, inverted, and fractional work-rest regimes were used in experiments, which lasted from 9 to 11 d. The pulse and respiration rates, body temperature, electroencephalogram, and work capacity were recorded. He found nonuniform rearrangement of daily variation indices and considerably faster rate of adaptation to the new regime for human subjects than for animals (5–7 d compared to 14–21 d). The greater adaptability of the human subject was explained by his concentration on adapting to modified scheduling, will power, motivation, strictness in observing the new regime, and isolation from influence of social and physical time sensors.

Stepanova, while studying social time sensors, observed:

> The social time sensors include those social phenomena which repeat with sufficient sys-

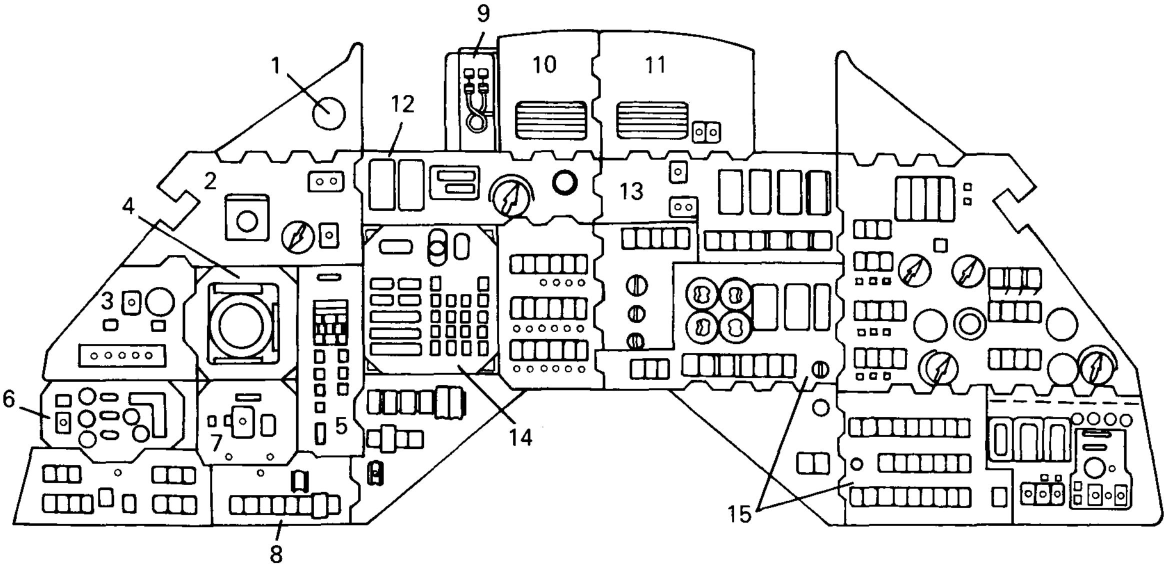

FIGURE 3a.—Main control console panel in crew compartment of Apollo spacecraft (after [55]). 1, altimeter; 2, switches for attitude indicator and longitudinal accelerometer; 3, indicators for booster and spacecraft engine parameters; 4, attitude indicator; 5, booster condition lights; 6, attitude system instruments; 7, pressure indicators; 8, switches for various on-board systems; 9, switches for the meter-band antennas; 10–11, light indicators for various purposes; 12, auxiliary engine system indicators; 13, radio equipment switches; 14, computer light panel and control buttons; 15, various indicating systems.

> tematicity and thus signal definite times of the day. These are primarily such phenomena as the sequence of our activity in the waking period, which embrace the daily procedure of morning and evening toilet, morning gymnastics, looking through the morning paper, travel to and from work, the hours of business activity, mealtimes, listening to the radio and watching television broadcasts; this category of phenomena also includes the view of the city streets in the evening, brightly lit by street lights, lighted advertising signs, and so on. An important social factor affecting man's daily rhythm is the daily sleep-waking rhythm of society as a whole [73].

It is not only difficult, but apparently impossible to foresee all the consequences of a multimonth interplanetary flight. Extrapolation based on the results of experiments under Earth conditions cannot replace the entire complex of interplanetary flight characteristics.

Available data obtained in orbital flights on the reduction of the cosmonauts' sleep requirements may be decisive in converting to a new work-rest regime. Such a change appears to be necessary in interplanetary flight and may not always be without problems. Conversion to the new rhythm and shortened days compared with the day length on Earth leads to obvious or latent forms of desynchronization. An entire complex of prophylactic measures must be taken in order to alleviate negative consequences of desynchronization, accelerate the body's physiologic function adaptation process, and maintain a satisfactory level of the cosmonauts' work capacity. A careful study should be made of individual cosmonauts' psychophysiologic characteristics, particularly their adaptability to a work rhythm with shifted and inverted days. In general, organization of the

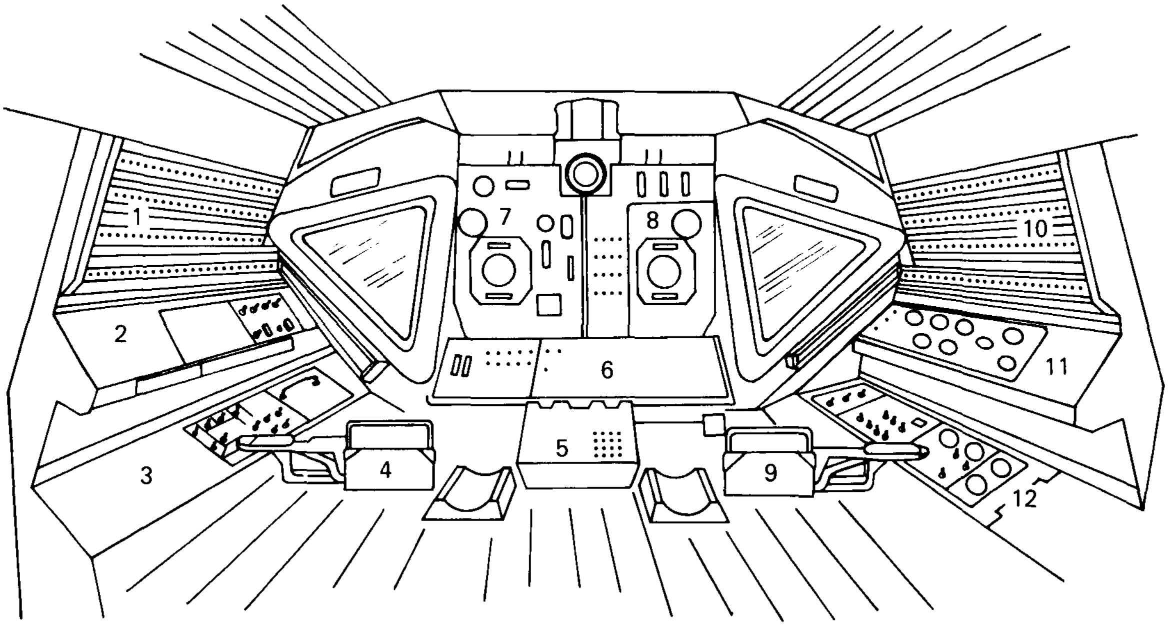

FIGURE 3b.—Lunar module control console of Apollo spacecraft (after [55]). 1, switch panel for various on-board systems at the spacecraft commander's station; 2, switch panel for the electric power system and radiotelephone communications controls; 3, switch panel for pyrotechnic devices, radars, and emergency guidance system; 4, light-source switch panel; 5, guidance and navigation system main instrument panel; 6, switch panel for power sources, attitude and stabilization system, cryogenic fluid reservoir conditioning system; 7, spacecraft commander's central panel; 8, lunar module pilot's central panel; 9, light-source switch panel (at lunar module pilot's station); 10, switch panel for various on-board systems; 11, electric power distribution system switch panel; 12, radio system switch panel.

work-rest regime should be based not only on data from psychophysiologic research similar to that already cited but also on factors such as detailed planning of the flight, spacecraft design, its living and working quarters, and the number and composition of the crew.

ILLUMINATION OF SPACECRAFT WORKING AND LIVING AREAS

The cosmonaut receives his basic data flow through the visual system as in most other forms of activity. Since this information is fundamental for controlling the spacecraft's flight and onboard systems, it is particularly important for crewmembers to have proper lighting of the work and rest areas. During extended interplanetary flights, the cosmonauts will make use of artificial illumination almost continuously [1, 3, 4, 5, 71, 74].

Most studies of the illumination problem have been directed to the needs of industrial or living areas. In discussing illumination requirements in industry, it has been noted that the best lighting for reducing eye fatigue is diffused or reflected in all directions. The controlling factors in light scattering under industrial conditions are walls, ceilings, floors, and objects in the working area. Selective painting of ceilings, walls, and floors is recommended for greater lighting effectiveness and to regulate lighting intensity, a function of various factors such as efficiency of lighting fixtures (Table 7).

These principles are applicable to spacecraft and orbital stations as well, although studies on submarines have shown that rules for indirect lighting, providing for a high degree of overhead reflection, are not applicable in submarines because of low ceilings. Glare from lighted surfaces at eye level [22] is particularly undesirable. Some peculiarities of space stations, such as restricted internal volume, irregular configuration of compartments, multipurpose use of particular zones, and compact construction of the work consoles markedly restrict the application of conventional lighting standards.

Recommendations on spacecraft lighting are based to a considerable degree on studies made for submarines. Tinker points out that only artificial lighting is used in submarines, which is adequate. The basic factors to be considered in artificial illumination are: (1) quality and color of light; (2) intensity of light; (3) distribution of lighting in the surrounding medium. These combined factors should provide the most pleasant appearance and proportions possible as well as give the inhabitants a feeling of comfort and a "homey atmosphere." Illuminants differ in spectral characteristics and thus have characteristic color which has a definite effect on visual acuity.

On the basis of many studies, Tinker [22] concludes that in normal vision, visual acuity increases very little with increase of illumination above 269 lm/m^2 (25 ft-ca). It changes practically not at all if intensity is higher than 538 lm/m^2 (50 ft-ca). For large objects with angular dimensions of 4 min or more, there is practically no improvement in visual discrimination of objects when illumination is above 215.2 lm/m^2 (20 ft-ca). For smaller objects, there is improvement of visual discrimination up to 434.4–538 lm/m^2 (40–50 ft-ca).

With regard to brightness contrast, when the contrast between the object and the background is great, discrimination of objects with angular dimensions of 1 min improves with illumination up to 538–645.6 lm/m^2 (50–60 ft-ca). The greater the brightness contrast, the better the visual discrimination, although the process of visual perception becomes more fatiguing with high contrast. Excessive illumination does not compensate for small object size or low contrast.

Thus, according to Tinker, increase of illumination up to 53.8 lm/m^2 (5 ft-ca) leads to rapid increase of visual effectiveness; up to 107.6 lm/m^2 (10 ft-ca), improvement is slower; up to 215.2 lm/m^2 (20 ft-ca) improvement is very slow; above 215.2 lm/m^2 (20 ft-ca), improvement is negligible. This is valid for an angular dimension of the object being discriminated of about 3–6 min. If the object is smaller, vision continues to improve noticeably with illumination up to 434.4–538 lm/m^2 (40–50 ft-ca).

Reflectivity of Surfaces

Neither color nor hue has any significant influence on perception effectiveness. The reflection coefficient of the walls, ceilings, and furnishings of the living or working space is more important than the color in which they are painted since the reflecting surfaces effectively become secondary sources of illumination [22]. The reflectivity of any surface is the ratio of the light flux reflected from the surface to the flux incident on the surface. Depending on the nature of the surface, the reflection may be diffuse (from a matte surface), specular (from a polished surface), or mixed. A mirrorlike surface leads to glare. The reflection from various surfaces has a significant influence on the overall illumination level. Therefore, less light source intensity is required for illumination of areas containing highly reflecting surfaces than for areas with weakly reflecting surfaces.

The following magnitudes of reflection in work areas are recommended: 20%–40% from console panels; 80%–100% from instruments; 15%–30% from floors; 40%–60% from walls; and 60%–95% from ceilings [22].

During the spacecraft launch, the cosmonaut must be able to evaluate the status of systems being monitored on the basis of instrument indications. Visual acuity decreases under the influence of positive load factors and vibration. With load factors up to 2 G, effectiveness of instrument indication readout decreases only slightly; as load factors increase, readout effectiveness decreases markedly [75].

Illumination Level

Decrease of visual acuity can be compensated by increase of lighting level (Fig. 5). With illumination of 1×10^{-6}cd/m^2 (42 mL), load factors up to 4 G do not reduce scale reading efficiency. However, if the illumination level is reduced to 1×10^{-7}cd/m^2 (4.2 mL), there is a reduction of readout efficiency at 4 G [75]. Decrease of visual acuity under the influence of vibration can also be compensated by increase of the illumination level of display system screens [75]. Figure 6 shows that, as the lighting level is increased from 1.4×10^{-6}cd/m^2 (0.046 ft-L) to 4.9×10^{-4}cd/m^2 (15.0 ft-L), instrument reading effectiveness in-

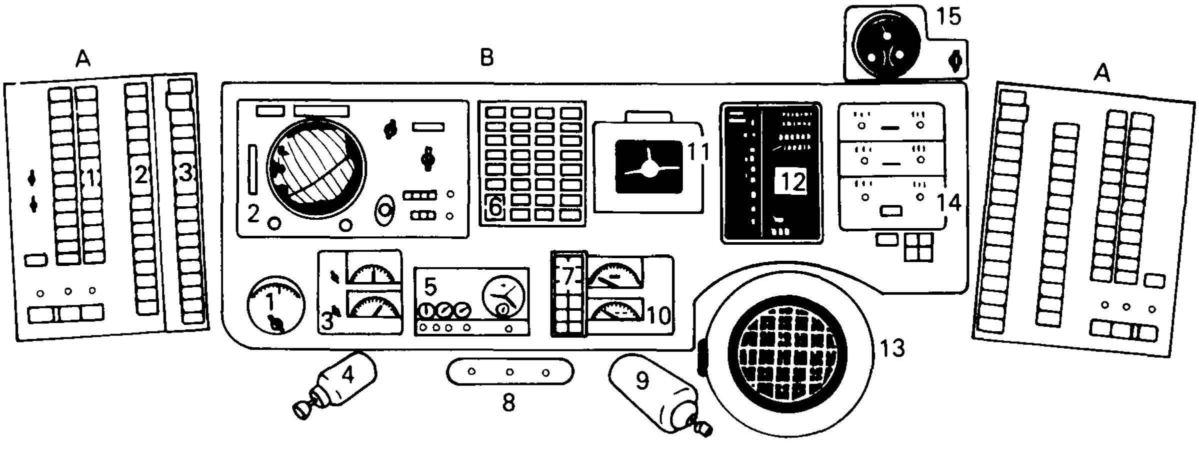

FIGURE 4.—Control console of Soyuz spacecraft (after [55]). A—command and warning equipment: 1, microphone and throat mike activation switches; 2, volume controls for HF and UHF radios, interphone, and long-range compass radios; 3, knobs for adjusting warning panel annunciator; B—cosmonauts' console; 1, voltage and current indicator; 2, navigation indicator; 3, indicator for pressure and temperature in the spacecraft compartments; 4, stick for controlling spacecraft displacement in space; 5, ship's clock; 6, electroluminescent warning panel for basic systems; 7, buttons for controlling command and signaling device; 8, volume controls; 9, attitude control stick; 10, distance and rate indicator; 11, combined cathode-ray tube indicator; 12, program monitor indicator; 13, sight-orientator; 14, digital data unit; 15, air lock and pressure suit backpack indicator.

creases, although there is no noticeable difference in number of errors between illumination of 1.7×10^{-4}cd/m^2 (5.4 ft-L) and 5.0×10^{-4} cd/m^2 (15.1 ft-L). In this connection, lighting of no less than 1×10^{-7} cd/m^2 (5.0 mL) should be provided in the launch phase, in spite of weight and power limitations.

The illumination requirements during space flight also depend on specific tasks for the different phases of the flight. The cosmonauts perform visual tasks under conditions of abrupt change of lighting intensity while identifying familiar and unfamiliar objects.

Flight control under nominal conditions can be performed with a white-light illumination level of 3×10^{-9} cd/m^2 (10^4 mL) [75]. Filters of different density may be used to protect against outside illumination when it is necessary to make observations outside the cabin.

TABLE 4.—*Man-Machine Comparison* [78]

Man excels in	Machine excels in
Detecting useful signals with very low energy level	Monitoring (both men and machines)
Sensitivity to extremely wide range variety of stimuli	Performance of routine, very precise operations
Perceiving signals and making generalizations	Capability for very fast reaction to control signals
Detection of signals in high noise levels	Smooth and precise application of large forces
Capability for storing large amounts of information for long time and recalling relevant information at the appropriate moment	Storing and recalling large quantities of information in short time periods
Capability for exercising judgment with incomplete information on events	Performing complex calculations rapidly and with high accuracy
Finding and using flexible procedures	Sensitivity to stimuli lying beyond the limits of human sensitivity (infrared, radio waves, and so on)
Capable of reacting to unexpected, low-probability events	Simultaneous performance of varied actions
Applying originality in solving problems	Deductive processes
Capable of profiting from experience and altering course of action	Insensitivity to many extraneous factors
Capable of performing delicate operations, particularly in unexpected situations	Capable of repeating the same operations rapidly and precisely in the course of a long time period
Capable of continuing to perform even when overloaded	Operation in environments hostile to man or completely intolerable for man

In Earth orbit flights, illumination may vary from 2.02×10^{-2} cd/m^2 (10^4 mL) (sunlight reflected from clouds) to 3×10^{-14} cd/m^2 (10^{-6} mL). The light intensity in the cabin may change sharply in the course of a few seconds with only a few degrees change of the spacecraft's attitude. This is determined by the position of the porthole relative to the Sun. During spacecraft rendezvous and docking, cosmonauts repeatedly shift their gaze from instruments to the surrounding medium, and like the transition from the nighttime side of Earth to the daytime side, this causes readaptation of crewmembers' vision. It is desirable that the principal instruments in a space station or spacecraft be illuminated with individually controllable light sources in order to alleviate the negative influence of outside illumination (Table 8).

The ability of cosmonauts to see the instruments, after a bright flash, decreases until there is adaptation to the lower light level; this is a function of the duration and intensity of the light flash and the illumination level inside the spacecraft.

Metcalf and Horn (in [75]) have shown that recovery time at illumination level of 2.3×10^{-3} cd/m^2 (71 ft-L) is 4.8 s, at 2.2×10^{-4} cd/m^2 (7 ft-L), 11.6 s, and at 1.4×10^{-5} cd/m^2 (0.45 ft-L), 35 s. In determining standards for space station illumination, the necessity to seek and identify external objects and to make observations of celestial bodies during navigation must be taken into consideration. Solar light of great intensity can enter the spacecraft window directly or as reflection from clouds. In the first case, there is a "projector" effect. Sharply contrasting light effects make vision in the shadows difficult or impossible. The negative effect can be alleviated by painting all surfaces inside the spacecraft in light gray tones, using window filters to diffuse or eliminate high-intensity light sources. If filters do not help, point light sources should be used to illuminate important zones inside the spacecraft.

When using luminous indicators, techniques should be found to protect them against the "projector" effect. During flight on the night side of the Earth, cosmonauts will see weak light sources (stars, luminous points on the Earth), while at the same time, the lighting inside the spacecraft must permit observation of the instruments.

Matte finish on metal surfaces and applica-

TABLE 5.—*Crew Work Schedule in Long Space Flights* [17]

Specialist crewmembers	Phase III: Earth-Venus (844 working h/crewmember)		Phase V: Venus-Mars (1457 working h/crewmember)		Phase XI: Mars-Earth (1150 working h/crewmember)	
	Activity	Hours, no.	Activity	Hours, no.	Activity	Hours, no.
Biologist			Exobiologic preparation	56	Exobiologic studies	
	Physiologic studies	23	Physiologic studies	33	Physiologic studies	32
Physicist	Physical science studies	434	Physical science studies	835	Physical science studies	808
Geologist	Physical science studies	433	Physical science studies	834	Physical science studies	807
Monitor	Medical-psychologic monitoring	315	Medical-psychologic monitoring	419	Medical-psychologic monitoring	385
			Exobiologic preparation	16	Exobiologic studies	
Technician	Physiologic studies	23	Physiologic studies	32	Physiologic studies	31
	Physical science studies	773	Physical science studies	1393	Physical science studies	1050
Deputy	Operational monitoring	294	Operational monitoring	507	Operational monitoring	400
					Physical science studies	277
Engineer	Operational monitoring	294	Operational monitoring	507	Operational monitoring	400
Commander	Operational monitoring	294	Operational monitoring	507	Operational monitoring	400
			Exobiologic preparation	112		
Navigator	Navigation instrument readout	(1)	Navigation instrument readout	(1)	Navigation instrument readout	(1)
	Physical science studies	778	Physical science studies	1393	Physical science studies	1050
Psychologist	Physiologic studies	147	Physiologic studies	299	Physiologic studies	201
	Medical-psychologic monitoring	315	Medical-psychologic monitoring	490	Medical-psychologic monitoring	385
			Exobiologic preparation	56		

[1] Intermittent activity, minimal time cost.

tion of coatings to reduce reflection on glass surfaces are recommended to reduce light reflections. Screening the face side of instruments and other reflecting surfaces is difficult since the reflection angle depends on the relative position of the light source and the operator's eye [75].

Effective illumination of the spacecraft requires that:

1. White lighting be used throughout most phases of the flight;
2. Lighting intensity vary from 3×10^{-9} cd/m^2 (0.1 mL) to 1×10^{-6} cd/m^2 (40 mL) (with highest intensity in the launch phase);
3. Provision be made for switching on all lights in an area, for individual lighting of the most critical instruments, and for easy maintenance of balance between internal and external lighting;
4. Provision be allowed for adjustable light beams to reduce the influence of marked contrast by filling in the shadows;
5. All light sources be equipped with red filters (6400 Å) for dark adaptation;
6. Internal instrument lighting be protected against the masking influence of high-intensity light sources;
7. Lamps, indicators, and self-luminous instruments be located to prevent reflection from windows and other instruments;
8. Filters or shades be easily adjustable;
9. The color and intensity of warning and alerting light signals be selected so as not to affect the ambient illumination level and dark adaptation, particularly on the night (dark) side of Earth;
10. The most important colored markings on instruments and legends be identified so that they can be seen in red light.

TABLE 6.—*A Version of a Schedule for Flights to Mars* [17]

Activity	Time allotment, h:min
Free time	1:34
Hygiene	7
Eating	48
Hygiene	4
Exercise	28
Work cycle	1:58
Hygiene	4
Exercise	28
Work cycle	1:52
Free time	34
Hygiene	11
Eating	48
Exercise	28
Work cycle	1:45
Free time	34
Hygiene	3
Eating	48
Hygiene	30
Exercise	38
Sleep	7:41
Variables	2:35

Additional recommendations are made for long-duration flights:

1. Lighting should be indirect or diffuse;
2. Reflection coefficients of walls, ceilings, floor, and furnishings should be selected to maintain the correct ratio of light reflected from the surroundings and to increase the existing lighting level;
3. The general brightness contrast ratio should not be greater than 5:1;
4. The quality of light must maintain natural colors, particularly natural skin color.

The light level should be 269–323 lm/m^2 (25–30 ft-ca) on any work surface where discrimination is required, with additional lighting to 434.4 lm/m^2 (40 ft-ca) when necessary; 215.2–269 lm/m^2 (20–25 ft-ca) on the work surface in the general zones; 53.8–107.6 lm/m^2 (5–10 ft-ca) in the personal and other zones, with additional lighting where required [22].

HABITABILITY AND COLOR

Development of the proper artificial light and color climate is one means of optimizing living conditions aboard the spacecraft. The need to organize light and color into an integrated climate has been demonstrated by Ustinov, Povileiko, Rabkin, Lanin, and others [9, 42, 43, 62, 64, 65, 76]. Light-color climate is defined as the organized distribution of color and light inside an area. The light-color climate must provide favorable conditions for the functioning of the human eye. However, if it is developed without consideration for the nature of the operator work regime, crewmember condition, and the psychophysiologic properties of colors, brightness, and illumination, the effect may not only be weak, but even negative. Thus, the light-color climate markedly affects the physiologic and psychologic functions of man, and therefore, his work capacity and reliability. Most studies of light-color climate have been directed toward application to conventional working and living situations.

Psychophysiologic experiments have established that colors have different degrees of attractiveness. In decreasing order of preference, they are: blue, red, green, violet, orange, and yellow. The attractiveness of a color depends largely on the size of the colored zone. In small areas saturated colors are preferable, while shades and tints are preferred in large areas. Among the saturated colors the best are red, orange-red, and green-blue. Yellow and yellow-green sometimes lead to negative emotions.

In engineering aesthetics a terminology is adopted which characterizes the emotional effect of a given color. We say that colors are cold, warm, dry, rich, light, heavy, lifeless, ruthless, quiet, and dissonant. Blue, green, violet, and their tints are cool, quiet, and conducive to rest. Red, orange, and yellow colors stimulate the psychophysiologic functions and may, to a degree, be considered sympathicotropic factors. In accordance with their emotional effect, blue, green, and violet are recommended in sleeping and resting areas; red, yellow, and orange are used in work compartments, game rooms, and recreation rooms.

The principal factors which must be considered in formulating the light-color climate of spacecraft and space stations are:

1. Mission and overall dimensions of the spacecraft;
2. Flight duration;
3. Purpose of the given area (work compartment, sleeping area, general purpose area, eating area, and so on);
4. The possibility of varying the light-color climate during flight.

The light-color climate problem is solved in both static and dynamic versions. In developing the light-color climate, particular attention should be devoted to the problem of timely recognition by the operators of warning and coding colors, which as a rule are strictly standardized. Signaling colors are characterized by purity, brightness, and saturation. It is recommended that black, white, or shades of gray be used as background for signal colors.

Kahler [35] found that optimal conditions for

TABLE 7.—*General Levels and Types of Illumination for Different Tasks and Conditions* [22]

Tasks, conditions	Types of tasks or area	Illumination level		Illumination type
		lm/m^2	ft-ca	
Small elements, low brightness contrast during long period, high rate, high accuracy	Sewing, inspecting dark materials	1076	100	General plus supplementary (e.g., desk lamp)
Small elements, satisfactory contrast	Machining, detailed drafting, watch repairing, inspecting medium materials	538–1076	50–100	General plus supplementary
Details of normal size, long working time	Reading, laboratory work	215.2–538	20–50	General (e.g., overhead ceiling fixture)
Details of medium size, short working time	Washrooms, power plants, waiting rooms, kitchens	107.6–215.2	10–20	General (random natural or artificial)
Good contrast, fairly large objects	Equipment or facilities for recreation	53.8–107.6	5–10	General
Large objects	Restaurants, stairways, bulk-supply warehouses	21.5–53.8	2–5	General

visual perception occur when the luminosity of the working field of vision is greater than the background surrounding it. A color having a high coefficient of reflection (80%–90%) is recommended for the ceiling because of the desire to reduce the contrast between the light source and its background. The surface should have a matte finish to avoid highlights. It is advisable to paint the walls of operator stations in light tones having a reflection coefficient of 50%–60%, thus reducing the contrast between ceiling and walls. A color with reflection coefficient of 15%–30% is recommended for the floor and one with a coefficient of 15%–50% for the equipment and furniture.

When painting the ceiling, walls, floor, and objects surrounding the operator, it must be remembered that colors have distinctive emotional effects.

Small spots of a saturated color should be used for the overall background in order to alleviate the monotonous effect of a uniform range of colors. These spots should be of a complementary color with relation to the dominant interior color [22].

Mel'nikov recommends provision for a decorative center, using tapestries, decorative fabrics, lithographs, pictures, and other features. He formulates the basic requirements for this decorative center [54]:

1. Color should be general and subdued;
2. Saturation and brightness of color tone;
3. Contrast of color range of the decorative spot with color range of the interior;
4. Expressive texture;
5. Large scale.

The color spot should not fall in the field of view of the working operator, since it would then distract his attention.

The stationary light-color climate version has significant deficiencies as well as advantages. The primary drawback is the intrusiveness of the colors in the various elements of the interior. Moreover, in the course of protracted space flight, persistant deviations in the psychic status may arise and there may be emotional stress from certain physiologic functions. For example, violet, which under normal conditions would be

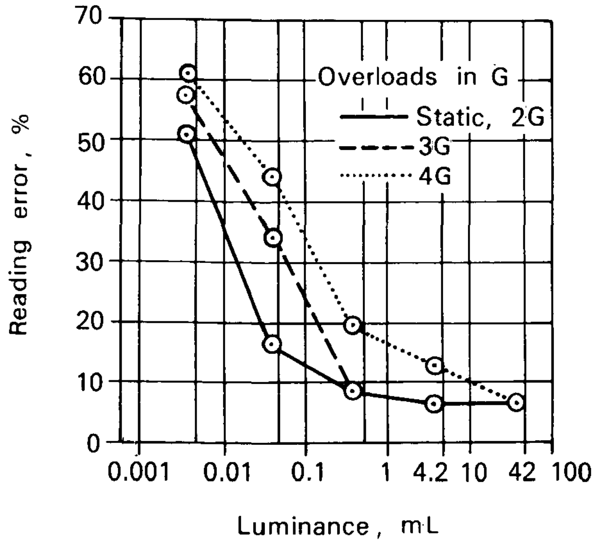

FIGURE 5.—Effect of load factors on accuracy of instrument indication readout as a function of illumination (after [76a]).

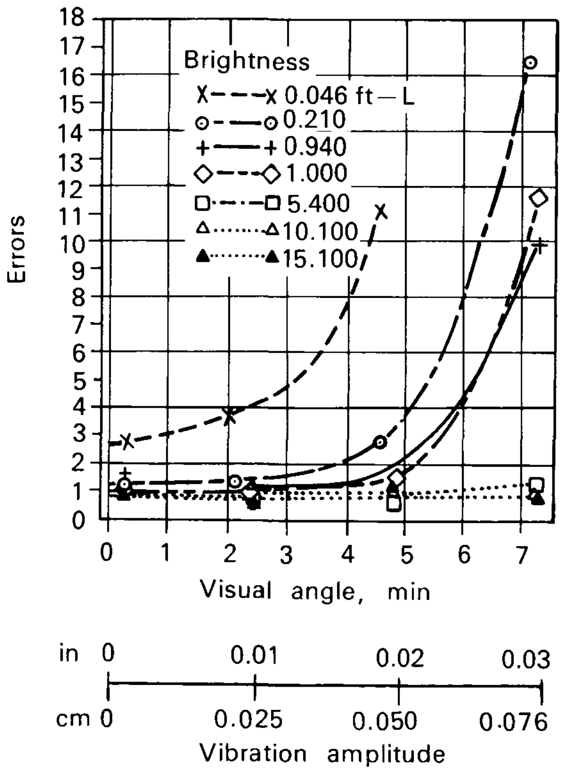

FIGURE 6.—Effect of vibration amplitude and visual angle on accuracy of instrument indication readout for various levels of brightness [14a].

natural in the relaxation area, is undesirable when crewmembers show signs of depression. A more effective solution of the problem would be a dynamic light-color climate in which painted interior elements and colored illumination provide a goal-directed effect on the crew as a whole or individual crewmembers as a function of their condition, the work regime, and the spacecraft flight stage.

Dynamic Color

The idea of dynamic presentation of color is not new. Fere [19] showed experimentally as early as 1904 that alternation of white and colored illumination improves work capacity when compared with constant lighting. Hebb [28, 29] noted a connection between the condition of the visual functions and change of the illumination color range. Deribere [15] worked with color in connection with the problem of protracted isolation (submarines). He noted alleviation of the depressive action of the enclosed compartment when the illumination and the color range were changed.

Lem [44] was one of the first to suggest simulating the daily and seasonal rhythms of terrestrial nature within the interior of the spacecraft. Zefel'd [82] in 1964 proposed simulation of man's terrestrial living conditions in stylized form aboard the spacecraft. The proposals of Mikushkin [56] were very close to this point of view. Dynamic colored illumination was recommended by Krasnikov [39] and Ivanov [31].

Man continuously senses a very rich dynamic range of color characteristics in his daily life. The color and light inputs of nature change seasonally as well as during the day. Color diversity is combined with strict patterns of certain colors replaced by others. The result is that man's visual perceptions are very important in his daily psychophysiologic process rhythm.

One of the unique ways of varying the color environment in the spacecraft cabin is the development and creation of color programs in

TABLE 8.—*Recommendations for Indicator, Panel, and Chart Lighting* [57]

Conditions of use	Recommendations			
	Lighting	Brightness		Brightness adjustment
		cd/m²	ft-L	
Reading indicator, dark adaptation required	Red flood or indirect (or both), at choice of operator	6×10^{-7} to 3×10^{-6}	0.02–0.1	Continuous throughout range
Reading indicator, dark adaptation not required but desirable	Red or "lower color temperature" white flood or indirect (or both), at choice of operator	6×10^{-7} to 3×10^{-5}	0.02–1.0	Continuous throughout range
Reading indicator, dark adaptation not required	White flood	3×10^{-5} to 6×10^{-4}	1–20	Fixed or continuous
Panel monitoring, dark adaptation required	Red edge, red or white flood, or both, at choice of operator	6×10^{-7} to 3×10^{-5}	0.02–1.0	Continuous throughout range
Panel monitoring, dark adaptation not required	White flood	3×10^{-4} to 6×10^{-4}	10–20	Fixed or continuous
Panel monitoring with possible exposure to bright flashes	White flood	3×10^{-4} to 6×10^{-4}	10–20	Fixed
Panel monitoring at very high altitude and with limited daylight	White flood	3×10^{-4} to 6×10^{-4}	10–20	Fixed
Reading charts, dark adaptation required	Red or white flood, at choice of operator (on white chart areas)	3×10^{-6} to 3×10^{-5}	0.1–1.0	Continuous throughout range
Reading charts, dark adaptation not required	White flood	1.6×10^{-4} to 6×10^{-4}	5–20	Fixed or continuous

the form of filmstrips projected on a white screen. The programs may be of a highly specialized nature, depending upon the schedule for the given day (intense work, rest before and after work, exercise, eating, games, conversation). The light-color programs should also assist the crew in maintaining awareness of the passage of months and changing of seasons.

Programs based on daily and seasonal light and color rhythms have been created in our laboratory by Mel'nikov [53]. In order to establish the changing patterns of the meteorological and astronomical phenomena, analyses were made of hydrometeorological data from which annual maps and tables were prepared. Material for the filmstrips was selected in accordance with the light and color characteristics of the season and time of day. The spectral composition of the solar-ray flux and the reflective properties of the Earth's surface were also taken into account.

Krinov [40] has classified natural landscape objects according to the capability of reflecting various segments of the solar radiation spectrum:

> Class 1—neutral with achromatic or nearly achromatic tones (snow, water expanses, withered vegetation); Class 2—red (dried vegetation, soils); Class 3—green (vegetation cover).

Light and color composition will have more than the psychophysiologic effect of alleviating sensory deprivation and regulating within limits the operator's functional status. The sociological aspect is no less important. While literally separated from life on Earth, which is "saturated" with social motifs, the cosmonaut maintains, with the aid of realistic colored pictures, his spiritual link with the social motifs to which he is accustomed. He senses the breathing of the city and countryside, reproduces the patterns of daily life on Earth, refreshes his memory of engineering and scientific achievements, and maintains connection with the rhythm of terrestrial life.

Mel'nikov [53, 54] has prepared detailed color schemes:

Winter: Neutral coloring of dormant nature, sharp contrast between light and dark regions, absence of any vivid colors.

Spring: Vigorous and dynamic in the color sense, dominantly vivid; bright colors express the idea of awakening nature.

Summer: Balanced colored masses with domination of the three characteristic colors.

Fall: Saturated colors of fall express the magnificient finery of nature as the leaves fall; yellow tones dominate the color scale.

January: The range of black and white describes the coloring of severe midwinter.

February: Blue tones transmit the change of color at the threshold of spring.

March: The gamut of blue, white, and gold tones expresses the essence of this month—the "blue spring of light."

April: Golden pearly colors are equivalent to the first heat of this month.

May: The end of spring is expressed by a green color scheme (the distinctive features of this month are greenness and clouds).

June: Two colors are characteristic: yellow (Sun) and green (vegetation).

July: A hot color pattern expresses the temperature characteristics.

August: A mixed gamut of colors corresponds to those of August flowers and fruits.

September: Bright colors of falling leaves define the coloring of this month.

October: Dull colors of the first cold month of nature as it becomes torpid and sleepy.

November: The monotonous color range of the prewinter month—the "twilight of the year."

December: Silvery tones express the coloring of ice-cold, misty, and foggy days.

Seasonal changes are representative of the middle belt of the European section of the Soviet Union. Naturally, for other regions of the Earth, for example, southern California, the color arrangements will be different for the times of year.

The use of color and music to influence crewmembers aboard interplanetary spacecraft is very promising [61]. Significant advances have been made in developing the theory and achievement of light and music synthesis [7, 24, 61, 63].

Colored Light and Music

Basic steps in developing colored light and music programs include: analysis of the emotional content of musical compositions; finding color equivalents of musical images and their expression in pictures; developing color dynamics and techniques for recording the color score; photography of dynamic color compositions on movie film; and synchronization of color with music. The most important step is finding color images which correlate emotionally with musical images. Artistic compositions of color then become the starting point for development into the dynamics of color accompaniment for music.

Since music is the fundamental factor in the formulation of color-music programs and the subsequent realization into films, the first step is the selection of musical compositions to obtain an activating or sedative effect. The color portion of the programs is derived from visual image-color associations obtained by listening to specific musical compositions. Image-color perception is a function of sound-pitch relationship (melody), tonal-harmony structure, tempo, rhythm, timbre, and dynamics of the musical composition.

The preparation of color-music films was accomplished with the aid of a device, called the color variator, especially designed to obtain dynamic color images which correlate with the character of the music. The color variator is a raster-type optical device; its screen is a mosaic of 520 differently colored small incandescent bulbs with light filters. The spectral characteristic is selected in accordance with the color-music composition. The control console, a continuous pushbutton field, duplicates the relative positioning of the bulbs. As the artist touches the buttons with his fingers, palm, or edge of his hand, contacts close and control activation and deactivation of the corresponding bulbs.

Color in spacecraft interior decoration has a promising future; it has psychophysiologic and aesthetic functions without negative psychopharmacologic qualities. Color alone, and in combination with music, is an effective means for maintaining the life tone of the cosmonauts, high work capacity, and stabilizing the sociological bases of life under conditions of protracted interplanetary flight.

ORGANIZATION OF COSMONAUT OFF-DUTY TIME

During interplanetary flight, spacecraft crewmembers will have a considerable amount of free time, which they can spend as they wish[18]. The longest periods will occur in the trajectory segments when power plants are not operating and the on-board equipment is working in the nominal regime.

Eberhard [17] examined several studies on the activity of individuals in relative isolation for long periods (in bunkers, rocket launch sites, Antarctic expeditions, spacecraft simulators), and drew these conclusions:

1. Individuals in isolation prefer work to inactivity.
2. Individuals in isolation show more abnormal symptoms than those exposed to normal conditions.
3. Off-duty activities should depend on the wishes of each crewmember.
4. Individuals in isolation invent original occupations to fill off-duty time.
5. The nature of off-duty activity of isolated groups is not the same as that for individuals under normal conditions; moreover, the nature of individual activity in isolation changes with time.
6. The most popular activities among isolated groups include conversation, reading novels, watching movies, and television.
7. Individuals in isolation spend nearly twice as much time eating as they do under normal conditions.
8. Adults studied rarely engaged in physical activity.
9. Interest in self-education is individual and was observed only in certain cases.
10. Activities such as painting, and playing cards, chess, and checkers were mentioned relatively rarely by most individuals studied.

Eberhard sent a questionnaire concerning tastes in spending off-duty time and the equip-

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ment used to 30 astronauts working at the NASA Space Center. The results of the questionnaires are shown in Tables 9 and 10; each table shows the relative importance of individual forms of relaxation. It should be noted that activity associated with work occupies first place, followed by reading, physical exercise, studies, and athletic games.

Table 11 presents the relative frequencies of ways in which space engineers spend leisure time. Reading heads the list, followed by watching television, participation in musical activity, and handicrafts. In athletic relaxation, preference is for swimming, softball, football, and basketball (Table 12). The preference for reading, radio, television, movies, and music is apparently associated with the simplicity and availability of these forms of relaxation.

Intended and Actual Activities

The desire to engage in certain forms of activity under confined conditions is not always carried out. Rorer (cited in [17]) indicates, on the basis of experiments in the Antarctic, that prior to finding themselves in isolation, expedition members made plans to constructively utilize their free time: read serious novels or technical books, study foreign languages, listen to scientific and technical lectures, and increase their qualifications. However, in time, these good intentions began to be replaced by simpler activities such as bull sessions, telling tall tales, and the like. This conflicts with the data obtained by Ebersole (cited in [22]), who studied leisure activities aboard an atomic submarine and reports a tendency toward increased desire to read serious material.

In the early stage of the voyage, dramatic and adventure novels were selected; as time passed, books requiring greater concentration were preferred. Kinsey (cited in [22]) presents similar data on the change of interests toward serious literature among crewmembers of the submarine *Nautilus*. The conflict between the data of Rorer, and Ebersole and Kinsey may be explained, according to Fraser [22], by higher motivation of submarine crews, who were more goal-directed than members of the Antarctic expedition.

Chess and cards were very popular aboard the submarine. It was found that playing musical instruments gives great pleasure to the one playing but not always to the listeners.

Passive recreations such as radio, television, movies, and reading are the primary free-time

TABLE 9.—*Off-Duty Activities of 30 Astronauts, in Order of Preference*

Activity	Importance
Activity associated with work	1
Reading	2
Physical exercise	3
Studying	5
Sports	5
Listening to records	5
Family-associated activity	7
Watching television, movies	8
Seclusion	9
Composition on technical themes	10.5
Rest, relaxation, doing nothing	10.5
Composition on personal themes	12
Resting, relaxation, idleness	13
Snacking	15
Building models	15.5
Playing cards	15.5
Sketching, sculpting, photography	17.5
Table games	17.5
Gambling	19
Playing musical instruments, singing	20
Collecting stamps, coins	21

TABLE 10.—*Equipment Used by 30 Astronauts for Relaxation, in Order of Preference*

Use of equipment in spacecraft	Importance
Viewing through windows	1
Physical exercise equipment	2.5
Tape recorder, record player	2.5
Books	4
Sports equipment	5
Radio	6
Newspapers	7
Magazines	8
Photographic equipment	9
Radio equipment for personal communication	10
Television	11
Writing equipment	12
Playing cards	13

activities for most people. Data from 7000 interviews in the US during a single week show that approximately 72% of the population above age 12 spend nearly 2 billion hours watching television, about 60% spend more than 1 billion hours listening to the radio, more than 80% spend more than 400 billion hours reading newspapers and magazines, and nearly 30% spend 150 billion hours at the movies [22]. Table 13 shows the frequency of various leisure activities of an urban population.

The importance of the proper organization of recreation during rest periods was shown in the Tektite program [58]. Subjects were in isolation for long periods under water during this research program.

Fiction, scientific, and technical literature are excellent possibilities for recreation and self-education. However, reading presents serious difficulties during long-duration space flights. Microfilming cannot resolve all the problems. Reading long microfilms is not only tiring, leading to development of negative emotions, but also the equipment is very bulky. Sound recording equipment that reproduces the text through earphones would be preferable.

Art (painting, sketching, sculpting) is a promising way of spending leisure time during extended space flights. If talent is available among crewmembers, musical or dramatic groups might be formed, although the main handicap for such a group would be the absence of an audience. Consequently, the group's productions would be in the form of private rehearsals. At present, it is practically impossible to foresee evolution of the relationship of cosmonauts to various forms of recreation for flights lasting 10, 12, or 15 months. Salons of interplanetary spacecraft should have books, a film library, recordings of musical productions, table games and others especially devised for cosmonauts, a controllable color generator, small musical instruments, and other equipment. The true value of each item in filling cosmonauts' leisure time would be determined only during multimonth space flights.

TABLE 11.—*Time Spent in Off-Duty Hours by Space Engineers* [18]

Rank	Activity	Relative frequency
1	Reading	0.725
2	Television	0.300
3	Music	0.275
4	Handicrafts	0.213
5	Bridge	0.163
6	Educational activity	0.150
–	Miscellaneous work	0.125
–	Social activity	0.125
9	Traveling, driving car or motorcycle	0.100
–	Family activities	0.100
–	Photography	0.100
12	Sports	0.088
–	Hunting, fishing	0.088
14	Gardening	0.075
15	Chess	0.063
16	Art	0.050
17	Golf	0.038
–	Sailing	0.038
–	Crossword puzzles	0.038
–	Walking	0.038
21	Model building	0.025
–	Movies, theater	0.025
23	Other activities	0.025

HOUSEKEEPING PROBLEMS IN SPACE

Living conditions and housekeeping problems of the cosmonauts require solution of an entire series of urgent questions. During extended space flights, tidying the area and individual

TABLE 12.—*Sports Preferred by Space Engineers* [18]

Rank	Activity	Relative frequency
1	Swimming	0.463
2	Hardball, softball	0.425
3	Football	0.413
4	Basketball	0.350
5	Tennis	0.275
6	Billiards	0.263
7	Table tennis	0.238
8	Golf	0.213
9	Walking, hiking	0.150
10	Sailing, motorboating	0.113
11	Hunting, fishing	0.100
–	Badminton	0.100
13	Volleyball	0.050
14	Other activities	0.050

stations in the living compartments, food preparation, washing underwear and other garments, and body care will be performed by each crewmember. Dirty clothing will be washed and dried either with the aid of cold (vacuum sublimation) or by squeezing in bags similar to those used for collecting wastes. Hairs and small trash will be collected with the aid of vacuum cleaners. Most surfaces inside the spacecraft are accessible for wiping with a damp cloth, which, in many cases, is more convenient than vacuuming. Disposal of trash and kitchen wastes is a difficult problem—nearly every gram of material expended is converted into a gram of waste.

Personal hygiene must be observed for a favorable environment. Procedures include tooth and oral hygiene, washing hands and face, washing the body, trimming hair and nails, shaving, and changing and washing clothing.

A significant factor in spacecraft habitability is satisfying the requirements of personal hygiene—particularly removal of perspiration and other surface accumulations from the body. Mattoni and Sullivan [50] divide human life-activity wastes, other than metabolic wastes, into three groups:

1. Skin and appendages: desquamated epithelium, hair, nails.
2. Secretions of glands: sweat, sebum, saliva, mucus, seminal fluid.
3. Gases, microflora, products of bacterial metabolism; also possible contamination by blood, fungi, and vomitus.

TABLE 13.—*Activity of Urban Population in Leisure Hours*

Activity	% Total in group
Radio, television, movies	62
Reading	48
Other activities	42
Outdoor activities	35
Arts, handicrafts	25
Music (playing or listening)	24
Hobbies	15
Spectator sports	13
Social work	9
Self-improvement	3
Doing nothing	3

In addition to physical manifestations (oil, sweat, dandruff), the sensation of body contamination may have a negative psychologic connotation. Dandruff may lead to serious complications; particles of dandruff in the atmosphere may be inhaled, get into eyes, or stick to instrument scales.

Experiments by Slonim have shown that not washing or taking a sponge bath leads to unpleasant body odors after 7–10 d. The subjective reaction to the odor decreased the second week. There were complaints of dandruff and itching, and the impossibility of removing underwear which eventually sticks to the body [72]. Table 14 lists key steps in a sponge bath under simulated weightlessness with handholds and restraints. Table 15 summarizes an evaluation of oral hygiene procedures.

Nutrition organization is largely determined by hygienic and physiologic standards for consumption of proteins, fats, carbohydrates, salts, water, and other elements. Let us examine nutrition in more detail as a factor in interplanetary spacecraft habitability.

Meals—Nutritional and Social Importance

Interplanetary space flights are a matter of the distant future; therefore, there is particular interest in empirical data from the field of nutrition, obtained under conditions which more or less approach prolonged spaceflight conditions. In this regard, the results of the US project, Tektite, are particularly interesting. Four scientist-aquanauts lived and worked for 60 d in an underwater station having a volume of about 60 m^3 (2000 ft^3) [58].

Eating meals became the major social event of the day. During mealtime, the aquanauts actively discussed various problems and shared impressions. The process of food preparation itself gave particular pleasure to two of the four crewmembers. This example clearly shows that the nutrition process goes beyond the bounds of physiology and hygiene; here, the social psychology of man becomes dominant.

In organizing nutrition for interplanetary spacecraft, it is particularly important to select the proper assortment of food products. Along with most of the cosmonaut foodstuffs which are packaged, there should be some natural products—fresh vegetables and fruits, eggs, fowl, caviar, cheese. The range of products must not only permit varied assortment of dishes during the day and week, but must also at least partially satisfy individual requirements. A selection of 15–20 dishes, corresponding to the capability of a good restaurant, is recommended [34].

The kitchen equipment must provide for a variety of food preparation techniques such as baking, boiling, roasting, or stewing. Both the appearance and aroma of food should be attractive. Serious attention should be given to table settings, with restraints for plates, dishes, cups and glasses to prevent "floating." Knives, forks, and spoons must be lightweight and easy to use. The cosmonauts must be particularly careful about splattering to prevent liquid food and crumbs from floating around the cabin. The use of spices such as pepper and mustard require particular attention.

Jones [34] recommends the use of food in the form of prepared chunks which need not be cut. While this technique may eliminate some problems, some loss of the usual ritual dining atmosphere will occur. The size of the eating area aboard the interplanetary spacecraft must be adequate to accommodate all crewmembers. The illumination level of the eating area should be 70–100 lx, and the color of the walls should create an illusion of increased space. In addition to the use of lively colors, it is recommended that the wall decoration include paintings of

TABLE 14.—*Procedures for a Sponge Bath in Weightlessness* [47]

Task	Task description	Time, s	Handholds and foot restraints
Unstow checklist	Opens compartment; removes hygiene task checklist and inserts in bulkhead receptacle; closes compartment	17	Stands firmly on Velcro foot restraint pads; uses right handhold on worktable with his left hand to aid in positioning body when bending to reach compartment
Unstow glove	Opens compartment; removes protective bag containing one cloth glove; closes compartment	7	Frees himself from foot restraint; uses compartment door as handhold
Remove glove	Opens protective plastic bag; removes glove and disposes of bag	20	Uses no restraints while opening protective bag or when disposing of bag in compartment (8.0 s); repositions body on Velcro floor pads after disposing of plastic bag; uses handholds on worktable to position feet against Velcro to gain a stable position (3.0 s); reads checklist
Don glove	Inserts right hand in glove	23	Uses foot restraints to maintain position while donning glove
Cleanse all parts of body	Touches all possible parts of body: left arm, left side, left leg	17	Uses foot restraints to maintain position and periodically uses left handhold to steady position
Don glove	Removes glove from right hand and puts on left hand	26	Drifts free of foot restraints while donning glove; regains foothold with aid of right handhold and continues to don glove
Cleanse all parts of body	Touches all possible parts of body: right arm, right side, right leg, back, chest	18	Uses left handhold on worktable as main restraint for this maneuver; occasionally feet engage Velcro foot restraints
Dispose of glove	Removes glove from hand and places in waste compartment	12	Uses combination of Velcro foot restraints and right handhold to position body when reaching for compartment
Restow checklist	Removes checklist from bulkhead receptable and stows in compartment	13	Stands firmly on Velcro restraints; uses right handhold to aid in maintaining position when bending to reach compartment

still lifes, seascapes, and picturesque mountain scenes.

A 60-d manned experiment in 1968, which used a regenerative life-support system in a closed chamber, has yielded considerable information on the problem of nutrition under conditions of life in a closed space. The four participants in this experiment were offered four types of menus which provided about 2400–2800 cal/d, and daily change of food during the week. Each type consisted of four to six dishes prepared from packaged products. Once a week the subjects were served a complete dinner prepared by specialist cooks, which was served hot, and was equivalent to a good restaurant meal. It usually consisted of beefsteak, a large baked potato, sour cream, salad, bread and butter, fresh milk, and a dessert [34]. The restaurant-quality meal, served on Fridays, became a major event for the experimental subjects. They often reckoned time by the special dinner day and if the meal was not served on time, they began to show signs of nervousness. This meal was without doubt a positive factor in creating a good mood among the experimental subjects.

It is obvious that a meal prepared from natural products has a significant advantage over packaged food. Therefore, the problem of preparing rations for interplanetary flights is still very complex and important.

TABLE 15.—*Evaluation of Oral Hygiene Procedure* [22]

Procedure	Results
Toothbrush and toothpaste	Adequate oral hygiene
Gum and interdental stimulator	Ineffective—gingivitis in all subjects, stained teeth, halitosis
Electronic toothbrush and interdental stimulator	Improvement of teeth status in all subjects
Interdental stimulator only	Ineffective—gingivitis, stained teeth, halitosis
Toothbrush and water only	Varying degree of gingivitis, stained teeth, mild halitosis
Toothbrush and edible dentifrice	Adequate oral hygiene
Toothbrush, water, and dental floss	Improvement in dental health in all subjects

Additional ways to optimize cosmonaut nutrition in spacecraft habitability should be sought in improved food product packaging, special dishes compatible with the capabilities of the space kitchen, expanded (directly or illusorily) space of the eating area (dining room), selection of tableware and development of table setting techniques, and portable multifunction devices for handling food products and preparing meals.

PHYSICAL FITNESS DURING PROLONGED FLIGHTS

The weightless state and living space limitations aboard the spacecraft inevitably lead to hypodynamic (hypokinesic) phenomena, change in the operation of various muscle groups, and in the functioning of the central nervous system.

Studies by Korobkov and Shkurdoda et al [37, 38] have shown the role of physical training in increasing resistance of the organism to unfavorable ambient factors. Working with animals, Shkurdoda found that the introduction of daily 30-min exercise markedly increased the survival rate of rats. In a group with complete hypodynamia, 60% of the animals had died by the end of 20 d, while in the group exposed to physical exercise the number of deaths was less than 30%.

A detailed study of the influence of physical exercise on people in a hypokinesic state was performed by Yeremin et al in 1969 [80]. The subjects were two groups of young people, each of which spent 70 d confined to bed, simulating to a degree the hypodynamia of cosmonauts during flight. The first group remained in a condition of complete hypokinesia throughout the entire experimental period. The individuals of the second group performed a complex of exercises, isometric and isotonic, for 1 h every day without changing the horizontal position of their bodies. The equipment included expanders, a veloergometer, and a treadmill. The bed suspension was designed so that the subjects could simulate walking and running. At the end of the 70-d experiment, the subjects who had performed the daily exercises could walk immediately without obvious deviations from their normal gait. Their muscle force, endurance, and functioning of the cardiovascular system were at normal level. The subjects of the second group (complete hypokinesia) showed obvious signs of the hypokinesic syndrome. Nearly a month was required to recover their normal gait.

Similar experiments were conducted by Kakurin and Cherepakhin [36] in which duration of the bed confinement regime was 20 to 62 d. The subjects performed a complex group of physical exercises during the experiment. In the 62-d experiment, the physical training sessions were conducted twice a day for a total of 2.5 h and an energy expenditure of about 1100 kcal/d.

At the end of the experiment, the nonexercising subjects (control group) showed 14%–24% decrease in the force indices of various muscle groups, 26%–55% decrease in dynamic endurance, and 24% decrease in static endurance. These subjects tolerated physical exercise poorly, showing shortness of breath, tachycardia, and skin pallor. The results were just the opposite for the subjects exposed to exercise: the basic characteristics improved by 19%–21%, dynamic endurance increased by 25%–27%, and static endurance by 20%–30%. The group's overall level of conditioning improved, as noted from the nature of autonomic reactions.

Studies by Iseyev and Nefedov [30] on subjects confined for 4 months in an enclosed space are of interest. An increase was found in the subjects' energy expenditure during physical exercise. Because of the clear-cut decrease of work capacity, each subject performed a complex of physical exercises regularly in the fourth month. Work capacity improved from 30%–70% of the reference level.

In special experiments [47], the clothing of subjects performing physical exercises was the standard flight suit with Velcro sandals and tethers. The subject began by standing on the Velcro floorpad facing the worktable and the compartment containing exercise equipment. While resting on the worktable, the subject bent over and withdrew the needed equipment. Then he pulled on the tethers until he was in a suspended position. In this attitude, he could touch the floor with his toes. Turning his body 90°, he then placed his feet on the front wall of the compartment, fixing his body in this position. After relaxing the tethers, the subject assumed a standing position on the Velcro footpad. In this position, he could insert his legs into the stirrups of the exercise device and move his arms in circles.

This system for fixing the subject's body makes possible both isotonic and isometric exercises under spaceflight conditions.

After performing the last exercise, the subject loosened the tethers and returned to the standing position in front of the worktable. Using the handholds on the worktable to establish the required body position, the subject placed the exercise device and equipment in the corresponding compartments.

The spacecraft must have a "gymnasium" which will include equipment for physical exercises [47]: isometric exercise equipment, restraint straps, and a specially fabricated veloergometer. If artificial gravity is provided, a miniature exercise bar setup may be valuable. Various types of dynamometers and rubber or spring-type expanders will be a necessary part of interplanetary spacecraft equipment.

The studies previously cited on the effectiveness of physical exercise under hypodynamic (hypokinesic) conditions do not correspond completely to characteristics associated with cosmonauts in interplanetary flight. The space hypodynamia complex will differ markedly from Earth-bound models primarily because of the continuous action of weightlessness. However, studies on Earth form a viable basis for design and utilization of physical exercise routines during prolonged space flights. The physical exercise program outlined for a flight to Mars will be of a provisional nature. During the actual flight, the type and duration of physical exercise sessions will be selected for their maximal effect depending on the condition of the crewmembers.

Cosmonaut Movement Inside the Spacecraft

The mechanism of body movement in the inhabited compartments and outside the spacecraft in open space differs significantly from that on Earth because of weightlessness. Therefore, cosmonauts will be forced to acquire new skills to control their bodies; the old, phylogenetic ingrained skills lose importance under conditions of complete weightlessness. The development of new locomotion skills must be accomplished by extensive auxiliary means.

A study [47] of tasks performed in space flight has been carried out at the NASA Langley Research Center, using water immersion to simulate weightless conditions. The primary objective was to determine applicability of various restraints (tethers and the like) and locomotion aids when used in spacecraft. The subjects wore wet suits under standard US Air Force flight suits; slippers were equipped with Velcro pads; and weights were attached to provide neutral buoyancy. Air was supplied from HOOKAH tanks. The experimental setup, which included a movie camera, was submerged 0.61 m (2 ft) under the water surface.

Four types of tasks were performed: (1) general maneuvers and housekeeping; (2) operations with equipment; (3) transporting weight and placing it in a compartment; and (4) experimental operations (care and overhaul of life-support systems). The subjects donned and doffed flight suits, rested (slept), prepared food, and performed physical exercises and various hygienic procedures.

Performance of hygienic tasks was not shown to require locomotion aids or development of complex restraints for weightless conditions; handholds are the most convenient devices. Fixed handholds are effective in all operations using equipment; toe straps are convenient when the arms are occupied. The limited space of the cabin acts as a restraint to establish body position when both hands are occupied. Couch belts serve as restraints in guidance and navigation operations. Handholds are also the best locomotion aids. When free-floating, handholds help to establish or change body position. Recommendations on the use of restraints and locomotion aids in general and housekeeping tasks are presented in Table 16.

Special studies by Morris et al indicate that various handholds must be used for locomotion under unusual conditions. Protuberances and handles having other functions can serve as handholds. The spacecraft should also be equipped with a special system of handholds for rapid locomotion in any direction. After short indoctrination, cosmonauts can master new locomotion mechanics by combining free-floating with brief grasping of supporting elements. A telescoping handrail for assistance in manipulating loads and tools is recommended for assembly operations in open space [47].

A chair system with restraint straps is advisable for long-term operations at work consoles (Table 17). Special panels with locating devices must be provided for tools. A safety tether must be used when the cosmonaut floats freely during extravehicular activity (EVA). The necessity for tethers when the cosmonauts leave the spacecraft will disappear as self-contained backpack propulsion units and reliable individual navigational devices are developed.

SOCIOLOGICAL PROBLEMS IN PROLONGED FLIGHT

The prospect of prolonged interplanetary flights poses social psychologic considerations in addition to biologic and psychophysiologic problems. The spacecraft crew cannot be considered as just the arithmetic sum of individuals; it is

TABLE 16.—*Optimal Restraints and Locomotion Aids for Performing General and Housekeeping Tasks*

Tasks	Restraints	Locomotion aids
Don-doff	Handholds Handrails Velcro sandals	Handholds Handrails Velcro sandals
Rest-sleep	Seatbelt restraints Velcro sandals	Velcro sandals
Food preparation	Handholds Handrails Velcro sandals	Handholds Handrails Velcro sandals
Exercise	Handholds Handrails Velcro sandals	Handholds Handrails
Hygiene	Handholds Handrails	Handholds Handrails Velcro sandals

instead a complex group united by responsible tasks. The crew includes individuals of different ages and professions, each with his own life experience. The psychologic characteristics of cosmonauts, who may have choleric, sanguine, phlegmatic, or even melancholic temperaments, are very important factors.

Individuals whose psychologic characteristics are clearly unsuited for such group work will, of course, be screened out in the crew selection and training process. Still, the psychologic tension among the crew at certain stages of spaceflight may become a complex problem for the commander.

Critical social psychologic problems are alleviated only slightly by current ways of determining psychologic compatibility. For example, in finding a leader using "homeostatic" equipment [26, 59], certain psychologic characteristics may be discovered and hierarchic coordination established. However, it is not clear whether the stability of this hierarchy under other conditions can be prognosticated by extrapolation.

The very long flight duration, rigid, irreversible and continuous isolation, and emotional strains brought on by complex, dangerous situations can completely demoralize a crew which on Earth was harmonious and monolithic.

Isolated groups on Earth, subjected to real danger while performing their activities, yield some data on the social psychology of small groups. However, analogy with these groups is not sufficient to draw definite and reliable conclusions regarding the evolution of social bonds on an interplanetary journey.

TABLE 17.—*Locomotion Aids and Restraints Used During Gemini EVA*

Device	Gemini flight			
	9	10	11	12
Large cylindrical handrail	+	–	–	+
Rectangular handrail	+	+	+	+
Small cylindrical handrail	–	–	–	+
Telescopic handrail	–	–	–	+
Fixed handhold	–	–	+	+
Rigid Velcro-backed portable handhold	–	–	–	+
Flexible Velcro-backed portable handhold	+	–	–	–
Waist tethers	–	–	–	+
Pip-pin antirotation device	–	–	–	+
Foot restraints	+	–	–	+
Standup tether	–	+	+	+
Leg straps	–	–	+	+

From the sociological viewpoint, Sells [67] analyzes 11 "microsocieties" which include: exploration parties, submarines, seagoing ships, remote monitoring stations, professional athletic teams, production worker teams, prison societies, and mental hospitals. He considers the living conditions of submarine crews, exploration parties, and long-range bomber crews closest to those in interplanetary spacecraft. Just as aboard the spacecraft, these crews may get into a critical situation without any real possibility of assistance, advice, or instructions from the "mainland." But the submarine can terminate its voyage and proceed to the nearest base to remedy the emergency situation; the exploration party and the bomber crews can do likewise. On the other hand, during a flight to Mars, the return trip is essentially impossible at any moment. Therefore, to take proper action, the commander must have more than excellent knowledge of his functions and the ability to evaluate quickly and in depth the existing situation; his morale and willpower are no less important. A weak-willed individual cannot maintain in difficult times the strict Earth commander-crew subordination, cannot find the correct approach to the faltering of his crew, and may lose control of the situation.

In critical situations in which stable two-way communication with Earth is maintained and detailed information transmitted to the flight control center, recommendations from the ground station will be of decisive importance. However, if events require immediate action from the crew, or radio contact does not provide adequate information, the commander must resolve independently all immediate problems, consulting as he sees fit with various specialists among the crewmembers.

In considering compatibility of crewmembers, it should be noted that in principle, a psychologic conflict between individuals can arise at any time; yesterday's friends may become today's antagonists. Therefore, the motivational basis of human behavior is decisive for stability of crew functioning under both nominal and emergency flight conditions.

Special attention must be devoted to evaluating somatic pathologic and psychopathologic problems to be faced during a flight of several months. The crew will undoubtedly include a number of doctors and biologists whose mission is careful observation of all functions of the human organism. Research results will be obtained in interplanetary flights which are not possible on Earth.

Work periods and duties will be determined by the dynamics of crewmembers' health. Serious difficulties will arise if significant changes in internal organs appear in the majority of crewmembers. Different manifestations of such difficulties require operational decisions according to the specific situation.

The interplanetary spacecraft crew should include highly qualified psychologists and psychiatrists (three or four). If psychopathologic signs and symptoms develop in an individual, immediate measures must be taken to diagnose, provide treatment, and if necessary, restrict the patient's activity. The latter is particularly important, since an individual in a mentally disturbed state can irreparably harm spacecraft equipment, with catastrophic consequences for the crew.

Solutions to psychosocial problems in cosmonautics are still in an embryonic stage. The consistent resolution of such problems will improve markedly the probability of flights being successful to the near and distant planets of the solar system.

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Chapter 7

INDIVIDUAL LIFE-SUPPORT SYSTEMS OUTSIDE A SPACECRAFT CABIN, SPACE SUITS AND CAPSULES[1]

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The space suits used in current space activities by the United States and the Soviet Union are sophisticated garments developed during at least 40 years of relatively sustained effort by many nations. Although years of study and continuous refinement are reflected, the suits were developed around a principle which is quite simple. The basic operational principle of space suits is provision of a movable pressure vessel around the human body. It insulates a man from the surrounding medium, creates and maintains uniform atmospheric pressure around his body, and provides for normal respiration and heat exchange, food, drink, excretion, and locomotion, allowing for useful work. The principal function of a space suit is analogous to the function of any pressurized cabin; the design problem may be solved in different ways, depending on the tasks and conditions of the specific space flight, and on the general construction of all other life-support systems and components within the vehicle. The suits used in present space activities are designed to allow an astronaut to work safely in the free space vacuum, to operate on the lunar surface independent of the primary space vehicle, and to survive in the event of accidental decompression of the space cabin—always maintaining a reasonable level of comfort and retaining capability for useful manual activities. This chapter discusses space suit systems, the particular physiological and operational requirements which must be met, and describes the technologic advances incorporated in the more advanced suits.

HISTORICAL DEVELOPMENT OF SPACE SUITS

Armored suits intended to protect the human from hyperbaric pressures were first conceived in 1838 when Taylor designed an articulated armored suit for undersea operations [6]. Jules Verne, probably the first to conceive of using pressure suits for protection against reduced barometric pressures at higher altitudes, described, in 1872, a closed-circuit, extravehicular pressure suit operation for a flight around the Moon [20]. The Soviet chemist, Dmitri I. Mendeleev, suggested (around 1875) using a gas-type gondola for personnel protection in stratospheric balloon flights. Although patents were issued on pressure flying suits in France in 1910, and in the United States in 1918, Haldane and Davis in Great Britain were first to design and test a carbon dioxide-absorbing protective suit in actual low-pressure chamber operation. In 1933, in response to a request from the American balloonist Mark Ridge, the physiologist Haldane and the diving suit

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[1] Grateful acknowledgment is expressed to L. G. Golovkin, compiler of the material concerning Soviet space suit systems. The author expresses sincere gratitude for the valuable contributions of William L. Smith, James F. Parker, and Vita S. West (USA), and to the other colleagues, Stanley Deutsch, Thomas Herrala, Joseph J. Kosmo, Charles C. Lutz, Dan C. Popma, Robert E. Smylie, and Hubert C. Vykukal, who collaborated in preparing this chapter.

specialist Davis designed and built a suit intended to permit ascent to stratospheric altitudes. Ridge wore the suit in a number of low-pressure chamber tests, in the last of which he achieved an ambient pressure of 17 mm Hg (25.6 km) for 30 min and suffered no ill effects. These were the world's first tests where a human was successfully protected in a pressure suit at low barometric pressure simulating an extremely high altitude [21]. An actual balloon ascent with this suit was never accomplished.

Interest in aircraft speed records in the early 1930s brought about further efforts in pressure suit development. By the midthirties, a number of countries were developing prototype high-altitude pressure suits: the United States and the Soviet Union in 1934, Germany and Spain in 1935, and Italy in 1936 [20].

The first aircraft flight in a pressure suit was made by the American, Wiley Post, in his aircraft *Winnie Mae* at Akron, Ohio, in August 1934. The suit worn by Post had been tested previously in low-pressure chamber runs up to a simulated altitude of 7015 m which was tolerated for 35 min. The suit incorporated a large neck opening in lieu of a waist entrance and was constructed of two layers: an inner rubber bag to contain gas under pressure, and an outer cloth fabric to maintain the desired suit shape. Post made at least 10 flights wearing this pressure suit prior to his untimely death, in August 1935, in an aircraft crash unrelated to the pressure suit testing project. The efforts of Wiley Post clearly demonstrated the feasibility of pressure suits in high-altitude aircraft and of using liquid oxygen to provide pressurization and breathing gas [20].

In 1936, Vladislav A. Spasskiy of the Soviet Institute of Aviation Medicine began a program to determine medical criteria for design engineers making stratosphere equipment. In parallel, several models of suits were developed and underwent laboratory and flight tests under the guidance of Soviet engineers E. E. Chertovsky and A. I. Boiko [10, 17].

Little additional work on pressure suits was accomplished in the United States until World War II. At this time, the US Army Air Corps and the US Navy embarked on developmental programs [9] featuring a Plexiglas bubble-type helmet and detachable arm and leg sections fitted to a basic torso pressure garment.

In the 1950s, military aviation directed attention increasingly toward high-altitude performance capabilities of aircraft. Simulated high-altitude pressure chamber flights in pressure suits gave aviators confidence to break existing world altitude records. A 72-h simulated flight to 42 395 m altitude, in 1958, in a US Navy (Goodrich) lightweight full-pressure suit was the forerunner of the 1959 recordbreaking flight of Comdr (USN) L. E. Flint to 30 060 m in a US Navy F-4 *Phantom* jet [19]. The US Air Force also developed a very successful partial-pressure suit using a capstan principle which provided a porous, cool garment, eliminating the need for cooling equipment required in the full-pressure suit. It was used extensively by the military during this period.

The Navy full-pressure suit, with some modifications, ultimately provided the first US space suit—the Mercury space suit. This suit was developed largely under the auspices of the Navy Aircrew Equipment Laboratory (ACEL) at Philadelphia, Pa., with several civilian contractors.

Members of ACEL, in 1949, developed a combined compensated breathing regulator [7] which was an important advancement in pressure suit science. This regulator made possible the use of a respiration system completely separate from the pressurizing gas, and the use of a simplified breathing mask which required no check valves. The suit featured zipper closure, permitting a variety of possible suit openings and enhanced the ease of donning and doffing. The leakage problem was largely solved by a method of suit construction which used vulcanization. Mobility was enhanced by incorporating airtight rotating bearings and fluted joints. An automatic suit pressurization device, developed by the Firewel Co., made possible for the first time effective experimentation with subjects in pressure suits at very high altitudes in low-pressure chambers. The automatic pressurization feature permitted assessment of protection afforded by a suit system under extreme altitude conditions and subsequent explosive decompression.

Figure 1 shows the results of explosive decompression studies of humans conducted at ACEL in which subjects wearing the full-pressure suit were decompressed from 5490 to 22 875 m in as short a time as 110 ms [7]. Note that suit pressure was maintained and lowered gradually to a safe, life-sustaining pressure. Figure 2 presents a schematic of the control system for

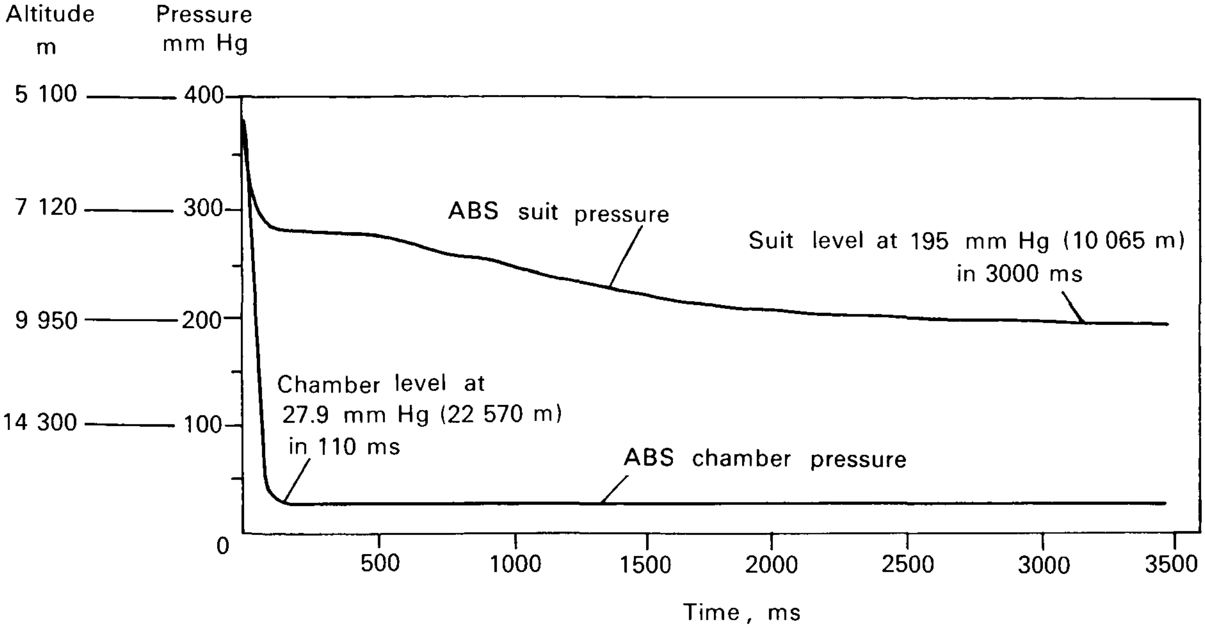

FIGURE 1.—Performance of pressure suit system during explosive decompression (5490 m to 22 875 m in 110 ms) [7].

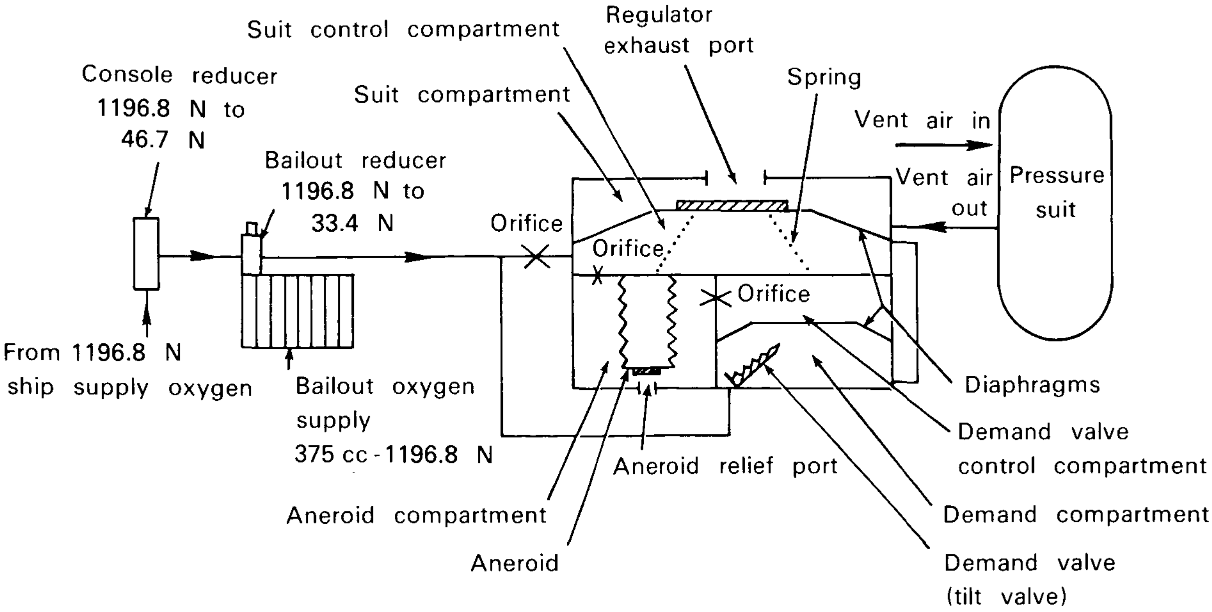

FIGURE 2.—Schematic of pressure suit control system [7].

one of the first successful versions of the Navy pressure suit.

The Navy pressure suit was given a strenuous operational test in May 1961 when a world record balloon altitude of 34 668 m was reached in a two-place open gondola *Stratolab* by Comdr Malcolm D. Ross, and Lt Comdr (MC) Victor A. Prather. This balloon, launched from the *USS Antietam*, was the largest one ever employed for a manned flight. The operational Navy pressure suit, basically the same as that worn by Comdr Shepard on the first US manned space launch, can be seen in Figure 3. The balloon reached maximum altitude 2 h 36 min after takeoff. During the high-altitude portion of the 9-hour flight, thermal control in the gondola was achieved to some extent by a unique arrangement of venetian blinds on the side, which could be manually opened to allow the desired amount of direct solar radiation. The pressure suits became operational at 7930 m altitude and provided needed protection for the balloonists throughout the flight, which included a 2-h stay at the crest [14]. The flight clearly demonstrated reliability of long-term use of pressure suits as sole protection for life at high altitudes.

Pressure suits worn during US space missions originated in military pressure suit development programs. In 1959, the Navy MK IV Full Pressure Suit was adapted for use by Project Mercury astronauts. Gemini suits were an adaptation of an Air Force suit developed for the X-15 research aircraft. The Apollo suits were developed especially for NASA purposes.

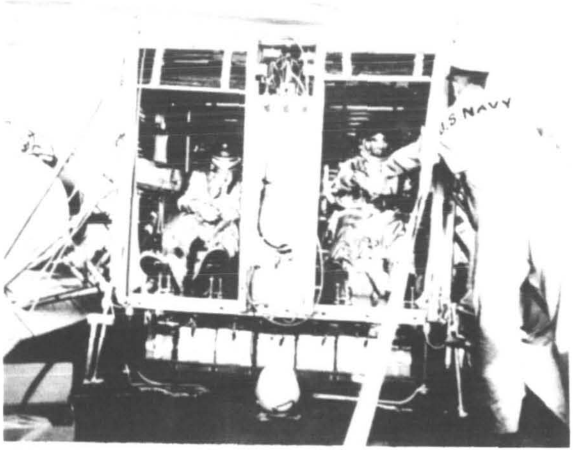

FIGURE 3.—High-altitude balloon flight of Comdr. Ross and Lt. Comdr. Prather. Balloonists in open gondola prior to launch protected only by their pressure suits.

By 1961, pressure suit technology had advanced to the point of permitting man's safe journey into space. That year Cosmonaut Yuri Gagarin (Fig. 4) and Astronaut Alan Shepard (Fig. 5) made the first USSR and US flights. In 1965, Soviet Cosmonaut Alexei Leonov became the first human to venture into the cosmic void wearing a specially designed pressure suit (Fig. 6). He accomplished a 10-min extravehicular activity during the Voskhod II mission in March 1965.

Edward White was the first US astronaut to perform extravehicular activity (EVA) wearing a space suit during the Gemini IV mission in June of the same year. White's EVA, pictured in Figure 7, lasted 21 minutes. With the aid of a hand-held maneuvering device (to be discussed in a later section, EXTRAVEHICULAR ACTIVITIES AND SYSTEMS—*Hand-held self-maneuvering unit*), astronaut White was able to execute short translations and small angular maneuvers. He did not become disoriented at any time, nor lose control of his movements; the mobility of his space suit was adequate for EVA tasks. The results of early extravehicular operations indicated the need for greater cooling capacity in EVA space suits and, more importantly, showed that EVA activity could be conducted routinely and safely.

DESIGN REQUIREMENTS AND FEATURES OF CURRENT SPACE SUITS AND PORTABLE LIFE-SUPPORT SYSTEMS

General Requirements for Extravehicular Space Suits

Space suits may be considered as falling into two classes based upon fundamental requirements for their utilization.

1. *Free space EVA space suits* allow astronauts to operate in space and perform various types of work on the outer surface of the spacecraft or space station, as well as at some distance from them.
2. *Surface EVA space suits*, for use on

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other celestial bodies, include those worn by crews walking and working on the lunar surface.

In planning for a technology base to provide space suit systems for 5, 10, and 15 years in the future, Smith [16] listed four major factors in the design of space suit systems: (1) mission-determined, (2) systems-determined, (3) use-determined, and (4) man-machine.

Mission-determined factors in Figure 8 list a number of the types of missions proposed for future US programs, the principal functional phases in most of these missions, and performance requirements which must be satisfied by the space suit developed in support of these missions. In general, these requirements relate to the astronaut's capability to perform specific tasks required during these missions.

System-determined factors, shown in Figure 9, include system type, specific space suit subsystem, design concepts subsystem, and design constraints. The "soft" space suit in the design concepts subsystem is a suit system fabricated almost entirely of flexible materials; the "composite" space suit is constructed of approximately equal proportions of flexible and nonflexible materials; and the "hard" space suit system utilizes nonflexible materials throughout the major part of its design. (It should be noted that some designers use the term "hybrid" rather than "composite.") The design constraints (system-determined factors), i.e., power, weight, volume, and others, are of principal concern to the design engineer who must integrate requirements of life-support systems with those of other elements of the spacecraft.

Use-determined factors, shown in Figure 10, relate principally to the physical conditions under which space suits will be employed: logistics, maintenance, general deployment, and the physical stressors under each condition of deployment. Psychologic stressors likely to be in operation during conditions of deployment are also considered. These factors, of concern to the space suit designer, may bring about an increased use rate for system stores.

Finally, the man-machine factors, shown in Figure 11, relate principally to the allocation and definition of man-machine tasks and a survey of potential limitation or capabilities of the man-space suit system as they affect task performance.

The requirements described above relate primarily to the functional characteristics of the suit. There are, however, five other important requirements to consider which can greatly influence the final design of a suit. Foremost is the need for *mobility* to perform useful work. This important aspect of suit design will be discussed in greater detail in a later section. Appropriate *sizing* is associated with this requirement. *Fire protection* is a third requirement. Under some circumstances, a pressure suit may be ventilated by an oxygen-enriched gas. It may also be used inside a spacecraft where the atmosphere may have a high partial pressure of oxygen. Numerous nonmetallic, flame-resistant fabrics have been developed in conjunction with the manned spaceflight program. Table 1 presents a comparison of combustion rates of these fabrics as well as their physical and outgassing properties. Ease of *donning and doffing* the suit is another requirement. Finally, *strength and durability* are very important qualities in selecting space suit materials. The material must not only be fully capable of withstanding all pressure differentials, but also must not tear or suffer serious wear as astronauts walk, kneel, occasionally fall, and otherwise do useful work, and conduct experiments inside the space vehicle and on an external surface, for example, that of the Moon.

General Requirements for Backpacks

The lifeline of a space suit is provided by a portable life-support system (PLSS) which the astronaut may carry on his back. The package supplies breathing oxygen; controls suit pressure; reprocesses the recirculated gas by removing carbon dioxide, odors, some trace contaminant gases, and excess moisture; controls system temperature by rejecting excess heat; and provides for warnings of certain malfunctions, voice communication, and telemetry of essential data. The heat rejection system must accommodate (in addition to metabolic load and heat generated by functioning PLSS components) the heat gained from or lost to the lunar or planetary environment through the system insulation [2].

Physiological and Performance Parameters

The physiological and performance characteristics of current and future portable life-support systems are summarized in Table 2. As early as 1940, Spasskiy had made design recommendations for regenerative equipment for spacecraft cabins, many of which were remarkably close to those provided by present systems, typified in Table 2.

Breathing Gases, Ventilation Gases, and Thermal Control

The basic parameters of the atmosphere in a suit (barometric pressure, gas composition, temperature, humidity, and ventilation) must be selected on the basis of physiologic requirements of the human body at the desired level of its physical activity, and the technical possibility of meeting these requirements.

Physiologically, it is most important for an astronaut that the amount of pressure within the space suit be analogous to pressure in the cabin of a spacecraft or station. However, the creation of a space suit with such an atmosphere, especially if it is close to that of Earth atmosphere, is technically difficult, basically because of man's severely limited mobility in a suit with a large differential pressure across the garment.

To provide better mobility in a space suit, to lighten it, to reduce leakage, and for other technical considerations, it is desirable to maintain minimal physiologic pressure within the suit in relation to the surrounding medium.

Until recently, these factors forced designers and physiologists to find a compromise solution for specific conditions and tasks of the planned flight. Features recently developed providing increased mobility and almost no compromise solutions are described later in this chapter.

FIGURE 4.—Cosmonaut Yuri Gagarin—first Soviet flight into space in 1961.

Depending on actual flight conditions and the possibility of desaturating the body of nitrogen, the pressure regime in the suit designed for prolonged wear is usually selected in the range of 200 to 300 mm Hg [8]. In extreme cases, in which pressure in the suit may be reduced to the lower amount (but not lower), a level of oxygen supply is still maintained to enable an astronaut to perform his work.

During any of the selected pressure regimes, a gas mixture enriched with oxygen is required to assure necessary partial pressure of oxygen in the alveolar air. To determine optimum percentile oxygen content in the gas mixture, a somewhat modified formula may be used to control the proper percentile oxygen content in the mixture supplied by an oxygen device [8]:

$$C_{O_2}=\frac{150\cdot 100}{P_{sp}-47}$$

where P_{sp} = absolute pressure in the suit in mm Hg, and C_{O_2} is the concentration of oxygen in percent.

Using this formula, with pressure in the suit of 300 mm Hg, the inhaled gas mixture must contain not less than 60% oxygen; at a pressure of 200 mm Hg, it is necessary to use practically pure oxygen. Current Apollo/Skylab practice is a single gas atmosphere at a nominal pressure of 194 mm Hg pure oxygen.

Carbon dioxide exhaled by a man is removed from the atmosphere of the suit by forced ventilation. The volume to be ventilated depends upon the quantity of carbon dioxide given off by the astronaut, its permissible content in the atmosphere of the suit, and its concentration in the gas mixture supplied from outside or from a regenerating cartridge (breakthrough concentration). This may be approximately determined by Pettenkofer's classic formula which was first used for calculating ventilation of space suits by

FIGURE 5.—Astronaut Alan Shepard—first US flight into space in 1961.

V. A. Spasskiy [17]. For convenience, the formula was somewhat modified [9].

$$V=\frac{q\cdot 760\cdot \mathrm{l/min}}{P_{\mathrm{per}}-P_{\mathrm{par}}}$$

where

V = rate of ventilation (l/min)

q = quantity of carbon dioxide given off by the subject (l/min)

P_{per} = permissible partial pressure of carbon dioxide in the atmosphere of the suit (mm Hg)

P_{par} = partial CO_2 pressure in the gas mixture from the regeneration cartridge (mm Hg)

In calculating volume of ventilation, approximation of the average expected liberation of carbon dioxide and its permissible partial pressure (7 to 8 mm Hg) is recommended by Gozulov and Golovkin [8], and Ivanov and Khromushkin [10]. This content of carbon dioxide in the inhaled gas mixture does not produce significant response reactions in the functional state of the human body, even during exposure for several days.

The method of calculating ventilation is based on the average level of carbon dioxide liberated, and it is assumed that carbon dioxide concentration may exceed the recommended value by a factor of 2 during periods of increased physical activity. In this case, carbon dioxide concentration will be close to the value established by Spasskiy [17] as the limiting value (15 mm Hg).

The Apollo backpack performance specification for P_{CO_2} is as follows: (1) the first 2.5 h at P_{CO_2} levels no greater than 7.6 mm Hg; (2) the next 0.5 h at 10 mm Hg; and (3) the remaining time at 15 mm Hg. The actual P_{CO_2} levels on the Apollo lunar EVAs have been less than a P_{CO_2} of 2 mm Hg throughout the total mission. The 414 mm Hg extravehicular suit development calls for P_{CO_2} levels that do not exceed 7.6 mm Hg (oronasal area), with a vent flow of 3304 cm^3/s (actual) at a stabilized metabolic rate of $1.26552\cdot 10^6$ J/h (1200 Btu/h), an important design consideration for the delivery system of breathing gas for the helmet. The increased partial pressure of carbon dioxide in the space suit in a relatively short time does not lead to negative results, although it produces a certain load on the physiological systems of the body during this period.

Temperature and humidity are the parameters

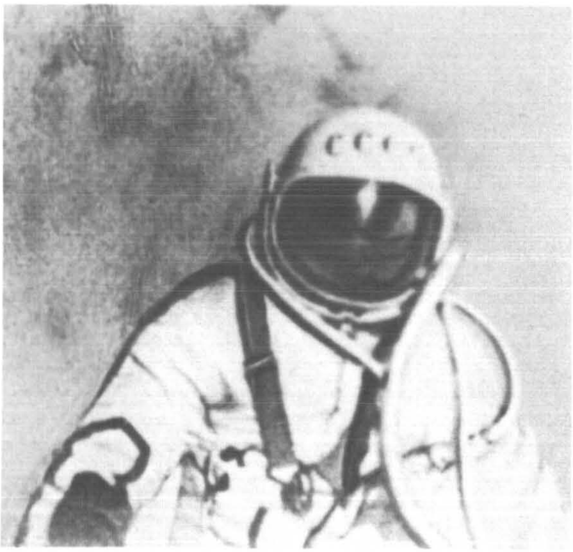

FIGURE 6.—First extravehicular activity in a space-type pressure suit, performed by Soviet cosmonaut Alexei Leonov, March 1965.

FIGURE 7.—Astronaut Edward White engaged in extravehicular activity in the G-IV-C space suit system, June 1965. (NASA photo)

of the gaseous medium within the space suit which are least amenable to standardization. This may be explained by the specific conditions of heat control systems in space suits. It may also be explained by the great adaptability of the human body to changing conditions of heat exchange and considerable fluctuations in the heat and moisture liberated by the astronaut when performing different operations in a space suit. When performing heavy physical work, the heat production of a human being exceeds his heat liberation at rest by a factor of 5 to 6 (450 to 500, and 80 to 90 kcal/h, respectively). The difference in the amount of moisture given off by a human being is even greater (from 600 to 800, and 40 to 50 g/h, respectively) [13].

Fluctuations in the amount of heat and moisture given off by an astronaut require that the space suit system for heat control and dehumidification have a wide range of controls in order to provide normal heat exchange for the body under different heat production conditions.

When significant individual human differences are taken into account in terms of thermal comfort, as well as the complexity of designing automatic control devices which can follow change in the level of heat production and moisture given off by a human being, the removal of heat and moisture in space suits should be controlled manually. This makes it possible for the astronaut to produce conditions in his space suit corresponding to his individual requirements and the degree of his physical activity.

A traditional method of heat control and dehumidification used in the majority of space suits worn in airplanes and spacecraft is ventilation by air which is dried (moisture content no greater than 5 to 8 g/m^3) and cooled or heated to the desired temperature (from + 10° to + 80° C) [1a, 8]. An estimate of the possibilities of this method for heat control indicates that, for space suit ventilation volumes which are realistically possible (up to 300 l/min), the use of ventilation air makes it possible to remove up to 200 kcal/h heat from the space suit, and up to 200 to 270 g/h water vapor.

The anticipated higher level of energy expenditure by astronauts when performing operations in a closed space, and the significant re-

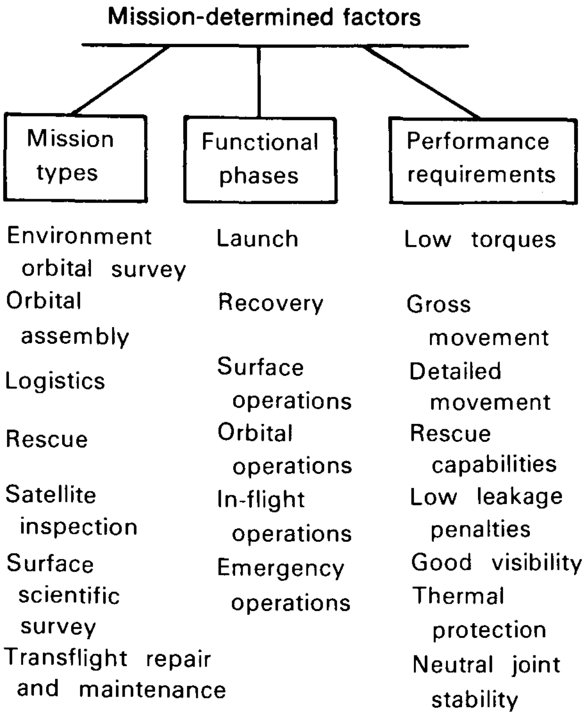

FIGURE 8.—Mission-determined factors considered in the design of space suit systems.

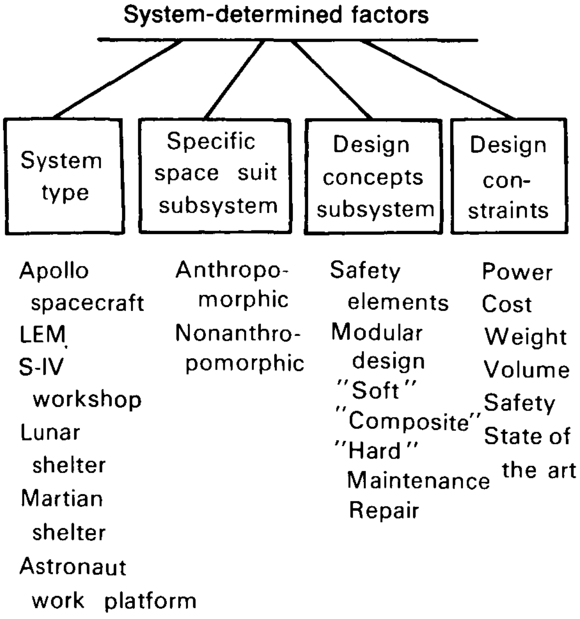

FIGURE 9.—System-determined factors considered in the design of space suit systems.

duction in heat exchange between the space suit and the surrounding medium, require that space suits use ventilation as well as new, more effective methods of heat control. These methods must be capable of removing all heat and moisture produced by the astronaut from the space suit, as well as heat and moisture resulting from the operation of individual systems and units of the space suit.

For these purposes, the use of contact or radiation methods for cooling the astronaut may produce a certain irregularity of temperature and humidity within the space suit, which is difficult to calculate and standardize. Values given in previous studies [1a, 8] for space suit ventilation (50 l/min), temperature (+10° to +15° C), and humidity (20% to 85%), do not take into account fluctuations in the amount of heat and moisture given off by astronauts and therefore can hardly be used for standardizing conditions in the space suit.

The US engineering design and operational practice for astronaut cooling utilizes two cooling modes for extended extravehicular operations. Ventilation of 2832 cm^3/s (actual) in extravehicular operations provides some supplementary evaporative cooling. The main cooling function is achieved by utilization of the liquid cooling garment (LCG) through the process of conduction. The layup of the LCG consists of polyvinyl chloride tubing between layers of nylon chiffon designed to make the garment comfortable. An elastic spandex layer maintains the tubing in a fit closely conforming to the body for adequate conductive cooling. This cooling strategy allows a thermal load, such as 300 kcal/h metabolic rate with a 75 kcal/h heat leak rate, for a duration of 5 hours.

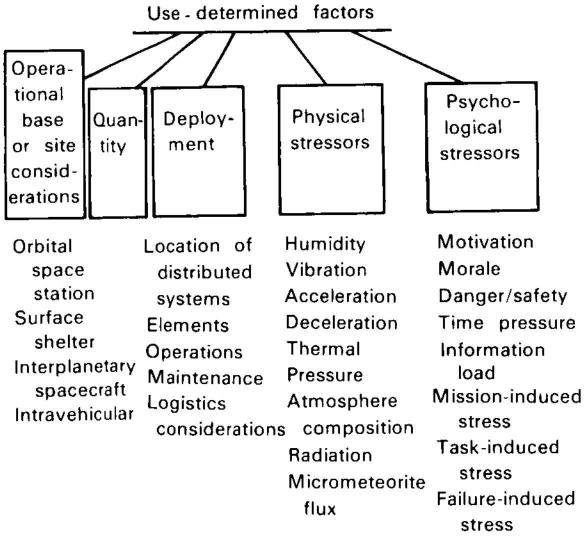

FIGURE 10.—Use-determined factors considered in the design of space suit systems.

Several methods for removing heat from extravehicular space suits described by the Soviets are:

1. Cooling the gas mixture circulating in the space suit in radiation, evaporative, or sublimation heat exchanges, or heat exchanges where liquid oxygen is the cold source.
2. Removal of heat by evaporation of water in special panels located within the space suit or sleeves.
3. Removal of heat by a refrigerant circulating along tubes of a special cooling system, carried on the belt, with subsequent cooling of the circulating liquid in heat exchangers. This type of water cooling system can remove up to 400–500 kcal/h heat from the space suit. The water temperature at the space suit input must be 10° to 12° C; the water consumption is 1.5 to 2 l/min.

These heat removal methods may be combined and may supplement one another. In Soviet space suit design, the heat control problem of

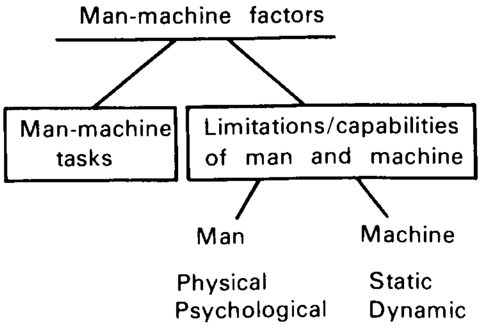

FIGURE 11.—Man-machine factors considered in the design of space suit systems.

extravehicular suits is minimized, either by choice of an outer space suit covering of materials with carefully chosen coefficients to reduce to a minimum the radiant heat exchange between the space suit and the surrounding space, or by the use of screening-vacuum thermal insulation. Aluminized film is also used for this purpose.

Measurement of Metabolic Costs

The assurance of maximum function in using a space suit requires a thorough investigation of the biomechanics of the man-suit system under all work conditions. Roth [15] presents a number of biomechanical analyses of human work performance and energy expenditure in various working environments. These data, regarding expenditure of energy during various activities, serve as a useful starting point in designing a space suit compatible with the general metabolic cost of work. However, direct extrapolations cannot be made since the characteristics of the lunar environment differ significantly from those on Earth.

A major planning and design problem prior to the lunar surface missions was to predict the metabolic rate of the crewman [4]. Metabolic rate is the major parameter affecting duration of supplies carried in the backpack, and the crewman's comfort. As a man works harder, he generates more metabolic heat, consumes more oxygen, and generates more carbon dioxide and water vapor. These differential rates have great impact on design and utility of the portable backpack. While metabolic rates can be predicted for given tasks in Earth gravity, it was not known whether metabolic rates in lunar gravity would be lower or higher than those on Earth. The reduced weight of the man, suit, backpack support system, and so forth on the Moon would suggest that metabolic rates would be lower. However, reduced weight could mean reduced traction for walking, which, combined with loose lunar soil and a potential crewman/equipment imbalance, could lead to a net increase in metabolic rate [4].

Considerable work has been concentrated on determining actual crewman metabolic rates during lunar missions. This information is valuable for mission planners in predicting metabolic rates and in developing life-support system components for future missions. Table 3 lists average metabolic rates for Apollo 11 through 17 astronauts engaged in lunar surface activity. These metabolic rates have been determined from telemetric data by three methods: thermal balance, oxygen consumption, and heart rate. Thermal balance was determined by comparing inlet and outlet temperatures in the water-cooled undergarment during lunar surface activity; oxygen usage from the portable life-support system was measured; and heart rate during lunar activity was compared to that on an energy cost calibration curve which was obtained preflight by bicycle ergometry. Berry [3] reports that for the Apollo 11 mission, thermal balance and oxygen-use methods yielded similar data and accurately reflected the physical activity observed by telemetry. Heart rate data proved the least reliable method for determining metabolic rates. The oxygen usage and thermal balance methods gave energy cost levels 61% below those estimated by the heart rate method in the Lunar Module Pilot. The thermal balance and oxygen consumption methods described in detail by Carson [4] are summarized below.

Thermal Balance Method

The thermal balance method (Fig. 12) involves calculation of the total heat removed by the liquid-transport loop and the latent heat removed by the oxygen-ventilation loop. This total is equated to the sum of metabolic heat, heat leakage into the suit, and heat stored by the crewman. The sensible heat removed by the ventilation loop is considered negligible and is disregarded.

The basic equations are:

$$\dot{Q}_{\mathrm{TL}} + \dot{Q}_{\mathrm{VENT}} = \dot{Q}_{\mathrm{MET}} + \dot{Q}_{\mathrm{HL}} - \dot{Q}_{\mathrm{ST}} \tag{1}$$

$$\dot{Q}_{\mathrm{TL}} = \dot{m}_{\mathrm{TL}} C \Delta T \tag{2}$$

$$\dot{Q}_{\mathrm{VENT}} = \dot{m}_{\mathrm{O_2}} \Delta h \tag{3}$$

where

$\dot{Q}$ = heat transfer, storage, or generation, cal/h

$\dot{m}$ = mass flow rate, kg/h (determined in preflight tests)
C = specific heat, cal/kg — °C
ΔT = delta temperature across LCG, °C (determined from telemetry)
Δh = delta enthalpy, cal/kg

subscripts are defined:

TL = transport loop
VENT = ventilation loop
MET = metabolic
HL = heat leak
O_2 = dry oxygen
ST = stored

Latent heat removal by ventilation flow is calculated by multiplying the enthalpy change of the ventilating gas by the actual flow rate of dry oxygen. Enthalpy can be determined from psychrometric charts for oxygen at suit pressure if inlet and outlet dew points are known. The portable life-support system (PLSS) outlet dew point is equal to sublimator-outlet gas temperature. The PLSS inlet dew points are assumed, based on preflight manned-test data. Ventilation-loop flow rate is then determined by using fan-pressure rise compared with flow curves and suit pressure drop compared with flow curves. Dry oxygen flow rate is obtained by subtracting water-vapor flow rate from ventilation flow rate.

With this method, metabolic rates ranging from 229 to 265 kcal/h were indicated for the Apollo 12 commander during EVA–1. The method necessitates assumption of PLSS inlet dew point and has several other error sources, among which are uncertainties in determination of the transport and ventilation flows, change in temperature across the liquid-cooling garment, and heat leak.

Oxygen-Consumption Method

Oxygen consumption is a function of metabolic rate only. Hence, this method is the most direct measure of metabolic rate and suit leakage available from PLSS telemetry data. For the relationship between oxygen consumption and metabolic rate, the basic equation is:

$$Q_{\mathrm{MET}} = \frac{m_{O_2}}{0.0003074 \cdot \left[\left(\frac{RQ - 0.707}{0.293} \right) \cdot 0.0000221 \right]} \quad (4)$$

where

Q_{MET} = metabolic load in *kcal*
m_{O_2} = mass of oxygen consumed in *kg*
RQ = respiratory quotient (dimensionless) — volume of CO_2 produced divided by volume of O_2 consumed.

The mass of oxygen supplied by the PLSS is calculated from the pressure decay of the bottle (telemetered data) using compressibility factors to account for deviation of oxygen from the ideal gas law. The mass of oxygen consumed is found by subtracting suit leakage from the mass of oxygen supplied by the PLSS. The respiratory quotient is assumed, based on ground-test data.

With this method, a metabolic rate for the Apollo 12 Commander's first EVA was calculated at 211 kcal/h. Error sources in this method are determination of suit leakage, error in oxygen pressure reading, and assumption of respiratory quotient.

Mobility

Mobility has been a major problem with pressure suits, dating from the days of Wiley Post. A pressurized suit tends to lose flexibility and severely restricts the occupant's ability to move and to assume new positions. For this reason, designers have attempted to use minimum suit pressurization consistent with other life-support and decompression physiologic requirements.

The requirement of mobility in a pressure suit is the most difficult to solve from an engineering point of view [6]. The articulations of the skeletal system allow two kinds of movements: rotations and deflections (shaftlike and hingelike, respectively). Complex motions, such as those by a ball-and-socket joint (shoulder, hip) can be resolved into simple motions of these two kinds. The technical success of a rigid, articulated suit depends on allowing joints to move like body articulations with minimum friction and volume variation. The number, positions, and orientation of articulations required to allow the human body adequate freedom of motion must correspond quite closely to the number, position, and orientation of the anatomical articulations present in the human body. In these terms, the principal body motions necessary for adequate mobility are listed in Table 4. Thirteen different articulations can be mechanized. Nine of these are hingelike, two are rotational, and two can be mechanized in different ways since complex anatomical motions are resolved into motions about reference axes at inaccessible points inside the body (shoulder, hip).

The problem of elbow and knee joint mobility can be solved by use of "orange rind" sections in a suit with strong longitudinal cords (whose length does not change in bending) placed along a neutral line. The hinges of the shoulder and femoral suit joints are most frequently made of corrugated metal sheets which have additional rods sliding along rollers or guide rods. Hand mobility is provided by hermetically sealed joints with a small amount of rotation. A shoulder joint provides free movement of the hands in a vertical plane. The joint between the wrist and elbow permits movement of the hand along its longitudinal axis.

Space suit gloves provide mobility and comfort by being laid out in a pattern with fingers half-curved and having orange rind-type drawing joints. Helmets are of two types: three-dimensional or rotational. Three-dimensional helmets are large enough to permit free movement of the head within the helmet; rotational helmets, on the other hand, turn when the head turns. The latter types rotate in a hermetic joint at the neck opening of the space suit.

Vision and Visual Protection

Extended space flight requires that man operate in truly unique visual environments where the intensity of visible and nonvisible radiation changes, contrast levels are altered, and visual cues based on shadow effects and the scattering of light are very different. A most critical problem for space suit designers is supplying a visor system which provides the needed protection. Table 5 lists a number of principal problem areas to be considered in designing a visor for a space helmet.

The visor assembly for the lunar landing version of the Apollo space suit was designed specifically to deal with problems listed in Table 5. The outer visor of this double-visor assembly is highly reflective of infrared (IR) radiation (total transmittance 18%). This is accomplished by a vacuum deposition of a layer of gold (375 Å thickness). The problem of back-reflection of the wearer's image, a situation that could cause a measure of visual confusion, is prevented by an interference coating. Back-reflectance is limited by this device to 8% or 9%.

The inner visor shields the wearer from ultraviolet (UV) radiation. It features high visible light transmittance vital for lunar nighttime operations. The visor is IR reflective, permitting the wearer's facial heat to prevent breath-condensation fog or frost on the visor's inner surface [18]. Space suit light filter design in the Soviet Union calls for reduction of solar light intensity to 3% – 15%; the portion of solar radiation shorter than 0.35 μm, which is biologically harmful, must not be passed, and intensity of the infrared region of the spectrum must be limited to 5% – 10%.

SPACE SUIT AND PORTABLE LIFE-SUPPORT SYSTEMS

The space suit systems used in the United States program are briefly described below, along with promising systems for the future. Table 6 compares the functional and design features of US space suits.

Table 7 lists data concerning extravehicular suit systems and activity statistics.

Space suits in the Soviet program have been of two types. Vostok and Voskhod-II space suit systems have featured open cycle ventilation. Figure 13 is a diagram of the space suit system used on Vostok spacecraft. Extravehicular activity was performed in this space suit, with pure oxygen provided by tanks on the cosmonaut's back.

The second type of space suit employed in the Soviet space program is regenerative. This suit was used in Soyuz missions. A block diagram of the life-support system for these space suits is shown in Figure 14.

The basic elements of space suits are: a covering layer, detachable gloves, pressure helmet, and autonomous or on-board life-support system. The covering layer, a strength layer, features a system of cables and cords on the covering. This system provides strength, and reduces pressure, and also makes size adjustments possible. A layer of rubberized material covers the strength layer. Thermal insulation is provided by an elastic layer with low heat conductivity. In the internal surface of this layer, a ventilation system supplies the gas mixture to various sections of the space suit. The layers of the space suit are either single or combined, depending upon the particular model.

The first US extravehicular suit, known as the G—IV—C suit, is illustrated in Figure 15. The outer layer was of temperature-resistant nylon material; the next layer was a link net material especially designed to provide pressurized mobility and control ballooning of the suit. The pressure layer was a neoprene-coated nylon. The suit incorporated an inner aluminized layer for thermal and meteorite protection. The helmet featured a removable visor to protect the inner visor from impact damage and provide additional visual protection from increased levels of UV radiation encountered outside Earth's atmosphere.

Oxygen flow to the extravehicular suit was supplied through a 7.6-m umbilical hose connected

TABLE 1.—*Comparison of Fabric Combustion Rates*

Fabric	Weight g/cm [1]	Combustion rate, cm/s					Physical characteristics	
		Air	517 mm Hg 35% oxygen 65% nitrogen	320 mm Hg oxygen	853 mm Hg oxygen	853 mm Hg 60% oxygen 40% nitrogen	Elongation, %[2]	Breaking strength (warp), g/cm[2]
Nylon	1.6	NA[14]	NA	2.0	NA	NA	22	62 559
Beta 4190B	1.5	0	0	0	0	0	8.1	18 946
Beta 4484/Teflon	1.4	0	0	0	0	0	8.9	25 381
Teflon—bleached T162-42	2.0	NA	0.29	0.3	1.1	NA	67	10 546
Teflon—natural	4.0	NA	NA	0.5	1.8	NA	56	30 743
Nomex (HT 90-40)	1.5	NA	0.121	1.6	2.54	NA	40	58 090
Nomex—treated $POCl_3Br_2$	1.7	NA	NA	1.1	NA	NA	10	22 879
Polybenzimidazole—untreated	1.2	NA	NA	0.01	.02	NA	20	26 632
Polybenzimidazole—treated—$POCl_3$	1.9	0	NA	0	NA	NA	60	33 603
Polybenzimidazole—treated—$POCl_3Br_2$	1.4	NA	NA	0.36	NA	NA	20	32 888
Durette (X-400)	1.5	NA	SE[15]	0.78	2.1	NA	30	24 666
X-410	1.2	NA	SE	0.74	NA	NA	14	35 748
X-420	1.3	NA	NA	0.76	NA	NA	13.3	22 163
Nickel chromium (Karma cloth or Chromel-R)	4.3	0	0	0	0	0	NA	31 458
Fypro 5007/7	1.4	0	0.29	1.8	NA	2.0	24	27 526
Kynol fiber	NA	NA	0.27 (SE)	1.8 (SE)	NA	12.7 (SE)	20	304[16]

[1] Physical test method according to Federal Standard (FED STD) 191, method 5041.
[2] Physical test method according to FED STD 191, method 5104.
[3] Physical test method according to FED STD 191, method 5132.
[4] Physical test method according to FED STD 191, method 5302.
[5] Physical test method according to American Society for Testing Materials specification ASTM-D 2176.
[6] Physical test method according to FED STD 191, method 5202.
[7] Physical test method according to FED STD 191, method 5306 (C517 wheel).
[8] Physical test method according to FED STD 191, method 5304 (600-grit paper).

to the spacecraft oxygen system through a small chest-mounted pack to the space suit inlet fitting at the other end. The small chestpack controlled suit pressurization and ventilation flow. Figure 16 includes a flow diagram of the extravehicular life-support system.

Urine and feces collection in the Gemini suit was by means of collection bags, similar to the Mercury suit that preceded it. The urine collector, a latex, roll-on cuff receptacle was attached to a rubberized fabric bag. The defecation system was a plastic bag with adhesive-lined circular top.

During all US manned space flights, biomedical monitoring in real time has been accomplished through telemetry of data obtained through a biosensor harness device. This made it possible to obtain electrocardiographic data, respiration rate measurements, and additional physiological information, including suit or body temperature and carbon dioxide levels. Figure 17 shows the bioinstrumentation harness.

An extravehicular suit, together with a liquid-cooled undergarment, portable life-support system (backpack), emergency oxygen system, lunar extravehicular visor assembly, and other

and Other Properties of Space Suit Fabrics [12]

Physical characteristics—Continued										Outgassing		
Tear strength, g[3]	Wear resistance, no. cycles [4]	Folding endurance, no. cycles [5]	Stiffness, cm/g[6]	Abrasion, no. cycles [7]	Abrasion, no. cycles [8]	Air permeability, cc/cm²/s [9]	Electrostatic charge, nC [10]	Thermal conductivity cal/s/cm² (°C/cm) [11]	Sample thickness, in.[12]	Odor [13]	CO μg/g	Total organics, μg/g
>6400	174	>5000	1×10^{-5}	2468	870	4.06	8.0	1.49×10^{-4}	0.0145	12	1.2	0.0003
2400	148	>5000	1×10^{-5}	198	85	0.25	2.0	1.69×10^{-4}	0.008	NA	NA	NA
>6400	151	>5000	1×10^{-3}	125	1200	11.5	18.0	1.2×10^{-4}	0.008 to 0.009	NA	NA	NA
5100	93	>5000	1×10^{-6}	584	600	2.4	20.0	2.1×10^{-4}	0.009	0.9	0.7	34.0
5400	343	>5000	1×10^{-5}	1075	1952	5.7	32.0	1.8×10^{-4}	0.018	1.7	4.2	9.0
>6400	689	>5000	5.6×10^{-4}	943	260	2.5	8.0	1.58×10^{-4}	0.013	7	0.4	1.0
3000	353	>5000	2×10^{-5}	450	227	5.5	0.06	1.6×10^{-4}	0.014	NA	NA	NA
4600	206	>5000	2×10^{-5}	629	143	50.1	40.0	3.0×10^{-5}	0.0135	5	2.4	3.0
>6400	234	>5000	1×10^{-5}	2481	1651	13.7	2.6	3.2×10^{-5}	0.017	NA	NA	NA
5700	721	>5000	1×10^{-5}	1200	1500	19.7	2.4	4.8×10^{-5}	0.014	NA	NA	NA
5900	126	>5000	1.7×10^{-6}	467	116	45.3	2.0	1.3×10^{-4}	0.012	NA	3.7	0
3000	96	>5000	5.6×10^{-4}	145	65	14.7	18.0	1.8×10^{-4}	0.0118	11	2.8	1.0
4100	93	>5000	1×10^{-5}	100	350	22.1	0.01	2.0×10^{-4}	0.013	NA	NA	NA
5400	869	>5000	4×10^{-5}	2304	977	34.9	0	NA	0.010	NA	NA	NA
3800	836	>5000	1×10^{-5}	217	41	24.9	12	2.0×10^{-4}	0.015	0.7	4.0	1.0
NA	NA	>5000	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA

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[9] Physical test method according to FED STD 191, method 5450.

[10] Physical test method according to Sweeney test method.

[11] Physical test method according to Cenco-Fitch test method.

[12] Physical test method according to FED STD 191, method 5030.

[13] Physical test method according to MSC specification MSC–PA–D–67–13; 2.5 or lower is acceptable.

[14] Not available.

[15] Self-extinguished.

[16] Breaking tenacity, g/denier.

components make up the Apollo Extravehicular Mobility Unit (EMU), used during lunar exploration. Figure 18 provides a cutaway view of the Apollo lunar surface activity assembly. The photograph indicates that the extravehicular suit comprises the basic Apollo space suit over which is worn an integrated thermal/meteoroid garment.

The basic space suit contains a nylon comfort liner, neoprene-coated nylon pressure bladder, and nylon restraint layer. The outer layers (from the inside out) are made of Nomex material and two layers of Teflon-coated Beta cloth. The oxygen connection, communications and biomedical data lines are attached to fittings on the torso. Under this entire assembly, a liquid-cooling undergarment is worn, which is of knitted nylon-spandex with a network of plastic tubing through which cooling water is circulated.

Life support requirements during extravehicular activity are provided in the Apollo assembly by a backpack, known as the portable life-support system (PLSS), which supplies oxygen to the helmet, and cooling water to the liquid-cooling undergarment (Fig. 19). It also contains communications and telemetric equipment and power supply, and removes CO_2 from vent flow. An oxygen purge system mounted at the top of the unit provides a contingency 40-min minimum supply of gaseous oxygen (Fig. 18).

Operating Principle of the PLSS

The portable life-support system operates by water circulated through the liquid-cooling garment which picks up metabolic heat and provides cooling through conduction. Warm water from the cooling garment enters the sublimator and is cooled by conduction of heat to the sublimating mechanism. The oxygen ventilating system supplies oxygen, removes carbon dioxide and other body gases, and controls humidity. Contaminants are removed from the oxygen as it enters the backpack by an activated charcoal cartridge. Carbon dioxide is eliminated by reaction with lithium hydroxide. Excess water is

TABLE 2.—*Portable Life-Support Systems (PLSS) Comparison*

PLSS	System type	Weight (kg)	Volume (m^3)	Oxygen supply	Metabolic capacity	Cooling method
PECS [1] prototype	Closed loop	46	0.057	Sodium chlorate candles	2000 kcal total 500 kcal/h for 4 h 875 kcal/h for 3.2 h	Gaseous flow (GF) Liquid-cooling garment (LCG)
PECS prequalification prototype	Closed loop	64	0.075	Gaseous oxygen	2400 kcal total 400 kcal/h for 6 h	GF LCG
Apollo PLSS with oxygen purge system	Closed loop with OPS open loop for emergency operations	66	0.104	Gaseous oxygen	300 kcal/h for 6 h short term 500 kcal/h	GF LCG
Skylabs ALSA PCU [2] (Umbilical 18.2 m long)	Open loop O_2 Closed loop H_2O power and tether	14	0.002	Gaseous oxygen	175–400 kcal/h for 4 h Failure of cooling LCG – 250 kcal/h for 1 h	GF LCG
ALSA SOP [3]	Open loop	22	0.016	Gaseous oxygen	175 kcal/h for 0.5 h	GF

[1] Portable environmental control system.

[2] Astronaut life-support assembly, pressure control unit.

[3] Secondary oxygen pack. (Adapted from Reference [11])

removed from the gas stream by a wicking water separator. The heat exchanger (sublimator) cools the gas stream. The oxygen purge system is an independent, open-loop unit which can either provide makeup oxygen if the primary supply does not function properly or open-loop flow in the event of complete failure of the PLSS ventilation system.

Waste management in the extravehicular suit assembly is accomplished by means of a fecal containment subsystem and a urine collection and transfer assembly (Fig. 20). The fecal containment subsystem consists of a pair of elasticized undershorts with an opening in front for the genitals and an absorbent liner material added in the buttocks area, which permits emergency defecation when the astronaut is in the suited, pressurized condition. The containment subsystem collects feces and prevents fecal matter from escaping into the pressure garment. Fecal moisture is absorbed by the liner and evaporated into the suit atmosphere where it is expelled through the ventilation system. The system's capacity is approximately 1000 cc solids. The fecal containment system (FCS) has not been utilized so far by astronauts in extravehicular activity. The urine collection and transfer assembly (UCTA) provides for collection and intermediate storage of liquid waste during launch, EVA, or emergency modes when the spacecraft waste management system cannot be used. The system can collect up to 950 cc fluids at rates up to 30 cc/s. No manual adjustment is required to operate the system. A flapper check valve prevents reverse flow from the collection bag. Stored urine can be transferred through the suit wall

TABLE 3.—*Metabolic Rates During Lunar Extravehicular Activity*

Mission	Crewman	Launch date	EVA time, min	Average metabolic rate, kcal/h
Apollo 11	Armstrong	6/69	168	194
Apollo 11	Aldrin		168	279
Apollo 12	Conrad (EVA-1)	11/69	241	231
Apollo 12	Bean (EVA-1)		241	232
Apollo 12	Conrad (EVA-2)		235	210
Apollo 12	Bean (EVA-2)		235	237
Apollo 14	Shepard (EVA-1)	1/70	288	187
Apollo 14	Mitchell (EVA-1)		288	225
Apollo 14	Shepard (EVA-2)		275	225
Apollo 14	Mitchell (EVA-2)		275	262
Apollo 15	Scott (EVA-1)	6/71	393	262
Apollo 15	Irwin (EVA-1)		393	262
Apollo 15	Scott (EVA-2)		432	237
Apollo 15	Irwin (EVA-2)		432	200
Apollo 15	Scott (EVA-3)		290	250
Apollo 15	Irwin (EVA-3)		290	212
Apollo 16	Young (EVA-1)	4/72	431	200
Apollo 16	Duke (EVA-1)		431	262
Apollo 16	Young (EVA-2)		443	187
Apollo 16	Duke (EVA-2)		443	212
Apollo 16	Young (EVA-3)		340	212
Apollo 16	Duke (EVA-3)		340	225
Apollo 17	Cernan (EVA-1)	12/72	432	269
Apollo 17	Schmitt (EVA-1)		432	275
Apollo 17	Cernan (EVA-2)		475	219
Apollo 17	Schmitt (EVA-2)		475	212
Apollo 17	Cernan (EVA-3)		436	231
Apollo 17	Schmitt (EVA-3)		436	237

by a hose to the command module or lunar module during pressurized or depressurized cabin operations. The urine collection device is worn over or under the liquid cooling garment and is connected by a hose to the urine transfer connector on the pressure garment assembly.

The lunar extravehicular visor assembly (LEVA), like the Gemini equipment, features two visors which are pivot-mounted on a polycarbonate shell which clamps to the helmet. The visor assembly is attached over the pressure helmet to provide impact, micrometeoroid, thermal, and ultraviolet-infrared light protection to the EVA crewman. The inner visor, used for darkness or shadow operations, features high visible light transmittance; it is made of polycarbonate which affords ultraviolet radiation protection. The outer visor protects the astronaut from infrared reflectance of the lunar atmosphere by means of a gold coating on its inner surface. Since Apollo 12, a sunshade has been added to the outer portion of the lunar extravehicular visor assembly in the middle portion of the helmet rim. Figure 21 shows details of the Apollo extravehicular visor assembly.

Since Apollo 12, a 1080 cc drinking water bag has been added, which is attached to the inside neck rings of the EVA suits (Fig. 22). The crewman can sip water from the 15.3 × 20.3-cm bag through a 0.32-cm diam tube within reach of his mouth. The bag is filled from the lunar module potable water dispenser.

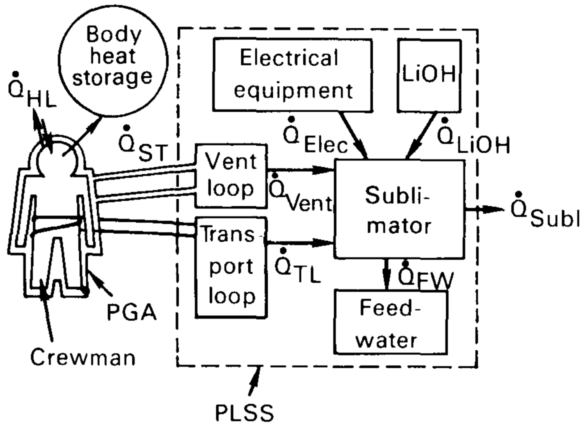


FIGURE 12.—Heat-balance diagram [4]. (PGA—Pressure Garment Assembly)

TABLE 4.—*Classification and Mechanization of Principal Body Motions*

Joint	Motion	Suit mechanization
Wrist	Flexion-extension	Hinge
Wrist	Abduction-adduction	Hinge
Wrist	Supination-pronation	Rotational
Elbow	Flexion	Hinge
Shoulder	Flexion-extension	Rotational (hinge)
Shoulder	Abduction-adduction	Hinge
Ankle	Flexion-extension	Hinge
Ankle	Abduction-adduction	Hinge
Knee	Flexion	Hinge
Hip	Rotation	Rotational
Hip	Flexion	Hinge (rotational)
Hip	Adduction-abduction	Hinge
Waist	Flexion	Hinge

Advanced Space Suit Technology

To eliminate problems and shortcomings of previous space suits and assemblies, considerable effort has been exerted, resulting in improvements in space suit mobility (Fig. 23).

The reduction in torque values and extended joint cycling lifetimes achieved in all joints of advanced extravehicular suits represent a state-of-the-art breakthrough. This was achieved through utilization of the constant-volume joint principle where no pressure-volume work is incurred. For comparison, the primary Gemini joint systems utilized the link net principle (nonconstant volume) and the Apollo primary joint system utilized molded convolutes which were volume-deformable (nonconstant volume).

The RX-1 suit features constant volume joint

TABLE 5.—*Physiological Problem Areas That Influence Visor Design*

Type of Radiation	Problem areas
Ultraviolet	Photophthalmia
Visible	Glare Visual acuity Dark adaptation Retinal burns Corneal heating
Infrared	Retinal burns Corneal heating

TABLE 6.—*US Space Suit Features*

Characteristics	Space suit			
	Mercury	Gemini	Apollo	Advanced
Weight (kg)	11.4 kg	18.2 kg	29.5 kg,[1] 31.8 kg[2]	35.4 kg
Don/ease (min)	>15	>15	>15	<5
Torque/design cycle	High/10 000	High/10 000	Moderate/10 000	Low/>100 000
Leakage (sccm/min)[3]	~1000	~1000	<180	<200
Sizing	Custom fit	Custom fit	Custom fit	Multiple sizing
Visibility	Constrained	Constrained	Nominal	Improved optics
Fire-retardant	Adequate	Adequate	Improved	Improved
EV meteoroid protection	NA	Short-term	Long-term	Long-term
Joint type	Nonconstant volume	Nonconstant volume	Nonconstant volume	Constant volume

[1] Apollo 11.

[2] Apollo 16 improved operational capability.

[3] Standard cubic centimeters per minute.

TABLE 7.—*Summary of Free Space Extravehicular Activity Statistics and Systems*

Mission	Crewman	Launch date	Life-support system	Maneuvering device	Free maneuvering umbilical EVA time[1] (h:min)	Free space standup EVA time[1,2] (h:min)	Total EVA time[1] (h:min)
Voskhod 2	Leonov	3/65			0:12		0:12
Gemini 4	White	6/65	VCM[3]	HHMU[4]	0:36		0:36
Gemini 9–A	Cernan	6/66	ELSS–AMU[6]	AMU	2:07		2:07
Gemini 10	Collins	7/66	ELSS[5]	HHMU	0:39	0:50	1:29
Gemini 11	Gordon	9/66	ELSS	HHMU	0:33	2:10	2:43
Gemini 12	Aldrin	11/66	ELSS		2:06	3:24	5:30
Soyuz 4 [7]	Yeliseyev	1/69			0:15		0:15
Soyuz 5[7]	Khrunov	1/69			0:15		0:15
Apollo 9	Schweickart	3/69	–5 PLSS		0:47		0:47
Apollo 15[8]	Worden	7/71	PEV System[9]		0:38		0:38
Apollo 16[8]	Mattingly	4/72	PEV System		1:24		1:24
Apollo 17	Evans	12/72	PEV System		1:07		1:07
Skylab (SL–2)		5/73					
SL–2 EVA–1	Weitz		Spacecraft ECS[10]			0:35	0:35
SL–2 EVA–2	Conrad		ALSA[11]	Pole translation device	3:23		3:23
SL–2 EVA–2	Kerwin		ALSA		3:23		3:23
SL–2 EVA–3	Conrad		ALSA	Vehicle handrails	1:36		1:36
SL–2 EVA–3	Weitz		ALSA		1:36		1:36

[1] Time from hatch opening to hatch closure.

[2] Includes mission equipment jettison time.

[3] Ventilation Control Module.

[4] Hand-Held Maneuvering Unit.

[5] Extravehicular Life-Support System.

[6] Astronaut Maneuvering Unit.

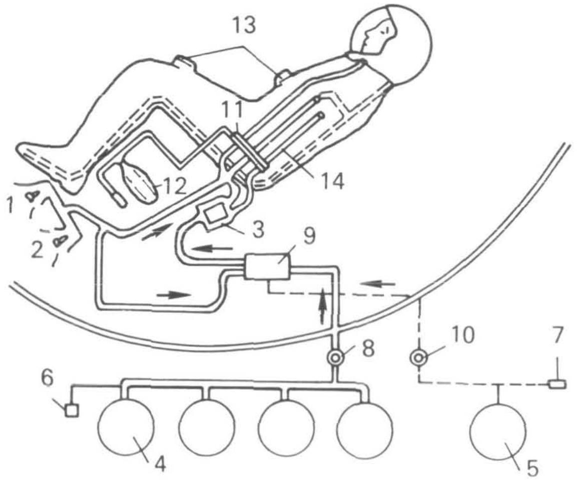
[7] Cosmonauts emerged into deep space simultaneously during spacecraft rendezvous and docking. After 1 h in space, both entered Soyuz 5.

[8] Outside Van Allen belts.

[9] Pressure control valve with umbilical; extended time capability.

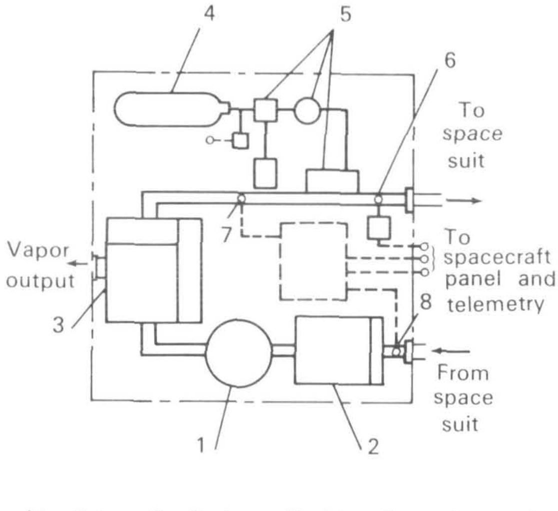
[10] Command Spacecraft Module Environmental Control System.

[11] Astronaut life-support assembly consisting of life-support umbilical, pressure-control unit, and secondary oxygen pack.



1—Main ventilator; 2—Reserve ventilator; 3—Economizer; 4—Tank; 5—Oxygen tank; 6,7—Charging tubes; 8—Speed reducer; 9—Oxygen device; 10—Oxygen reducer; 11—Connecting joint; 12—Oxygen tanks; 13—Pressure regulators; 14—Ventilation hose.

FIGURE 13.—Life-support system of a space suit on the Vostok spacecraft. [18]



1—Ventilator; 2—Carbon dioxide absorption unit; 3—Heat regulation and moisture removal unit; 4—Main oxygen tank; 5—Oxygen equipment; 6—Absolute pressure indicator in the space suit and the system; 7—Temperature indicator of the air supplied to the space suit; 8—Carbon dioxide indicator

FIGURE 14.—Diagram of main units in the autonomous life-support system [1].

technology (Fig. 24). This suit maintains a pressurized, constant volume exoskeletal enclosure while accommodating nearly the full range of body motions with minimal energy expenditure by a suited subject. The key to the constant volume concept lies in practical articulation through the rolling convolute joint [6].

The rolling convolute joint uses rigid, directionally restrained rings, which permit the joint fabric to roll easily—controlled and volume-compensating—through the maximum range of joint movement. The metal hoops in a convolute joint nest in each other. A rubberized fabric sleeve is held captive between hoops and acts as the pressure barrier. The hoops contain and shape the fabric so that folds or convolutes are formed between hoops. The axial load in this case is pure tension that can be conveniently

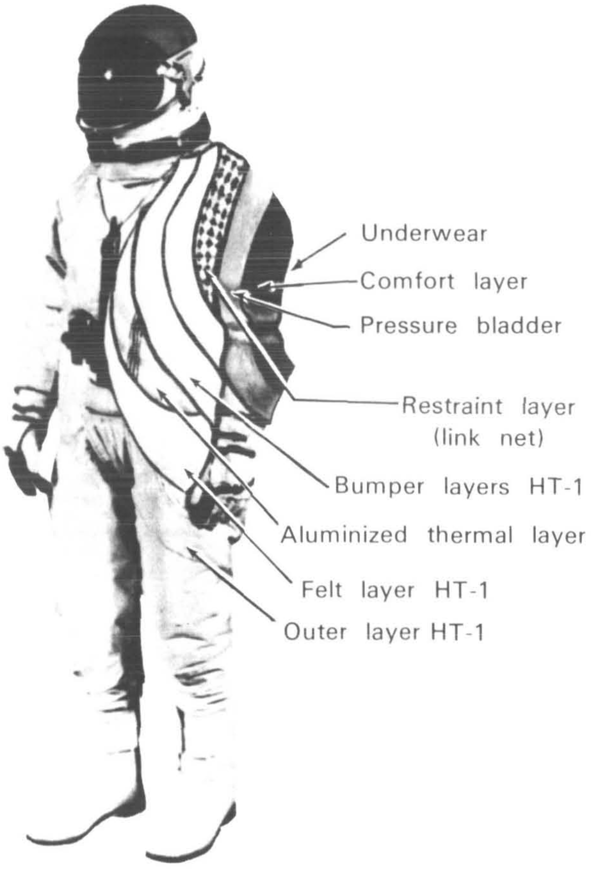


FIGURE 15.—Gemini G-IV-C extravehicular space suit. (NASA photo)

absorbed by a flexible steel cable joining all the hoops. The first and last hoops are welded to the rigid portions of the suit structure. When the articulation is flexed, the fabric convolutes roll in and out of the spaces between the hoops, and the symmetry is such that conceptually the volume generated on the side that opens is exactly balanced by an equal volume disappearing on the side that closes. The net change of volume, therefore, is zero, and no work is done on the internal pressure, so that the only torque to be supplied to bend the articulation is associated with internal friction of the fabric and the cable [6].

Another type of hard suit, the AX suit, was developed by the NASA Ames Research Center. Except for soft gloves, the suit is constructed completely of hard materials and allows for exceptional mobility with low torques and leakage. A key feature of this suit development program, which permits excellent mobility, is the "pseudo-conic" or "stovepipe" joint arrangement for compound articulation at the joints. Figure 25 shows the use of pseudo-conic joints in the suit.

In order to overcome the stowage disadvantages of "incompressible hard suits," yet take advantage of the excellent mobility provisions of the constant volume joint technology, NASA undertook the development of a "hybrid" suit, which is made of hard material along with softer fabric material (Fig. 26). The suit combines the best features of hard and soft space suits. It utilizes the hard space suit-derived "stovepipe" joint in the shoulder and hip areas and molded nesting bellows convolutes in the elbow, waist, thigh, knee, and ankle sections. The cloth rolling convolute joints collapse to facilitate

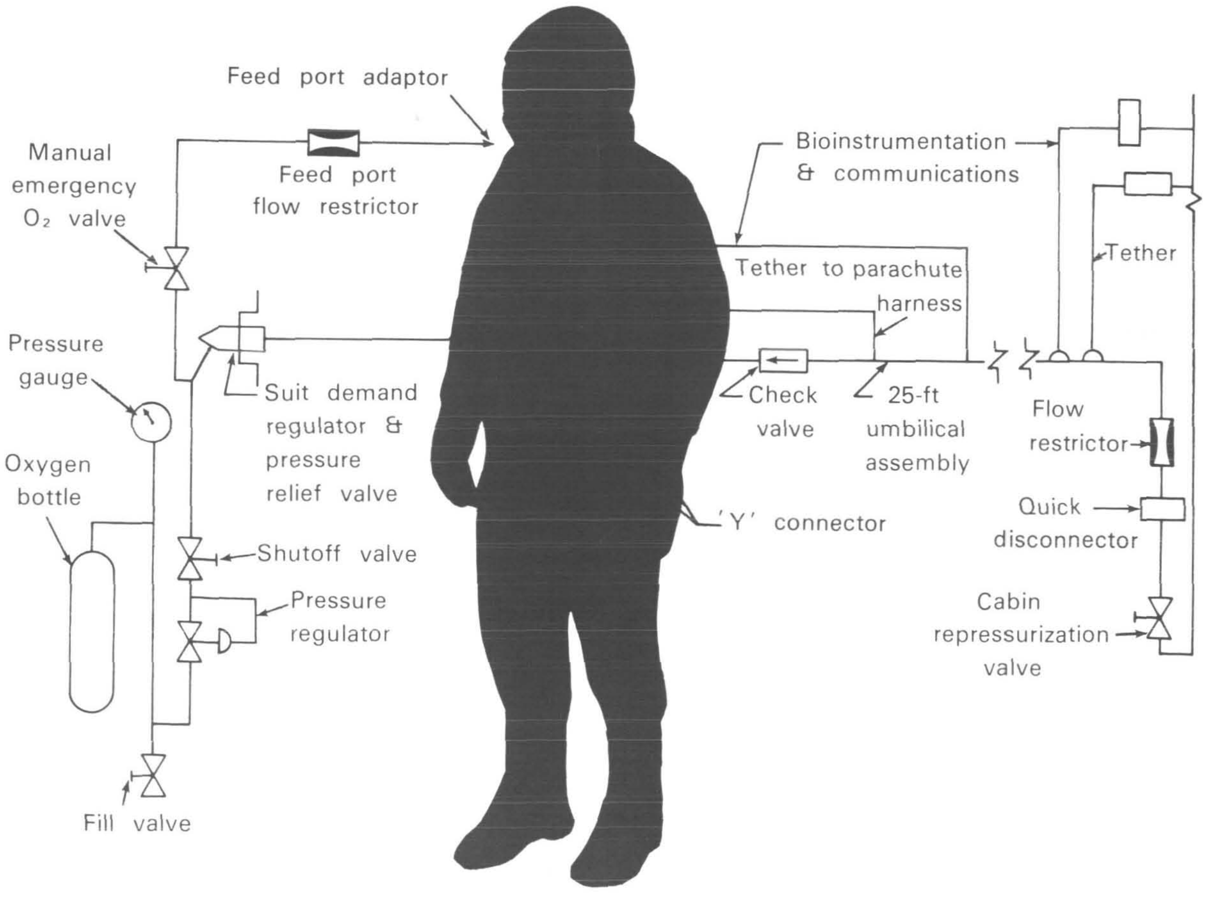


FIGURE 16.—Gemini 4 extravehicular life-support system.

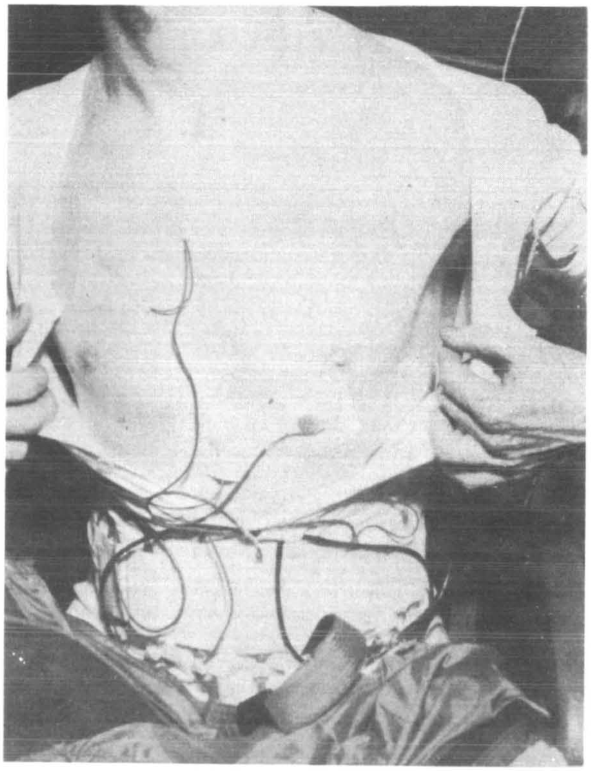


FIGURE 17.—Gemini biosensor harness. (NASA photo)

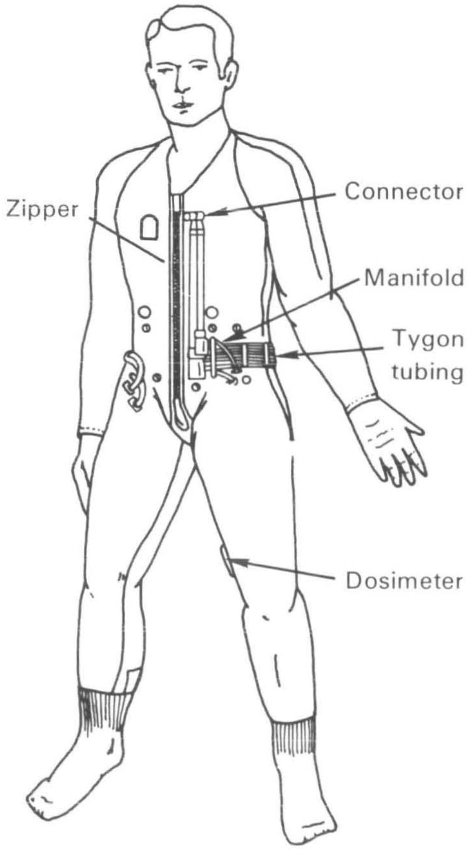


FIGURE 19.—Liquid cooling undergarment. (Sketch from NASA photo)

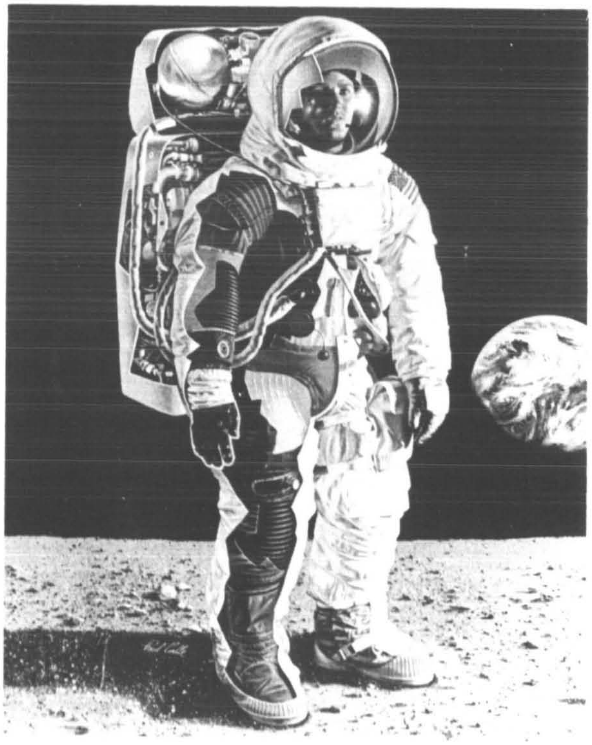


FIGURE 18.—Cutaway view of Apollo lunar surface activity assembly. (NASA photo)

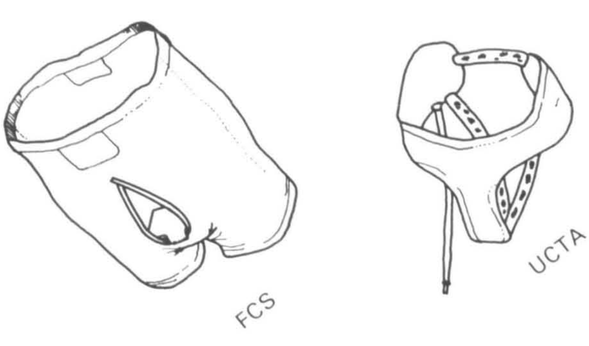


FIGURE 20.—Fecal containment subsystem (FCS) and urine collection and transfer assembly (UCTA). (Sketch from NASA photo)

stowage; a single axis waist entry facilitates donning. Torques in this suit system have been reduced about 50% compared with those in previous systems. A multiple sizing feature is also included as well as a newly developed five-bearing shoulder joint. The entire suit, including the integral thermal meteoroid garment, can be stowed in a volume of 37.46-cm high × 71.1-cm long × 66-cm wide.

The hybrid character of this suit, plus the improved constant volume joints, affords excellent mobility. The shoulder joint consists of four wedge sections and five rotary seal bearings. Wedge angles are determined so that the arm may be moved in any plane without restriction or programing. The elbow joint uses a single-axis constant volume convoluted joint. The waist joint consists of two elliptic, convoluted sections, single-axis joints so constructed that planes of flexure are 90° to each other. Waist abduction is provided with approximately ±20° range. Waist flexion has 65° range compared to smaller ranges in earlier suits. Figure 26 illustrates the mobility characteristics of the suit. This is

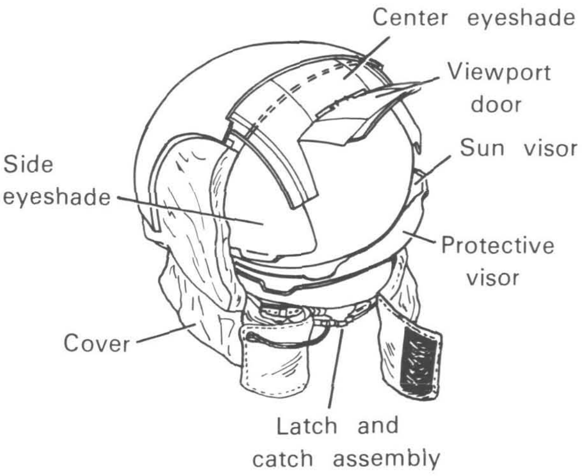


FIGURE 21. – Lunar EVA visor (LEVA). (Sketch from NASA photo)

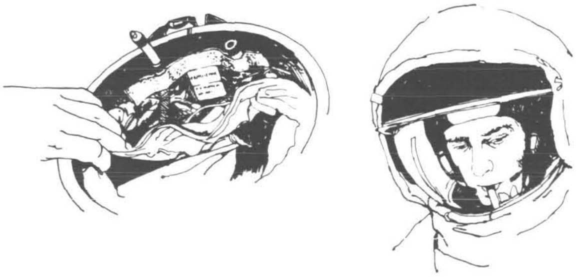
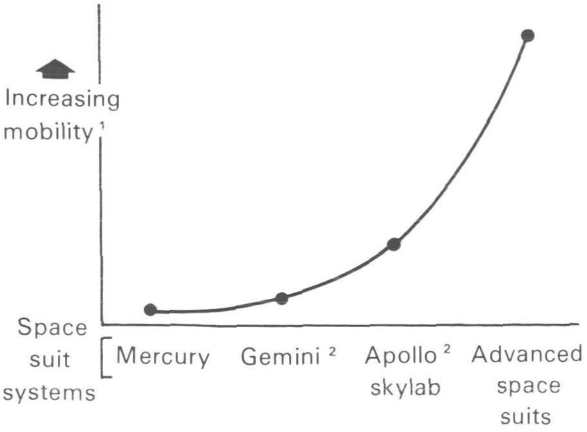


FIGURE 22. – Apollo space suit waterbag for use during EVA. (Sketch from NASA photo)



[1] Increasing mobility is defined as increased degrees of motion around all body planes plus reduced overall joint torques, plus increased multipositional joint stability

[2] EV Orbital and lunar surface operations

FIGURE 23. – Space suit mobility function.

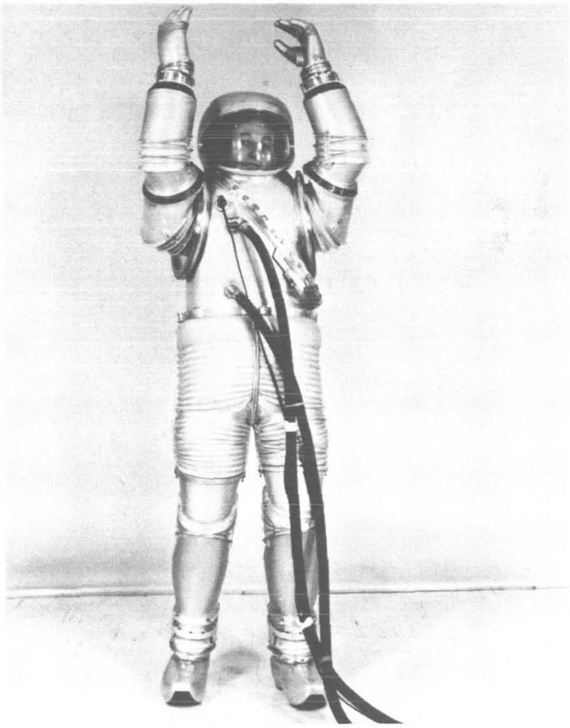


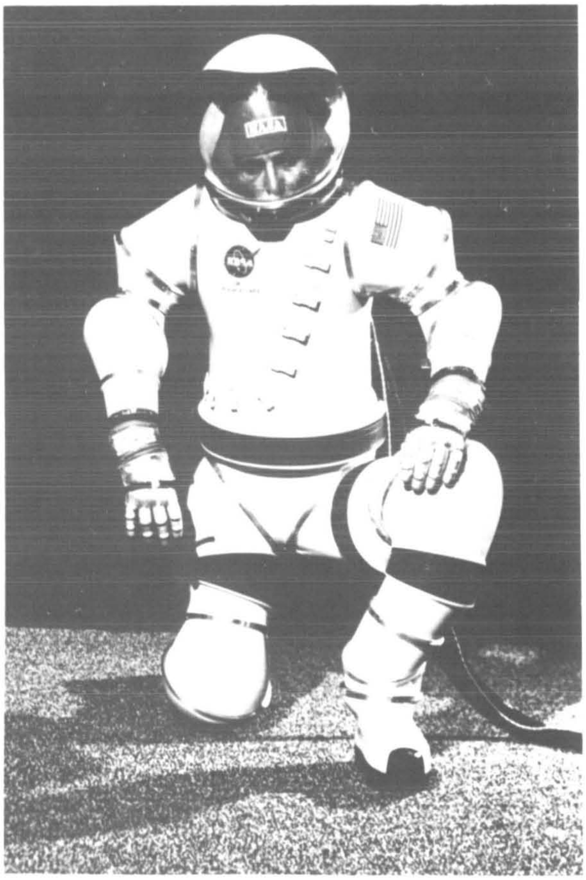
FIGURE 24. – RX-1 space suit. (NASA photo)

further indicated in Figure 27, which shows the torque requirements for various degrees of waist flexion for state-of-the-art nonconstant volume suits compared with the constant torque feature of the hybrid suit, even to flexion ranges greater than 100°.

Eight Psi (414 mmHg) Suit

A US development program, based on technology derived from the hybrid suit, is under way to produce a 0.5624 kg/cm^2 (8.0 psi) (414 mm Hg) extravehicular space suit. The suit pressure will be equivalent to that encountered at an altitude of slightly less than 4880 m.

The 414 mm Hg suit development could eliminate the requirement for prebreathing oxygen to prevent decompression sickness. Apollo astronauts have prebreathed pure oxygen for approximately 3 h before being subjected to the spacecraft single gas (oxygen) atmosphere at a pressure of 252 to 264 mm Hg. With this practice, no decompression incidents have been experienced in the US space program. However, if



Advanced hard space suit

FIGURE 25. – AX-1 space suit. (NASA photo)

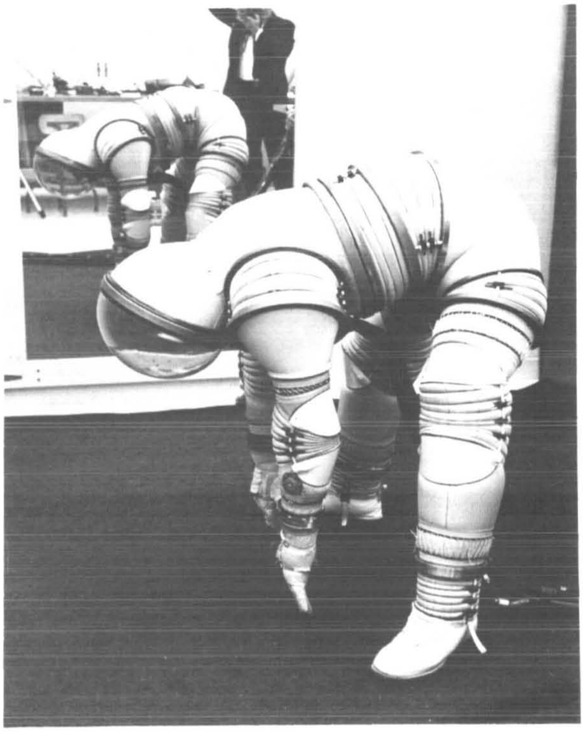


FIGURE 26. – Advanced extravehicular (hybrid) suit. (Courtesy, Garrett Corp.)

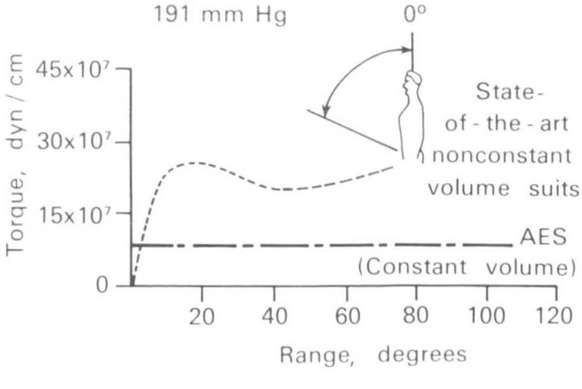


FIGURE 27. – Torque versus range of waist flexion for state-of-the-art nonconstant volume space suits compared with the advanced extravehicular suit. (Suit pressure = 191 mm Hg.)

the 414 mm Hg suit development is successful, this requirement will be unnecessary when transitioning from the 760 mm Hg mixed gas atmosphere of the space shuttle to an EVA suit pressure.

In development activities so far, space suit joint systems have been fabricated which will operate in the 258–362 mm Hg range. These higher pressure systems are based on constant volume joint technology and use fabrication processes which appear to meet the operating, proof, and burst pressure requirements for a successful 414 mm Hg suit.

Advanced Gloves

The need for increased finger and hand dexterity will grow as the work requirements for a suited astronaut in space become more extensive and more complex. Space tools will increase in variety and become more sophisticated. Improvement in space suit glove technology to meet these needs can be seen in Figure 28. This glove uses constant volume joint concepts to achieve improvement in grasp. A better finger fabric combination provides improved tactile characteristics.

EXTRAVEHICULAR ACTIVITIES AND SYSTEMS

EVA Aids

Space tools. The various types of tools required for space work activities, such as during exploration of the lunar surface, are shown in Figure 29. Research studies indicate that (1) power tools must be compact, (2) some restraint system is required for a man no matter what types of tools are used during EVA activities, and (3) when a man is restrained, reactionless tools lose the small advantage they may have over conventional tools [5].

Extravehicular activity platform. Research studies on an EVA work platform (Fig. 30) indicate a maneuverable, open base can assist an astronaut in performing tasks in space. A propulsion system in the platform would bring the astronaut to the worksite. Manipulators could assist the astronaut in docking and serve as arm extensions or "extra arms" after docking is achieved. Anchors tie the work platform to the worksite.

Teleoperators. Teleoperators may be used to project man's capabilities across distances and through physical barriers into hostile environments, and to amplify his energy and force capabilities. Teleoperators may take many forms. Figure 31 shows the shoulder and arm of the NASA Extravehicular Hard Space Suit modified for use in a master-slave manipulator operation. A one-for-one control relationship is between the arm movements of the astronaut in the suit and the slave follower located at the worksite. The broad function of an operations teleoperator will include satellite deployment, retrieval, servicing, construction, and emergency use.

Free Space Maneuvering Devices

Hand-held self-maneuvering unit. Hand-held maneuvering devices have been used in extravehicular operations with considerable success. Figures 32 and 33 show the hand-held self-maneuvering unit used by astronaut Edward

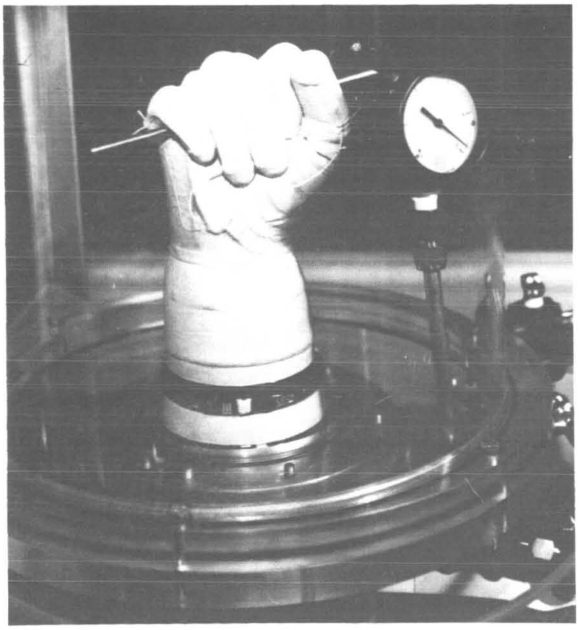


FIGURE 28.—Highly articulated space suit glove. (NASA photo)

White in the Gemini 4 mission. This system contains its own high-pressure cold gas supply together with the necessary metering valves and nozzles required to produce controlled thrust. To move forward, the astronaut squeezes the front half of the trigger; to stop or move backwards, he squeezes the rear half of the trigger. This system allows EVA movement to be accomplished at considerably less energy cost to the astronaut.

Astronaut maneuvering devices. More sophisticated maneuvering devices tested in Skylab missions include the astronaut-maneuvering research vehicle (AMRV) and the foot-controlled maneuvering unit (FCMU). The AMRV (Fig. 34) employs four methods of operation: a hand-held maneuvering unit (HHMU), and the direct, rate gyro, and control moment gyro (CMG) modes. It provides six degrees of freedom maneuverability with self-contained rechargeable subsystems and extensive instrumentation to measure in-flight system performance, man motion, and umbilical perturbations. The FCMU (Fig. 35) employs foot-operated controls, unbalanced attitude thrusters, and translation thrusters acting along near-vertical body principal axes. The unit is straddled by the operator in much the same manner as on a bicycle. The thrusters, attached to the framework, provide translation accelerations on the order of 0.03 m/s^2 and nominal attitude accelerations on the order of 4°/s^2.

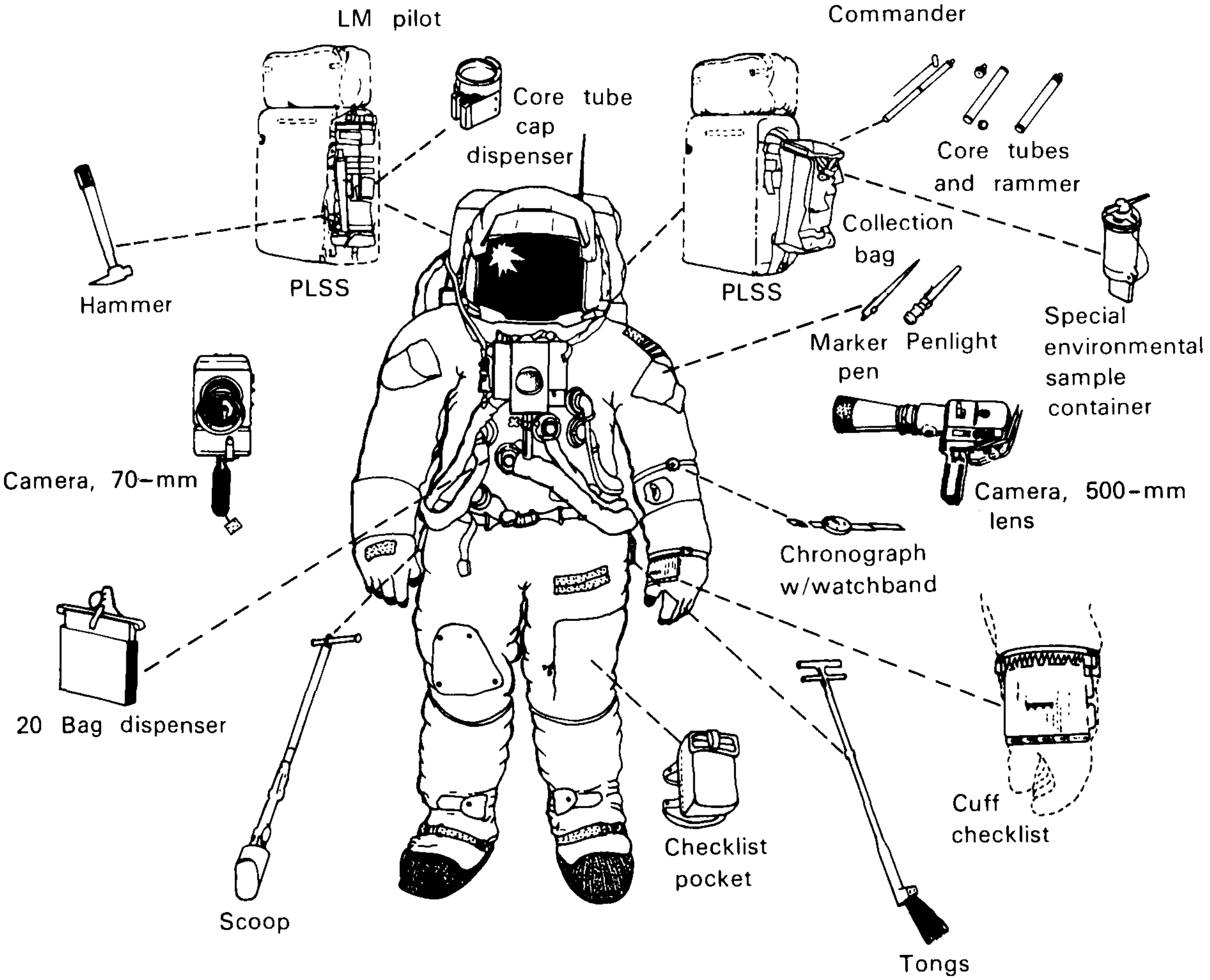


FIGURE 29.—Space tools.

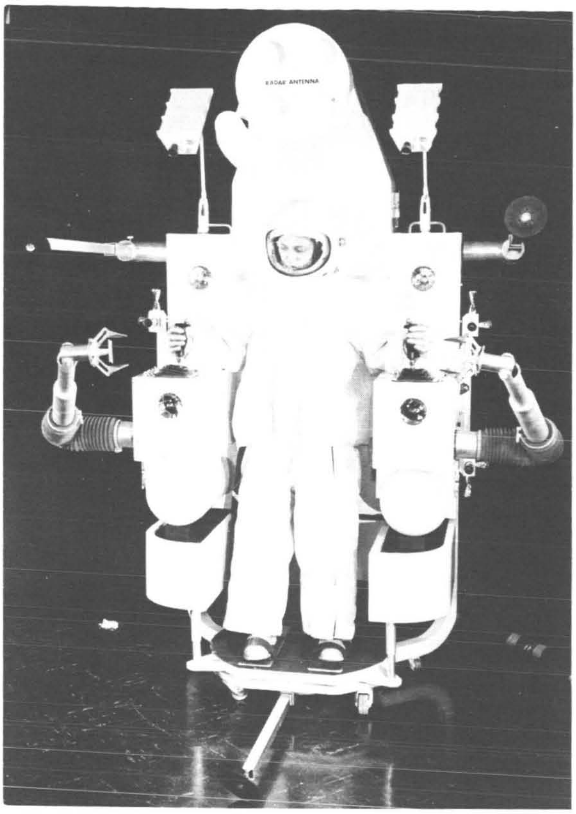


FIGURE 30.—Extravehicular activity work platform. (NASA photo)

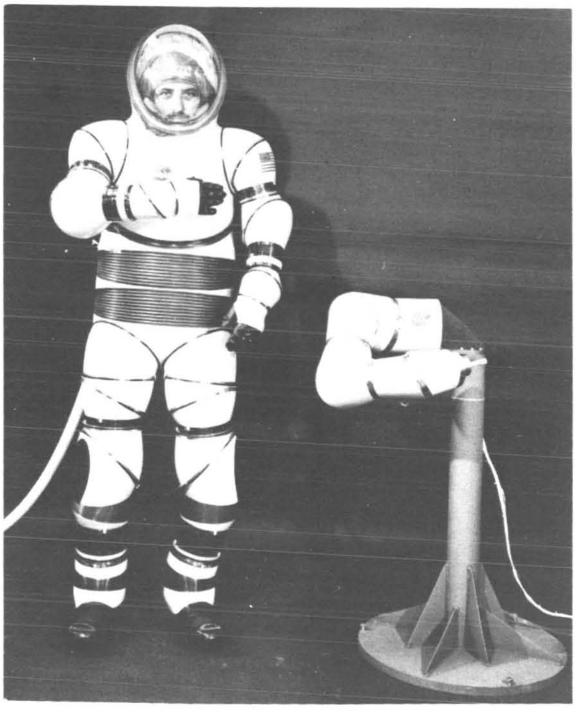


FIGURE 31.—Teleoperator (on right). (NASA photo)

Lunar Excursions

Walking on the lunar surface. The 1/6 G-force and the lunar soil composition, when combined with equipment load borne by an astronaut, make the simple act of walking on the Moon a much different matter than on Earth. For this reason, a unique gait was adopted by the astronauts. Astronaut Conrad noted that a conscious effort had to be made to learn to walk in this altogether different manner. To aid lunar locomotion further, a thermal and abrasion-protective boot was worn over the usual boot assemblies during Apollo lunar extravehicular operations.

Lunar Rover. Extended exploration of the lunar surface was made possible through the de-

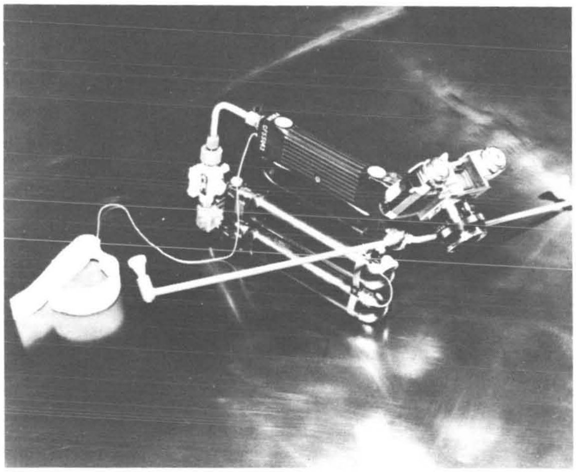


FIGURE 32.—Hand-held self-maneuvering unit. (NASA photo)

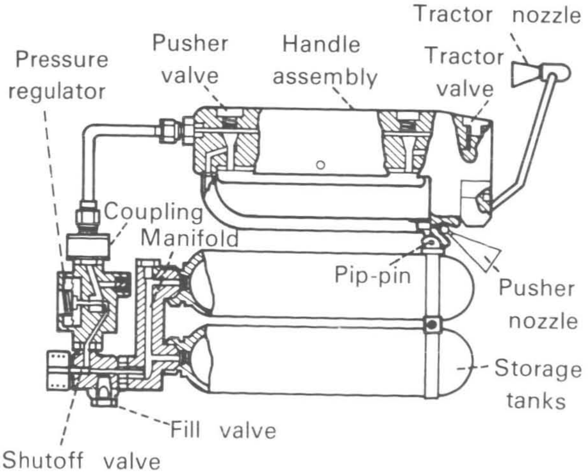


FIGURE 33.—Cutaway view of unit. (NASA photo)

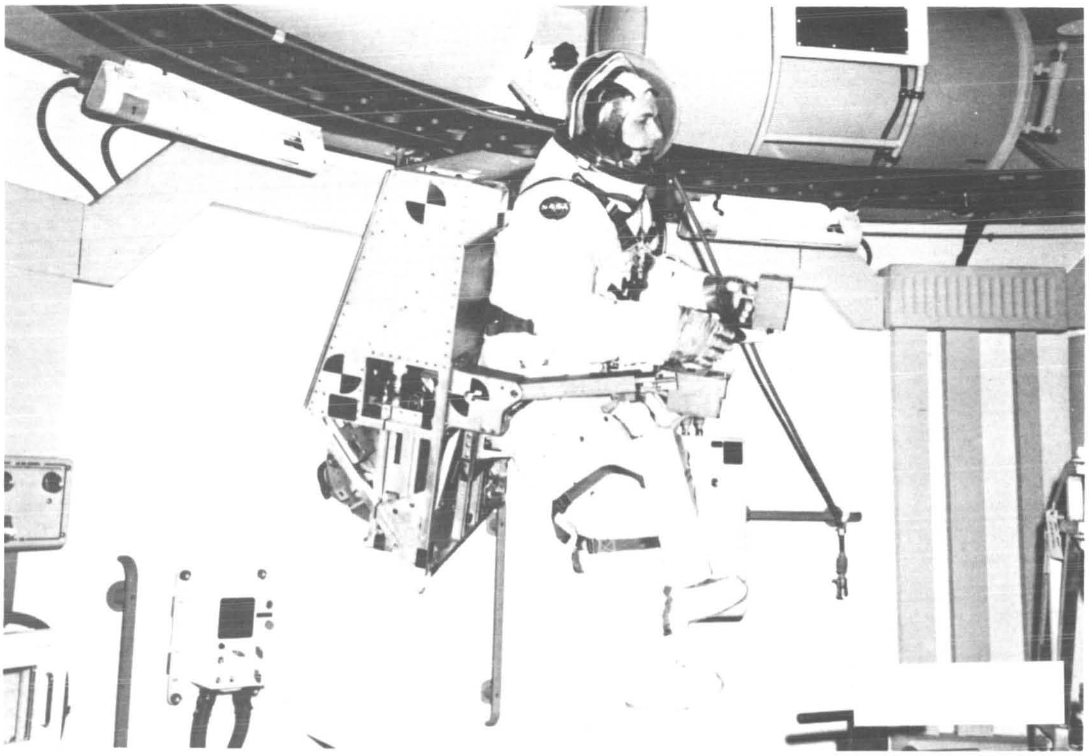
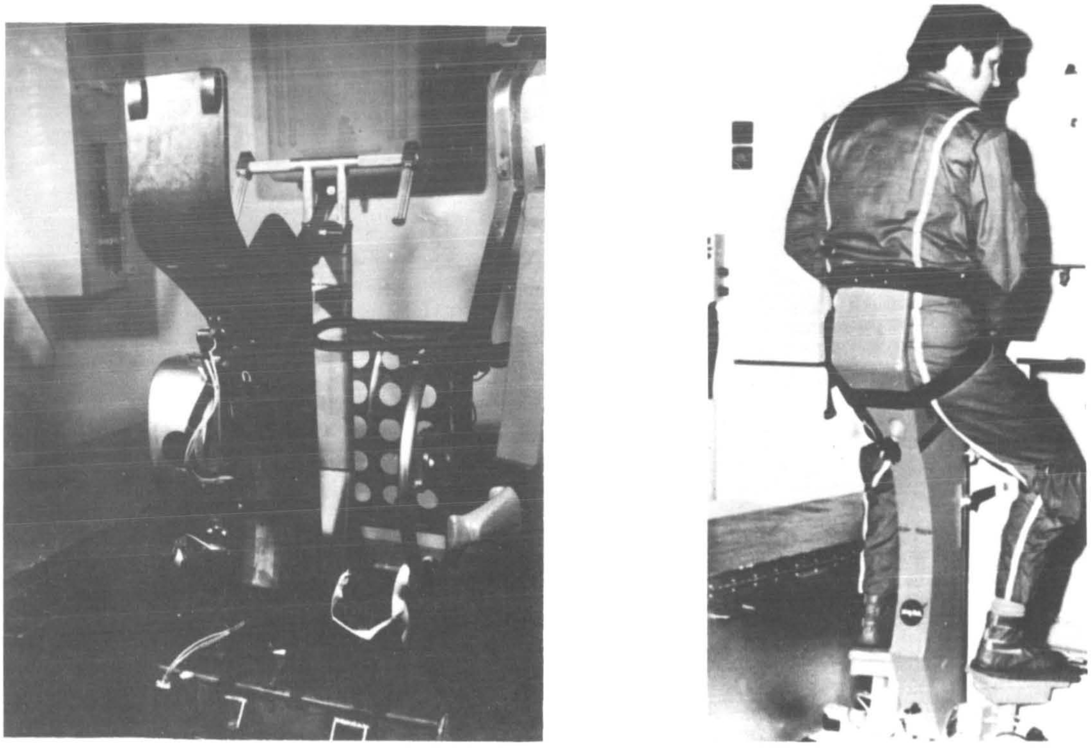


FIGURE 34. – Astronaut maneuvering research vehicle, (NASA photo)



FCMU Stowed

FCMU Operational

FIGURE 35. – Foot-controlled maneuvering device. (NASA photo)

velopment of a transportation system, the Lunar Rover Vehicle, which reduced metabolic expenditures for suited astronauts. The four-wheeled vehicle (Fig. 36) weighs about 218 kg and carries a total weight of more than 454 kg, including two astronauts and their portable life-support systems (181 kg for each man and his equipment), plus about 90 kg scientific equipment, astronaut tools, and lunar rock and soil samples. It is manually operated by either of the astronauts. The driver operates the vehicle much as he would on Earth, using a small hand-grip control to steer the vehicle at variable speeds, forward and reverse. The vehicle's range (22 km) was restricted to a radius of about 9.6 km from the lunar module, the distance astronauts can walk back to the base vehicle in an emergency. Driving the Lunar Rover Vehicle

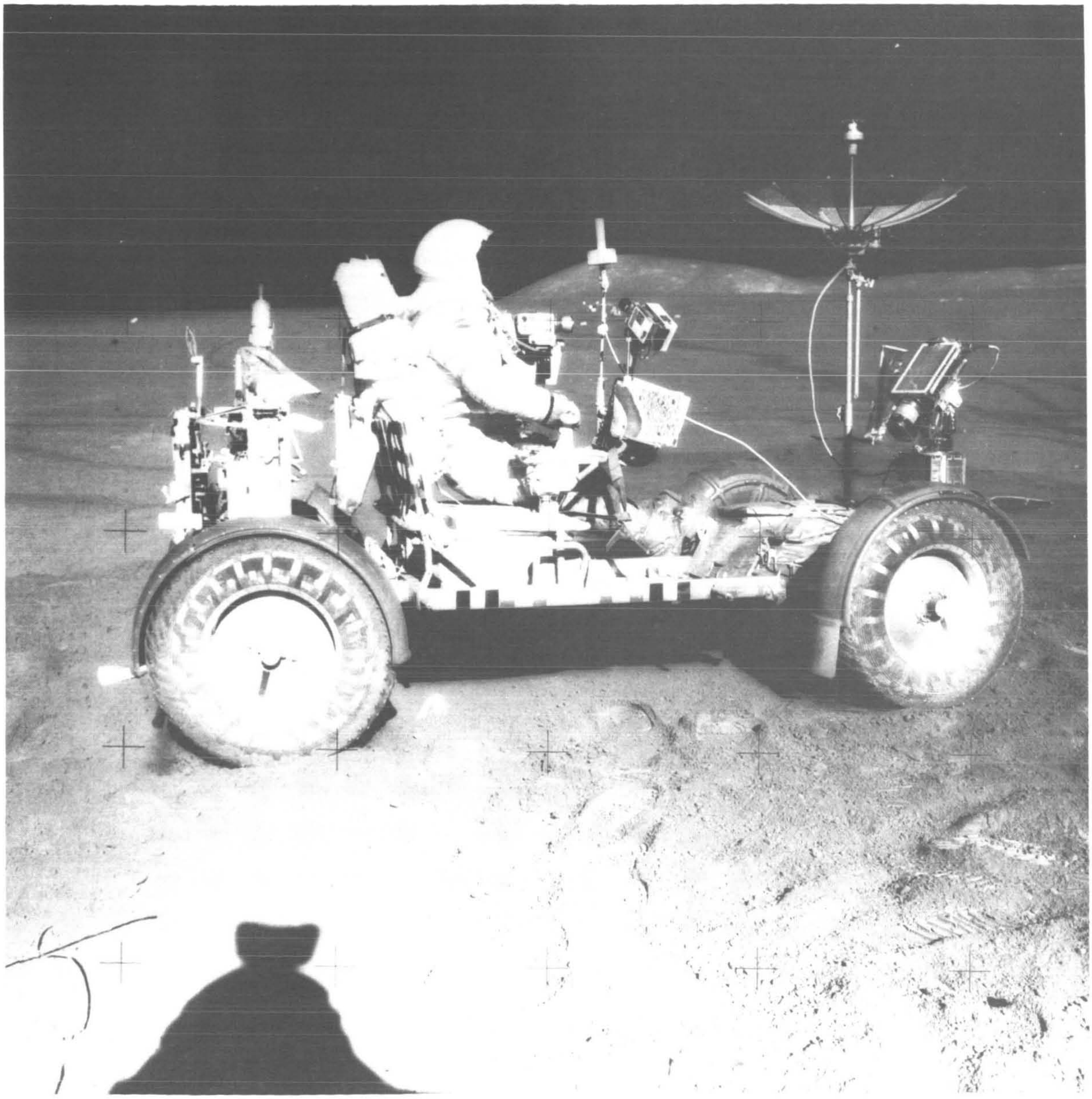


FIGURE 36.—Lunar roving vehicle. (NASA photo)

demanded improved mobility in the Apollo extravehicular space suit; such improvements were effected by a change in the waist joint articulation in the space suit.

Rocket jet belt. Work was begun in 1953 (by Bell Aerosystems) on an individual rocket system which would allow a man to move for great distances effectively under "his own power." The initial flight of this system (Fig. 37) in 1 G occurred in 1961, for 13 s to a distance of 34 m. In the years that followed, more than 3000 demonstration flights, with 100% reliability, have been made. Since such a system might be of value in 1/6 G, the Bell system was tested at the NASA Langley Research Center in a 1/6-G simulator. This test was performed successfully by a test pilot wearing a pressurized space suit.

FIGURE 37.—One G rocket belt. (Courtesy, Bell Aerosystems Co.)

SUMMARY

Pressure suit technology has, over the course of less than 40 years, progressed from crude demonstration models to fabrication and use of highly sophisticated space suit systems which permit man to operate at reduced barometric pressures efficiently and with a reasonable degree of comfort. Work has been initiated toward the design of an 0.5624 kg/cm^2 (8.0 psi) (414 mm Hg) space suit which will remove the requirement for a long period of preoxygenation and purging of the space suit prior to transfer from a 760-mm Hg mixed gas environment to a reduced pressure environment. Efforts are also being made to reduce space suit weights.

Portable life-support systems restrict the amount of time which can be spent in extravehicular activity because they do not yet regenerate the necessary supplies. Current development efforts are aimed at regenerating those supplies needed.

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Part 2

CHARACTERISTICS OF INTEGRATED LIFE-SUPPORT SYSTEMS

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Chapter 8

NONREGENERATIVE LIFE-SUPPORT SYSTEMS FOR FLIGHTS OF SHORT AND MODERATE DURATION[1]

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The problem of supporting human life in space has recently become the subject of careful scientific investigations conducted on Earth and in space. Man's further penetration into space to discover the secrets of nature and their practical application depends, to a great extent, upon the solution of this problem.

Tsiolkovskiy [27], the pioneer of cosmonautics, was the first to give a great deal of attention to this important question of conquering space—i.e., to insure conditions necessary for the normal vital activity and work of man aboard spacecraft.

A favorable, habitable environment must be created to successfully accomplish a flight program in a cabin primarily limited in size. The vital environmental conditions are maintained by a combination of crew life-support systems that make up part of the spacecraft. This combination must provide man with food products, drinking water, oxygen for breathing, and sanitary-technical facilities. The composition, weight, and volumetric characteristics of this complex depend upon the number of crewmembers and duration of the space flight. These problems, in short-term and intermediate-duration flights (20–30 d), are solved by using necessary food products, drinking water, oxygen, and other crew life-support systems of the spacecraft, which can be stored on-board [3, 5, 8, 23, 28, 31].

All spacecraft built so far in the USSR and the USA have been designed for flights of short and intermediate duration; thus, the life-support systems examined in this chapter can be illustrated by the Vostok, Voskhod, Mercury, Gemini, Soyuz, and Apollo spacecraft.

BASIC REQUIREMENTS FOR LIFE-SUPPORT SYSTEMS

A life-support system is designed to provide cosmonauts with all the necessities of life in the cabins of the spacecraft with regard to materials and maintenance of environmental parameters within the limits determined by physiologic and hygienic norms.

The basic requirements for crew life-support systems of flights of up to 30 d can be generally formulated as [10, 17, 28]:

- reliable functioning at all stages of the spaceflight
- crew safety

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[1] Translation of Sistemy Zhizneobespecheniya dlya Kratkovremennykh Poletov i Poletov Sredney Prodolzhitel'nosti, Volume III, Part 2, Chapter 1, *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*), pp. 1–47. Moscow, Academy of Sciences USSR, 1973.

The chapter is based upon materials prepared in the USSR by B. A. Adamovich and A. D. Seryapin, and in the USA by Dr. W. L. Jones. Sincere appreciation is expressed to Drs. Jones and Seryapin for their painstaking work in preparing the materials.

- preventing the need for prophylactic servicing of systems during the flight
- maximal provision of comfortable conditions for the crew
- capacity for the crew to alter conditions in the cabin within the limits of medical and biological norms
- the convenience of control of the telemetric, and, if necessary, on-board qualities of system functioning
- convenience of conducting prelaunch checks in servicing of systems
- minimal systems weight
- minimal energy requirements
- minimal volume occupied by life-support systems [2, 8, 16, 20, 26, 29, 31].

These requirements can be exactly defined for each type of spacecraft, taking into account the design and component peculiarities of the spacecraft, and specific limitations of the craft imposed by its rocket system. However, independent of the purpose of the spacecraft, duration of flight, and design of life-support systems, a list of such systems' basic functions remains unchanged [1, 3, 7, 16, 17, 19, 21, 25, 30]:

1. Regeneration of the atmosphere of habitable compartments, maintenance of its composition, and pressure in accordance with medical requirements by means of—
   - removal of CO_2 gas expired by the crew from the cabin air and replenishment of oxygen used by the crew
   - removal of harmful impurities from sources of both crew and equipment within the compartments
   - removal of dust and microorganisms
   - maintenance of ion composition of the atmosphere
   - compensation for air lost from the spacecraft
2. Providing drinking water
3. Providing food
4. Satisfying sanitary and hygienic requirements.

In accordance with these functions, the life-support system consists of subsystems for: atmospheric regeneration, water supply, food supply, sanitary and hygienic support, and waste products processing.

Various technological principles, which could be used in life-support systems for short-term and intermediate-duration flights [1, 2, 9, 18, 26, 28] are:

1. Removing carbon dioxide gas from the air by means of —
   - absorbents based on alkali and alkali Earth metals
   - synthetic zeolites; activated charcoal or other absorbents
   - solid regenerable absorbents based on alkali metal carbonates
   - superoxide compounds of the alkali metals
   - reversible amines
2. Supplying oxygen by suitable on-board reserves—
   - compressed gaseous oxygen
   - liquid oxygen
   - potassium perchlorate
   - hydrogen peroxide
   - superoxide compounds of the alkali metals [6, 28, 31]
3. Supplying the crew with drinking water by—
   - using water stores on board or as hydrogen-oxygen fuel cell product water preserved by means of silver ions, chlorine, or iodine preparations
   - using water supplies in combination with regeneration of drinking water from atmospheric condensate of moisture
   - by impurity absorption on a complex gas absorber with ion exchanging resin included
   - regeneration of water from liquid and solid products of vital activity on-board the spacecraft relative to the specific flight duration (up to 30 d) is inefficient; its use requires significant increase in the size of the spacecraft's energy-supply system [28, 31]
4. Purifying the air of harmful waste prod-

ucts other than CO_2 eliminated by crew and by equipment—
  - various sorbents, such as activated charcoal can be used
  - oxidation of these impurities to CO_2 and water in special catalyzers is also possible
5. Purifying the air of dust and microflora by—
   - various dust catchers: mechanical and electrostatic catchers, bactericidal filters, and cyclone separators
6. Supplying the crew with food with—
   - stores of natural foods
   - canned, frozen, and freeze-dehydrated products
7. Satisfying sanitary and hygienic requirements—
   - use of various technological processes and variants
   - cleanliness of the skin, achieved by washing with water and various washing substances
   - wiping with special hygienic pads
   - replacing soiled underwear with clean from on-board stores
   - isolating waste products with hermetically sealed containers, various methods of storage, and removal from the spacecraft.

To insure the crew's vital activities and high-working capacity in a sealed cabin, conditions must be created according to the parameters of the artificial environment similar to the natural conditions to which the crew is accustomed. A slight deviation of the environment from permissible limits adds stress and taxes physiologic systems, which, in turn, can lessen tolerance for G-forces, weightlessness, and other flight factors. On the other hand, the specifics of space flights require a certain compromise between the effort to create optimal comfort conditions for crewmembers and the technically possible accomplishment of such measures. Consequently, in the present stage of astronautics, it is hardly appropriate to determine rigidly set boundaries of permissible fluctuations of the artificial environment's parameters without relating them to a specific spacecraft and program [14, 15, 29, 31].

From biomedical investigations, norms were developed for conditions of crew life support for short-term and moderate-duration flights. These norms, used in planning Soviet and American spacecraft, determine the capacities, and depend upon the specific flight conditions of a range of changes in basic parameters. They are shown in Table 1.

TABLE 1.—*Basic Norms for Life Support During Flights up to 30 D*

	Parameters	Scale	USSR	USA
			[16, 23, 28]	[18, 24, 26]
1.	Caloric makeup of food ration	kcal	2500–2700	2500
2.	Total quantity of usable drinking water	l/man d^{-1}	2–2.2	3.63
3.	Elimination of CO_2	kg/d	1	1
4.	Consumption of O_2	kg/d	0.95	0.95
5.	Total amount of solid and liquid waste products	kg/d	1.5–1.9	1.61
6.	Loss of moisture through skin and with expired air	kg/d	1–1.2	2
7.	Atmospheric pressure in cabin	mm Hg	740–800	259–264
8.	Partial pressure of O_2	mm Hg	160–200	259–264
9.	Partial pressure CO_2	mm Hg	up to 7	up to 5
10.	Relative atmospheric humidity	%	30–70	40–70

CREW LIFE-SUPPORT SYSTEMS ON VOSTOK, VOSKHOD, AND SOYUZ SPACECRAFT

The flights of manned spacecraft were preceded by many experimental flights of animals aboard rockets launched vertically and aboard artificial Earth satellites. Life-support systems for animals in these flights became a prototype of systems designed for life support in human flights [3, 4, 5, 6, 13, 20, 22, 31]. However, there were also significant differences related to the anatomic, physiologic, and behavioral characteristics of animals.

Flights of the first Vostok spacecraft were planned for comparatively short terms in orbit. However, during the planning stage of the spacecraft and its capacity, the possibility of its use in longer flights was taken into account. Provision was also made for the possibility of an emergency situation in which flight duration could increase 7–12 d with a gradual increase in air temperature and in the temperature of cabin equipment to +35°C.

In this connection, the systems for air regeneration and conditioning, food and water supply aboard the spacecraft, were based on a 12-d support system for one cosmonaut in a hermetically sealed cabin. In the event of sudden decompression of the cabin, a rescue space suit was to be used for the time necessary to select a favorable region and to land the spacecraft [29].

Systems for Air Regeneration and Conditioning

Systems for air regeneration and conditioning for the Vostok, Voskhod, and Soyuz spacecraft were based on stores of oxygen and sorbents that absorb water vapor and CO_2 gas at small values of their partial pressure. A certain portion of the moisture (i.e., condensation on the surface of the heat exchanger) was extracted from the cabin air. Oxygen in the chemically bound state was stored in the form of superoxides of alkali metals (chemically bound oxygen was chosen for high systems reliability and comparatively good weight characteristics). The superoxides, in absorbing moisture, released oxygen, while the alkali formed thereby absorbed CO_2 gas.

The chemical reactions occurring in the regenerative substance, based on potassium superoxide, have the following form in reaction with cabin air:

$$4KO_2 + 2H_2O \rightarrow 4KOH + 3O_2 \qquad (1)$$

$$4KOH + 2CO_2 \rightarrow 2K_2CO_3 + 2H_2O \qquad (2)$$

$$2K_2CO_3 + 2H_2O + 2CO_2 \rightarrow 4KHCO_3 \qquad (3)$$

The regenerative substance first absorbs moisture from the air, liberating a corresponding quantity of oxygen. The potassium hydroxide thus formed reacts with carbon dioxide to form potassium carbonate and water. Potassium carbonate, in the presence of moisture and carbon dioxide, can form the terminal product—potassium bicarbonate.

Potassium superoxide in air regeneration systems of hermetically sealed small cabins causes difficulties in maintaining a constant level of the partial pressure of oxygen in the artificial atmosphere.

The amount of oxygen producible by the oxygen regeneration compound depends upon the concentration of water vapor in the atmosphere of the hermetically sealed cabin, and on the ventilation rate of the atmosphere via the regenerator. In reacting with moisture, the superoxide liberates approximately 1.9 l O_2/g absorbed H_2O. Consequently, to supply one man with oxygen (at 25 l/h), 13.2 g water must be added to the regenerator. At an atmospheric relative humidity level of 50% and a temperature of +20° C, this quantity of water is absorbed by the superoxide at a ventilation rate of 1.53 m^3/h. However, to maintain the necessary concentration of CO_2 at 1% in the hermetically sealed cabin, the ventilation rate should be approximately 2.1 m^3/h. Hence, the substance will absorb not 13.2 g H_2O/h, but significantly more, i.e., 18 g, which means that it is not 25 l O_2/h which is liberated, but rather 35 l. The liberation of oxygen in excess of consumption leads to an increase in concentration in the cabin. With large quantities of the superoxide, the concentration of oxygen which is simultaneously put into operation and the small size of the cabin can rapidly lead to an amount of oxygen reaching maximal permissible limits. To overcome this difficulty, the regenerating installation must have a regulating device based upon such principles as limiting the amount of regenerating compounds in operation at any time or drying the air before it enters the regenerator.

One method of regulating the rate of oxygen liberation, in accordance with the rate of its consumption by a man, is the preliminary partial or complete drying of the air entering the regenerating cartridge. In case of an excess of partial oxygen pressure, the air passes preliminarily through a dryer and then proceeds to the regenerator. A decrease in the amount of water in the air slows the liberation of oxygen and its partial pressure decreases. With a decrease in partial pressure of oxygen, the regulating device decreases the degree of preliminary air drying, and, consequently, the amount of oxygen liberated increases. Hence, a relatively stabilized concentration of oxygen in the cabin air is achieved.

The system of atmospheric regeneration and conditioning in the hermetically sealed cabins of the Vostok spacecraft consisted of four basic assemblies which automatically maintained an assigned gaseous composition of the air, temperature, and humidity, and which maintained control of basic atmospheric parameters.

The assembly for automatically maintaining the necessary composition of the atmosphere, shown in Figure 1, consisted of a ventilator with electric motor, indicated by "1"; regenerator with regulating device, indicated by "2, 3, 4"; filters for dust and harmful impurities, indicated by "26"; and connecting air passages.

A double ventilator with an electric motor insured constant flow of air through the regenerating installation. In case of breakdown of the basic ventilator, the duplicate ventilator automatically switched on. The automatic ventilator switching reacted to short circuits and breaks in the current

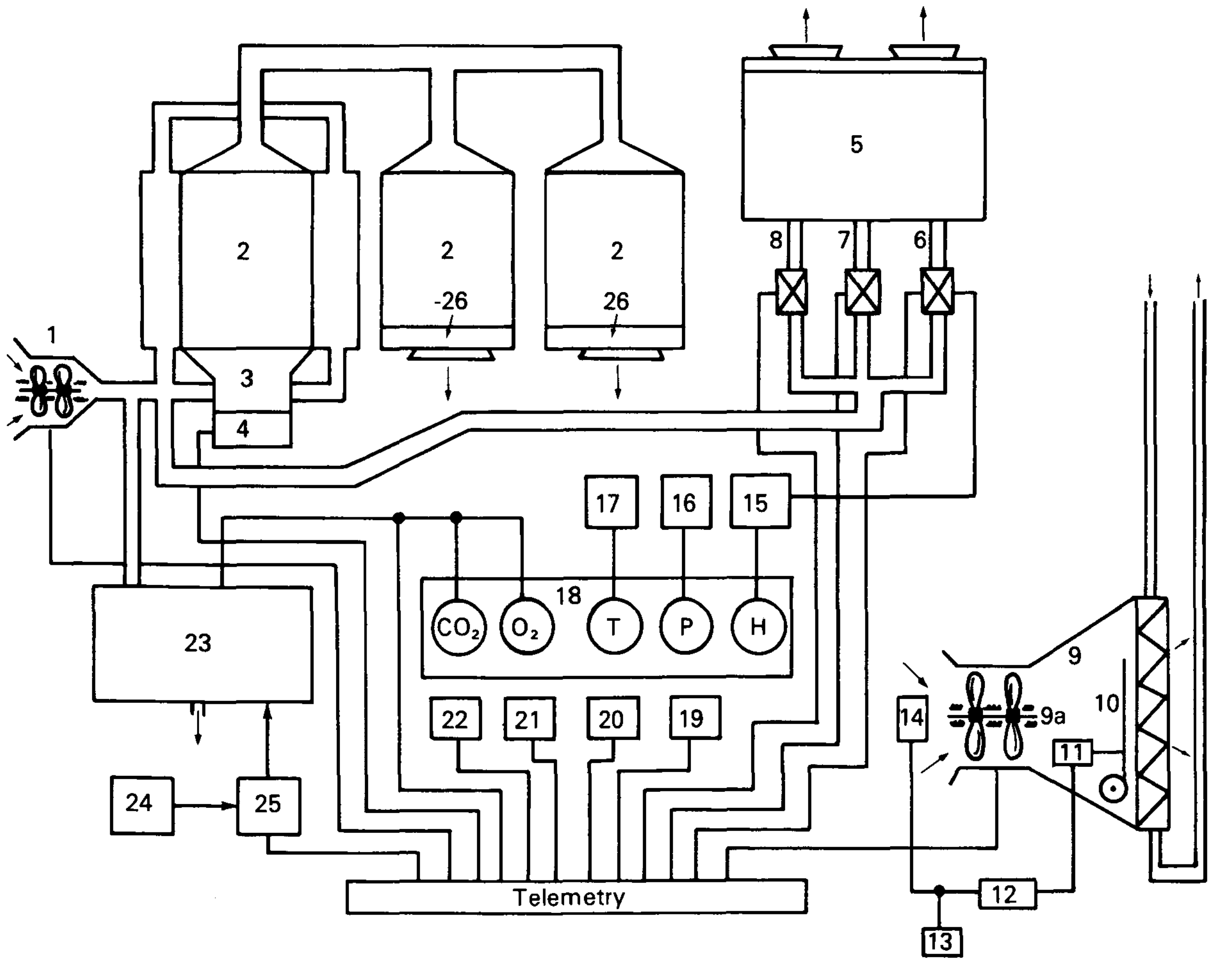

FIGURE 1.—System for regeneration and conditioning of the atmosphere of a hermetically sealed spacecraft cabin of the Vostok. (Explanation in text)

supply circuit and to a sharp decrease in the number of fan blade rpm. The ventilator was connected to the regenerator unit with the aid of the air collector. The air collector distributed the flow of air throughout the regeneration system.

The magnitude of ventilation through the regenerating system was calculated to maintain the concentration of CO_2 gas at a level of 0.5%–1% with elimination of up to 20 l CO_2/h by one cosmonaut. With a decrease in the absorptive capacity of the superoxide proportional to its exhaustion, the magnitude of ventilation was set at 50 l/min for the Vostok and 180 l/min for the Voskhod spacecraft. Current for the ventilator and automatic switching device was supplied from a low-voltage direct current source.

The regenerator with its regulating device was joined into a single unit. It consisted of a metal container holding the regenerating superoxide, the dust and harmful impurities filters, and the automatic regulating device.

The cabin air, charged during human vital activity by carbon dioxide gas, water vapor, and harmful impurities, was constantly circulated through the regenerator by the ventilator. Harmful impurities were partially absorbed by superoxide, partially fixed at the output of the filters.

Regulation of Atmospheric Humidity

One possible emergency situation in flight was an increase in air temperature to 35° C. Thus, the system of regulating atmospheric humidity was particularly significant since humidity influences thermal balance of the cosmonaut. The assembly for automatically maintaining humidity (Fig. 1) included the block with moisture absorber indicated by "5"; automatic valve, indicated by "6"; humidity signaling device, indicated by "15"; two valves with a manual actuator indicated by "7, 8"; and connecting pipes.

A container filled with moisture absorbent, with the aid of the air transport pipe, was connected to the air collector of the air regenerating system. Filters were placed in front of the output pipes of the container. The flow of air passing through the container was regulated by automatic and manually operated valves.

Permissible limits of humidity were set by a contact sensor, which fed the signal for the lower and upper limits of relative humidity to the automatic valve. Simultaneously, a signal went from the signaling device to the humidity indicator mounted on the instrument panel in front of the cosmonaut. The time of actuation delay of the humidity signal device was decreased by a forced stream of cabin air, which was fed to the sensitive element.

The automatic regulator accomplished discrete regulation of atmospheric humidity within an assigned range, reacting only to the lower and upper limits of relative humidity. This method of regulation required a minimum quantity of energy, permitting efficient use of the dryer under the given conditions, and preserving its absorptive capacity throughout the duration of the system's operation. The system also provided for manual humidity regulation, duplicating the operation of the automatic valve in case of breakdown and permitting an increase in the amount of air fed into the dryer. The latter was particularly necessary in case of a sharp increase in humidity resulting from intensive perspiration, and for decreasing humidity in case of an emergency increase in temperature within the cabin, thus improving tolerance of high temperatures to a significant degree.

Temperature Regulation

The system for automatically maintaining the assigned temperature regime consisted of two circuits: the air in the open space of the hermetically sealed cabin; and the liquid sealed in the heat radiator, located on the inner surface of the Vostok spacecraft. Contact of the two circuits was accomplished by a liquid-air temperature exchanger (radiator) located in the hermetically sealed cabin, indicated by "9" in Figure 1. The system of temperature regulation included a liquid-air temperature exchanger indicated by "9"; ventilator with electric motor—"9a"; automatic temperature regulator—"10, 11, 12, 13, 14"; and liquid circuit pipes. A large portion of these elements was joined in a single block, assembling the ventilator, liquid-air radiator with a device for collecting moisture condensate, and the automatic temperature regulator.

The desirable temperature in the Vostok cabin was set by the temperature sensor located on the control panel—within limits of 11°–25° C. If air temperature in the cabin varied from the setting on the sensor, an imbalance arose in the bridge circuit of the automatic regulator and a signal of a certain value passed to the amplifier. The amplifier, which magnified the signal, supplied power to the actuating mechanism, which set into motion the radiator cover. This altered the amount of air entering the liquid air radiator, which was constantly washed by a cooling agent.

Thus, when temperature rose above the assigned value, the cover opened a large fraction of the radiator's cooling surface. Cooling of air was more effective in this case, and temperature in the cabin decreased. The reverse process occurred when temperature fell below the assigned value.

The accuracy of maintaining temperature by the regulator was ±1.5° C. Effectiveness of regulator operation depended basically upon the drop in temperature between cabin air and cooling agent. The greater the drop, the higher the effect of regulation and the lesser the amplitude of fluctuations between extreme values of cabin air temperature.

The system for controlling parameters of the atmosphere in the hermetically sealed cabin of the Vostok spacecraft included such instruments as automatic oxygen and carbon dioxide gas analyzer, "23, 24, 25" in Figure 1; humidity measuring device—"15, 19, 20"; thermometers—"17, 21"; and pressure sensors—"16, 22." This system made it possible to control basic parameters of atmosphere: gaseous composition with respect to content of O_2 and CO_2 gases, relative humidity, temperature, and absolute pressure in the cabin. Indicator dials of all these instruments were placed on the instrument panel.

Provision was made in the system for observing the operation of regeneration and air-conditioning on the Vostok spacecraft, and for controlling the cabin atmosphere during flight. This was accomplished by radiotelemetric control of the basic parameters that characterize operation of the system components and the condition of the artificial atmosphere. The system for air-conditioning and regeneration aboard the spacecraft underwent a series of terrestrial experiments during its development and prior to completion of the first flight of the Vostok manned spacecraft-satellite. Test subjects participated in these experiments. Concurrently, two flight experiments with animals were conducted aboard Vostok-type satellites. All characteristics of the system were revealed during these experiments: the regime of its operation and the possible nature of change in parameters of the atmosphere depended upon the duration of the experiment and thermal regime. The final variant of the system underwent test trials for 12.5 d. Data on the nature of changes in parameters of the artificial atmosphere in this experiment are shown in Figure 2.

The system operated for nearly 5 hours during the first space flight with cosmonaut Yu. A. Gagarin. The parameters of the atmosphere varied within these limits: 750–755 mm Hg, humidity 62%–69%, temperature 19°–20° C, oxygen concentration 21%–22%, carbon dioxide gas concentration 0.4%–0.6%.

The longest flight was that of Vostok-5. Figure 3 gives the dynamics of the atmosphere indices during this flight. The figure shows that the parameters of the cabin atmosphere were within the limits of the norm providing the cosmonaut with comfortable conditions, and contributing significantly to the accomplishment of the flight mission. Hence, results of the operation of the spacecraft air-conditioning and regeneration system in both terrestrial and flight experiments showed high quality and reliability in maintaining the necessary conditions in flight.

Systems of air-conditioning and regeneration aboard Soyuz spacecraft did not differ in principle from those described. Basic characteristics were: a method of regulating the partial pressure of oxygen (introduction of the regenerating substance in portions), and transference of the primary air-drying role from chemical absorbents to heat exchangers.

The conclusion, then, is that these systems of air-conditioning and regeneration based upon the use of superoxide compounds can be successfully employed for comparatively short-term flights [23]. In prospective, long-duration flights, these systems can be utilized as emergency systems in case of breakdown of the primary regeneration and air-conditioning systems.

Food Supply

During flight preparations aboard Vostok and Voskhod spacecraft, a great deal of attention was given to developing food rations for their crews. Necessary experimental data were obtained on the amount of food substances required under conditions of acceleration, weightlessness, isolation, and temperature variation. These studies determined the basic requirements and caloric makeup of the ration, its content of proteins and other nutrients. Requirements for the ration were: full value, quantitatively and qualitatively at minimum volume and weight; appetizing qualities; toleration to long periods of storage under various conditions; and minimum content of unassimilable substances. Means of heating food under conditions of weightlessness were also needed. The requirements were worked out to a significant extent and tested under laboratory conditions on highly nutrient foods and easily assimilable preserved foods with puree-like consistency, in tubes [8, 25, 31].[2]

The food ration aboard the Vostok spacecraft consisted of two parts. The first, to conform to the planned flight duration, had caloric content of 2500-2700 kcal/d, with average protein content of 120 g/d, fats 85 g/d, and carbohydrates 300 g/d. The second, designed as a supplement in an emergency situation of increased flight duration, had caloric content of 1450 kcal/d. The composition of

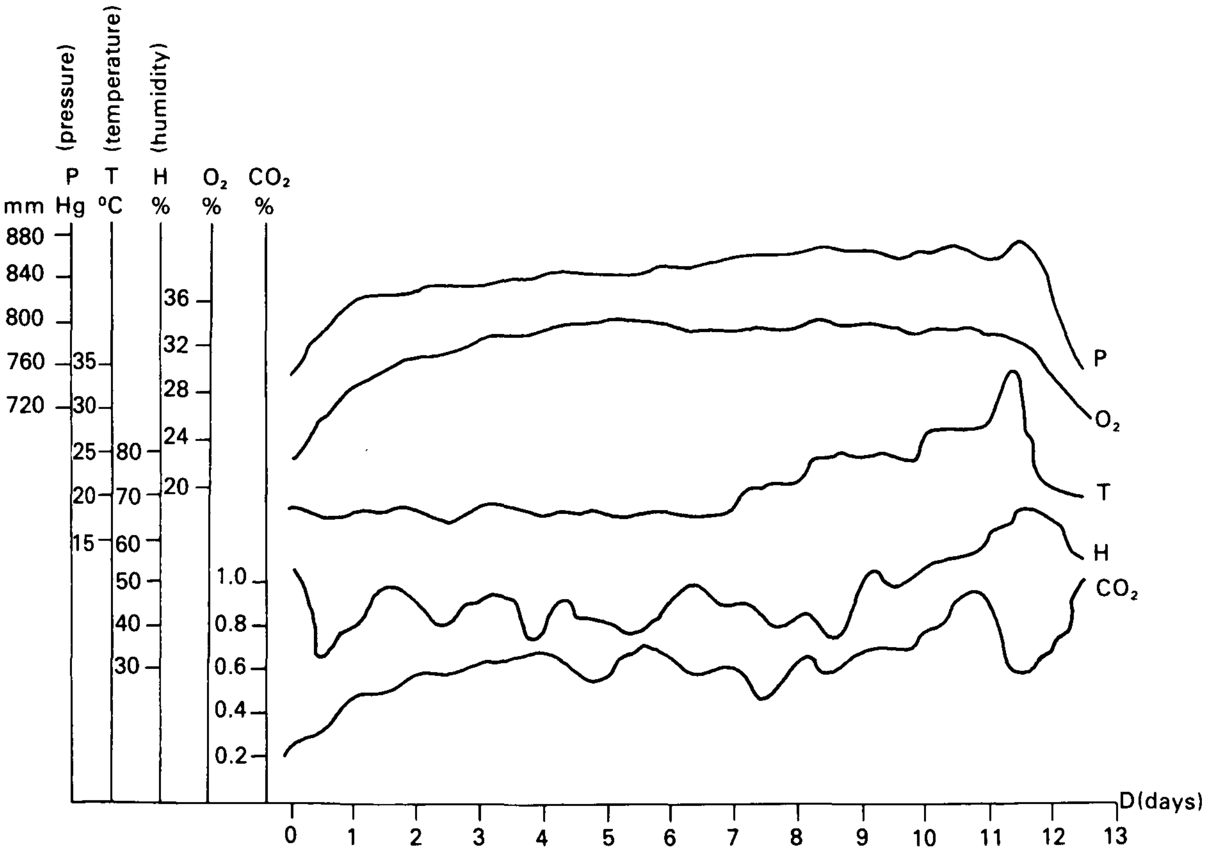

FIGURE 2.—Change in parameters of the atmosphere in a planned experiment.

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[2] See also Volume III, Part 1, Chapter 2, of this publication.

the food ration underwent certain modifications from flight to flight. The basic intent was to replace partially the puree-like canned food which basically made up the food ration of Vostok and Vostok 2; natural products were substituted on all subsequent spacecraft. The puree-like canned goods were packed in aluminum tubes with a 160-g (net) capacity, equipped with metal screw caps, and sealed with an edible resin; a canning lacquer covered the inner walls of the tubes. The stored foods were sterilized in autoclaves with an aqueous counterpressure.

The food products included small loaves of bread in the form of spheres, cured sausage, vitamin-enriched chocolate bars, and lemon drops. The solid food products were vacuum-packed in polymer sheets. The food containers for the Vostok and Vostok 2 spacecraft also had a 1-day cosmonaut ration and store of food in case of emergency.

The flights of Yu. A. Gagarin and G. S. Titov demonstrated that man is capable of eating normally in a state of weightlessness. The favorable results from a diet of puree-like foods during the first space flights and discovering the capacity for eating solid food under conditions of short-term weightlessness made it possible to expand the assortment of foods for the rations of A. G. Nikolayev and P. R. Popovich. This resulted from a broader use of natural food products with dense consistency.

A wide assortment of products was added to the ration's composition to increase nutrient value; included were meat products such as cutlets,

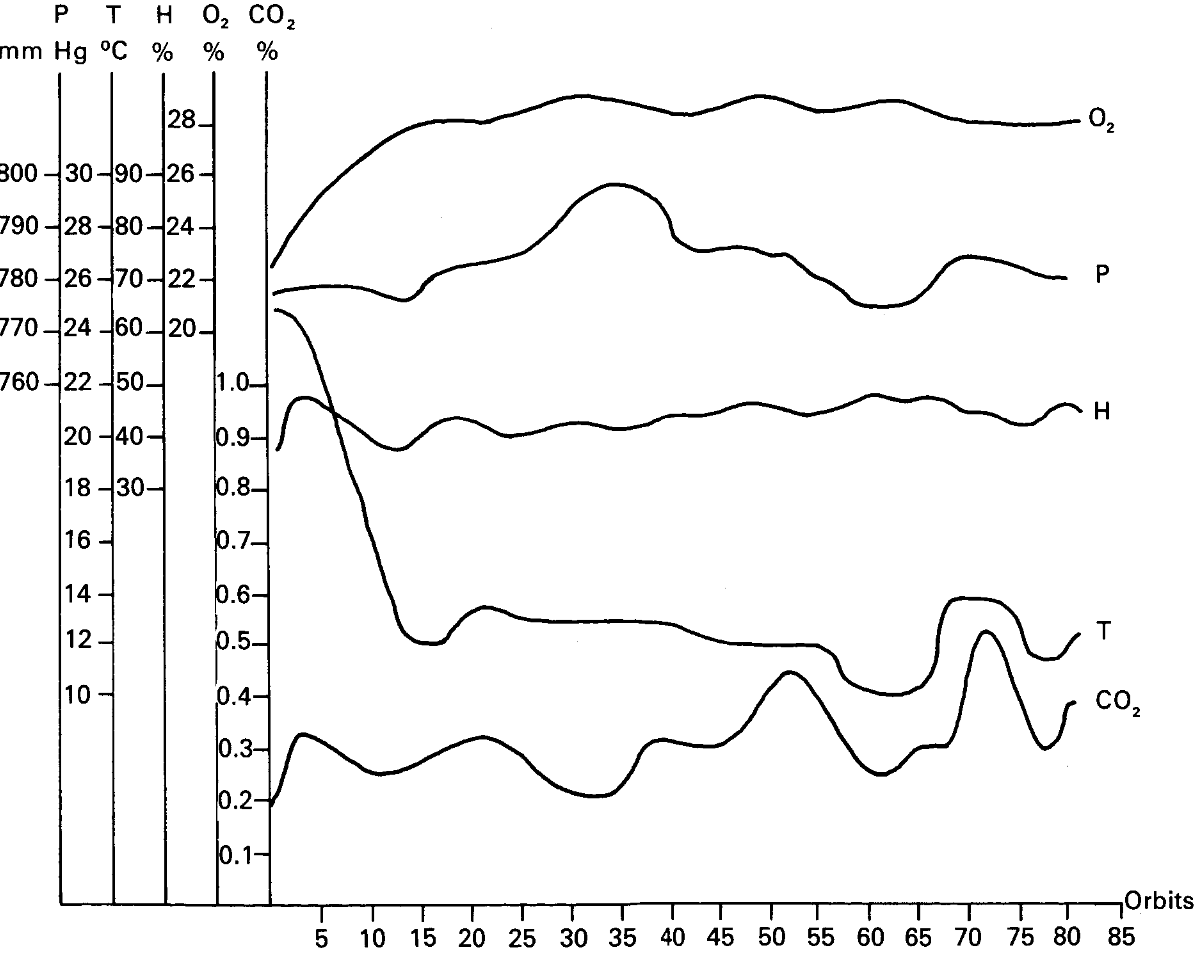

FIGURE 3.—Change in parameters of the atmosphere in the cabin of the Vostok 5 spacecraft in flight.

roast veal, chicken filet, beef tongue, meat puree, sausages with sprat, pressed and salmon caviar, vobla (dried and salted fish); fresh fruits included oranges, lemons, and apples and there were fruit juices and confections. All products were in the bite-size pieces and portions for easy and convenient consumption.

The daily ration was divided into four meals. The food value of average daily rations and their caloric content are given in Table 2.

The approximation of food rations to ordinary food during trial in space flight was highly esteemed by the cosmonauts. An additional ration with maximum biologic energetic value at minimum weight and volume was developed for maintenance of life and work capacity in case of an emergency landing in an unpopulated area. The ration, stored in the portable emergency equipment, included these dry products: milk, cream, cheese, cottage cheese, roast meat, bread, nuts, chocolate, salt, and sugar, as well as multi-vitamins. A comparison was made of mixtures of such products which took into account their caloric content combined with taste (Table 3).

During development of the food ration, its use both with and without heating was considered, as well as storage stability at various temperatures, stability of seal, and ease and stability of packaging.

Water Supply

The problem of crew water supply for the spacecraft was equally important. The use of stores of water kept on-board the spacecraft was efficient for supplying water on short-term and intermediate-duration flights. For the Vostok and Voskhod spacecraft, the following tasks were required: development and creation of a system enabling the cosmonaut to drink water under conditions of weightlessness; selection of materials for manufacturing a system; selection of a reliable water preservative; study of the capacity of preserved water to be stored in containers made of the selected material; and testing of the water supply system under terrestrial conditions and in flight experiments [23, 25, 30].

A change in water's organoleptic and physicochemical properties occurs during storage. Water in closed glass containers at room temperature deteriorates in taste qualities in 18–36 h.

Silver preparations were used for preserving water aboard the Vostok, Voskhod, and Soyuz spacecraft. The best effect was achieved with ionic silver. Water, preserved by ionic silver in concentration of 0.1 mg/l and stored in a glass container, completely maintains organoleptic and physicochemical properties for several years. The ionic silver dose has a rapid sterilizing effect for the first 3 h contact with microflora and provides practically 100% disinfection. At the same time, this dose (0.1 mg/l) is significantly

TABLE 2.—*Food Rations of Vostok Crews—Nutrient and Caloric Content*

Spacecraft	Nutrients in daily ration			
	Proteins	Fats	Carbohydrates	Average daily ration, kcal
Vostok	99.6	118.2	308.1	2772
Vostok 2	99.6	118.2	308.1	2772
Vostok 3	119.2	84.7	305.5	2529
Vostok 4	119.2	84.7	505.5	2529
Vostok 5	105.0	78.5	332.4	2526
Vostok 6	120.0	85.0	305.0	2529

TABLE 3.—*Daily Food Ration in Emergency Food Store—Chemical Composition and Caloric Content*

Product	Protein g	Fats g	Carbohydrates g	Calories, kcal
Cheese	5.0	7.0	5.7	88.0
Cream	15.0	28.6	20.0	408.6
Dried roast meat	28.6	6.8	—	180.3
Milk	12.2	13.0	19.3	253.3
Cottage cheese	8.3	11.0	10.0	117.3
White bread, dry	2.8	0.4	17.8	88.0
Nuts	2.9	8.6	1.6	93.0
Chocolate	6.0	37.9	47.6	570.0
Sugar	—	—	122.0	458.0
Vitamins, tea	—	—	—	—
Total	80.8	122.9	234.0	2316.5

lower than a toxic dose, determined by long-term experiments involving animals and man.

A drinking water supply system consists of a container calculated to hold water consumed at a level of 2.2 l/d for one crewmember. The container was made of two layers of high-strength polyethylene film. Both parts were hermetically sealed within a metal cylinder which served as the securing base of the system in a rigid container. The outside of the valve nipple was also hermetically connected by means of a pipe to the mouthpiece. The closing device of the mouthpiece made it possible to drink water only when pressure was applied to the device switch. The design of the mouthpiece provided for sterilizing and deodorizing the water entering it. To drink water it was necessary to grasp the mouthpiece in the mouth, open the closing device by pressing the button, and then suck in the water. The vacuum created in the oral cavity was entirely adequate to induce water to flow from the polyethylene container.

All cosmonauts evaluated the food ration favorably during space flights and remarked on the convenience and simplicity of using drinking water under conditions of weightlessness.

Sanitary Facilities

A sanitary device based on the principle of drawing off human excretion by means of an air stream created by the waste-removal device ventilator was used aboard the Vostok and Voskhod spacecraft. The urine and feces receiver permitted the waste-removal device to be used by a man clothed in a space suit. During this process the urine receptacle "funnel" or "spoon" for moving the rubber insets for collecting the feces with the reticulated device, for drawing off air and liquids, were placed in a special compartment after release. The design of the urine and feces receiving unit permitted simultaneous collection of urine and feces, even when the user was wearing a space suit. The collector for solid human waste was equipped with a cotton wiper for hygienic cleansing after defecation. Regular facilities were not provided for cleansing skin and other body areas, nor for cleansing the oral cavity or for shaving.

Facilities, both developed and experimental, for air regeneration and conditioning, food and water supply, and sanitation and hygiene fully supported successful space flights of Vostok, Voskhod, and Soyuz spacecraft.

CREW LIFE-SUPPORT SYSTEMS OF MERCURY, GEMINI, AND APOLLO SPACECRAFT

Atmosphere for Cabin and Crew

Mercury. The single-place Mercury spacecraft with hermetically sealed cabin having a volume of 1.42 m^3 was designed for flights with maximum duration of 28 h [18]. A life-support system weighing 38.5 kg was placed in the hermetically sealed cabin beneath the astronaut's seat. The atmosphere of the cabin was pure oxygen at a partial pressure of 264 mm Hg. The astronaut, throughout the flight, remained in the space suit which had an atmosphere analogous to that of the cabin. In the event of cabin depressurization, the partial pressure of oxygen in the space suit was automatically maintained at 238 mm Hg.

Gaseous oxygen compressed to a pressure of 527 atm in two tanks was supplied as an oxygen source in the amount of 1.8 kg oxygen per tank.

The schematic of the life-support system for the Mercury spacecraft is shown in Figure 4. There are two circuits for gas flow circulation: space suit circuit indicated by "18," and cabin circuit—"19." The first circuit, designed for oxygen supply for the astronaut, is kept at a constant level of atmospheric pressure and temperature; carbon dioxide and moisture are removed from it.

Oxygen from the primary tank, indicated by "6," passes through output regulator "5," to the space suit for breathing and cooling the astronaut's body. A complex gas mixture forms at the output from the space suit, consisting of oxygen and metabolic products (CO_2, moisture, harmful impurities). This mixture, passing through the solid particle filter, "4," and enriched with an additional amount of oxygen, is forced by compressor "8" to a harmful impurities filter (activated charcoal) "9" and then passes into two cylinders "10" containing a CO_2 absorbent—lithium hydroxide (1.18 kg each). The purified atmosphere is subsequently cooled in the evaporative heat exchanger "11," excess moisture is removed, and again enters the space suit at a temperature of 8° C.

In the aluminum evaporative heat exchanger, water under the influence of the space vacuum evaporates at a temperature of 2° C, removing heat from the atmosphere, and at a rate of 0.77 kg/h. Condensation of the water vapor occurs in the airduct of heat exchanger "11," with cooling of the gas stream, while the formed condensate is collected by a vinyl-formol sponge in water separator "12." The sponge is periodically wrung out mechanically and the water enters the condensate collector, where it remains. The reserve oxygen-supply system, using tank "7," is actuated manually in the presence of malfunction in the basic oxygen supply life-support system and during reentry of the spacecraft. Oxygen then passes directly into the space suit in an amount adequate for respiration and body ventilation and also through a valve into the cabin. The other oxygen supply life-support aggregates do not operate in these cases.

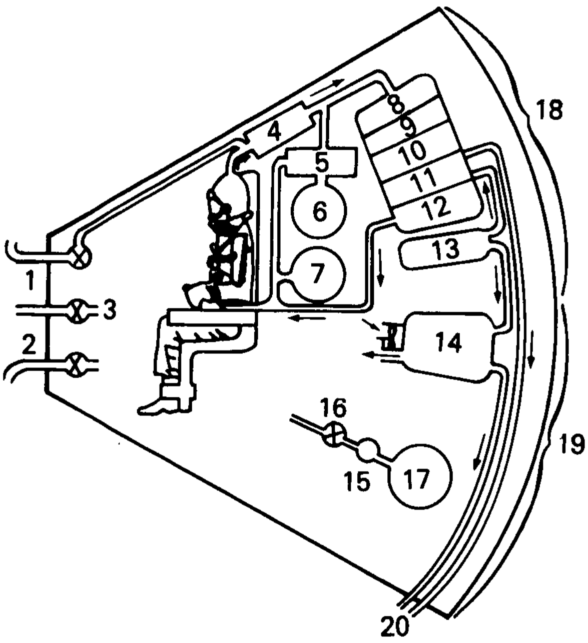

FIGURE 4.—Life-support system of Mercury spacecraft. 1, input assembly of the snorkel; 2, output assembly of the snorkel; 3, valve for cabin pressure release; 4, solid particle filter; 5. oxygen expenditure regulator; 6, primary oxygen tank; 7, reserve oxygen tank; 8, compressor; 9, activated charcoal; 10, lithium hydroxide; 11, space suit heat exchanger; 12, water spearator; 13, water for the evaporative heat exchanger; 14, cabin heat exchanger; 15, barometric valve; 16, pressure regulator; 17, oxygen tank used for oxygen at launch; 18, space suit circuits; 19, cabin circuits; 20, exhaust of water vapor from spacecraft.

The second circuit is designed to maintain an assigned partial pressure of oxygen and cabin temperature, as well as gas circulation under conditions of weightlessness. The oxygen supply is maintained only from the primary tank, "6." The cabin circuit has no devices to remove metabolic products since they are absent in the cabin and the astronaut is constantly in his space suit. In this circuit there is an evaporative heat exchanger "14," which feeds a stream of cool oxygen into the cabin to maintain its temperature at 21 ± 3° C.

The astronaut, during launch, uses oxygen for breathing from tank "17," while during descent to Earth, a barometric valve opens ventilation ducts "1" and "2" at an altitude of 6000 m. Through these ducts, the astronaut receives ventilation for his space suit, and the spacecraft is repressurized by atmospheric air during final descent and after landing on water.

The life-support system during all flights of the Mercury spacecraft worked satisfactorily. The only exception was regulation of air temperature in the space suit. Manual regulation of small water expenditures (0.77 kg/h) in the temperature exchanger of the space suit turned out to be a very complex task.

Gemini. The life-support system of the Gemini spacecraft was designed for life support of two astronauts for 14 d in a hermetically sealed cabin having a volume of 2.3 m^3. The system included elements providing for astronaut oxygen supply during ejection from the cabin in an emergency, for cabin depressurization prior to astronaut extravehicular activity (EVA), and for repressurization of the cabin following astronaut return from EVA. It also provided for cooling of radioelectronic and other heat-producing equipment by means of continuous circulation of liquid coolant. These additional tasks significantly complicated the life-support system. Thus, if the Mercury life-support system contained 49 major components, in the Gemini system this number increased to 114, and the life-support system increased in weight by more than 100 kg.

The basic points distinguishing this system from the Mercury life-support system were:

- integration of a closed system of liquid coolant for the atmosphere and equipment with the space radiator;
- linkage of the life-support system with the hydrogen-oxygen electrochemical generator (fuel cell) was carried out as a source of electrical energy and drinking water [12].

The fuel cells produce water in the amount of 225 g/h, suitable only for hygienic requirements and for the evaporative heat exchanger. The basic components of the life-support system, together with stores of gaseous oxygen were placed in the sealed cabin. The stores of liquid oxygen for breathing and fuel cells, the cooling system with the space radiator, the pumps, and the evaporative heat exchanger were placed in a removable compartment attached to the support module that was removable upon reentry into the atmosphere.

The schematic of the Gemini spacecraft life-support system is given in Figure 5. The basic

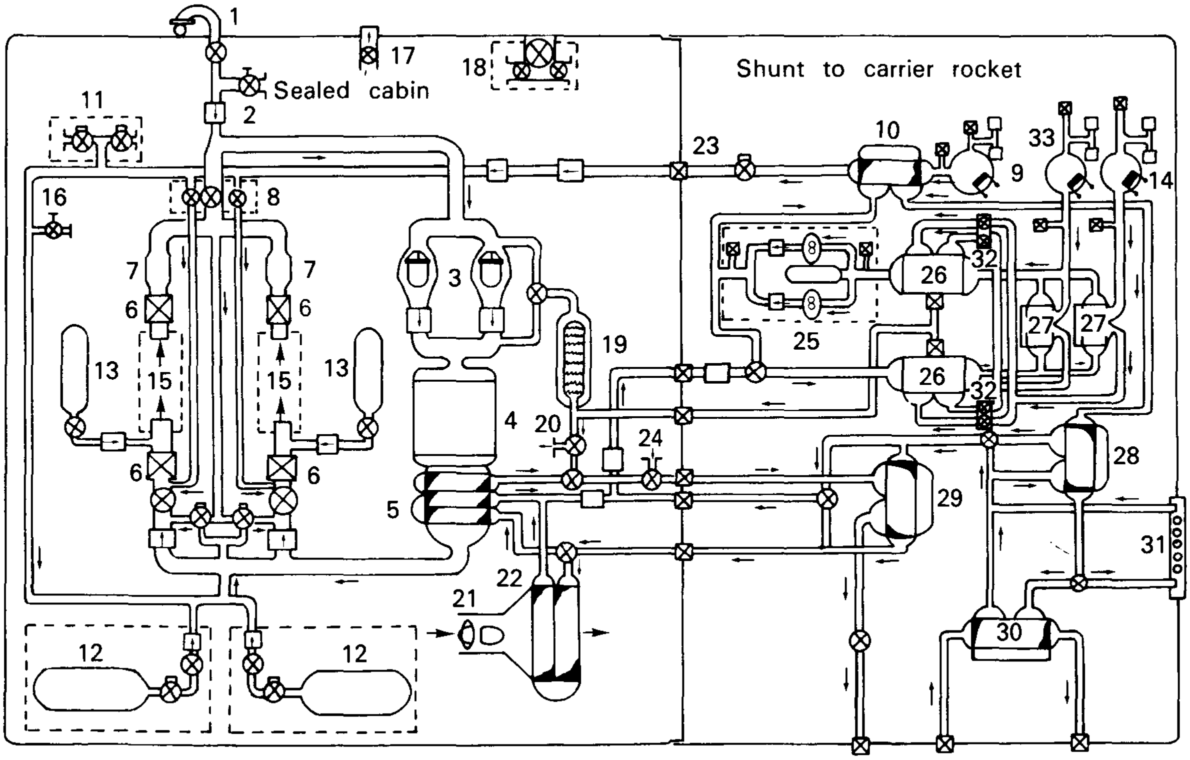

FIGURE 5.—Life-support system of Gemini spacecraft. 1. snorkel valve; 2, recirculation valve; 3, compressors; 4, absorber for CO_2 and odors; 5, heat exchanger and water separator for space suits; 6, nozzle for space suit hoses; 7, solid particle filters; 8, valve for regulating expenditure and compartment for oxygen supply from reserve tanks; 9, main oxygen tank; 10, heat exchanger for heating oxygen; 11, duplicate pressure regulator in cabin; 12, reserve oxygen tank; 13, system for supplying oxygen during ejection; 14, container of liquid oxygen; 15, two space suits; 16, valve for repeat cabin pressurization; 17, cabin pressure relief valve; 18, bilateral reduction valves; 19, water tank; 20, valve for drinking water; 21, cabin ventilators; 22, cabin heat exchanger; 23, quick disconnect and self-sealing unit; 24, water pump valve for cabin; 25, block of fuel cell pump; 26, fuel cell; 27, heat exchanger; 28, regenerating heat exchanger; 29, evaporative heat exchanger; 30, heat exchanger for cooling on the Earth; 31, space radiators; 32, duplex pressure regulator for hydrogen and oxygen supply to fuel cells; 33, container of liquid hydrogen.

stores of liquid oxygen for breathing, stored at super critical pressure, were kept in tank "9" (weight of oxygen for a 2-d flight—6.9 kg; for a 2-wk flight—47.2 kg). The cold oxygen, passing from the tank into the system, is heated in heat exchanger "10" to 10° C, and then sequentially reduced to a pressure of 264 mm Hg and supplied to the space suit at the rate of 38 g/h man^{-1}.

Parallel to the primary oxygen tank, two reserve tanks "12" containing gaseous oxygen were included. These were under a pressure of 340 atm. The tanks, equipped with an individual system of regulation of supply, contain approximately 60 kg oxygen which would supply the astronauts in an emergency and during landing for over 2 h. The emergency oxygen system for abandoning the spacecraft at altitudes up to 21 km consists of tanks "13" mounted on the lower side of the ejection seat.

The space suit's circuit provides for body cooling, inflation of space suits, and removal of CO_2, moisture, and harmful impurities from the atmosphere. Space suit ventilation at a rate of 0.65 m^3/min is provided for by centrifugal ventilators "3." Following removal of the atmosphere from the space suit it passes through solid particle filter "7" and cartridge "4" containing activated charcoal and lithium hydroxide. The purified oxygen then is dried and cooled in the combined heat exchanger-separator "5," where moisture is condensed, and with the aid of wicks is drawn off into a condensate collector, while the oxygen returns to the space suit. The cabin circuit includes a vaned heat exchanger "22" and a ventilator "21" by which ventilation of the cabin is accomplished at a rate of 2.5 m^3/min. The cabin circuit also provides a dual cabin pressure dump valve "18," and a cabin pressure regulator "11" to automatically maintain cabin pressure; a manual cabin pressure dump valve "17," and a manual repressurization valve "16," were used for manual control of the cabin pressure. Planned temperature in the cabin during orbital flight is about 27° C, while partial pressure of oxygen is 264 mm Hg. The store of oxygen in the primary tank was calculated to take into account depressurization occurring three times during flight.

Supply of oxygen during launch and after separation of the life-support system in the support module is accomplished only from reserve tanks "12." At an altitude of approximately 8 km, when outside pressure is equal to pressure in the cabin, valve "18" opens to permit free access of outside air to the cabin. At an altitude of 6 km the breathing ducts "1" are manually opened; these provide air from the atmosphere into the space suit circuit and ventilator "3" switches automatically at that time to obtain current from the storage battery.

Apollo. The life-support system of the Apollo spacecraft was designed for a flight with three astronauts to the Moon with a duration up to 14 d. The size of the hermetically sealed cabin (command module) was 7.65 m^3 [24].

All basic subsystems in the Apollo spacecraft are duplicated to increase the system's reliability, and good access to the subsystems is provided to facilitate repair or replacement. The atmosphere of the cabin is made up of nearly 100% oxygen which is at a partial oxygen pressure of 259–264 mm Hg. The astronauts in flight can work either in, or without, space suits.

The life-support system of the Apollo spacecraft is shown in Figure 6. The basic stores of liquid oxygen for breathing are concentrated in tanks "6."

The space suit circuit has two compressors "24," each having a flow capacity rating of 1 m^3/min. The gas flow from the space suits enters the solid particle filter "17" and then cartridge "19" for absorption of CO_2 and harmful impurities. Replacement of the cartridges is provided for each 12 h of operation. During the astronauts' stay in the cabin without space suits, removal of CO_2 and harmful impurities from the atmosphere is accomplished by the same cartridges with valve "16" open.

The cabin circuit also has two ventilators, "25," and a liquid heat exchanger "28" working on antifreeze (a water-glycol mixture), which maintains temperature in the cabin within the limits of 21°–27° C. In the event of cabin depressurization from cabin puncture, a supply of oxygen is provided for the cabin at a rate of 0.32 kg/min through emergency valves "1." This permits the maintenance of cabin pressure at 181 mm Hg for 15 min, if the puncture in the cabin skin is 13 mm diam or less.

The astronaut standing watch in the cabin wears his space suit; the other two crew members may doff their space suits. Oxygen in this case is supplied to the space suit from the cabin through a control valve. If the cabin depressurizes and all three astronauts are in space suits, they can use either the automatic or manual control for the space suit oxygen-supply system.

In the first case, oxygen pressure at the input to the space suit ventilator is maintained at a level of 194±13 mm Hg by the aid of distributing reducer "3." In the second case, the astronaut controls a calibrating valve installed in the oxygen-supply line running from tanks "6" and before it enters distributing reducer "3." The interaction of subsystems of the thermoregulating system can easily be traced using the schematic of Figure 6.

The circuit of the life-support system of the lunar module is designed to supply oxygen and water for two astronauts for 49 h. The astronauts, during this time, make their landing on the Moon, investigate its surface, and return to the command module awaiting them in lunar orbit. In the lunar module (volume 6.65 m^3), the astronauts

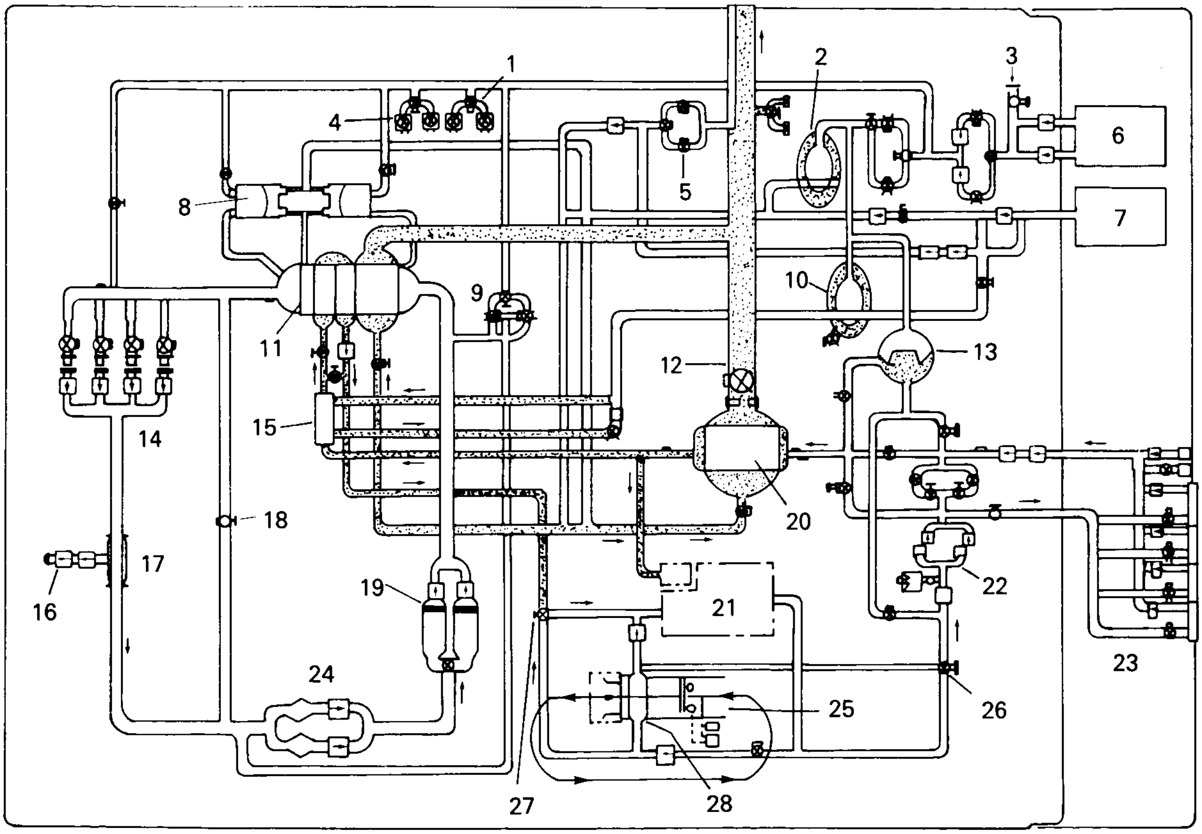

FIGURE 6.—Diagram of life-support system of Apollo spacecraft. 1, emergency valve for cabin oxygen supply; 2, potable water tank; 3, main distributing reducer for high pressure oxygen; 4, oxygen cabin pressure regulator; 5, water drainage valve; 6, oxygen tank; 7, supply of water from fuel cells; 8, cyclic water accumulators; 9, oxygen expenditure regulator; 10, drinking water tank; 11, space suit heat exchanger; 12, drinking water pipe; 13, glycol reservoir; 14, combined connector for space suit air lines; 15, drinking water filter; 16, valve to permit cabin air to enter or leave space suit ventilation circuit; 17, cartridge for absorbing solid particles; 18, space suit bypass valve; 19, cartridges for absorbing carbon dioxide and odors; 20, glycol water evaporator; 21, electronic equipment thermal load cold plate; 22, glycol pump; 23, radiator; 24, space suit compressor; 25, cabin ventilator; 26, valve for regulating input temperature; 27, valve for regulating output temperature; 28, cabin heat exchanger.

remain at all times in their space suits; but, according to the program, they have the capacity to remove their gloves and helmets for brief periods.

A schematic of the life-support system of the Apollo spacecraft lunar module is shown in Figure 7. The atmosphere subsystem provided for supply of oxygen with the aid of ventilators

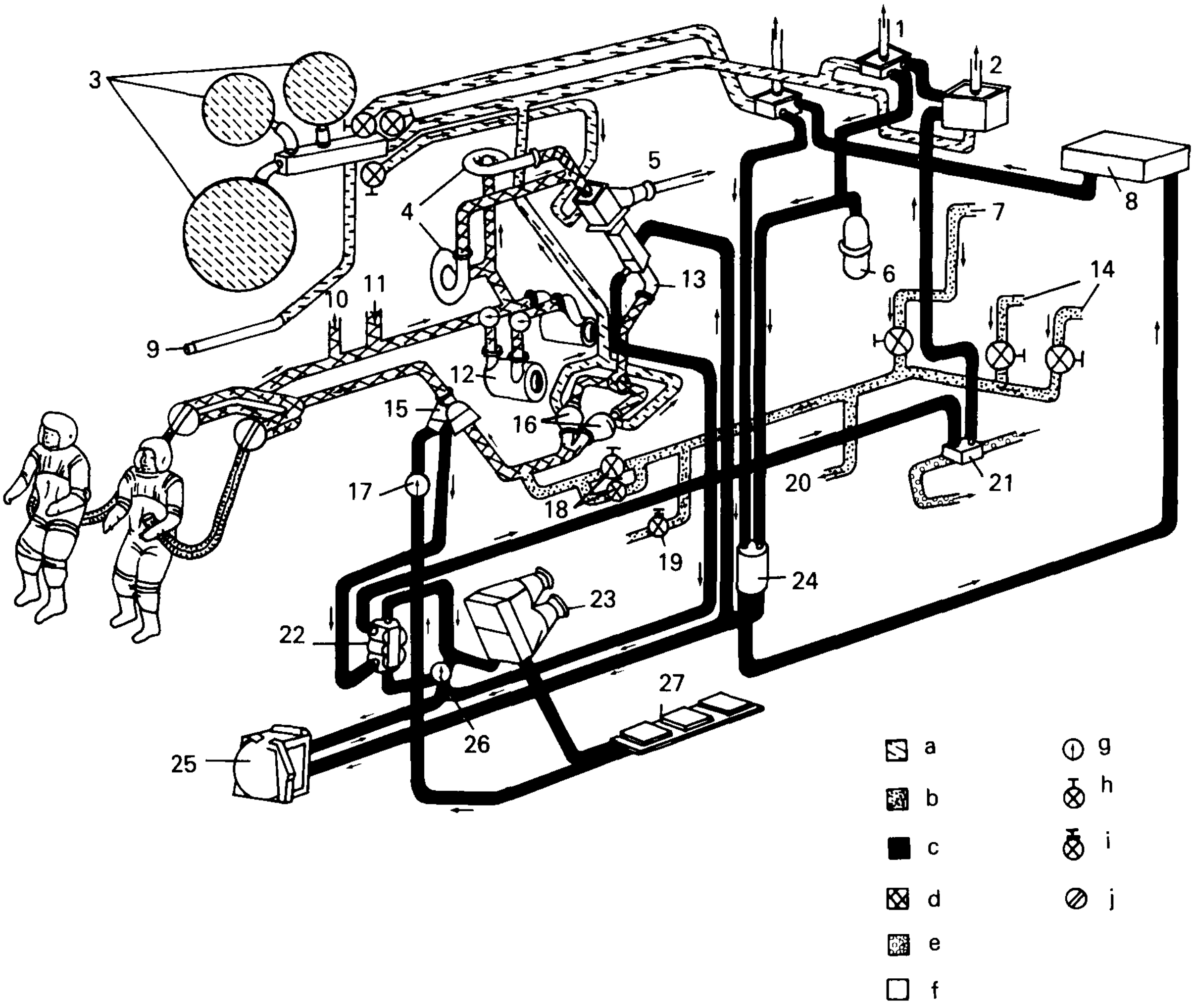

FIGURE 7.—Life-support system of the lunar module of Apollo spacecraft. a, water; b, "fresh" oxygen; c, glycol; d, oxygen; e, freon; f, vapor; g, mixer valve; h, compartment (manual) valve; i, electromechanical (manual) valve; j, compartment valve. Number key: 1, water evaporator; 2, sublimator for cooling glycol mixture; 3, water tank; 4, space suit ventilator; 5, sublimator for cooling oxygen; 6, glycol mixture accumulator; 7, supply of oxygen from tanks located in landing stage; 8, electronic equipment for reserve guidance system; 9, nozzle for adding water to portable life-support system; 10, exit for oxygen to cabin; 11, entry of oxygen from cabin; 12, cartridges for absorbing CO$_2$; 13, heat exchanger for cooling glycol mixture with oxygen; 14, supply of oxygen from tanks located in takeoff stage; 15, heat exchanger for cooling glycol mixture with oxygen; 16, centrifugal water separator; 17, valve regulating space suit temperature; 18, manual valves of module oxygen; 19, valve for emergency supply of oxygen to cabin; 20, nozzle for filling portable life-support system with oxygen; 21, freon evaporator for cooling glycol mixture on the Earth; 22, regenerating heat exchanger of glycol mixture; 23, cabin heat exchanger with ventilator; 24, pump block of glycol system; 25, guidance system; 26, cabin temperature regulator; 27, cooling layers.

"4," first to the space suits and then to the cabin through nozzle "10."

The astronaut's space suit was disconnected from this subsystem during his exit onto the surface of the Moon, where he operated on the portable life-support system, the charge of oxygen and water of which was derived from the primary life-support system through nozzles "20" and "9." The gas stream from the space suits subsequently passed into the solid particle filter, and cartridge "12" with its CO_2 absorber and absorber for harmful impurities, then to heat exchanger "5," where it was cooled by a water-glycol mixture to 4.4° C. The condensate of water vapor was removed from the gas stream by two centrifugal separators, "16." Heat exchanger "22" was used subsequently to heat the atmosphere and add oxygen to it to restore pressure; heat exchanger "22" was infused with a heated glycol mixture.

The circulation of gas in the cabin was accomplished by ventilators "23" at a rate of 5.66 m^3/min in each operating ventilator. The oxygen subsystem consists of four spherical tanks in which gaseous oxygen is stored at a pressure of 70 atm (three tanks) and 210 atm.

The subsystem supplies the astronauts with oxygen for breathing and compensates for possible loss of gas into space caused by leaks. The design permitted a leak rate of 90 g/h at cabin pressure of 259 mm Hg. It provides additionally for a fourfold replacement of cabin atmosphere after exit of the astronauts, and for five chargings of space suit portable life-support systems.

During short-term flights of Mercury spacecraft, the supply of food products was minimal; primary attention was paid (as it was for Vostok 1 and 2 flights) to study of the physiology of swallowing under conditions of weightlessness. The use of feeding tubes, it was noted, significantly eased eating under conditions of weightlessness. A method of swallowing dehydrated pieces of products which were moistened during mastication was tried during later flights of Mercury [11]. These products were stored on-board in four-layered vacuum-sealed plastic containers.

The observations of Mercury spacecraft astronauts indicated that longer flights would require the use of food products more nearly like those in normal terrestrial diets. The Gemini astronauts were provided with dehydrated foods; the addition of cold water to the products gave them color, consistency, shape, and taste similar to that of the fresh product. These products were also significantly lighter than the natural ones and more stable during long-term storage under normal conditions.

The Apollo astronauts, like their predecessors aboard Mercury and Gemini spacecraft, used prepared dehydrated food. But the diet was more varied (beef, chicken, eggs, and bacon), and to restore the products both cold and hot water were used. The food products for Apollo crews were stored in plastic containers similar to those developed for Gemini spacecraft, which used a feeding port at one end of the container and a valve for supplying water at the other end. A special supplying "pistol" was used to add water to the container. The calorie content of the food ration, 2500 kcal, was entirely adequate.

Parts of the dehydrated products were in small pieces which could be placed in the mouth without breaking up, and were packed in polymer wrap. The broken briquettes were wrapped in edible containers. These products were used without preliminary restoration (rehydration). The other dehydrated products were packaged in bags (tubes) without a wrapper. On one end of the tubes was a device through which water was supplied, on the other was a device through which the astronaut could use the food rehydrated by either hot or cold water.

Packages were of a four-layer wrapper (polyethylene, fluorohalocarbon, polyester, and polyethylene), in which dehydrated food was rehydrated. This multilayer package was not permeable to gases and was very elastic. Because of the elasticity of the material, the astronauts could squeeze the sides of the package forcefully to force out the food. However, this led to loss of food structure and extended the time required to eat; also 10%–15% of the food was left unusable in the package.

The same rations were used on Apollo 7 and 8 flights as those used on Gemini. The single exception was the introduction of natural products into the menu of the Apollo 8 crew.

Significant changes were made for a number of reasons in both the form and packaging of food products during the 6-month period of Apollo 9, 10, and 11 flights. Food used in the earlier flights was inadequate to maintain energy balance, notwithstanding the diminished expenditure of energy under conditions of weightlessness. Crewmembers noted an absence of hunger. The preparations for and the process of eating occupied too much time and required a great deal of effort. Water from the electrical fuel cell, used to restore the dehydrated products, gave an unpleasant taste and contained a large amount of undissolved hydrogen and oxygen. The packaging frequently ruptured during food rehydration. Crewmen emphasized the need for food products which were familiar with regard to external appearance, taste, and method of preparation.

The new food consisted basically of sterilized meat dishes with a high moisture content (60%–70%), which were packaged so that after opening the container, they could be eaten in the ordinary way (with spoon or fork). Packaging was modified for dehydrated products so that following rehydration, they could be eaten with a spoon. Tasty substances—powders, fruits, and sweets—were added to the food ration, which had an average moisture content of 10%–30%. Sandwiches, prepared with fresh bread and sterilized in a thermal chamber under increased pressure in order to maximally preserve the structure of the product, were also added. Meat products and sandwiches were packaged in rigid or aluminum containers.

Products not requiring rehydration simplified the preparing of food and saved a significant amount of time. The problem of package rupture in preceding flights was eliminated, thanks to design changes and additional methods of controlling quality. Members of the spacecrews rated all the new forms of food products and packaging highly. The amount of food required during the flights did not increase, since the astronauts ate, primarily, the new products which were substituted for the original products.

Water Supply

Water supply for Mercury spacecraft crews was provided only from on-board stores. The creation of electrical fuel cells for flights in the Gemini and Apollo programs simplified the problem of water supply to a great extent. Water from the fuel cells could be used for drinking with the use of appropriate filters. Inasmuch as Gemini spacecraft had fuel cells which were used without filters, water from this source was not used for drinking.

The water supply system for Apollo crews was from three fuel cells and on-board stores. Each of the three fuel cells produced 230 g water/h under normal operating conditions. The water supply system was placed in the command module; it included the gas-liquid separator for removing dissolved hydrogen (based on microporous palladium and silver), a pipe along which water flowed from the support module into the command module, a distributing panel, and a container for storing water.

The second source of water was located in both the command and lunar modules. In the command module, the stores of water were used in case of breakdown of the fuel cells and to serve possible increased requirements of the crew. Water storage and purification were carried out by means of a compound based on chlorine + sodium hypochlorite and monoderivatives of sodium phosphate ($NaOCl + NaH_2PO_4$). In the lunar module, water was stored in three containers. The primary container held 181 l distilled water, preserved by iodine (10 mg/l). This container supplied water to the astronauts during their descent to the lunar surface, also during their stay on the Moon. Water used during the period after blastoff from the lunar surface was stored in two containers having a volume of 18.1 l.

Facilities for personal hygiene on Mercury, Gemini, and Apollo spacecraft were quite simple. The nature of the flights permitted the ejection of liquid waste products (urine) from the spacecraft. Feces were collected in plastic bags containing charcoal preservatives. Hygroscopic pads (dry and moistened cloths) were used for hygienic body cleansing. Teeth were cleaned with ordinary toothbrushes and toothpaste. The crew used safety and electric razors with vacuum collection of cut hairs in shaving.

An examination of the life-support systems of the Vostok, Voskhod, Mercury, Gemini, Soyuz, and Apollo spacecraft indicates the variety of possible solutions in achieving high reliability, effectiveness, and economy.

The selection of life-support systems is determined by general design solutions of spacecraft and their cabins, by preceding traditions and experience of industry in solving similar problems, and by attention in the USSR and the USA given to various criteria on the basis of which the systems are selected. Despite certain differences, the solutions are similar for many subsystem problems, such as the food and water supply and personal hygiene. The systems developed so far can serve as prototypes for prospective craft making short flights.

Life-support systems using partial regeneration of expended materials can be effective. however, even during flights of intermediate duration (1 month). This pertains both to regeneration of carbon dioxide sorbents (in the orbital station Skylab, such a system has already been successfully employed), and to the regeneration of water from the condensate of atmospheric moisture. A further increase in flight duration renders systems based upon stores of substances consumed by man infeasible.

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Chapter 9

LIFE-SUPPORT SYSTEMS FOR INTERPLANETARY SPACECRAFT AND SPACE STATIONS FOR LONG-TERM USE[1]

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The impressive successes of the United States and Soviet manned space flights have all been scored in the brief period of slightly more than one decade. All these missions employed expendable life-support systems because the weight of stored supplies was not prohibitive for the brief periods involved. Small laboratories have been put into Earth orbit, and larger space stations and extended space exploration are contemplated. The first of these missions, the Soviet Salyut, was launched in April 1971 and remained in orbit for nearly 6 months; it was manned for more than 3 weeks of this period. The longest of the US Skylab missions, which was launched in mid-November 1973, lasted 84 days. Experience gained during such missions will be available for application to the development of longer-term stations.

Regardless of when extended missions come about, life-support systems will have to function for far longer periods than at present, and must therefore be highly reliable. Since carrying expendable supplies, particularly water and oxygen, will quickly become disadvantageous from a weight standpoint, long-term missions must employ a method of regenerating vital supplies. This chapter is concerned with life-support systems for missions of 1 to 2 years or longer, with periodic resupply and crew rotation.

Life-support systems for long-duration missions undoubtedly will regenerate certain of the elements needed to support life. The systems being developed are referred to as integrated regenerative life-support systems because they are configured so that the byproducts of one system (including mass) become useful material for another.

When the system is completely closed, all matter is theoretically conserved. This cannot, in the foreseeable future, be fully achieved, since it is virtually impossible to design a leak-free vehicle, nor will it be possible to produce all of the nutritional requirements on-board. Nevertheless, it is toward this model that designers strive. At the most advanced level, these systems would regenerate all expendables except food. Regenerating food does not appear feasible or, for that matter, necessarily desirable for near-

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future missions. In their basic form, integrated regenerative life-support systems imply regeneration or reclamation of water and the principal atmospheric gases, and elimination or disposition of waste products.

SYSTEM SELECTION CRITERIA

The process of selecting a life-support system for long-term use in space is exceedingly complex. Many variables are involved; some are mutually exclusive. For example, a system that is theoretically most reliable may not necessarily be one with reasonable weight-, volume-, and power-requirement characteristics. Mission factors, including mission length, potential for resupply, abort criteria, power, cooling availability, and crew complement, all affect selection criteria. A change in any or all of these elements necessarily impacts the choice of a life-support system.

A complicated interplay of factors is involved in choosing a life-support system for long-term space missions; the selection criteria in Table 1 are suggested as representing a realistic framework within which to identify acceptable systems. The factors involved, listed in order of importance, are grouped at three levels of priority.

First-Order Selection Criteria

The sine qua non for a life-support system designed to maintain man in space for more than 1 year is a certain degree of regenerative capability, particularly the regeneration of water and atmospheric gases. The elements to be regenerated and to what extent depend on numerous factors, which will be discussed.

The life-support system of choice must meet the minimum technical requirements for performance, reliability, and safety. The system must perform its intended functions with an acceptable record for mean time between failure; in short, it must be reliable.

Reliability can be achieved in a number of ways. Space missions so far have guaranteed reliability by means of redundancy: each system has one or more backup systems which are automatically activated or can be activated in the event of failure of the primary system. With increasing length of mission and crew size, redundancy becomes a less acceptable mode of achieving reliability because of the weight and other penalties involved. In the future, reliability of long-term life-support systems will depend more heavily upon system maintainability. Ease of maintenance, therefore, becomes an important selection criterion. Redundancy is, of course, not eliminated; it is merely minimized by designing for maintainability.

Design for maintenance can be accomplished in a number of ways. Figure 1 lists some of these. Since the object of system maintenance as an approach to reliability is to minimize the weight involved in achieving reliability through redundancy, commonality of parts is a key element in design for maintainability. Spare parts such as valves, regulators, couplings, gages, meters, and so forth should be maximally interchangeable, not only to restrict the number of spares required but also to simplify the overall maintenance task. Equipment should be laid out in a manner so that the operator has direct access to the component that failed. Wherever possible, modular construction is desirable because it reduces the time required for maintenance. Modularity may, however, carry with it some weight penalty. Design for maintainability must also include a built-in system for detecting a

TABLE 1.—*Selection Criteria for Semiclosed Life-Support Systems*

First order	Second order	Third order
Regenerative capability (gases, water)	Crew stress	Commonality
Performance	Functional packaging (modularity)	Interfaces
Reliability (redundancy, maintainability)	Total equivalent weight	Volume
Safety		Power (type, amount)
Confidence/development status		Crew training, acceptability
		Resupply
		Controllability
		Cost

system malfunction and isolating the malfunction; these systems must be compatible with other on-board checkout systems. It must, of course, be fail-safe. In the final analysis, the weight penalty paid for modularization may represent a satisfactory trade-off for it not only reduces the maintenance time required for repairs but also reduces the crew skills needed, thus minimizing stress on crewmen responsible for maintenance activities.

A single component, a manual shutoff valve, was specifically conceived for space station use and may be deployed at as many as 80 different locations throughout a space station of the type considered here. Other components, such as quick disconnect and fans, may be used in as many as 6 to 98 different locations [2].

The development status of a life-support system or subsystem must be advanced to where its performance is proved reliable, its failure rate is acceptable, its failure modes are known, and its required maintenance times are minimal. Problems of degradation, contamination, and sensitivity of interfacing equipment or systems must be taken into account in the system design. Confidence in the system is probably the overriding selection criterion; it can outweigh other variables such as maintenance time, weight, and the like.

Many ground-based tests, both manned and unmanned, have been conducted to test the reliability of life-support equipment; a 90-d manned test was conducted in 1970. In this test, the feasibility of performing maintenance and repair operations was closely examined. The life-support system was regenerative for atmospheric gases and water. No attempt was made to close the food loop, an issue which will be discussed further in the final section of this chapter. Table 2 summarizes the maintenance and repair activities required during the test, including the number of items needed to perform the maintenance operations and time required. The life-support units listed are discussed elsewhere in this chapter and in other chapters in this volume.

Second-Order Selection Criteria

A selected life-support system must, to the fullest extent possible, minimize stress on the crew. Excessive unscheduled maintenance tasks, excessively long scheduled maintenance time, difficulty in failure detection or repair, operating instability, and any other factor associated with the system that produces either psychologic or physiologic stress on the crew are undesirable. If these stresses are too great, and redesign is not possible, the candidate system should be eliminated. The time the crew must give to the maintenance or monitoring of life-support systems can be minimized by a degree of automation. Such automation should include design for manual override should this be desirable, but it must always be fail-safe. Until a practical answer is found to gravity simulation in space, all life-support equipment must be designed for zero-G operation.

Modularity (already mentioned) is part of a functional packaging scheme which not only

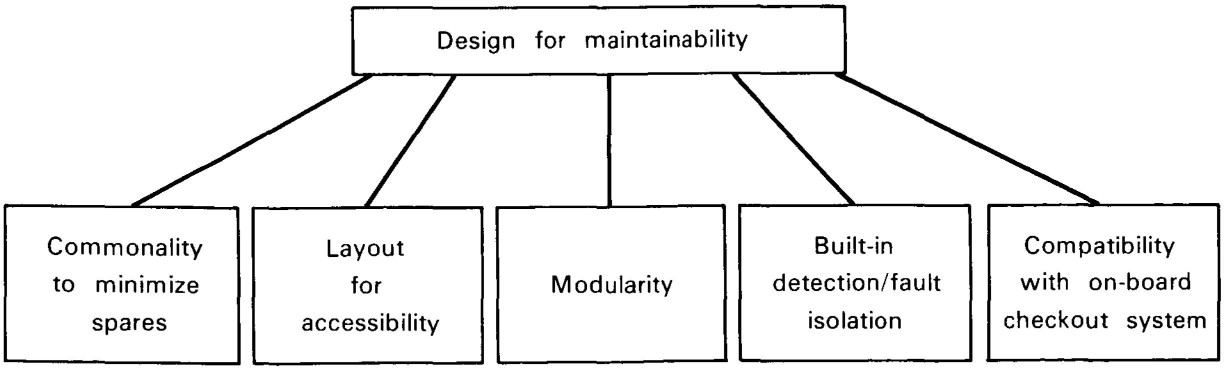

FIGURE 1.—Elements in designing for maintainable life-support systems.

facilitates repair but also increases the flexibility of a life-support system, so that the system can be enlarged or reduced easily to accommodate crews of various sizes. Total equivalent weight of this system, it has been noted, must be considered against a background of numerous factors: maintenance time, mission duration, crew complement, morale considerations, and many others. Determination of the total equivalent weight of the system must include: (1) fixed weight, (2) fluid trapped in lines, (3) spares, (4) expendables, (5) electric power penalty, (6) heat power penalty, and (7) heat rejection penalty.

Third-Order Selection Criteria

Items that rank third in importance in selecting a life-support system are enumerated in Table 1. The order of listing, however, does not represent priority designation; importance varies from mission to mission. Several of these factors have already been discussed in connection with other selection criteria, and most speak for themselves. Concerning power, a word of amplification is required. In considering any of the available power sources, including electric, thermal, and radioisotope dynamic power systems, the amounts and qualities of power must be examined. Low power, low amperage, and a constant demand are desirable. While thermal power is available at lower weight penalties than electric power, it imposes interface difficulties. A somewhat higher electric-power penalty can eliminate some liquid line plumbing and thus should probably be considered.

In actual practice, then, life-support system selection takes place in a general way. As system concepts are identified which appear better

TABLE 2.—*LSS Maintenance and Repair Summary*

Life-support unit	Repair		Maintenance		Unit totals	
	Items	h	Items	h	Items	h
Waste management:						
Commode[1]	2	0.7	2	5.5	4	6.2
Urine collector	8	14.3	0	0	8	14.3
Water management:						
VD[2]-VF[3]	20	19.9	1	4.0	21	23.9
Wick evaporator	0	0	4	0.3	4	0.3
Humidity control	3	1.2	30	15.0	33	16.2
Potable multifilter	3	5.3	1	0.3	4	5.6
Wash water recovery	18	4.1	1	0.7	19	4.8
Atmosphere purification:						
Solid amine concentrator[1]	33	30.1	14	3.3	47	33.4
Molecular sieve concentrator	7	3.7	1	0.7	8	4.4
Toxin control	0	0	0	0	0	0
Thermal control	0	0	0	0	0	0
Atmosphere supply and pressurization:						
Sabatier reactor	20	18.6	0	0	20	18.6
Electrolysis (Allis-Chalmers)[1]	47	26.5	0	0	47	26.5
Electrolysis (Lockheed)[1]	16	83.2	0	0	16	83.2
Two-gas control[1]	0	0	0	0	0	0
Mass spectrometer[1]	0	0	5	4.1	5	4.1
Baseline two-gas control	0	0	0	0	0	0
Baseline two-gas sensors	0	0	1	0.5	1	0.5
Life-support system totals	177	207.6	60	34.4	237	242.0

[1] Advanced subsystem unit.

[2] VD=vapor diffusion.

[3] VF=vapor filtration.

suited for long-term missions than those currently available, these, in turn, receive development emphasis so that the best possible system will be available in sufficient time for a given mission. Choice of the optimum life-support system for a particular mission, a selection process that takes place well in advance of projected launch dates, takes into consideration the interplay of mission objectives, mission duration, crew complement, power supply systems, man-machine interfaces, and the like. System performance, safety, and reliability are all carefully assessed in the framework of the probable availability of the system. Systems are designed for maintainability. Adamovich points out that a life-support system that must operate for a long time is a system which, by definition, must be serviced and repaired in case of breakdown. Reliability depends not only upon reliability of the system components but also upon the presence of necessary expendable materials and spare parts, the degree to which the system has been studied on the ground, and the availability of crew time in case of breakdown.

Solar cell batteries and isotope dynamic power systems are under consideration for very long missions—solar cell battery development is more advanced at present. However, the isotope dynamic *Brayton* system, when available, will offer an additional advantage—it will produce both waste heat (approximately 191° C or 464° K), which can then be used as a heat source, and electric power.

In system genesis by both the US and USSR, life-support system characteristics, including reliability, are studied at all phases of development, beginning with research in the area of technologic processes which can be used in the life-support system in question. Development of a total life-support system then proceeds in these stages:

1. Component parts and subsystems are fabricated, first in breadboard and then in prototype form.
2. Ground-based tests are conducted featuring increasingly complete integration of life-support system components. Human crews are a critical link in integrated systems; their capability for maintaining the systems in good working order is a vital part of such tests. (Ground-based tests also provide an opportunity for testing flight prototype equipment in the back-up, rather than the primary, mode.)
3. In-flight testing of advanced subsystem components is accomplished wherever feasible and not in conflict with primary mission objectives.
4. Conceptual design studies conducted are aimed at evaluation and selection of appropriate systems for long-term missions, for example, space bases that might remain in Earth orbit for as long as 10 years.

BASIC LIFE-SUPPORT SYSTEM FUNCTIONS

A life-support system of semiclosed type, the type being considered for missions as long as 3 years, must provide the needed consumables, regenerate those materials which can be regenerated, and treat and remove all wastes. Basically, on-board systems must provide a safe and comfortable environment for the crew. The elements outlined in Figure 2 involve four principal basic functions, to provide: safe and habitable breathing atmosphere, drinking water, food, and sanitation and hygiene. The atmosphere-control system must regenerate breathable gases, regulate temperature and humidity, provide appropriate ventilation and a certain quantity of extra breathing gases to make up for the inevitable gas leakage, monitor and control toxic gases in the atmosphere and give early warning signals of unacceptably high levels of any toxic gaseous constituent, and, finally, control particulates in the atmosphere including dust and microflora.

Drinking water must be provided, which must be recycled from waste waters because of the substantial weight savings involved when compared to water storage. Drinking water is regenerated principally from wash water. The sanitation and hygiene system is, therefore, linked to the drinking water system. The sanitation system consists of a urine collection system, a method for whole-body cleansing, various housekeeping systems, and, finally, a fecal collection system. Wherever feasible, water must be purified and recycled. In the design of all sanitation and hygiene systems, human engineering aspects must be meticulously attended to. However good a system technically, it is a total failure if it is meant to be used by man and a man will not use it. Any number of examples can illustrate the importance of this.

Early fecal collection systems disregarded human engineering considerations almost entirely. It is difficult to imagine a less satisfactory system of collecting fecal matter in a zero-G force field than the system which was used prior to Skylab. Technologic efforts have improved and will continue to improve this situation. In another situation, that of whole-body cleansing via a shower system, where preferences were considered and provided, a critical human engineering factor was, unfortunately, overlooked. A shower was provided on the Skylab mission with sufficient water to allow a weekly shower for each crewman. On the second manned Skylab mission, however, this facility was scarcely used at all because of the excessive time required to prepare for showering and to close down the system after showering. In the design of hygiene systems, as well as in the design of many other elements of the life-support system, available crew time must be considered.

In the life-support system under consideration here, the food provided is not of the regenerable type. Although various systems of bioregeneration and chemical synthesis of food are theoretically available, these foods cannot, for the foreseeable future, provide the positive morale factor of natural foods. The food supply element of the basic life-support system features lightweight, low-volume food as its mainstay, which is supplemented by frozen, natural foods which can be quickly heated in microwave ovens. For missions of extremely long duration where space and weight are not absolutely critical, the inclusion of some hydroponic farming is theoretically possible to supply fresh, nonstorable, morale-boosting foods such as salads.

Life-support system functions envisioned for long-term space missions are shown in Figure 2, and Figure 3 is a schematic of the integration of these functions into a total system. Table 3 lists the optimum environmental design requirements,

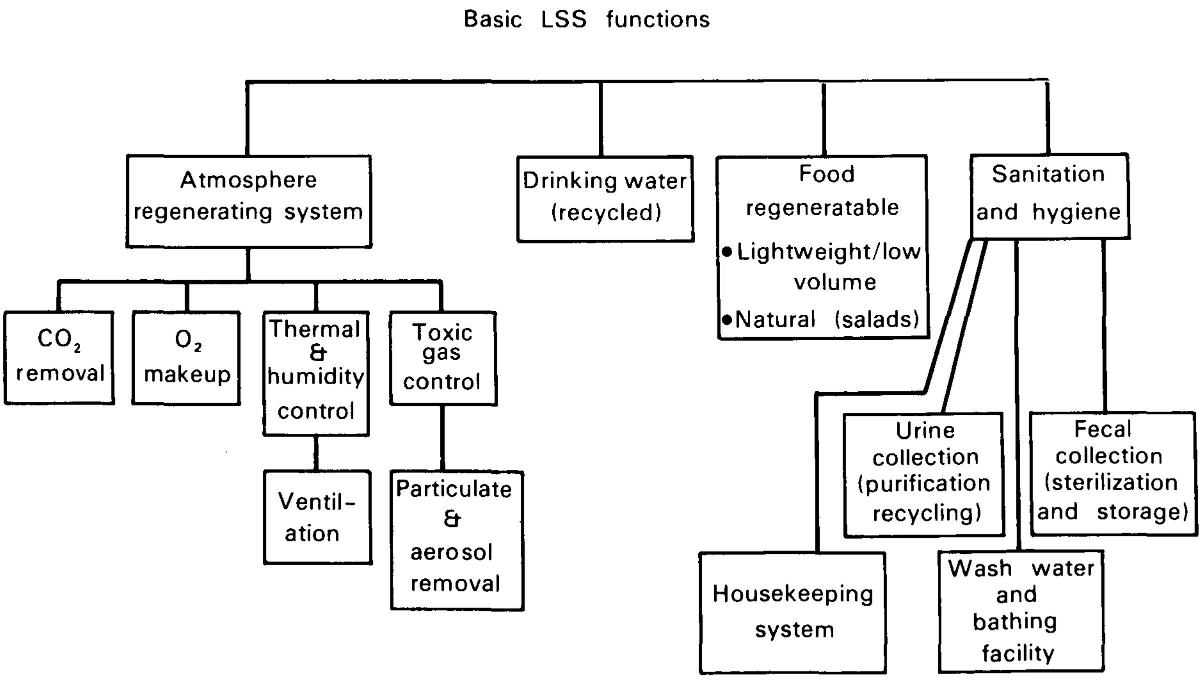

FIGURE 2.—Elements involved in provision of basic life-support system functions.

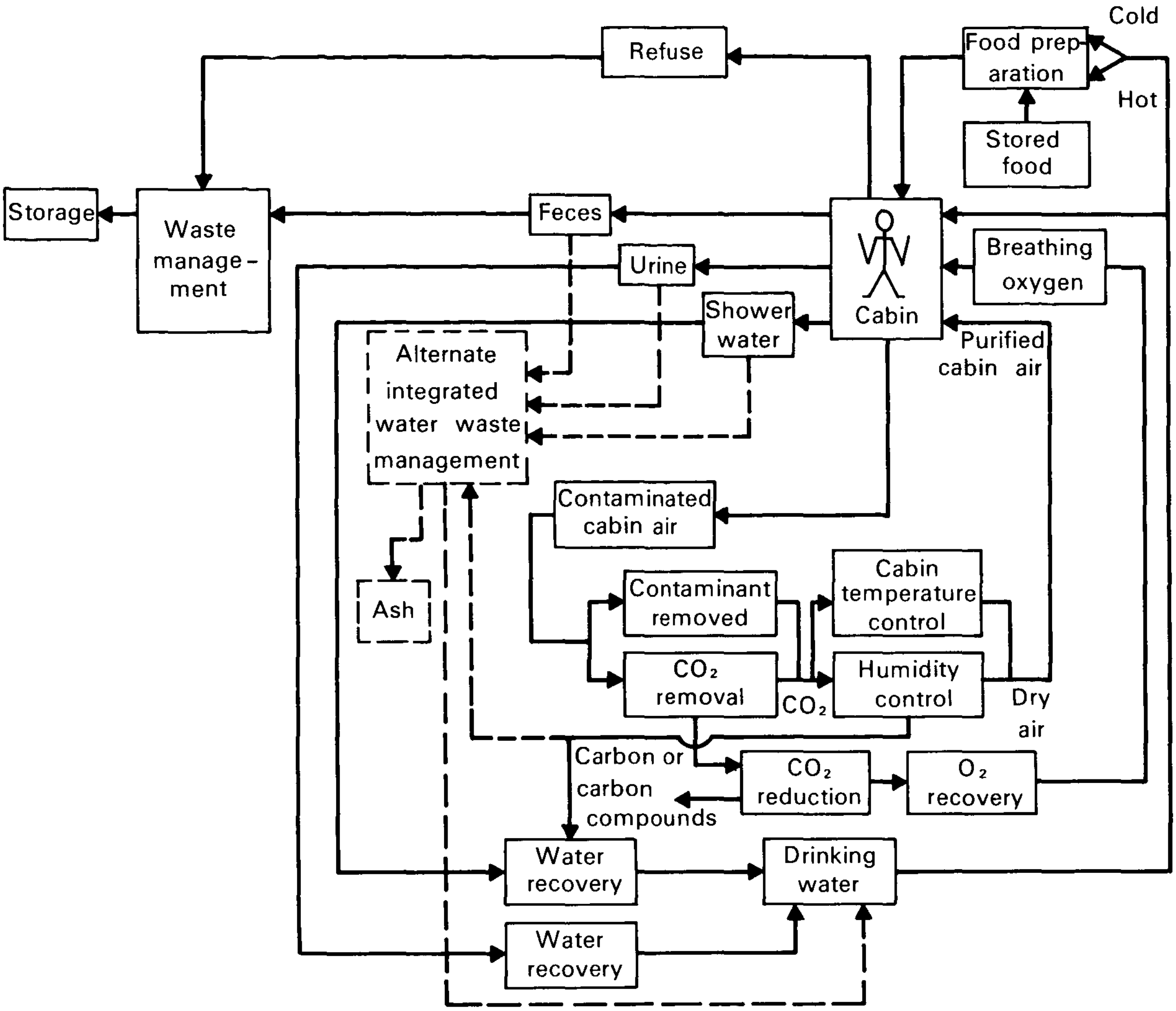

FIGURE 3. – Life-support system for long-term use.

TABLE 3. – *Optimum Environmental Design Requirements*

Environmental factor	Soviet	US
Temperature	291° K	297±3° K
RH	50%	40–50%
Carbon dioxide	270–400 N/m^2	< 400 N/m^2
Oxygen	$213 \times 10^2 N/m^2$	$207 \times 10^2 \pm 667 N/m^2$
Nitrogen	$800 \times 10^2 N/m^2$	$807 \times 10^2 N/m^2$
Total pressure	$1013 \times 10^2 N/m^2$	$1013 \times 10^2 N/m^2$

TABLE 4. – *Food, Water, and Oxygen Data*

Substance	Soviet $(g\ d^{-1}/man)$	US $(g\ d^{-1}/man)$
Water	2600	2800
Oxygen	940	875
Food (dry)	650	675

and Table 4 indicates the quantities of food, water, and oxygen which would be required per man-day for each man in the space vehicle using such a semiclosed system.

The priorities for regeneration are abundantly clear from the data in Table 4. Regeneration of water takes the highest priority, followed by regeneration of breathing gases, and last (perhaps for very long-term missions of the future), food. In Figure 4 there is a comparison of the weight advantages of regenerative over nonregenerative life-support systems for water, oxygen, carbon dioxide, and food for a 1-yr mission with a six-man crew as the model. Approximately 14 000 lb (6350 kg) can be saved by closing the water cycle and 4000 lb (1814 kg) by closing the oxygen cycle. These estimates include a weight penalty of 500 lb (227 kg/kW) for a radioisotope dynamic power system. Man's water requirements represent almost 50% of his life-support needs. Metabolic water requirements amount to approximately 6 lb (2.73 kg) water/d. Three to 4 additional lb (1.36 to 1.81 kg) of wash water are required. If this water were stored, 9934 kg would be added to the payload for a six-man, 1-yr mission.

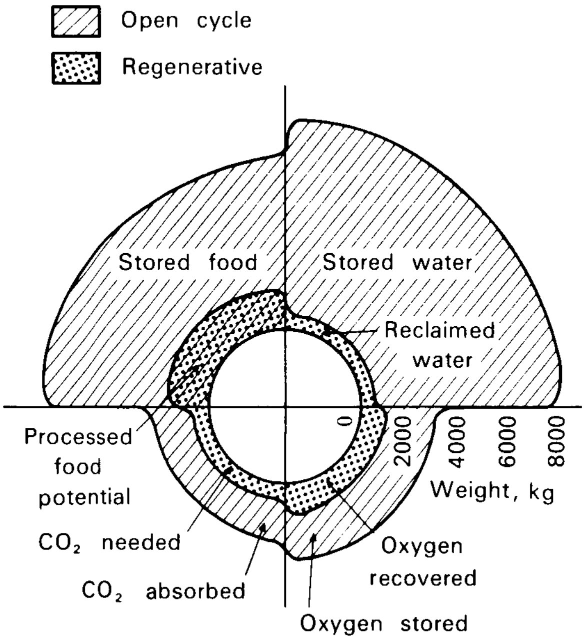

FIGURE 4. — Weight of 1-year life-support systems.

THE CANDIDATE LIFE-SUPPORT SYSTEM

The systems described here are those considered at present the best choices for life support for long-term space missions. Space limitations of this volume preclude detailed descriptions of many other systems which may be somewhat competitive with those being discussed. Systems are not described in great technical detail because this material is treated elsewhere in this volume. However, the basis for selecting one system over another is indicated.

Table 5 lists typical subsystems which meet the criteria of availability, performance, safety, and reliability required for long-duration, manned space missions.

TABLE 5. — *Complete Life-Support System*

Function	Selected subsystem
Atmosphere revitalization group:	
CO_2 removal/O_2 generaation	Hydrogen depolarized cell Sabatier with methane dump or use in attitude control Solid polymer electrolyte (water electrolysis)
Atmosphere contaminant control	Catalytic reactor, particulate filters
Atmosphere gas sensing	Mass spectrometer
Water/waste group:	
Urine processing	Vacuum distillation/pyrolysis
Wash water and condensate processing	Reverse osmosis
Water pre- and posttreatment	Heat plus bacterial treatment
Waste collection and storage	Slinger type collection with vacuum drying
(Alternate: integrated water-waste processing)	(Pyrolysis)
Whole-body cleansing	Shower
Thermal-control group:	
Cabin temperature and humidity control	Condensing heat exchanger/water separator
Food	Freeze-dried (principally) with minor on-board cultivation

Atmosphere Revitalization Group

Storage of atmospheric gases may not be logistically preferable for multiman missions to the near planets or for lunar bases, space stations, or other long-duration Earth orbital missions where resupply proves uneconomic [7]. For such missions, methods of revitalizing the atmosphere must be selected. The overriding consideration in the choice of a system is reliability.

Numerous systems proposed for regenerating oxygen feature physical, biological, and chemical approaches and combinations of these; the inclusion of small biological links has been demonstrated as feasible. However, at present, systems based on a combination of physical, chemical, and biological processes are less reliable than those based on physicochemical processes alone. Systems that include biological links are more sensitive to the effects of spaceflight factors and less reliable in terms of output characteristics. They are heavier, and their use becomes practical only for extremely long flights.

Carbon Dioxide Removal

A key function of the atmosphere revitalization group is removal of carbon dioxide, a principal gaseous byproduct in the space cabin atmosphere. Carbon dioxide must be removed because: first, crew safety demands it, and, second, it is the starting material for oxygen regeneration. It was noted in an earlier chapter that there are numerous approaches for handling carbon dioxide which involve its removal, concentration, and recovery of the oxygen contained therein. Some of these concepts are the molecular sieve method (the approach used in the Skylab life-support system), the steam desorbed amine approach, and the hydrogen depolarized cell.

The molecular sieve is a cyclic four-bed process. Two beds are needed as predryers because water will poison the molecular sieve, as noted earlier, for further carbon dioxide adsorption. Desorption of carbon dioxide requires heat, vacuum, or a combination of these, and the capacity of the molecular sieve for carbon dioxide declines exponentially with decreasing carbon dioxide partial pressures.

The molecular sieve concept was used in a recent 1-year chamber study in the USSR. Air within a sealed cabin was cleared of carbon dioxide, and the concentration of carbon dioxide in the cabin was then controlled by an atmospheric purification system using synthetic zeolites (molecular sieves). This was performed by two units, the first for drying the air and the second for removing and concentrating the carbon dioxide. Drying the air was required prior to carbon dioxide removal because of the preferential affinity of these zeolites for water over carbon dioxide. Subsequent to the removal of carbon dioxide, the air was rehumidified and returned to the cabin. The carbon dioxide was directed to a Sabatier reactor, where it was mixed with hydrogen and water produced by catalytic hydrogenation. Hydrogen for this process was obtained from an alkaline electrolyte water electrolysis unit, which also produced oxygen for crew consumption. The methane produced by the hydrogenation of carbon dioxide was jettisoned.

The molecular sieve system was selected for the Skylab program on the basis of availability and trade-off with lithium hydroxide. This system is similar in operation to the typical molecular sieve concept, previously detailed, with the exception that some water is desorbed to space vacuum, from the 13X molecular sieve, along with the carbon dioxide from the 5A molecular sieve. Both these zeolites are contained in a common packed bed.

This regenerable CO_2 removal system operated as expected, according to available data, and the average CO_2 partial pressure aboard Skylab was about 5 torr (600 N/m^2). The hydrogen depolarized cell and solid amine systems were not state of the art at the time that Skylab system selection was made.

The carbon dioxide concentration method of choice is probably the hydrogen depolarized cell (HDC), on the basis of current development and test data. HDC is a continuous low-temperature electrochemical process with no moving parts and with satisfactory capability for absorbing carbon dioxide at low partial pressures.

The solid amine system eliminates some drawbacks of the molecular sieve since it regenerates more easily (lower temperature), has better capacity for carbon dioxide at low partial pressures, and does not require predrying, as does the molecular sieve. It is a cyclic system, however, and the water content of the amines must be fairly well controlled.

Interface requirements are also important with regard to the selection of a carbon dioxide control system. The molecular sieve will provide a dry carbon dioxide to the CO_2 reduction subsystem, but it requires considerable heat and pumping power. The solid amine provides wet carbon dioxide, which presents no problem, with moderate heat and pumping requirements. HDC provides a mixture of wet carbon dioxide and hydrogen which can be fed directly to Sabatier and Bosch reactors if the mixture ratio is correct. No heat or pumping is required unless the CO_2 is stored and/or used at pressure.

The HDC system is compared with the molecular sieve and solid amine systems in Figure 5. It is evident that the hydrogen depolarized cell concept imposes the lowest weight penalty, particularly at very low P_{CO_2} levels. By comparison (the figure shows), the molecular sieve concept becomes impractical below about 266 Pa of P_{CO_2}. One of the advantages of the hydrogen depolarized cell approach is that input power is not required. The concentration process is superimposed on a fuel cell-type reaction between oxygen and hydrogen, which generates a small amount of electricity. This electrical power can be either conditioned for reuse or dissipated as needed.

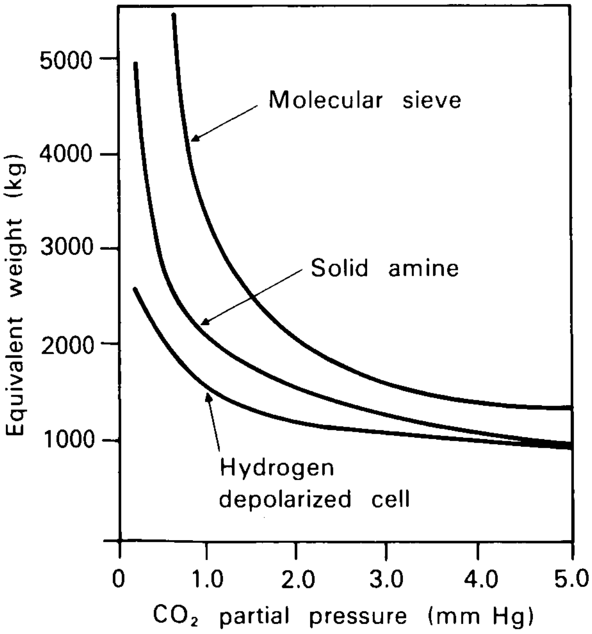

FIGURE 5.—Weight vs P_{CO_2} electric thermal source.

Carbon Dioxide Reduction and Oxygen Generation

Carbon dioxide collected by the hydrogen depolarized cell (or any other method which, at a later date, may be found more suitable) is then available as a starting product for the production of oxygen by catalytic reduction; the end products of the Sabatier reaction are methane and water. The water thus obtained may be electrolyzed, and oxygen thereby recovered.

Other methods of carbon dioxide reduction are available. The Sabatier process is, however, selected above the Bosch or solid electrolyte method because of system maturity. Considering system weight alone, the solid electrolyte method would be superior.

The three principal methods of reducing carbon dioxide for oxygen reclamation are compared in Figure 6. The equivalent weights noted include the weights for the apparatus required for carbon dioxide removal and transfer, water separation, and water electrolysis. The systems depicted in Figure 6 accommodate four men and presuppose a power penalty of 136 kg/kW. The weight advantage associated with the solid electrolyte method results from no separator water electrolysis unit being required, because the solid electrolyte is capable of concurrent water and carbon dioxide reduction.

A prototype Sabatier system was operated successfully during a 90-day manned, ground-based test. The system was in operation for nearly

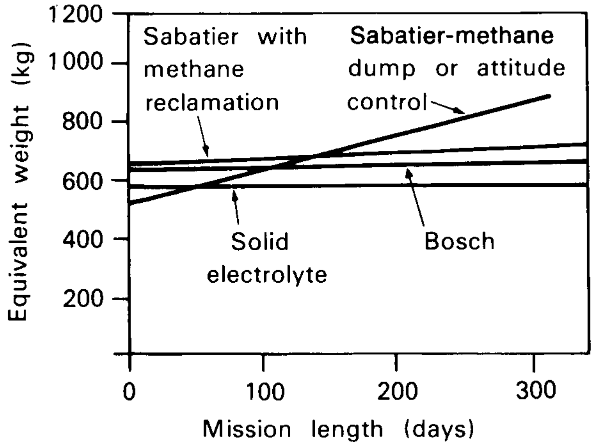

FIGURE 6.—Comparison of oxygen reclamation systems.

2000 h, and it performed with 95% efficiency in converting hydrogen, and with 66% efficiency in carbon dioxide conversion. Because one of the byproducts of the reaction is heat, a toxin burner (which requires heat) was interfaced with the Sabatier system to constitute an integrated Sabatier and toxin control unit. The toxin burner oxidized low molecular weight hydrocarbons, methane, and carbon monoxide to carbon dioxide and water in the presence of a catalyst. The mating of the two systems would reduce power requirements in a spacecraft. During the 90-day test, a considerable amount of maintenance activity was required for these units. This activity is summarized in Table 6.

Eighteen hours of maintenance activity during the 90-day test are not considered excessive in view of the development status of the life-support system used. In fact, much of the maintenance activity can be accounted for by one event. In order to clean a massive coolant spill that occurred a few days before the test, Freon 113 was used in substantial quantities. This substance, concentrated with the CO_2, poisoned the Sabatier catalyst (and probably the catalytic burner), necessitating most of the maintenance listed in Table 6.

The ideal system for carbon dioxide removal and oxygen generation would directly decompose carbon dioxide into carbon and oxygen. The solid electrolyte system, which performs the operation in a two-step process, would represent an improvement over present systems. In this system, carbon dioxide is fed to a solid electrolyte reactor, wherein, at temperatures of about 600° C (873° K), the carbon dioxide is dissociated into CO and O. A voltage potential across the solid electrolyte provides for the migration of these oxygen ions through the crystal lattice structure of the solid electrolyte and, upon losing electrons, for their release as gaseous oxygen. The carbon monoxide formed is circulated to a reactor, wherein it is disproportionated into CO_2 and C_S. The solid carbon is removed from the circulation loop by filters, and the CO_2 is fed back to the solid electrolyte. Water may be reduced by the unit, either concurrently with the carbon dioxide or by itself. A means of removing the hydrogen from the circulating loop is necessary and, for this purpose, palladium or palladium-silver membranes have been used. The advantage of this process, which has been tested with some success, is its relative simplicity (in that it potentially could replace carbon dioxide reduction-oxygen generation functions served, for example, by a Bosch reactor and water electrolysis).

The molten carbonate, or fused salt process, is a more recent advanced development. Considerable progress has been made in perfecting this most difficult process. The problem initially faced was formidable: selection of materials to resist the extremely corrosive nature of fused carbonate salts (lithium carbonate, lithium chloride, and others); perfection of the capability to deposit nearly pure, relatively dense carbon

TABLE 6.—*Sabatier Reactor Maintenance Activity*

Unit	Maintenance activity	Spares usage	No. times	Hours
Sabatier	Replaced fuse and primed water pump	Fuse	1	1.5
	Replaced CO_2 flow transducer[1]	Transducer	1	0.3
	Cleared water from methane pump[1]		1	0.2
	Installed carbon filter in CO_2 line[1]	Carbon column	1	3.0
	Changed catalyst	Catalyst	1	7.0
	Changed carbon[1]	Activated carbon	5	2.5
	Changed zero-G condenser	Condenser	1	1.5
	Attempted to unstick negative pressure device		8	0.6
	Replaced leaking tube at reactor outlet	12-in. tubing	1	2.0
			20	18.6

[1] Outside activity.

on the cathode of the unit; capability of removing deposited carbon in zero-G without interrupting the process; evolution of pure oxygen; and capability of absorbing carbon dioxide directly from a cabin airstream containing oxygen, nitrogen, and water vapor, in addition to the carbon dioxide. This concept is the ideal environmental control system. It can absorb CO_2 along with required amounts of water vapor to fill oxygen supply needs in a single-pass process, achieve near-complete CO_2 sorption per pass, and deposit the produced carbon in a dense, easily storable form. Conceivably, the molten carbonate or fused salt process could act as an excellent contaminant-removal system, since all gaseous hydrocarbons, carbon monoxide, hydrogen, and other expected contaminants would be readily oxidized in this unit.

Until a one-step process is available, a two- or three-step process will have to suffice. Whether the hydrogen depolarized cell concept, the Bosch process, or the Sabatier process is used, the byproduct water must be electrolyzed to obtain oxygen.

Again, choices are available and trade-offs must be made. The water electrolysis systems currently available include the solid polymer electrolyte and the circulating and wick-feed electrolysis concepts. The performance of the three electrolysis cells is compared in Figure 7, indicating clearly that the solid polymer electrolyte is far superior to the other two concepts. It is preferred for a number of reasons that include higher current density capability, lower voltage requirements, and, in general, a higher operating efficiency. It also has simpler thermal control and provides greater capacity per unit weight than the other two systems. Finally, with the solid polymer electrolyte, there is obviously reduced hazard of leakage, since no caustic electrolyte is used, making the unit both safer and more reliable.

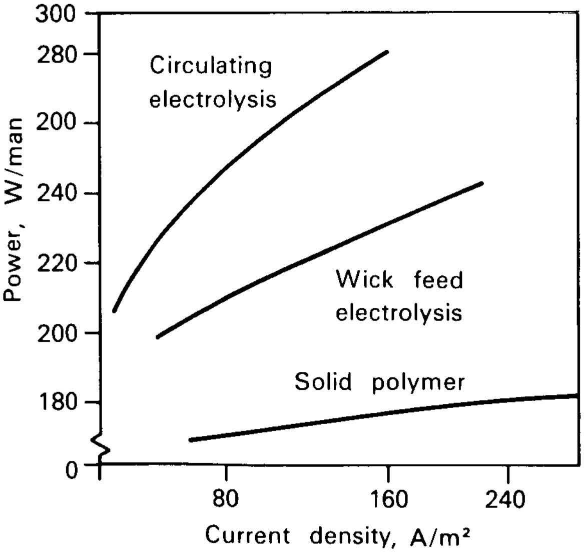

FIGURE 7.—Electrolysis cell performance comparison (power based on 1.84 lb O_2 per man-day).

Atmosphere Contamination

The concentrations of various substances in the atmosphere must be kept at acceptable levels to safeguard the health and well-being of spacecrews. The most potentially dangerous substances are toxic gases originating from life-support equipment and from man. Particulate matter and microbes, including lint, sloughed skin, hair, food debris, fungi, bacteria, and viruses, are also of concern. If these substances, particularly the gases, are not kept within safe limits, the space cabin atmosphere will quickly become dangerous to life.

As mission lengths increase, the need to carefully control the level of atmosphere contamination becomes increasingly important, particularly in a closed or semiclosed life-support system where toxic substances can rapidly build to intolerable levels. The first line of attack for minimizing toxicants in the atmosphere is meticulous control of materials used in spacecraft production. All materials used in life-support subsystems and/or materials from which the subsystems are built must be evaluated to determine the quality and quantity of any volatile substances produced. Any materials found to volatilize and produce undesirable products must be eliminated immediately from consideration. The second approach involves removal of toxic substances produced by man and machinery in the course of normal operations within a spacecraft. Finally, methods must be available for dealing with emergency situations which result in a sudden, abnormally or dangerously high level of atmosphere toxicant, for example, electrical fire.

Numerous contaminants in the spacecraft atmosphere have been identified through extensive manned spaceflight experience and ground-based chamber studies. These contaminants are enumerated in another chapter; hence will not be repeated here.

The gaseous contaminant-control system of choice is catalytic oxidation/sorption for missions of the type considered in this chapter. The chief advantage of the catalytic oxidizer is that it effects a considerable weight savings over the expendable charcoal absorption systems previously used, because the oxidizing catalyst does not take part in the reaction and is not consumed. At present, adsorbent beds must be included to remove contaminants that cannot be satisfactorily removed by the catalytic burner. The reason is that some substances, if oxidized or partially oxidized, are more toxic than their predecessors, e.g., NH_3 to NO_2, which are removed by an acid gas scrubber—lithium hydroxide ($LiOH$). Others, such as H_2S, will react with the catalyst, poisoning it, and they must be presorbed.

A catalytic toxin control system was included with the Sabatier reactor during the 90-day manned test of a regenerative life-support system. The operation of the burner throughout the test was routine, and no operational problems were experienced.

Other types of airborne contamination, in addition to gaseous contaminants, must be removed from the spacecraft cabin atmosphere to render it safe and habitable for the occupants. This contaminant includes particulates, aerosols, and other airborne debris, including dustborne microbes. Filtration is the method of choice for removing these contaminants. Adequate control can be obtained by traps in the fans which process cabin air. Mechanical, electrostatic, and bactericidal filters and cyclone separators are under consideration.

Atmosphere Sensing and Control

The atmosphere sensing and control system for long-term space missions must be far more sophisticated than that required for brief missions. There are two reasons: for the control of both oxygen and another gaseous diluent such as nitrogen, and for monitoring the concentration of various contaminant gases in the atmosphere. The system for such missions will require the capability to assess not only the concentrations of several principal atmospheric gases but also gases which exist in the atmosphere in *trace* amounts. It must be capable of providing advance warning so that necessary steps may be taken before toxic levels of any trace contaminants are reached. Sufficient sensitivity and stability must be available to allow for trend analysis of the trace contaminants.

The heart of one such system is the mass spectrometer atmosphere analyzer unit shown in Figure 8. Functional control of atmospheric gas pressures is maintained by the cabin pressure regulator. The regulator is connected to the diluent and oxygen supply lines downstream of their pressure regulators. Oxygen and diluent reach the cabin pressure regulator through check valves and solenoid valves which are controlled by the partial pressure signals received from the spectrometer detection unit. Actual control is established by valve arrangements set for maximum and minimum partial pressure levels. Figure 9 is a diagram of the total system [3]. This mass spectrometer is remarkably reliable. It is

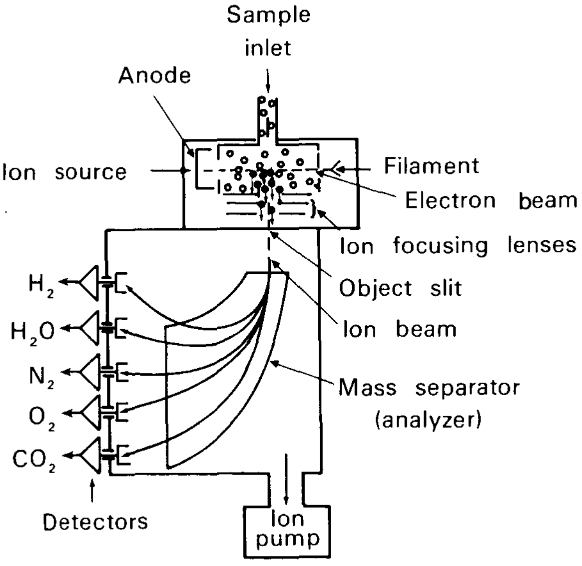

FIGURE 8.—Mass spectrometer schematic [3].

capable at present of monitoring simultaneously six constituents—hydrogen, water vapor, nitrogen, oxygen, carbon dioxide, and total hydrocarbons—and enables control of concentration of the two principal atmospheric constituents for which it was tested: oxygen and nitrogen. Its capability is being further extended to analyze the concentrations of potentially toxic gases present in the atmosphere in very small amounts. The controller, shown in Figure 9, was used in the 90-day manned test (cited previously) within a tolerance of 0.030%.

Water-Waste Group

The functions of a water-waste management subsystem are to collect and purify waste water, store and deliver potable water for use on demand, and collect, dry, and sanitize wastes.

Water Management

Potable water produced by the water management subsystems must be sterile and free of organic and inorganic materials and remain sterile during storage. Service operations must not contaminate stored water. Finally, complete and rapid subsystem sterilization must be possible in the event of contamination. A water management subsystem for long-term space missions must provide for the collection and purification of waste water derived from urine, wash water, and humidity condensate. Preferred subsystems for long-term missions are given in Table 7.

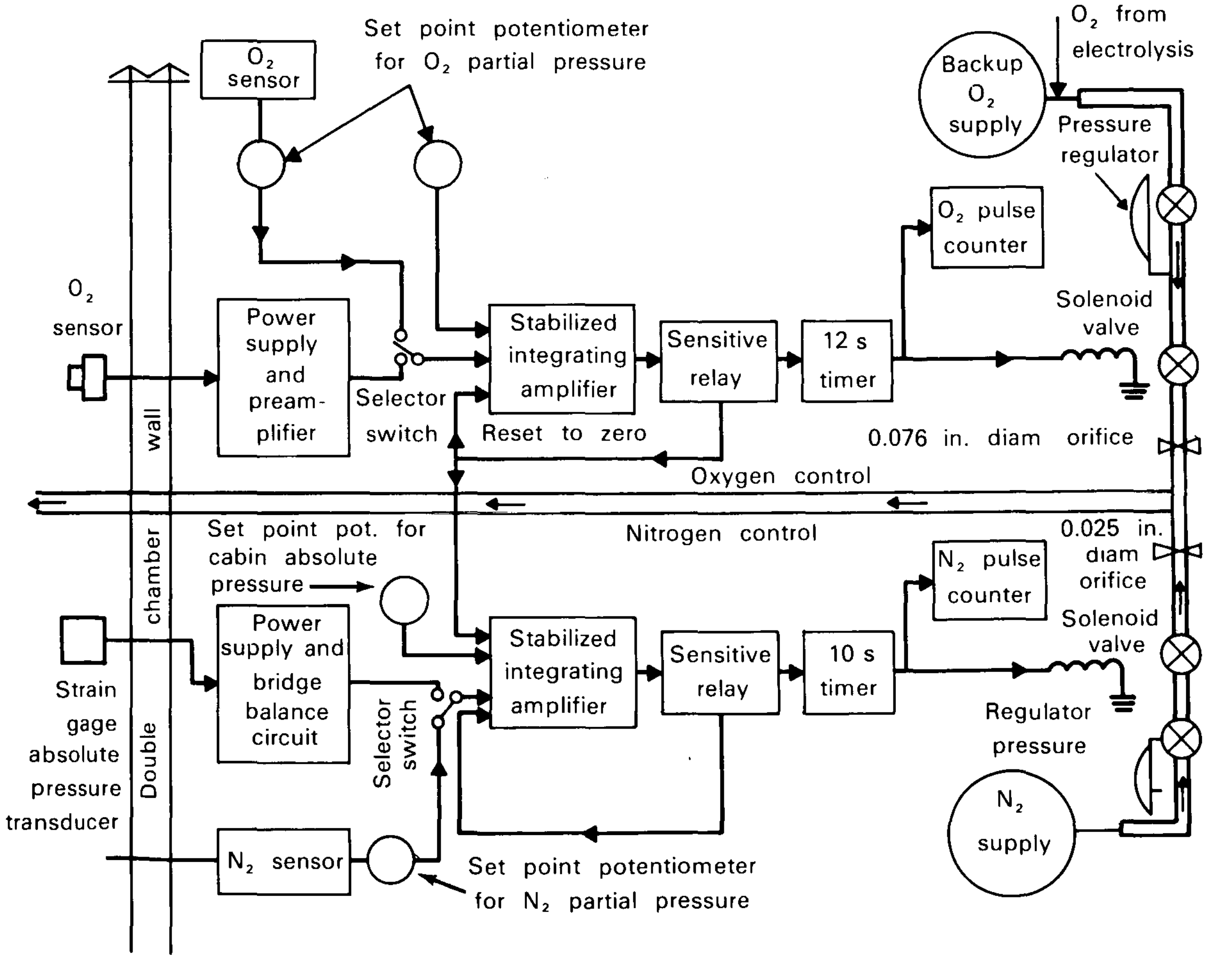

FIGURE 9.—Diagram of atmosphere supply control subsystem.

TABLE 7.—*Water Management Subsystems of Choice for Long-term Missions*

Function	System
Urine processing	Vacuum distillation/pyrolysis
Wash water and condensate processing	Reverse osmosis
Sterilization	Heat and bactericidal treatment (iodine, silver, and similar)

Detailed standards concerning potable water quality have been elaborated in another chapter. Suffice it to say here that potable quality standards applied to reclaimed water must be basically different from those applied to water for domestic use. These standards must take into account that (1) palatability and aesthetic acceptability will become more important on longer space missions to avoid increasing the already severe stresses of closely confined quarters, and (2) any lack of quality would tend to discourage normal water intake and, therefore, would compromise the crew's health. Water reclaimed from available sources (urine, wash water, and so forth) is more contaminated than water from sources on Earth; therefore, more care must be taken.

Chemical standards and biological standards are also discussed elsewhere. It might be mentioned in passing, however, with reference to biological standards for reclaimed water, that because the modes of hazard of biological contamination are so varied in water recycling systems, total sterility is out of the question. Consequently, an essential sterility criterion has been established by the US National Academy of Sciences (NAS) which requires that a maximum of 10 viable organisms/ml water not be exceeded.

Urine processing. Of the several promising candidate approaches that have been investigated for reclaiming pure water from urine, the selected approach uses vacuum distillation, coupled with pyrolysis of the distillate vapor, followed by condensation. This approach eliminates organic carryover and kills bacteria in one operation.

When selecting an approach to water reclamation, there are two major reasons for not having a clear-cut choice. First, vehicles for use in the immediate future, such as the Space Shuttle, will use fuel cells as the primary source of electric power. Fuel cells produce water as a byproduct, which can be purified for drinking without much difficulty. Second, when there is a clear need for water reclamation, selection must be made, to a degree, on vehicle energy and heat-sink penalties. Distillation systems require about 660 W · h heat/kg water for vaporization and another 660 W · h/kg heat-sink for condensation. Compression-distillation needs only about 220 W · h electric energy and heat-sink/kg water.

Wash water and condensate processing. The best available method, perhaps, for processing relatively large amounts of wash water (for example, 50 kg/d for a six-man crew) employs the principle of reverse osmosis. The technique is simple, involving pressure filtration through a semipermeable membrane. The capability of the process to remove almost any dissolved material from water is limited only by the properties and performance of the membranes employed. One weak link in the reverse osmosis system was, until recently, the inability of membranes to withstand the high operating pressures required for high recovery rates. An ongoing program to develop improved membranes has largely resolved this problem. Porous, hollow glass-fiber filters, as well as other advanced membranes, have been developed which are strong and permit heat sterilization. They also resist corrosion and reject organic materials, viruses, and bacteria. Figure 10 indicates the rejection characteristics of glass membranes for various impurities.

Reverse osmosis is inherently superior to distillation for wash-water purification because, since no phase change is involved, it requires far less energy.

Water pre- and posttreatment. A satisfactory means of sterilizing stored water is by pasteurization in combination with iodine generation. Pasteurization is very effective in killing most organisms; it requires a heating element in the storage tank which can raise the temperature of the tank to 71° C (344° K) for 30 min, continuously and routinely, or upon the discovery of contamination. Additional sterilization can be achieved by use of iodine generators.

Various methods considered for regenerating spacecraft water supplies include vacuum distillation, freeze drying, catalytic oxidation, and combinations of these methods [6]. In a 1-year Soviet manned space mission simulation, drinking water was regenerated from urine by catalytic oxidation in several stages: filtration of urine, evaporation, high-temperature oxidation of organic compounds of elementary gases and oxides with the aid of a catalyst, and, finally, condensation. Condensate water was enriched with salts and microelements and used as drinking water. In the same test, daily sanitation water was used for toilet, shower, and sink. Kitchen water (left after dishwashing) was regenerated by catalytic oxidation methods similar to those used for regenerating water from urine. The rest of daily sanitation water was purified by precipitation.

To supply minerals and electrolytes, one approach is through the food; another is to add minerals to regenerated water to insure that it has the required palatability and chemical composition. Regenerated water resembles distilled water and is characterized by the absence of mineral compounds present in natural drinking water which are physiologically important for the human. Shikina and coworkers [8] found that regenerated water could be artificially mineralized by introducing salts in the solid phase to yield drinking water that was fully adequate in its organoleptic and physicochemical properties. Regenerated water was enriched by passage through a batch of dicalcium silicate and by addition of tablets containing sodium chloride, potassium bicarbonate, magnesium sulfate, potassium iodide, and sodium fluoride; the water thus produced was close to Moscow tap water in composition.

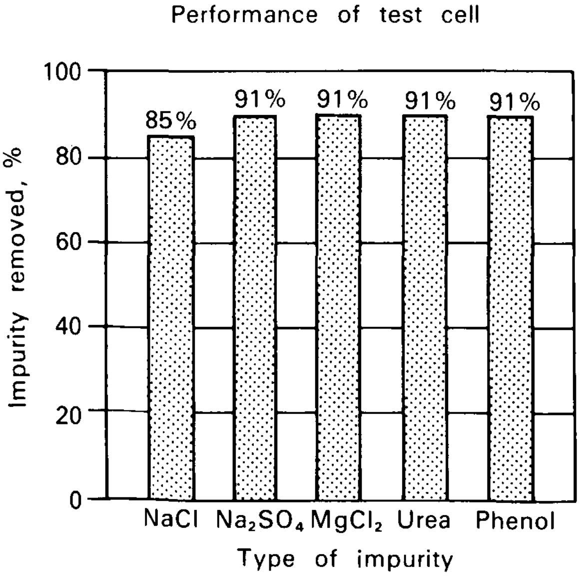

FIGURE 10. – Rejection characteristics of glass membranes for five impurities.

Waste Management

Fecal collection and storage. Waste collection and storage are accomplished by means of a fecal and urine collector. The fecal collector is a commode which incorporates a "slinger," air entrainment for zero-G collection, and vacuum dehydration of stored feces and waste tissues. This method of treatment reduces the waste matter to 10% water by weight, sufficient to stop microorganism activity and permit safe storage.

Integrated water-waste processing. Liquid and solid human wastes can be organized in various ways, depending on their subsequent use. If wastes are not intended to be used in producing water or other substances, they must be disinfected and dumped overboard or conserved and stored on board. If certain products are to be obtained from the wastes, urine must be transported first for preliminary treatment, and the solid wastes must be subjected to vacuum or thermal drying, or other treatment (including biologic treatment), to obtain the necessary components.

Systems for recovery and reuse of water from urine, wash water, and atmospheric condensate have been described in preceding sections. It is possible, and ultimately desirable, to integrate liquid-waste processing subsystems with the solid-waste recovery system. In this way, water can be recovered from all biologic wastes and trash simultaneously. Feces and other solid wastes would be decomposed and incinerated. The high temperatures (649° C or 922° K) required to insure effluent sterility would, ideally, be supplied by a radioisotope heat source which would render the process independent of the spacecraft's power system.

In a recent test of radioisotope heaters lasting for more than 180 days, distillation at 49° C (322° K) and catalytic oxidation at 649° C (922° K) were used to purify the water, and incineration at 649° C (922° K) to dispose of the solids [9]. Radioisotope heaters provide 420 W for the high-temperature process and 850 W for the distillation process. The high-temperature heater utilizes a specially reduced, high-purity plutonium oxide fuel encapsulated in a container. The low-temperature heater is fueled with plutonium oxide cement. Results of the test showed greater than 98% potable water recovery and approximately 95% reduction in solids, weight, and volume. All outflows are sterile, and the radioisotope capsule radiation level is only 7.9 mrem/h unshielded at 1 m (neutrons and gamma).

A laboratory model of an integrated waste-collection system has been fabricated and tested. The system provides for recycling of spacecraft waste water (including urine, wash water, condensate water, and fecal water), for disposal of nonrecoverable waste in a sterile manner, and for recovery of reusable gases; it also provides a solution to the vexing problem of a comfortable and psychologically acceptable system for human waste elimination in spacecraft cabins.

Whole-Body Cleansing

The maintenance of an acceptably high level of personal hygiene demands a method of whole-body cleansing for missions of the length considered here. A whole body shower concept was selected for the Skylab mission because it was the system chosen by most of the individuals involved. Showering provides a feeling of freshness and exhilaration and facilitates simultaneous cleansing of the scalp and body.

In the Skylab mission, a whole-body shower system was added late in the development program. Consequently, a collapsible system was used which required assembly in one of the working areas when a shower was desired. Despite the shower being the system preferred by all crewmen, it was used infrequently by two crewmembers of Skylab 3 and not at all by the third, even though sufficient water was available at all times. Inconvenience was cited as the reason. The crew felt that the time required to set up, use, dismantle, and stow the shower (over 1 h) was excessive in view of the time required for other tasks.

An improved zero-G whole-body shower system has been developed and tested as a concept for the Space Station Prototype [4]. The system uses the vacuum pickup method. In a demonstration test, six subjects each took one shower a day over a period of 10 days. The results showed that an average of 0.26 kg water were used per shower, which required approximately 9.7 min and consumed an average of 59.7 W power. With an in-place shower system, showering time obviously is not excessive, and the system should be used more than that in Skylab.

Thermal Control Group

Thermal control. Control of the thermal environment of a spacecraft is a delicate operation because of the thermal extremes to which the exterior of the craft is subjected. Effective performance of crewmembers requires that a comfortable cabin temperature be maintained throughout a mission. Under normal operating conditions, the problem is one of removing heat from the interior of the craft and venting it to space, because spacecraft are designed to produce heatloads in the interior. This interior load consists of crew metabolic heat, internal equipment heat generation, the external heat, including absorbed solar and planetary radiation, and heat due to reentry. Since these factors vary substantially during a mission, the thermal control system must be quite flexible.

Spacecraft thermal control systems to date have, in principle, used a fluid circulating within the craft to pick up internal heat and transport it to external space radiators.

The first step in the development of an appropriate thermal control system, and one which normally is not considered part of the life-support system but rather part of the basic engineering of the spacecraft, is to select an exterior coating with high infrared emissivity for maximum heat radiation from the craft and low solar absorptivity to minimize the heat absorbed from the Sun. As an internal heat exchanger, water, or water combined with another fluid, operates quite well. The high latent heat of vaporization of water and the low pressure in the space environment cause water to boil at low temperatures. In the boiling process, heat is absorbed from the gas or liquid in the opposite passages in an exchanger, and the resulting steam is vented to space. The vaporization of 1 kg water will absorb approximately 1045 Btu (2430×10^3J) heat in the process. For short missions, evaporative water-heat exchangers are quite effective and reliable. For long missions, other systems must be sought when the weight of water expended becomes excessive.

Space radiators, metallic configurations for transferring spacecraft heat into space, represent a major component in any thermal control system. Radiator structures may be an integral part of the vehicle or may represent separate attachments. In any event, they are lightweight, dependable, and easily integrated into vehicle design. In general, a liquid-coolant loop carries heat from a heat exchanger to the radiator. Use of the coolant-fluid loop allows any vehicle component to be tied in directly with the thermal control system. The use of coolant odor is needed to fully exploit the olfactory stimulus level of crews for detection of leaks in coolant systems.

Humidity control. Humidity control can be effected quite simply by cooling a gas stream below its dew point and collecting the resulting condensed water. In general, the temperature level required for thermal control allows for effective humidity control. If a higher thermal control temperature is required, a reheater or a regenerative heat exchanger may be necessary. In any event, the only complicating variable is the absence of a gravity field to collect the condensed water. In early US flights, water was collected from a heat exchanger in a sponge, which was then squeezed periodically by a piston device to force the water into a storage tank. A number of problems are connected with this system; later flights have used a cylindrical wick-type separator downstream of the heat exchanger. In this system, water trapped in the wicking material is bled off and transported by a low-pressure head to a collection tank.

Perceived comfort in the space cabin is affected by an additional factor: ventilation rate. The circulation flow required in the crew compartment is about 1.5 m^3/s with a velocity of 0.2 m/s.

Food Provision

Since food is a crucial morale-building or degrading factor, no attempt is being made to regenerate food for space missions of the foreseeable future. Clearly, reprocessing food would provide a substantial weight advantage, but because of the psychologic impact of food, it is considered far better to save weight in other ways. Ongoing efforts, however, have been extremely successful in reducing the weight of food carried by making freeze-dried food the mainstay of the space diet. Freeze-dried foods are very light in weight since they contain only a fraction of their original water content. Moreover, they are stable under prolonged storage at ambient temperatures. For long-term missions, further attention must be given to providing more natural foods, probably frozen foods which can be prepared quickly in small microwave ovens. A small amount of plant cultivation, principally for salads, is not out of the question.

The Skylab diet is a good example of the type of foods which would serve quite satisfactorily for long-term missions, except, of course, that no plant cultivation was considered for a mission of only 2 mo. Basically, there were five types of foods: beverages (powdered, rehydratable), frozen, convenient snack, thermostabilized, and rehydratable. The foods that comprise the Skylab diet, listed in Table 8, were developed during a long period according to strict specifications for chemical and microbiological composition. Nutritional and safety requirements were considered basic in food development. The criteria used to select the diet were:

- Crew-food compatibility
  - flavor
  - appearance
  - ease of preparation
  - safety
  - nonallergenic
  - fecal bulk and consistency
  - non-gas-forming

- Nutritional requirements
- Medical experiment requirements
  - calcium
  - phosphorus
  - magnesium
  - sodium
  - potassium
  - protein
  - energy
- Physical constraints
  - packaging size
  - preparation equipment
  - stowage
  - waste disposal
  - residue mass determinations

Although frozen foods were available for the Skylab diet, a microwave oven was not used because the metal food containers used were not compatible, and it was felt that electromagnetic interference might result from use of a microwave oven. However, a microwave oven was utilized during a 90-d manned test; it was used throughout the test by the crewmen for food warming as well as for preparing supplementary frozen foods. Acceptance of the food was high and no difficulty was reported with the operation of the oven.

Ease of preparation of foods is of considerable importance. In a ground-based Skylab Medical Experiments Altitude Test in preparation for the Skylab mission, certain freeze-dried foods required excessively long hydration. For long-term missions, such a situation would pose an undesirable strain on crewmembers, which could be improved through the use of a microwave oven. It would, therefore, be most important to test all foods and food packaging in advance to eliminate or modify those items which require prolonged preparation or are in any way inconvenient to prepare, consume, or dispose of in terms of the residues involved.

A complete food system comprises not only the foods consumed but also the storage, preparation, and consumption facilities. A convenient and satisfactory communal "table" was designed for the Skylab mission. It is equipped with water guns for rehydrating dehydrated food and all other items needed for meals. Figure 11 shows the configuration of the individualized food trays

TABLE 8. —*Skylab Foods*

BEVERAGES	
Lemonade	Fruit drinks:
Instant breakfast drink (cocoa-flavored)	Orange, grapefruit
Cocoa	Strawberry
Black coffee	Apple
Tea with lemon	Cherry
	Grape
FOODS	
Frozen	
Coffee cake	Pork loin with dressing and gravy
White bread	Prime rib of beef
Prebuttered roll	Vanilla ice cream
Filet mignon	
Lobster Newburg	
Wafer	
Dry roasted peanuts	Sliced dried beef
Dried apricots	Hard candy
Sugar cookie wafers	Mints
Vanilla wafers	Biscuit (cracker-type)
Cheddar cheese crackers	Butter cookies
Bacon wafers	
Thermostabilized	
Pineapple	Meatballs and sauce
Butterscotch pudding	Pears
Turkey and gravy	Hot dogs (tomato sauce)
Tuna sandwich spread	Peaches
Fruit jam	Chili with meat
Applesauce	Catsup
Peanut butter	Lemon pudding
Rehydratable	
Rice Krispies	Shrimp cocktail
Sugar-coated corn flakes	Salmon salad
Scrambled eggs	Sausage patties
Pea soup	Pork and scalloped potatoes
Potato soup	Chicken and rice
Asparagus	Beef hash
Mashed potatoes	Chicken and gravy
German potato salad	Veal and barbecue sauce
Cream-style corn	Spaghetti and meat sauce
Peach ambrosia with pecans	Turkey rice soup
Strawberries	Macaroni and cheese
Green beans	Mashed sweet potatoes
Creamed peas	

FIGURE 11. – Configuration of Skylab food trays.

used on Skylab, which provided both heating elements for food warming and utensils for eating. A variety of freeze-dried foods and a drink container-dispenser are also shown. Figure 12 is a photograph of astronaut Owen Garriott, in-flight science pilot, reconstituting a container of food during the Skylab 3 mission.

Trash bags were provided for easy cleanup in Skylab. For long-term missions where large amounts of trash will be generated, it will probably become necessary to use compactors to minimize the volume required for trash storage.

During the Skylab mission, a prototype can-crusher was tested, which had the disadvantage of requiring an excessively long time (45 min to 1 h) to accomplish its intended purposes. Compacting devices will be necessary, but refinement of the technology will be required.

Where plant cultivation is considered, the optimum method for use in space is a hydroponic farming system, which provides for accelerated growth of plants such as vegetables. A laboratory version of a hydroponic food cultivation device, designed for use in zero-G, is illustrated in Figure 13: it is a result of collaborative effort between NASA and the US Department of Agriculture. In a rotating drum, seeds are planted in an ion exchange matrix containing all the nutrients required for several generations of plants. Water is fed into the soil by a water reservoir. Seeds have been germinated successfully during rotation despite the abrogation of the directive force of gravity. Bib lettuce growth with this device, as shown in Figure 13, far outstrips the rate of that grown on sand. The lettuce itself, appearing as a natural green leafy vegetable in the diet, is a welcome addition to the other more processed foods.

In summary, the food technology required for long-term space missions, as outlined, is clearly in hand.

Tests of Long-Term Life-Support Systems

Two significant tests have been made of long-term life-support systems (previously mentioned). Their primary objectives were reclamation of both oxygen and water and testing a variety of foods suitable for a long-duration mission. The US test lasted for 90 days; that of the Soviet Union, a full year.

US 90-Day Test

An operational, 90-d manned test of a regenerative life-support system was completed September 11, 1970 [5], and was performed with a crew of four men. A two-gas atmosphere was selected; it had a design pressure of 68.9 kN/m^2 (10 psia) with oxygen partial pressure held at 21.0± 0.35 kN/m^2 (3.05±0.05 psia) and nitrogen as a diluent. The design level for CO_2 partial pressure was 0.507 kN/m^2 (3.9 mm Hg). This test was the second of a series conducted by an aerospace manufacturer (McDonnell-Douglas Astronautics Co.) for NASA, and enlisted the cooperation of various government and industrial organizations.

All crew equipment and expendables were stored on-board at the start of the mission to eliminate the need for pass-in operations. Pass-out operations, conducted in an autoclave-airlock, were limited to one each week to provide the required samples to verify the health of the crew, obtain basic medical data, and insure potability of the reclaimed water. Routine tests of blood, urine, and potable water were performed in an on-board laboratory to achieve mission realism and minimize the requirements for pass-out operations.

This most recent test of advanced technology systems utilized a solid amine system, two flight-breadboard water electrolysis units, as well as water-waste management, total food provision, and similar items. Significant features were the requirements for no transfer of supplies into the chamber, other than nitrogen from bottled stores outside the chamber for safety and volume reasons, and oxygen and hydrogen from the external water electrolysis system, used as backup to the unit inside the chamber. Both subsystems were completely and continuously plumbed to the interior of the chamber, thus preserving the integrity of the sealed-cabin simulator. One water electrolysis unit was the vapor-feed variety, which uses KOH as the electrolyte and asbestos matrix separators within the individual cells. The other was also a KOH electrolyte system, operating on the circulating electrolyte principle;

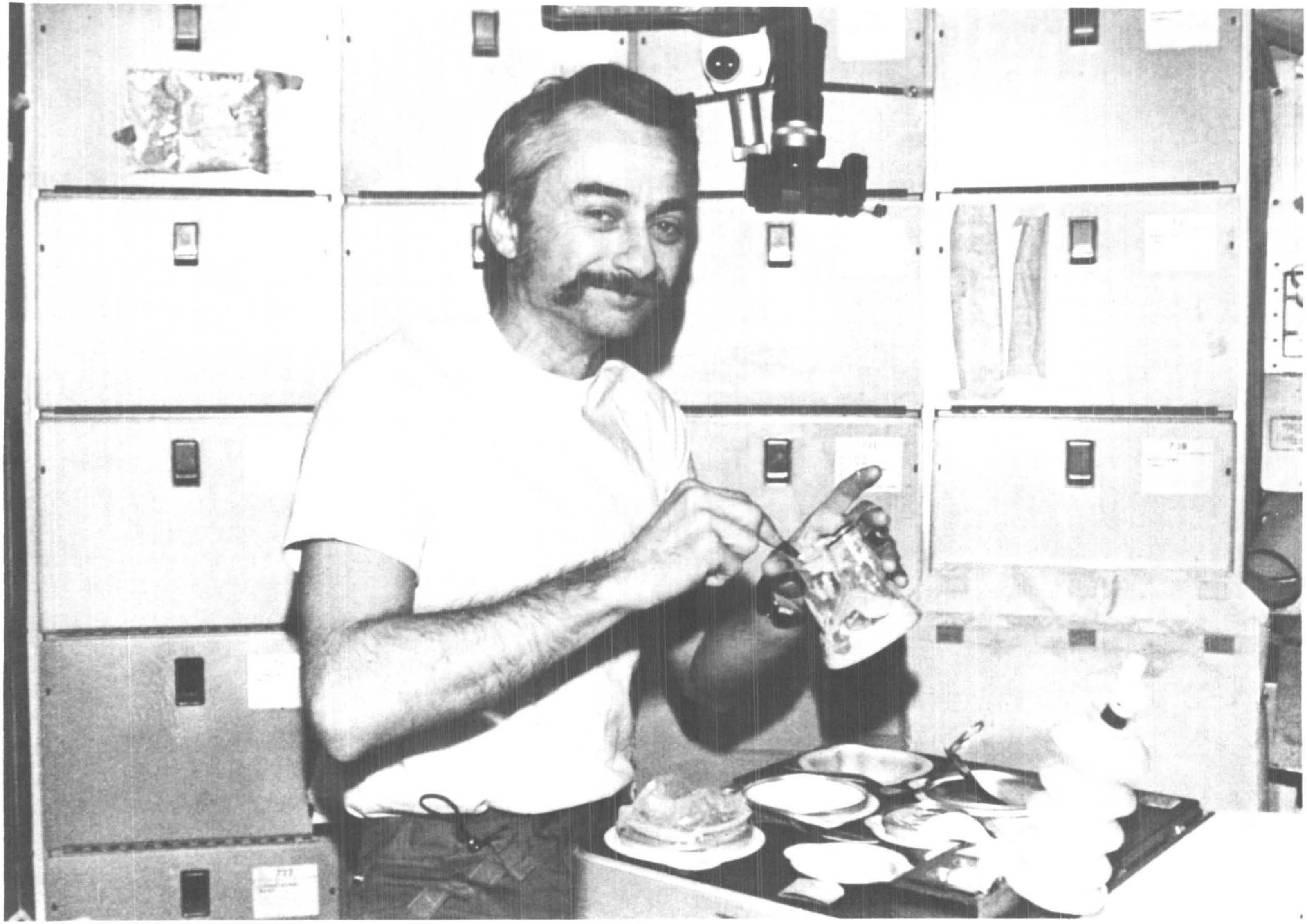

FIGURE 12. – Owen Garriott, science pilot, reconstituting container of food during Skylab 3.

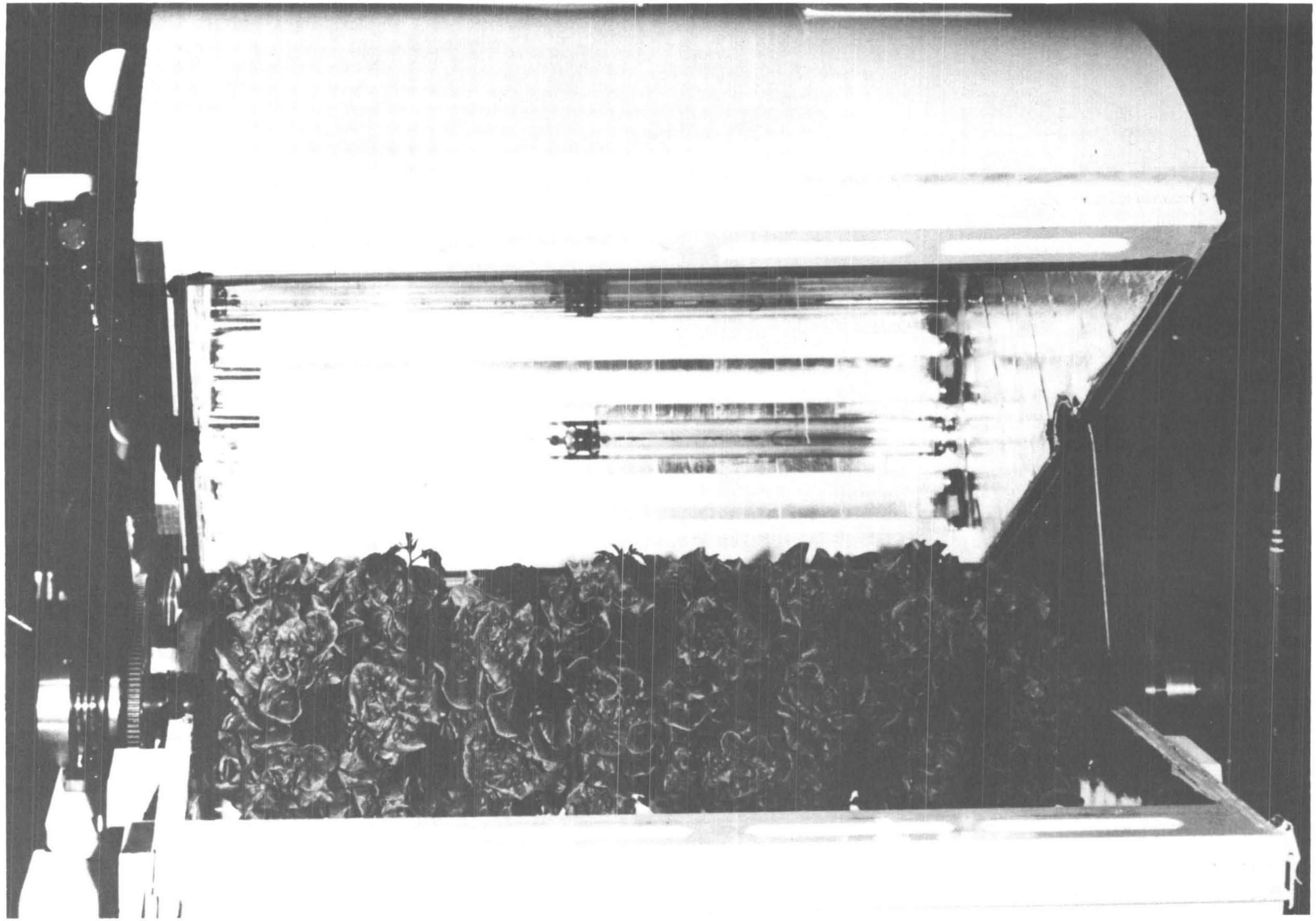

FIGURE 13.—Hydroponic food cultivation in zero-G.

it was utilized for most of the test due to irreparable failures with the vapor-feed unit. Even so, considerable maintenance and repair of the circulating unit was required.

A solid amine carbon dioxide removal and concentration unit was used for the majority of the test (already mentioned). Only during the last tenth of the 3-mo test was it found necessary to use the backup molecular sieve for CO_2 removal. Problems that forced shutdown of the solid amine unit were due to leakage of amine beads from the packed beds into the water outlet of the exit heat exchanger. This caused an overflow of the condensed water.

This four-man, 90-day test demonstrated the capability of the artificial environmental control systems to provide a habitable atmosphere for man. A great deal of essential data was collected: data concerning man's material balance under the test conditions, his ability to maintain and operate these systems for these time periods, and the suitability of the technology to provide life-support to man for these missions.

The program objectives for the 90-day US test, planned and accomplished, are listed in Table 9. It was found that the basic elements required in a regenerative life-support system (oxygen and water) could be reclaimed during a 90-day period with no significant problems.

Soviet Union 1-Year Test

A medical/technical experiment for 1 year was begun by the Soviet Union on November 5, 1967, to evaluate a long-term life-support system. Three subjects participated in the program. The problems studied were:

1. Establishing the feasibility of prolonged (up to 1-yr) human existence and maintaining adequate efficiency in isolation in a sealed chamber of limited dimensions with water and oxygen requirements regenerated from human wastes, and using almost completely dehydrated food products.

TABLE 9.—*Comparison of Planned and Accomplished Program Objectives*

Planned program objectives	Accomplished program objectives
Operate regenerative life-support systems for 90 d without resupply	Regenerative life-support systems were operated for 90 d with all maintenance accomplished on-board and no resupply
Obtain material and thermal balance and power requirements	Complete mass and energy balance was obtained on equipment and crew
Reach microbial and chemical equilibrium in a closed environment	Ninety d were completed without pass-ins, thereby assuring microbial and chemical isolation of test chamber and crew
Determine crew's ability to operate, maintain, and repair equipment	Performance of crew was outstanding in accomplishing normal operation of systems and in successful completion of many repair and maintenance tasks
Determine precise role of man in performing in-flight experiments	Computerized method for planning mission activities was evaluated, found a practical operational tool, providing necessary flexibility to adapt to changing program requirements; crew used an average of approximately 2 h/man-day for operational tasks, and during balance of workday demonstrated capacity for performing useful in-flight experiments
Obtain data on physiologic and psychologic effects of long-duration confinement	Nonintrusive method of evaluating crew behavior and performance (NIPA) was implemented for comparison with conventional methods of psychologic assessment, and found to be a practical operational tool; 90-d confinement caused no perceptible physiologic alterations and test environment was medically benign
Evaluate advanced life-support systems	Advanced life-support units evaluated: VD-VF potable water recovery Solid amine CO_2 concentrator Water electrolysis Two-gas controller & mass spectrometer sensor Microwave oven Commode

2. Studying the mutual effect of the systems and man, changes in the environment under these conditions, and verifying accepted methods of medical control and research to obtain reference data for developing a complex of medical-biological measures to support crews in space vehicles for long flights.
3. Studying and working out technologic regimes and constructions of individual units to obtain basic reference data for reasonable projection of life-support systems with more complete regeneration of water and oxygen from human wastes.

The ground complex of life-support systems included systems providing the greatest possible regeneration of oxygen and water as well as auxiliary and duplicate systems. The interaction of these systems in the complex makes a partially closed matter cycle possible. A schematic of such a system (Fig. 14) shows experimental values of material matter flows in g/d for three persons.

In the year-long experiment, the researchers were fed a specially developed diet consisting of vacuum-dried products containing an average 117 g fats and 361 g carbohydrates. The basic diet totaled about 3000 kcal, including meat, cereal, and dairy products, which were reconstituted before eating with water produced in the regeneration system. The daily packaged food ration for each man weighed 720 g. To satisfy the researchers' needs for fresh vitamins, salad greens cultivated during the experiment in the space greenhouse model were Khibin cabbage, cress, borage, and dill. High-intensity lights simulating the solar spectrum were used in the greenhouse. A special ion-exchange resin was used as a substrate, which was saturated preliminarily with nutrients. The growing area in the greenhouse was 7.5 m^2, and illumination was 45 to 50 W/m^2 at the surface level of the substrate.

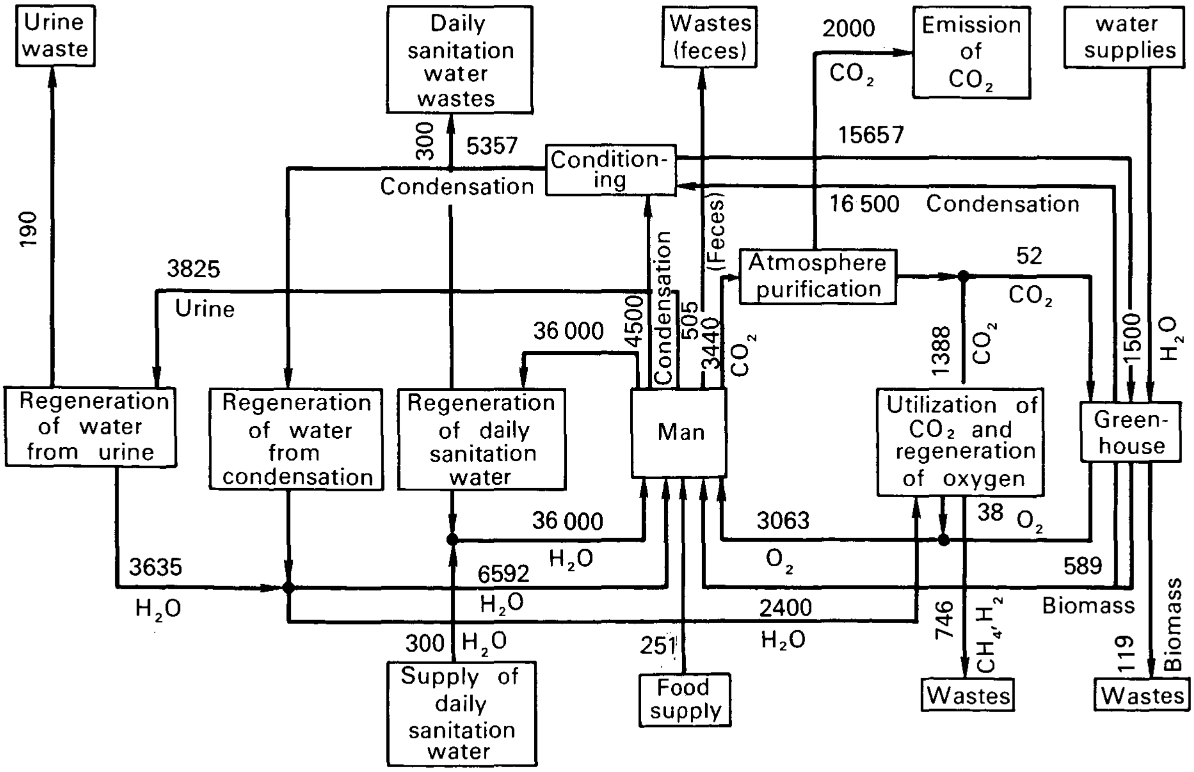

FIGURE 14.—Schematic of partially closed matter cycle in year-long medical-technical experiment (g/d for 3 persons).

Sources of drinking water for the researchers were excreted urine and moisture from respiration and perspiration condensed in the heat exchanger. Drinking water was regenerated from urine by oxidation-catalytic methods in several stages: filtration of urine; evaporation; high-temperature oxidation of organic compounds to elementary gases and oxides with the aid of a catalyst; and condensation. After the condensate was enriched with the proper salts and microelements, it was used as drinking water.

About 1300 g water were contained in the daily amount of urine, and 2200 g were consumed. The deficit of drinking water in the amount of 900 g/d was made up by atmospheric moisture condensed in a regeneration unit. Water was regenerated from the condensate by oxidation-sorption methods which included filtration, oxidation of organic compounds under ultraviolet light, additional purification in ion exchange resins and enrichment of the resultant water with salts and microelements.

Daily sanitation water was used for toilet, shower, and sink. So-called kitchen water, left after washing dishes, was regenerated by oxidation-catalytic methods similar to those used in regenerating water from urine. The rest of the daily sanitation water was regenerated by the coagulation method.

Oxygen was produced in a regeneration system composed of two units: an electrolysis unit and a unit utilizing carbon dioxide. After being purified of alkali aerosol, the oxygen entered the living compartment and the hydrogen entered the unit utilizing carbon dioxide. In the utilized unit, water was produced by catalytic hydrogenation of the carbon dioxide discharged by the researchers. Methane produced in the reaction was not regenerated and was jettisoned.

The air in the sealed cabin was cleared of carbon dioxide, and its concentration was controlled by an atmosphere purification system composed of a unit for drying the air, using regenerative synthetic zeolites, and a unit concentrating carbon dioxide with the use of these same zeolites.

Thermovacuum methods were used to regenerate zeolites in the absorption and concentration units. After being purified, the air was again humidified and returned to the living compartment, and the concentrated carbon dioxide was directed into the utilization unit.

Special catalytic furnaces and bactericidal filters were included in the atmosphere purification system to cleanse the air of toxic gases (organic substances, amino compounds, carbon monoxide, hydrogen sulfide, and the like) and microbes. Solid human wastes were not included in regeneration and utilization processes.

Auxiliary systems for providing oxygen and eliminating carbon dioxide in the experiment were provided by a regeneration unit with oxygen-containing compounds and an autonomous unit with chemical absorbents of carbon dioxide.

During the experiment, the researchers lived in a sealed cabin, consisting of a living compartment and the experimental greenhouse, which were connected.

Both the US and the Soviet tests demonstrated that life can be sustained and crewmen can perform useful work for long periods in a closed-loop system in which the basic elements for life support are regenerated.

SUMMARY

In early manned spacecraft, where the mission duration was only a few days, relatively simple systems were sufficient to provide for the support of man. Generally, highly reliable components were utilized, and built-in redundancy provided the necessary backup to allow successful completion of these missions.

As mission lengths have increased, subsystems have become more complex in order to do a more adequate and more economical job of supporting life, e.g., the CO_2 removal and waste management subsystems on Skylab versus Apollo. Increased system complexity does not benefit reliability; indeed, complexity tends to degrade reliability, and when increasingly complex systems are to be utilized for missions of greater duration, a new approach must be found to provide for successful system operation thoughout the lengths of the missions. Redundancy will not fill this need because of the resulting exponential growth of the weight and size of such a system for long durations. Maintainability, fail-operational/fail-safe criteria, and adequate spares provisioning will provide the only means of sustaining men in reasonable spacecraft environments for long-duration missions.

The most advanced life-support system design so far, the recently completed Space Station Prototype, is a modular system concept with commonality (for spares reduction), maintainability, and overall computer-monitored functioning. A special valve concept has been derived to make this system more maintainable: it allows replacement of failed units without system shutdown. A basic rule affecting backup functioning is that, in the event of a single failure, the system shall be capable of continuing to provide life-support functions for up to 8 h during which the fault may be corrected by on-board personnel. The status of the system is monitored continuously by the on-board computer, and, in the event of failure, automatic shutdown, if needed, is provided together with emergency backup, if needed. Further, the location and nature of the fault are displayed along with the appropriate spares inventory. Man's capability to perform repair and replacement tasks is a vital part of such a system, and long-term complex system functioning cannot be obtained without such means.

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Chapter 10

BIOLOGICAL LIFE-SUPPORT SYSTEMS[1]

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The establishment of human living environments by biologic methods, utilizing the appropriate functions of autotrophic and heterotrophic organisms, will be examined in this chapter.

Biologic methods of life support are usually considered when planning for long periods of autonomous existence by spacecraft crews. Human life support in an artificially produced environment over many years brings up problems of human ecology in addition to those connected with life support in space. Careful examination of the problems, further development of the basic concepts of the contemporary theory of the human living environment, and critical analysis of practical models of the planetary environment used to standardize the atmosphere, food supply, and drinking water in spacecraft are required. However, current concepts of the necessary elements in the environment may be insufficient for the biologic requirements of human beings under prolonged autonomous conditions.

The parameters of the cabin atmosphere required for prolonged space flight are based on the concept that the living environment must sustain the human organism under fluctuating physiologic conditions, in order to maintain an optimal level of organism reactivity [28, 29].

Our understanding of the basic requirements of the human environment is incomplete; this is particularly apparent when viewed from the periodic historical identification of vitamins and vitamin deficiencies. The concept of the atmosphere as a solution of oxygen and carbon dioxide in an inert gas does not reflect the complex composition of the Earth's biogenic atmosphere, which contains a great number of organic admixtures, primarily of plant origin. Their biologic action, first discovered by Tokin in the form of the bactericidal effect, is extremely varied [135]. These substances may include both inhibitors and stimulators of physiologic functions, some of which have a vitaminlike action [44]. Similar concepts of the microbial environment of human beings as the source of immunogenetic stimulation necessary to retain normal immunity have been developed recently [64].

A BIOLOGIC SYSTEM

The concept of a biologically adequate environment is being developed by Soviet authors [27, 29]. A biologic system does not just include

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[1] Translation of, Biologicheskiye Sistemy Zhizneobespecheniya, *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*), Volume III, Part 2, Chapter 10, Academy of Sciences USSR, Moscow, 1972.

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possible methods of regenerating individual substances, such as oxygen, food, and water, but should produce a biogenic environment similar to Earth conditions, which ought to satisfy all man's biologic requirements.

The advantages of a biologic system can be realized to the greatest extent when individual life cycles form a single functional system of higher order; this system does not simply regenerate components of the medium necessary for man, but also produces a complete medium despite inadequate knowledge of what is needed for prolonged autonomous human existence.

One of the advantages of a biologic system compared to nonbiologic systems is its stability, with a minimum of control and guidance apparatus.

This is related to the universal principle of mutual correlation of processes in biologic systems at all levels, beginning with homeostatic self-control processes in the metabolic and physiologic functions of the cell, and holding for the internal mechanisms of stability maintenance in populations and biogeocenoses.

The biologic methods of life support will be discussed primarily as a complete biologic system with a relatively closed metabolic cycle. Construction of this type of system entails the greatest theoretical, experimental, and technical difficulties, but is also of great scientific interest. From this viewpoint, the possibilities can be evaluated of using individual biologic subsystems to provide for regeneration in mixed biophysical or biochemical systems.

The development of a biologic life-support system (BLSS) involves theoretical and experimental biogeocenology, in which man in an artificially produced biocenosis is capable of relatively independent existence under conditions of prolonged dynamic equilibrium, primarily by internal control mechanisms in a relatively closed metabolic cycle. This is a new problem in biology which does not have an adequate experimental and theoretical base. Before discussing this material, the more important concepts[2] and terms pertaining to natural and experimental biologic systems are defined.

BASIC CONCEPTS AND TERMS

Abiotic medium—physical factors in the living environment of an organism.

Autotrophic organisms—organisms capable of synthesizing the organic compounds which they contain from inorganic compounds (carbon dioxide, water, mineral salts). Based on the source of energy used for organic synthesis, they may be divided into phototrophic, using electromagnetic emission in the visible spectral region, and chemotrophic, which receive energy as a result of oxidation of different substances (iron, sulfur, hydrogen, nitrates).

Biotic medium—the entire living environment of any organism.

Biomass—the sum of all substances comprising an organism or population of organisms.

Biosphere—the current concept [142] includes a combination of mixed portions of the lithosphere (solid covering of the Earth), hydrosphere, and atmosphere, which are connected (now or historically) with the organisms populating them.

Biocenosis—functionally related set (group) of organisms occupying a common region of land or water. Biocenoses of plants (phytocenoses), animals (zoocenoses), and microorganisms (microbiocenoses) may be individually distinguished.

Biogeocenosis—a group of certain biocenoses with a complex of factors in the abiotic medium. Biogeocenosis represents an elementary structural and functional subdivision of the biosphere, which performs a certain type of biochemical work [131]. Biogeocenosis is defined as part of the biosphere, through which no biocenotic, soil, geomorphologic, or climatic boundary passes [131].

Heterotrophic organisms—organisms incapable of primary organic synthesis, which require prepared organic substances for their existence.

Biological life-support system (*BLSS*)—a set of organisms typical of a biogeocenosis, a functionally united association of animals, plants, microorganisms, and man, and existing in a state of dynamic equilibrium in a relatively closed metabolic cycle.

Populations of organisms which perform certain functions in the systems cycle will be identified as links in a biologic life-support

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[2] The book by Odum [96] is recommended for general orientation to these concepts.

system. The heterotrophic link will include the crew of a spacecraft, who perform their work and consume oxygen liberated by plants and eat organic material which is decomposed into water, carbon dioxide, mineral salts, and organic refuse.

Population—a number of specimens of a given species which populate a relatively isolated homogeneous region.

Ecologic system—a unit of the biosphere, in contrast to biogeocenosis, which may refer to biologic systems of any scale, for example, from the ocean to individual tide pools or from forests to trunks of individual trees. The lack of size dimension enables a broader application than the term biogeocenosis. In the USSR it is not used to describe nonbiologic life-support systems.

Closed ecologic system—a hypothetical biologic system existing on the basis of a metabolic cycle without an exchange of matter over its boundary.

NATURAL BIOLOGIC SYSTEMS AND A MODELED BIOLOGIC LIFE-SUPPORT SYSTEM

The energy for biologic metabolism comes from energy assimilated from external sources, which is transformed and accumulated in the organism to produce energy-rich organic compounds. One source of energy may be the oxidation of certain inorganic compounds or elements (chemosynthetic bacteria), but the source most widely found in nature is energy in the visible spectrum of solar radiation.

The process takes place in plants during photosynthesis, and may be represented

$$6CO_2 + 12H_2O \xrightarrow[\text{chlorophyll}]{\text{light (672 kcal)}} 6(CH_2O) + 6O_2 + 6H_2O$$

This reaction proceeds with participation of the pigment, chlorophyll, and absorption of light energy (672 kcal). The energy of light is used for decomposition of water, which is connected in a very complex, and still unclarified way with the synthesis of macroenergetic phosphate compounds, serving as an energy reservoir for the subsequent synthesis of carbohydrates, proteins, lipids, nucleic acids, and the products of secondary metabolism in green plants. The process of photosynthesis underlies biologic regeneration of air and food production, resulting from absorption of carbon dioxide, liberation of free oxygen, and accumulation of organic matter.

In respiration of heterotrophic organisms, oxidation of organic matter occurs, with liberation of accumulated energy and its conversion into carbon dioxide, water, and minerals. Transformation of these simple compounds into organic substances requires energy from external sources; this occurs in green plants when they absorb light.

Thus, the turnover of matter in a biologic system incorporates two contrasting processes at the basis of life: (1) the primary (autotrophic) synthesis of organic substances, with their accumulation of free energy, and (2) the destruction of these substances for the energy used in the vital activity of organisms.

Therefore, a scheme for a closed turnover consists of two hemicycles, synthesis and destruction, which may be represented by organisms with autotrophic and heterotrophic types of metabolism. In natural biocenoses, representing complex systems of several species with a large number of parallel and sequential links, real material-energy relationships can, in principle, be described by this scheme, although specific relations may not always be apparent due to the great complexity of natural systems.

Figure 1 shows relationships in a multistage biologic system, in a sequential trophic circuit. The first trophic level is composed of photosynthetic plants; the second, herbivores, which may serve as food for carnivores (beasts of prey of the first order), which in turn may be part of the food chain of beasts of prey of the third order, and so forth. Each trophic level is usually occupied by several competing species.

The last stage of the food cycle is composed of different heterotrophic microorganisms, which complete the process of destruction of organic material and conversion into inorganic compounds. In the subsequent cycle of synthesis of organic substances and accumulation of energy, plants reuse these compounds. The conversion of energy from one trophic level to another is accompanied by loss of a significant amount of energy (more than 90%), decreasing the total energy reserve on each consecutive trophic level. In artificial BLSS, maintenance of vital activity of a certain mass of organisms at a given trophic level requires the production of a much greater mass of organisms at subsequent levels. Consequently, a large number of trophic levels to provide human food in BLSS is a disadvantage.

A unique example of a functioning life-support system is the biosphere [142], one of Earth's envelopes, in which exist living organisms and elements with direct material-energy exchange between them. A characteristic feature of the biosphere is the prolonged state of dynamic equilibrium among living components of the abiotic medium.

Usually the extent to which biologic turnover of matter in nature is closed, is considered low. In such ecologic systems, an outflow of large amounts of biogenic carbon accumulates in combustible minerals, limestones, and other carbonate rocks, the amount in limestone and coal being estimated at three orders of magnitude greater than the amount of carbon in living matter on the planet. However, if life on Earth has existed for 2.5–3 billion years, the average yearly carbon outflow from the biologic cycle during this time has been about $1 \cdot 10^7$ tons, which is on the order of one-thousandth percent of the yearly plant biomass production on the planet, estimated as $2.3 \cdot 10^{11}$ tons of dry material per year [10].

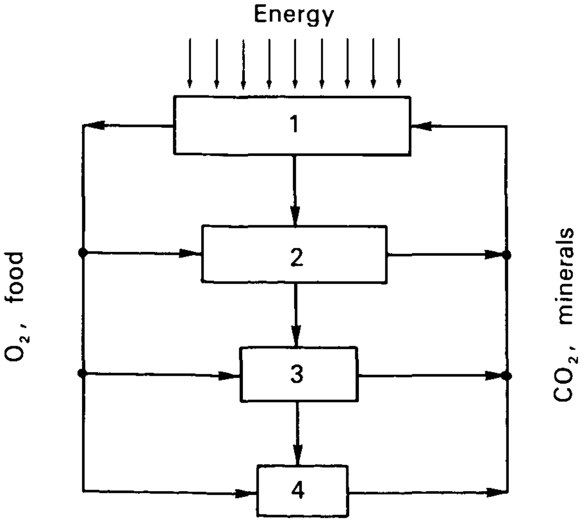

FIGURE 1.—Trophic links in biologic systems. 1, photoautotrophs; 2, herbivores; 3, carnivores; 4, microorganisms-mineralizers.

The biologic cycle, closed at such high level, is associated with enormous functional diversity of certain organisms responsible for the turnover of matter, which are in a position to trap most forms of organic matter for utilization in their own metabolism. It is primarily energy, not organic matter, that is lost in the global biological economy. Such a degree of closure in an artificially created BLSS is impractical, since the time to achieve stable operation of an artificial system must not be measured in geologic scales but in months or years.

Existing data and characteristics of the cycle of matter in nature will be examined, and certain parameters identified that can be used as criteria for comparison with proposed artificial systems. Such criteria may be masses of animate and inanimate matter, their ratio, and the circulation rate of substances. Planetary parameters and constants may be useful in modeling the basic biotechnologic structure of BLSS.

Parameters of Biologic Life-Support Systems

Before establishing absolute amounts of basic materials in the biosphere (water, oxygen, carbon dioxide per unit of living matter), it should be noted that not all of the space in the hydrosphere and atmosphere is active in material exchange between organisms and medium. For example, the active living zone of the ocean is only tens of meters deep, beyond which light does not penetrate, and photosynthesis cannot take place. The lower layers of the troposphere participate most actively in the biologic cycle by turbulent mixing of air. The air layers near Earth, which extend to certain phytocenoses at an altitude of several meters to tens of meters (as in the forests of the humid tropical and subtropical zones), participate most actively in photosynthetic gas exchange. Since the primary source of carbon dioxide in the atmosphere comes from the soil in dense grasslands and multilayer tropical forests, vegetation covering the soil is a powerful absorber of it. As a result, respiratory and photosynthetic gas exchange is localized in a small layer of air near Earth's surface, where the rate of gas exchange is maximum, and the rate of wind agitation at a minimum.

Table 1 presents estimates of the major components of Earth's biosphere, which clearly appear too low compared to the estimated amount of water and gases in the atmosphere which interact with living matter and comprise the real space of terrestrial and aqueous photosynthetic systems. Table 2 gives corresponding corrections based on these considerations.

According to Table 1, the biosphere contains three orders of magnitude (by weight) more air for each unit of biomass and five orders of magnitude more water than biomass, providing a natural damper which undoubtedly plays an important role in attaining stability by minimizing fluctuations in the volumes of air and water. If only zones of greatest photosynthetic activity are taken into account, then the portion of water per unit of biomass decreases by two orders of magnitude, and the atmosphere by at least one order of magnitude. Only in such zones as humid tropical forests does the effective volume of the atmosphere, which is practically excluded from wind mixing with the upper atmosphere, decrease to the same order of magnitude as the amount of biomass (by weight) or to several m^3/kg of phytomass. This value is close to that of existing greenhouses and hotbeds.

Biosphere Activity

An important index of biosphere activity is the turnover rate (calculations from data in Table 1), the ratio of yearly increase or consumption of matter and its present reserve. Thus, for the biosphere as a whole, the rate at which the phytomass is restored is about 10 years, and consequently the turnover of organic material, 0.1/year. However, this is an average value from very diverse restoration rates, such as in forests and deserts. The rate of turnover of the ocean phytomass is

TABLE 1.—*Quantitative Estimates of Earth's Biosphere*[1]

Components of biosphere	Absolute amount, tons	Per unit of biomass, ton/ton	Production or requirement, ton/yr	Duration of regeneration cycle, yrs
Phytomass (dry material)	$2.4 \cdot 10^{12}$		$2.32 \cdot 10^{11}$	10
Ocean phytomass	$1.7 \cdot 10^{8}$		$6.0 \cdot 10^{10}$	$3 \cdot 10^{-3}$
Ocean water	$1.37 \cdot 10^{18}$	$5.7 \cdot 10^{5}$		$1 \cdot 10^{6}$
Atmosphere	$5.1 \cdot 10^{15}$	$2.1 \cdot 10^{3}$		
O_2 in atmosphere	$1.18 \cdot 10^{15}$	$4.9 \cdot 10^{2}$	$2.32 \cdot 10^{11}$	$5.1 \cdot 10^{3}$
CO_2 in atmosphere	$2.35 \cdot 10^{12}$	1.02	$3.4 \cdot 10^{11}$	6.9

[1] Compiled from data in [10].

TABLE 2.—*Estimates of Biologic and Atmospheric Components in Tropical Forests with a High Concentration of Living Matter*[1]

Components of biosphere	Absolute amount, tons	Per unit of biomass, ton/ton	Production or requirement, ton/yr	Duration of regeneration cycle, yrs
Biomass (dry material)	$1.17 \cdot 10^{12}$		$7.7 \cdot 10^{10}$	15
Atmosphere	$1 \cdot 10^{14}$	$8.6 \cdot 10^{1}$		
O_2 in atmosphere	$2.3 \cdot 10^{13}$	$1.97 \cdot 10^{1}$	$7.73 \cdot 10^{10}$	$3 \cdot 10^{2}$
CO_2 in atmosphere	$4.7 \cdot 10^{10}$	$4 \cdot 10^{-2}$	$1.14 \cdot 10^{11}$	$4 \cdot 10^{-1}$

[1] Compiled from data in [10].

about 350 cycles/year, which means the yearly production of phytomass in the ocean is 350 times greater than its standing crop.

The relationships of the basic components of the biosphere and the magnitudes of biological cycling are shown in Table 1. The amount of phytomass and carbon dioxide in the atmosphere is approximately equal by weight, and the rate of restoration, about 10 years. For the available reserve of atmospheric oxygen, this covers a thousand years, while for water in the ocean, on the order of a million years. The limiting turnover rate in the biosphere is that of carbon dioxide, which is linked to photosynthesis. The stability of the biosphere turnover is determined by the equilibrium of the cycle between phytomass and carbon dioxide, since specific amounts[3] of oxygen in the atmosphere and water in the ocean are much greater (by 2–5 orders of magnitude) than that of carbon dioxide. Therefore, the possible fluctuations in amounts are smaller, and change to an unstable state, less probable.

In those zones with the greatest concentration of life (shown in Table 2), specific amounts of inanimate matter and its restoration rate are 1–2 orders of magnitude less than in the biosphere as a whole, although production in these regions is only about 35% of production in the entire biosphere.

Table 3 shows the magnitude of components of an artificial biologic system supporting a five-man crew. The ratio between the amount of carbon dioxide and biomass corresponds to highly productive natural macrobiocenoses (see Table 2). The amounts of the atmosphere and oxygen per unit of animate matter are only 1 order of magnitude less than in a real natural macrosystem. The absolute dimensions of the system (the amount of animate matter and atmospheric gases) are 13–15 orders of magnitude less than the dimensions of a natural system, which illustrates the enormous reduction in the dimensions of this model, compared with nature. A reduction of this magnitude may cause a loss of the model's stability, which is the main feature of a natural system, and makes it impossible to retain the diversity of the animate components, that is, to insure a completely closed cycle of matter within an artificial system. However, as already stipulated, this is not an absolute necessity.

Thus, it follows from an analysis of natural biologic systems that the basic requirements for retaining a high degree of stability in biologic cycling are a large amount of biogenic substances outside the organisms to provide damping of fluctuations, and a large amount of animate material to provide a high degree of closure. Other basic factors are redundancy of homogeneous functional elements (species) and the presence of many parallel functional links in the form of different species of organisms.

The problems of adequately modeling biologic systems, using different scales between the model and nature, and holding a critical mass of animate and inert matter in a system have been examined [114].

STRUCTURE OF A BIOLOGIC LIFE-SUPPORT SYSTEM

Only general problems of the BLSS structure are examined in this section: the purpose and function of the main elements, their interrelationship, and the principles underlying selection of organisms. The specific problems of biotechnology are discussed in Chapters 3 and 5 of Part 1, and Chapter 9 of Part 2 of this volume (III).

In accordance with the structure of natural systems, the main elements of an artificial biologic system shown in the block diagram (Fig. 2) will be examined.

Photoautotrophic Subsystems

Energy is introduced by the photoautotrophic subsystem, which may consist of higher plants and unicellular algae. Higher plant forms, traditionally necessary for food supply, must be the basic source of vegetable food products despite complicated cultivation under artificial conditions, inadequacy of the biomass to supply food for human beings, the frequent necessity for periodic illumination, and the frequent inability to self-pollinate. However, many plants can grow under continuous illumination.

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[3] A specific amount is an amount of substance per biomass unit.

An evaluation of higher and lower plant forms as photoautotrophic components from the point of view of stability and control is presented by Meleshko and Shepelev et al [78, 118]. The chief drawback of higher plant forms is great inertia, caused by the long growth period. Unicellular algae, used as an additional photoautotrophic element, significantly improve the biochemical composition of the biomass produced (high content of protein and fat), as well as the dynamic properties of the system. They show the least inertia of autotrophic organisms because of their high multiplication rate and ease of cultivation. These characteristics not only justify their inclusion in a biologic system, but also determine their minimal contribution.

If a certain variable allowing for periodic increases or decreases in gas exchange of the photoautotrophic element is presumed, then the minimum involvement of unicellular algae can be established. The upper limit will be determined by their maximum usefulness as food.

The nutritive value of algae, however, cannot yet be considered established despite significant research, especially in Japan, the US, and the USSR. Many investigations of variations in the protein, carbohydrate, and lipid composition of algae have been undertaken in the US [18, 120]. Data have also been obtained on the carbohydrate content in algae under different cultivation conditions [59]. Early experiments on animals have provided positive results. Algae are quite rich in vitamins and protein; for example, *Chlorella pyrenoidosa* contains from 40% to 60% protein, about 20% carbohydrates, from 10% to 20% fat, and from 5% to 10% ash. The amino acid composition of proteins in *Chlorella* is completely adequate for human requirements, with the exception of the sulfur-containing amino acids, methionine and cystine, in which algae are deficient. Data compiled to the present show that their permissible portion in the food supply of human beings does not exceed 20%, although in some cases, the requirement for algae has reached 500 g/d [101].

Algae and Human Food

Experiments in which 50, 100, and 150 g of a biomass mixture of *Chlorella* and *Scenedesmus* were added to human food showed that 50 g algae (dry weight) in the food supply of three test subjects caused dyspeptic phenomena (belching, nausea, and loss of appetite), which disappeared after 2–3 d [52]. In another test group, food supplemented with 100 g dry algae produced dyspeptic phenomena in the first few days in all four test subjects. The period of subjective adaptation to this diet was more prolonged; however, no objective disturbances in the gastrointestinal tract were observed throughout the entire experiment of 20 d. In another ex-

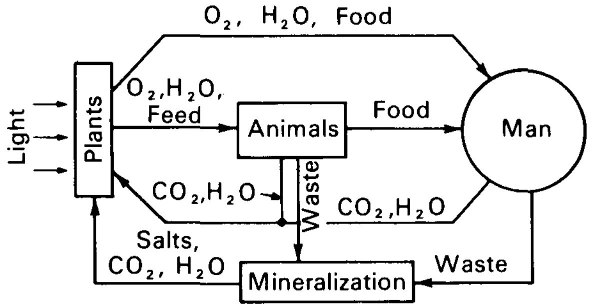

FIGURE 2. — Biologic life-support system.

TABLE 3. — *Parameters of Biologic Life-Support System for Five-Man Crew*

Components of biosphere	Absolute amount, tons	Per unit of biomass, ton/ton	Production or requirement, ton/yr	Duration of regeneration cycle, yrs
Total biomass (dry weight)	$1 \cdot 10^{-1}$			
Atmosphere	$6.5 \cdot 10^{-1}$	6.5		
O_2 of atmosphere	$1.4 \cdot 10^{-1}$	1.4	1.5	$1 \cdot 10^{1}$
CO_2 of atmosphere	$1.8 \cdot 10^{-3}$	$1.8 \cdot 10^{-2}$	1.8	$1 \cdot 10^{3}$
Water	1.0	10.0	7.8	0.14

periment, where five persons received 150 g/d of algae, four displayed prolonged dyspeptic phenomena as well as allergic reactions such as local hyperemia and edema of the face and distal portions of the extremities. In two cases, these phenomena appeared only after changing to the control diet.

The first studies on the nutritive value of algae, including these experiments, were performed with a biomass of different species and strains, cultivated in containers under the open sky, with a large portion of uncontrolled microflora as contaminants.

The cause of the observed allergic phenomena may be related both to the properties of algae and to bacterial admixtures in the nonsterile culture — particularly to biologically active lipopolysaccharides of bacterial membranes. A special study revealed the absence of allergens in *Chlorella* when given as intracutaneous and subcutaneous injections to animals and human beings [103]. Data indicate that human food may contain from 30 to 100 g of dry algae mass/d. Reduced data are given in the summary article [15] and in other articles [49, 50, 51].

A disadvantage of unicellular algae as food is their poor assimilability caused by indigestible walls [38]. Enzymatic destruction of algal cell walls by means of the cellulase enzyme of certain bacteria, lower fungi, and mollusks has been demonstrated [39]. A positive result was obtained with the enzyme obtained from the *Trichoderma* fungi [136]. Destruction of the cell walls and subsequent increase in the digestibility of algae protein was shown with cellulase derived from the alimentary canal of the snail, *Helix pomatio* [16]. Physical disruption has also been demonstrated, but the use of quite complex equipment has been necessary [23].

The use of unicellular algae for food, as with higher plants, depends largely on their biochemical composition. The use of unicellular algae in life-support systems at present has been limited to representatives of closely related species of the Protococcaceae, which are much alike in composition and nutrient properties. The different physiologic and biochemical characteristics of the best known species of *Chlorella* are described in a recently published monograph [120]. Problems in the mass culture of unicellular algae for food and other organic compounds have been examined [57]. Another useful reference is Spoehr and Milner's paper on the chemical composition of algae [128].

Selection Criteria for Artificial Biocenosis

Creation of an artificial biocenosis requires establishment of selection criteria for plants and animals most advantageous in the system. Criteria for selection of plants included [20, 75, 92]: high productivity, biochemical composition to satisfy human requirements, customary use as food, food requirements of human beings, compatibility between plants and human beings, and minimal technical complexity of food preparation. Complex technology is exemplified by the five technologic operations required to obtain bread from grains and cereals. In contrast is the simplicity with which salad greens may be used.

The criteria for selecting species in a biologic system are often complex and contradictory. The biologic components are primarily determined by two factors: the requirements of the human being, who is essential in the system, and the need to increase the effectiveness of the biologic system as a whole as well as each functional element (phyto- or zoocenosis). Since the first requirement is frequently opposed to the others, final selection of biologic components will be a compromise. All life-support systems are limited by weight, volume, and energy. For example, an adequate plant diet may include beans, grains, and oil extracts to provide the protein-fat portion of the diet. In studies of peanuts, beans, and lima beans [107] for use in biologic systems, and wheat as the plant component in an experiment with human beings [71, 72], it was found that these plants are least suitable, since a comparatively small portion of seeds (grain, beans) is used in the human diet. The remaining portion must be mineralized to be included in the subsequent cycle, thus sharply reducing efficient use. The criterion for complete consumption necessary for efficiency cannot be met if the other component is man. Consequently, limited use of grain and oil plants to satisfy the nutritive requirements of human beings must be examined.

The importance of given criteria may change, depending upon the system's biocenotic structure and the degree to which the cycle is closed. Thus, introduction into the system of heterotrophic organisms, which require plants that are inedible for humans, increases the degree to which a system is closed and reduces the weight of the criterion of complete consumption. The logic of introducing heterotrophic elements into a system has been partially examined [29].

Despite contradictions, there are criteria which determine whether some organisms are preferred over others: nutritive value for human beings, high level of productivity (per unit of volume, area under crop, or illuminated surface, per unit of time), complete use of the biomass, commonality between physical requirements of several species, and biologic compatibility of concurrent cultivation. The need for plants with high specific productivity and common environmental conditions leads to a search among tropical and subtropical forms; such plants will also have similar photoperiods. The final selection of components will be determined by the optimality of the system as a whole.

Heterotrophic Elements in a Closed Ecologic System

A closed food regeneration cycle may necessitate the introduction of heterotrophic elements to obtain the required minimum of animal food, even though the overall efficiency of the system may be decreased. The addition of animals will benefit the system particularly where plant waste products are edible for them, but not for man. The plankton crustacea, *Artemia salina* and *Daphnia magna*, were the first to be proposed [17, 130]. Later, the matter-energy balance was calculated for rabbits and poultry [1, 4] and preliminary studies made of the possible use of tropical fish, such as *Tilapia mossamica* [87, 88]. Goats have been considered for milk, while several researchers have recently been interested in mollusks which can be fed plant waste products and do not have shells, such as *Lymax* or *Arion*.

The most important, although perhaps contradictory, criteria to be considered when formulating an animal link are suitability as food, high specific productivity, and feasibility of continuous cultivation under artificial conditions. The accidental death of any individual disturbs the equilibrium of the system; the greater each one's contribution to the total mass, the more disturbance when it dies. Thus, it is advisable to select animals with the smallest mass and shortest life cycle to increase the system's reliability and ease of restoring equilibrium. The high metabolic rate of smaller organisms is also of value [145].

The problem of psychologic acceptability of unusual animal foods is naturally of great importance. The amount of exotic food and use of culinary techniques to conceal or modify the food properties must be taken into account.

Man and animals can mineralize up to 80%–90% of organic material in a life-support system. However, in order to complete mineralization and utilization of the waste products of man, animals, and plants, which is particularly important for maximum effectiveness of a BLSS, another special link must be introduced to achieve the most nearly complete closure of the system possible. Closure of the system will enhance its self-perpetuating properties.

Biologic Mineralization

Two solutions to the mineralization of organic waste products are being examined and studied, the physicochemical and biological. The preference for biologic mineralization has already been discussed in connection with the biologic value of a plant environment [114]. The requirements of plants over several vegetation cycles exceed those which can be met by laboratory nutritive media. Hydroponic cultivation ignores the important role of rhizosphere microflora and the general interaction of plants with soil microflora, which may explain the termination of flowering of hydroponic cultures after several generations [92]. The anaerobic processes of microbiologic mineralization were rejected because of slowness and formation of gaseous products of incomplete oxidation, such as hydrogen, methane, and others, which are not utilized directly in the biologic system. The biological method of mineralization may better employ aerobic oxidation in reactors similar to air tanks which purify waste waters. Similar processes and devices were first used to mineralize mixtures of urine and feces in algal reactors [32, 33, 73, 104, 106, 132, 137], for the mineralization of feces [12], and mixture of nutritive waste products and human excretory products [21, 22].

Lavery and Tischer [63] published the first summary of the literature on this topic. The utilization of aerobic decomposition of feces and urine in a "human algal" system was examined [67, 84]. Meleshko and others showed that the direct use of urine in an algal recycling reactor is only possible for a limited period, determined by the time required for accumulation of excess amounts (approximately 6 g/l) of chlorine ions [84]. A similar limitation with respect to creatinine and hippuric acid was shown by Lynch [73].

These attempts to utilize urine in algal reactors point to the necessity of developing a "human-human" cycle with respect to sodium chloride—a compound used by man as a palatable substance, which may not be required in an equivalent amount by other components of the system. This problem, whose solution is probably in the realm of physical chemistry, limits complete utilization of urine in the system. Significant difficulties are also encountered in mineralizing the organic matter of feces and plant waste products, consisting primarily of cellular tissues, which are very slowly decomposed by microorganisms.

Physicochemical Mineralization

Physicochemical mineralization studies have been made of thermal combustion as well as oxidation in the liquid phase at high pressures and temperatures (so-called moist combustion) [12, 121, 153]. However, subsequent studies have shown that the apparent simplicity of thermal or liquid phase oxidation is accompanied by difficulty in using the end products of these processes. Data show that the products of moist combustion of feces and urine, without additional processing, are toxic to higher plants [2, 3]. In studies of thermal combustion of feces [121], a difficult problem to solve in a closed system is the return of poorly soluble metal oxides as well as gaseous nitrogen, phosphorus, and sulfur into the cycle. This is a basic drawback for thermal mineralization.

The necessity of binding molecular nitrogen gave impetus to the study of nitrogen-fixing microorganisms, particularly blue-green algae, to eliminate the impasse in the nitrogen cycle [25]. Korydum [53], who studied several blue-green algae, showed they could bind up to 2.0 g nitrogen/m^2 of illuminated surface per day (with 24-h illumination). According to the data of Antonyan [8], the blue-green alga (*Anabaena variabilis*) may bind 6%–20% of atmospheric nitrogen in the cells.

In the future, mineralization may be accomplished by combining biologic and physicochemical methods; the latter can be used for combustion of cellulose to form carbon dioxide and water. The technique of "moist combustion," carried out at a pressure of 150–250 atm or more, is extremely inefficient compared with direct combustion, since the end products cannot be utilized without subsequent processing. Thus, physicochemical mineralization and particularly thermal oxidation, must be a part of the mineralization system of organic wastes.

The difficulties of utilizing the end products of physicochemical mineralization in a closed system indicate reverting to the biologic methods where the products merely correspond to plant requirements. The activity of microorganisms in a system of biologic mineralization also involves formation of vitamins, hormones, and other biologically active substances to provide a more adequate environment for plant growth, compared with autoclave liquid or a solution of furnace ashes.

DEVELOPMENT OF INDIVIDUAL FUNCTIONAL LINKS IN BIOLOGIC LIFE-SUPPORT SYSTEMS

A comparative evaluation was made in 1966 of the extent to which individual links in a biologic system could be developed [7]. A summary in Table 4 shows estimates (designated by numbers in parentheses) which should now be substituted after 6 years of intensive research. The relative position of the research subjects in this table has not changed in this period.

TABLE 4.—*Work on Various Biosystems as Applied to Space Conditions* [1]

Biosystem	Gas exchange	Utilization of wastes	Full value of products
Algae	4	2 (3)	2
Higher plants	2 (3)	1	1 (2)
Yeasts and molds	0[2]	1	0[2]
Animals	0[2]	0[2]	0[2]

[1] Compiled from data of [7].

[2] 0 = lack of data, or the data do not apply to space conditions; 4 = sufficient amount of data.

The development of any link in a biologic system primarily means selecting the most suitable forms of organisms and species, which will subsequently be the subject of biotechnologic research.

Autotrophic Link

The optimum structure of a photoautotrophic link may combine unicellular algae and higher plants. Attempts to regard unicellular algae as a single partner of man in terms of nutritive relationships as well as gas exchange, are only of historic value, and will not be discussed here. This does not exclude examining the problem of utilizing photosynthetic gas exchangers [91]. During flight tests on-board a spacecraft or at a lunar base, any biologic subsystem of the BLSS must function independently, backed up by the appropriate physicochemical devices or stored substances.

Unicellular algae. Early studies explored the possibility of using unicellular algae for the vital processes of spacecraft crews [14, 24, 26, 89, 133]. Myers [91] reported a reliable physiologic-biochemical and biophysical basis for the effectiveness of photosynthetic gas exchangers based on unicellular algae in 1964. Lockheed [36], in 1966, presented preliminary evaluations of life-support systems using algae as well as hydrogenous bacteria and higher plant forms. In the same year, the first review of experimental data was published by Miller and Ward [86] on the use of unicellular algae in biologic systems from an analysis of 173 sources in the literature, data which are still valuable.

Unicellular algae in biologic life-support systems (BLSS) were first studied in the USSR by Pinevich [100], Chesnokov et al [19], and Semenenko, Vladimirova, and Nichiporovich [93, 113, 147]. Generalized results of studies have been presented more recently by Shepelev and Meleshko [117]. Several reports by US authors [58, 59, 126] are on the relationship between suspension density and intensity of its illumination, which influences significantly the vital and photosynthetic activity of *Chlorella.*

The initial stage of comparative evaluation and selection of the most promising unicellular algae was already established, since several similar forms, particularly species of *Chlorella,* have served as traditional study objects of the processes of photosynthesis by plant physiologists. Consequently, it was assumed that they would be studied as potential components of biologic systems. As a result of selection, thermophilic strains of *Chlorella* were later produced: *Chlorella sorokiniana,* also called TX−71105 [127] used in the US, *Chlorella pyrenoidosa* sp K [56], and *Chlorella vulgaris* studied in the USSR.

Productivity of Cultures

In earlier experiments on cultures of low density (hundreds of thousands of cells per milliliter of suspension), 200−500 or more liters of culture were required for the gas exchange of one human being [36, 154]. To decrease the amount of algal suspension in the total weight of the photosynthetic gas exchanger, a large increase in productivity per unit of volume was required, leading to use of culture densities not previously studied. The optimum level of such cultivation parameters as illumination, carbon dioxide concentration in the air [82], and mineral salts in the culture medium was then examined.

The large gradients of carbon dioxide concentration in suspensions of great density brought about the problem of increasing partial CO_2 pressure at the boundary of the gas-liquid interface. This automatically led to creation of carbon dioxide concentrators or increasing the suspension surface in contact with the regenerated air, assuming it is unnecessary to maintain CO_2 concentration for man and algae at the same level (not more than 7.5 mmHg [86]). The same considerations pertain to the partial pressure of oxygen which will increase greatly in well illuminated, dense suspensions. The depressive action of oxygen on photosynthesis has been well known since the work of Warburg. Figure 3 gives an example of this influence [80].

The continuous intense cultivation of algae cannot be directly based on existing physiologic data on optimum conditions, which were obtained from experiments with suspensions of very low density.

The widest suspension density range (up to 16.6 billion cells per milliliter of suspension, or about 128 mg/l algae dry weight) has been studied [76]. The maximum productivity of this suspension in terms of oxygen per day was 246 l of O_2 from 1 liter of suspension. In all, 2 l of algae could be sufficient to provide gas exchange for one human being. However, the anticipated weight of the photosynthetic chambers and their auxiliary devices is so large that it is impractical to decrease the suspension volume in the reactors to such a low level. The use of suspensions with this density, where the volumes of cellular mass and culture medium are similar, is extremely difficult, and raises new biotechnologic problems.

In reactors which actually provide human gas exchange, 15–40 l of suspension are currently used, having a density of 7–15 g/l. With improved light distribution, this suspension volume can be greatly reduced.

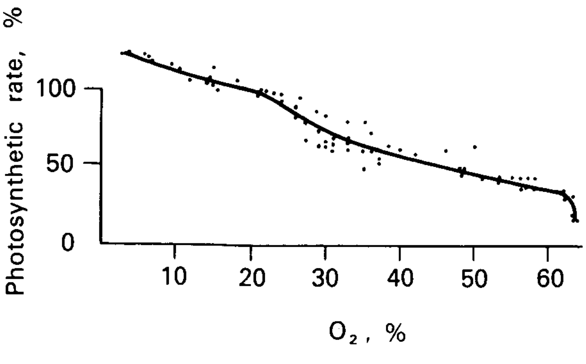

FIGURE 3.—Photosynthesis rate in suspension of *Chlorella* at various oxygen concentrations in air and normal barometric pressure [80].

The complex requirements for productive algal cultures coupled with weight and energy limitations on spacecraft have meant that there are still no operational photosynthetic reactors for use as prototypes of spacecraft photosynthetic systems. A useful project at this time would be to design a photosynthetic gas exchange system and install it aboard the space laboratory. The solution of this bioengineering problem would clear the way toward identifying potential problems and advantages of bioregenerative systems.

Use of Reactors

Reactors in different laboratories use various methods of illumination, mixing, and gas exchange. For example, results from studying dense cultures [76] were obtained from cultivation of thin films, a method similar to the one used in reactors described by Phillips [97]. However, the film was not produced as a result of centrifugal distribution of the suspension, but obtained by spreading over the internal surface of a rotating horizontal cylinder, the entire suspension volume being illuminated.

Reactors have been built with internal and external sources of light, direct illumination, distribution of light by means of wedgelike light guides, with different ratios of illuminated and dark portions of the suspension. Several laboratories equipped with identical types of photosynthetic reactors would be greatly advantageous in future collaborative research.

A problem with a photosynthetic gas-exchanger is the great loss of culture medium resulting from harvest of the cells during flow cultivation. With a single doubling of the algal population per day, the amount of medium, separated from the reactor along with the crop, equals the suspension volume in the reactors. This requires large capacity for regenerating and purifying the medium from organic admixtures. For example, polysaccharides can be deposited in the medium by algae at 20–45 $mg/l \cdot d^{-1}$ [36]. A method of continuous algal cultivation was devised by which the culture medium was returned directly to the reactor without preliminary processing [83, 85].

An anticipated problem, the accumulation of inhibiting concentrations of organic material, did not arise due to action of heterotrophic microflora in the algal reactor. An algae-bacteria association in relative equilibrium develops in a nonsterile algal culture. The activity of heterotrophic microflora provides relative stabilization of the organic metabolite level to a degree which does not reduce physiologic activity of algae [98, 99]. The accumulation of some organic metabolites in the medium stimulates algal growth and is one factor enhancing the biologic value of the medium.

A laboratory model of a photosynthetic gas exchanger has been devised in the US for a 1-liter algal suspension providing automatic harvesting and recirculation of the nutrient medium. This installation, termed recyclostat, has been described and used in week-long experiments [58].

A plateau in the increase of organic matter in the culture medium has not been observed. There is a small increase in the amount of organic matter a month or more after the beginning of cycled cultivation. An accumulation of humic material which is difficult to decompose, and which may be an obstacle to the complete closure of matter turnover is possible, and needs further study.

The development of continuous algal culture with recirculation of the medium is impossible without supplying a balanced nutritive medium, in which mineral elements would fully coincide with cell requirements. Ordinary laboratory media do not satisfy these requirements. A study was made of the actual requirements of algal cells for mineral elements in a dense culture [47, 60, 81, 86, 89]. The removal from the reactor of mineral elements with the crop biomass, as well as removal of the culture medium residue adhering to the centrifuged biomass was examined [30, 60, 65, 81].

Formulation of the correcting additive should take into account not only the chemical composition of the algal biomass but also all forms of elemental loss from the reactor, including that adsorbed on the cell surface.

These data were obtained for different strains of *Chlorella* grown on different nitrogen sources in a nutritive medium (see Table 5). On the basis of data obtained by Lebedeva et al [66], a formula was developed for a corrective mixture added to the reactor for each gram of biomass grown (dry weight):

HNO_3 – 0.300 mg
KH_2PO_4 – 0.057 mg
H_3PO_4 – 0.011 mg
$MgSO_4 \cdot 7H_2O$ – 0.059 mg
H_2SO_4 – 0.010 mg
$FeSO_4$ – 0.0015 mg

The subsequent quantitative study of cell metabolism in the culture showed a rigorous relationship between cell requirements for mineral elements, gas exchange, and accumulation of biomass. Thus, according to the data of Meleshko and coworkers, with the formation of 1 g dry weight of *Chlorella*, 1 liter of CO_2 is absorbed, and 1.2 l of oxygen are liberated [117], or 0.9 and 1.015 normal liters. Biomass is accumulated, characterized by the formula $C_{6.6}H_{12.2}O_{3.5}$, which is similar to the formula $C_{6.0}H_{11.1}O_{2.7}$ [90, 128]. The amount of carbon dioxide absorbed by 1 g of cells is within the range of the carbon content in the biomass, which is between 500 mg/g [117] and 453 mg/g [81]. The principle underlying the correlation between physiologic functions in the organism enables use of any parameter of those having a correlative relationship for control. In this case, the mineral supply is most advan-

TABLE 5.—*Loss of Elements from Nutrient Media per Gram of Biomass Produced*

Elements	Authors		
	Lebedeva [1] et al [66] mg/g	Kuznetsov [2] et al [60] % nitrogen	Gitel'zon [3] et al [30] mg/g
Nitrogen	82 ± 1.9	100	90
Phosphorus	17.6 ± 1.7	18	11–12
Sulfur	11.2	5.9	4–5
Potassium	16.0	19	10–11
Magnesium	5.7 ± 1.2	5.5	3–4
Iron	0.3		

[1] *Chlorella pyrenoidosa*. nitrogen source—nitrate.
[2] *Chlorella pyrenoidosa*. nitrogen source—urea.
[3] *Chlorella vulgaris*, nitrogen source—urea.

tageously controlled by the biomass increase and carbon dioxide absorption [77, 79].

Lack of agreement between the photosynthetic coefficient for algae and the respiratory coefficient for humans should be taken into account when algae are used to provide gas exchange for human beings. In one study, it was found that the photosynthetic coefficient for algae depends on the nitrogen supply[77, 90]. When nitrate nitrogen was used, it was minimal, amounting to 0.79 ± 0.01. With nitrogen in the form of ammonia or urea, it was 0.82–0.85 and 0.99, respectively. On this basis, Meleshko proposed dividing algal reactors into sections and utilizing different forms of nitrogen for the algae in different sections. In principle, then, it is possible to obtain the necessary photosynthetic coefficient between 0.79 and 0.99, which encompasses all possible fluctuations of the human respiratory coefficient.

Utilization of Algae in Food

The degree to which algae may be used in human food is limited by insufficient carbohydrates and sulfur-containing amino acids, and excess protein in their biomass. Many studies have been directed toward making the algal chemical composition approach human food requirements. Absolute correspondence is not required, since neither *Chlorella* nor any other organism can be the sole food source for human beings. On the other hand, removing disproportions in the biochemical composition of algae could contribute to an increase in their proportion in the food supply.

There are three ways to approach this problem. First, by the artificial production of mutations and subsequent selection of mutants, Kvitko and coworkers obtained strains of *Chlorella* with a quantity of cysteine which was four times greater than its content in the initial form, with an insignificant reduction in culture productivity [62].

In later studies on the mutants' nutritive value for rats, the amount of the mutant strain eaten in a mixed diet was 85%–100% compared to 40%–57% in the initial strain. The assimilability of the mutant strain biomass was 70%–90%, compared to 53%–83% assimilability of the standard strain [143]. However, in an intensive culture, competitiveness of the mutants was reduced with gradual elimination of the mutant strain during prolonged cultivation, with reversion to the wild form [61].

A second approach, exemplified by studies from the laboratories of Semenenko (USSR Academy of Sciences, Institute of Plant Physiology) and Gitel'zon (USSR Academy of Sciences, Siberian Branch, Institute of Physics) on the control of biosynthesis of microalgae, shows changes of chemical composition of algae under extreme cultivation. Intensified synthesis of lipids with increase in the content of free aliphatic acids up to 75%, and decrease in the degree of saturation [48, 113] occurs in *Chlorella* under nitrogen deficiency conditions (including complete absence of nitrogen in the medium) during extreme cultivation. Thus, the amount of oleic acid increases from 3.9% to 43% of total acids.

The carbohydrate content in *Chlorella* sp K, in the absence of nitrogen, may amount to 55% dry weight; up to 80% carbohydrates in a given strain is represented by starch. Synthesis of algal strains has been shown to be genetically determined and manifested in different ways in various forms and strains of algae. Figure 4 shows the results obtained [111] when *Chlorella vulgaris* was grown in a medium devoid of nitrogen. In general, the direction taken by changes

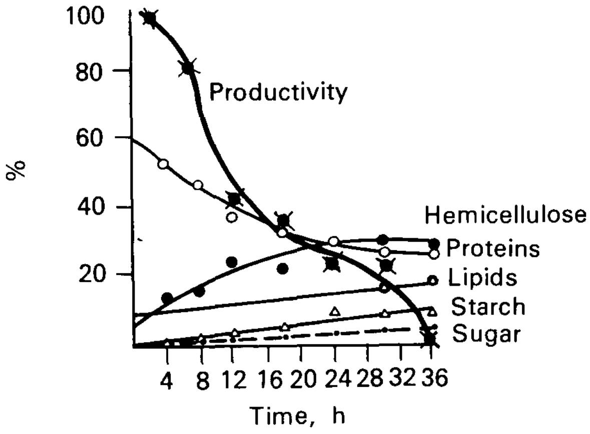

FIGURE 4.—Change of productivity and content of organic matter in *Chlorella* grown in a nitrogen-free nutrient medium (in % of the initial levels with normal nitrogen nutrient) [111].

in organic composition of the cell biomass is essentially the same as in a previous study [48]. However, it should be noted that a considerable portion of the carbohydrate increase is not starch, as in *Chlorella* sp K, but hemicellulose. After 12 h of cultivation, the amount of this nutritively inert substance represented 25% of the entire biomass; after 24 h, 30% of the biomass.

A sharp drop in algal productivity during the first hours of cultivation in a medium devoid of nitrogen is shown in Figure 4. Algal productivity decreases when there is a decrease in nitrogen content in the biomass below 75 mg/g dry matter. Growth stops when nitrogen in the cells is less than 50 mg/g.

Algal organic content is also changed by extreme temperatures. Figure 5 [112] shows a sharp increase in carbohydrates, with a simultaneous reduction in protein, when the suspension temperature increases from 37° to 43° C. At the same time, the lipid content in the biomass hardly changes. Table 6 [112] compares the changes produced under extreme temperatures, with the average human diet. The disproportion between the algae and the human diet is shown to be less under extreme temperatures. This may point to the possibility of increasing the amount of algae utilized by human trophic systems as well as other BLSS heterotrophic organisms.

Further research is necessary particularly with respect to the composition and nutritive value of synthesized lipids and carbohydrates. The reactions of microorganisms to extreme (unfavorable) conditions in the medium are related not only to rearrangements of the protoplasms, but also to the accumulation of cell wall material. Not all extreme influences may lead to optimal biochemical composition and an increase in the nutritive value of the algal biomass.

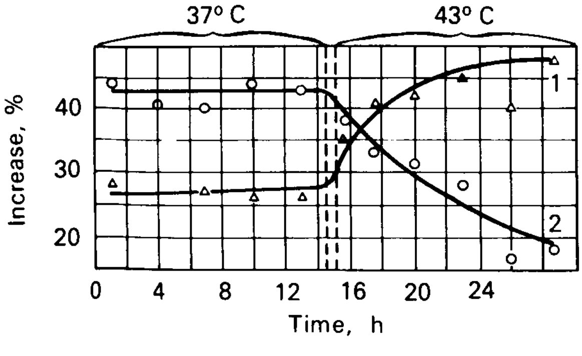

FIGURE 5.—Change in the content of carbohydrates (1) and proteins (2) in *Chlorella* biomass with temperature[112].

TABLE 6.—*Comparison of Chemical Composition of* Chlorella *Under Different Growth Conditions With a Human Diet* [112]

Material	Content of material in % organic mass		
	Proteins	Carbohydrates	Lipids
Human diet	16	69	15
Biomass of *Chlorella*			
at 37° C	55	13	32
at 43° C	20	50	30

The third approach to optimizing the biochemical composition of algae may be implemented on a biocenotic level, if many species of algae are used in the BLSS. Various algae have a different biosynthetic composition under normal conditions [78, 118]. The nearest relatives of *Chlorella* are not of primary interest, but representatives of distant taxonomic and ecologic species, such as flagellates are. In particular, Gromov et al [34] call attention to the prospects for the algae *Chlamydomonas* and *Chlorococcum*.

Characteristics of *Chlamydomonas reinhardii* have been studied for use in biologic systems [118]. Morphologically, these are rather large, oval cells up to 20 μm long. The larger cells may have a relatively small amount of wall material. The protoplasm of adult cells contains a large number of inclusions (Fig. 6), predominantly of a carbohydrate nature.

The growth rates of these algae in dense cultures amount to 65%–70% of the productivity of *Chlorella*. Table 7 compares the composition of organic material representative of the Protococcaceae, blue-green and flagellate algae. The strong carbohydrate biosynthesis of *Chlamydomonas*, which has a high growth rate, fully justifies including this genus, along with *Chlorella*, in the algal link of a biologic life-support system [118].

Productivity Control

In order to control the productivity of cultures during the prolonged use of photosynthetic systems, it is necessary to know the characteristics of the algal culture [5, 31, 35]. Productivity fluctuations in a dense culture during prolonged experiments under stable cultivation conditions have been studied [79]. Algal productivity changed, according to a periodic law, with an amplitude 25%–30% of the average productivity during the period under investigation. These productivity fluctuations may be of practical importance in the development of photosynthetic systems. Figure 7 shows that the growth rate of the culture has a clear periodic character with a period of 12–14 days. Fluctuations of smaller frequency, with a 3–4-d period, may be seen against a background of slow fluctuations.

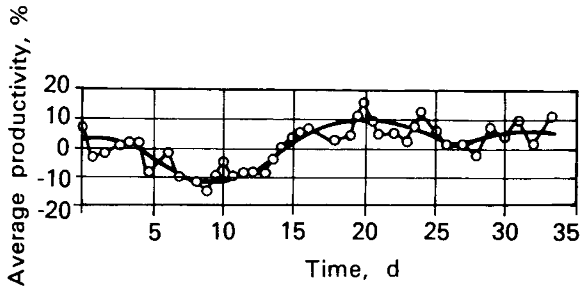

FIGURE 7.—Fluctuations in the productivity of a *Chlorella* culture under standard conditions.

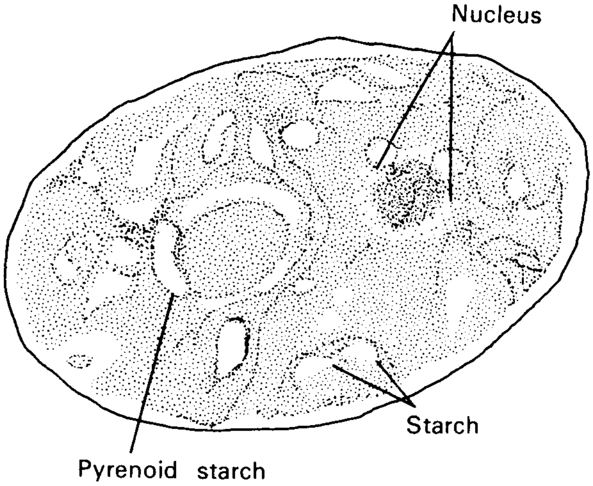

FIGURE 6.—Reserve food material stored in cells of *Chlamydomonas*.

TABLE 7.—*Composition of Biomass of Various Unicellular Algae* [118]

Algae	Dry weight, %			
	Proteins	Fats	Carbo-hydrates	Ash
Chlorella sp K	52	20	23	5
Anacystis nidulans	82	3	10	5
Chlamydomonas reinhardii	31	21	41	6
Spirulina platensis	64	11	12	13

The nature of transitions occurring with changes in cultivation conditions was first studied with stepwise changes in illumination [5, 35]. The transitional period was oscillatory in nature, lasting 8–12 min in a culture of low population density, when highly sensitive and low inertial capillary-manometric and polarographic methods were used to measure the photosynthetic rate. In abrupt changes in the suspension temperature between 36°–42° C, the duration of the transitional process was 25–30 min [6].

In cultures with a density of 7–12 g/l, the transitional change with stepwise illumination was much greater, from 3 to 160 min when measuring the photosynthetic rate via the suspension density [5, 148]. In this case, the magnitude and form of the transitional stages change greatly as a function of the conditions and structural features of each reactor (the suspension density, its mixing rate, the presence of unilluminated suspension volumes, and so forth).

Toxic admixtures. Data on the liberation of carbon monoxide by cells were examined in the first studies on algae [9, 24, 89]. A subsequent study showed that accumulation of carbon monoxide in a regenerated atmosphere is inversely related to photosynthesis rate [54], which was later confirmed by a great amount of experimental material [40, 42, 43]. It was established that the carbon monoxide content in a closed air circuit of a photosynthetic reactor is stabilized after a certain period of time, and more rapidly if the air flow for the algae moves through the cabin with humans.

Algal cultures can also absorb contaminants from the air, including carbon monoxide [41, 55, 154]. Apparently, a relative equilibrium is established in this system between the processes of liberation and absorption of CO.

Characteristics of unicellular algae as a functional BLSS link. The biotechnologic principles of an algal gas-exchanger are prolonged cultivation of high-density suspensions of algae and direct recirculation of the nutritive medium. Water drawn from the reactor in the moist harvest may be returned, if necessary, to the reactor in the process of drying. If condensation of water vapor from air which has left the gas-exchanger is added, water can be completely recycled.

Existing data show that an algal reactor in a BLSS may perform several functions. The first is to provide human gas exchange. Upon mineral nutrition of algae, oxygen or carbon dioxide in the cabin atmosphere increases, requiring an appropriate correction. It may become necessary to remove 5%–7% of oxygen consumed or carbon dioxide produced by man because of differences between the photosynthetic coefficient for algae and the respiratory coefficient for human beings. This disparity may be decreased or eliminated by using different nitrogen supplies in different reactors.

Air leaving an algal reactor is saturated with water vapor. The reactor fulfills the role of an evaporator in the water regeneration system when urine or wash water uncontaminated by cleansing agents is used. It also functions in part as an air purification filter by absorbing ammonia, which algae use as a source of nitrogen. Further research may reveal an expansion of this function of a reactor.

In current evaluations, algal reactors are compared with physicochemical gas-exchangers in terms of simple weight. However, there would be more validity in evaluations which take into account the multifunctional nature of photosynthetic reactors in a BLSS.

A criterion which has not been evaluated quantitatively is the qualitative difference between a biogenic atmosphere and a simple chemical solution of oxygen in nitrogen. In flights of long duration, this difference may be decisive for producing an atmosphere biologically acceptable and similar to the terrestrial one.

Higher Plants

Higher plant forms will probably comprise a portion of the photoautotrophic BLSS link, in terms of participation in the overall metabolic cycle. However, their role as a functional link in the biologic system has been studied far less than that of unicellular algae.

Species of Lemnaceae, which lack stems, grow in water or on its surface, and multiply primarily by vegetative means, were among the first higher vascular plants to be studied for life-support systems. Based on data from Lockheed [36], the first studies of representatives from the plant groups Lemnaceae, *Wolffiia* and *Spirodela*, were made by Wilkes in 1962–1964, who found that enough oxygen for one human being could be produced by members of Lemnaceae, using 75–100 l of culture medium and 25 kW electric power. The growth rate in an accumulative culture in a rotating tank with an illuminated surface of 1.16 m^2 amounted to 3.3 g/d dry matter [36]. The dry weight of *Spirodela polyrhiza*, which was 4% of the net weight, consisted of 33% protein, 39% carbohydrate, 4.9% cellulose, 5.3% fat, and 13% ash. Therefore, they barely differ from many vegetable plants, and are greatly inferior to unicellular algae, whose dry weight generally amounts to 20%–33% of the biomass [36].

Further research on higher plant forms has been done on vegetables, legumes, and grains but with still no solutions for such problems as the actual requirements of plants for mineral supply under given cultivation conditions, the gas exchange ratios and their correlation with mineral consumption and biomass synthesis. Methods are still being developed for stabilizing the mineral supply to plants in long cultures in an unchanging nutritive medium. There is much information on the hydroponic cultivation of higher plants, including considerable data on the composition of nutrient solutions and their effect on plants, but nothing concerning continuous cultivation of plants in an unchanging nutrient medium with recirculation of the nutrient solution or simultaneous utilization of human wastes by plants.

Although there is no basis for discussing any definite species composition of higher plant forms as part of a BLSS, many plants have been suggested for use in biologic systems, including: cabbages, lettuce, beets, carrots, potatoes, sweet potatoes, beans, kidney beans, wheat, rice, onions, and dill as well as starchy tropical plants such as Chinese yam, taro, cassava, Jerusalem artichoke, and peanuts for fats [20, 36, 69, 70, 71, 91, 107].

Table 8 presents variations of plant species for a space greenhouse which are still far from the desirable components of the human diet. The data indicate the planting area necessary to provide the plant component of the human diet.

TABLE 8.—*Variants of Species Structure in Plantings of Higher Plants* [20, 139]

Plant species	Planting area, m^2	
	Variant 1 [20]	Variant 2 [139]
Potato	11.2	
Head cabbage	1.5	1.1
Leaf cabbage	0.4	
Carrot	0.6	0.6
Radish	0.3	
Table beetroot	0.7	0.3
Tomato	1.6	
Rice		10.7
Sweet potato		2.1
Dill		0.2

Cultivation Methods

Two methods of artificial plant cultivation, as applied to BLSS, have been studied, using substrate and nonsubstrate techniques. The distinction between hydroponics and aeroponics lies in the method by which the nutrient solution is supplied to plants.

Hydroponics supplies mineral requirements to plants by periodic applications of the nutrient solution to the plant roots located in any or no substrate. Figure 8 shows a diagram of a hydroponic device using a substrate. In the aeroponic method, the nutrient solution is supplied to substrate-free plant roots by sprayers in the form of a "fog." A diagram of an aeroponic device is shown in Figure 9.

An advantage of aeroponic culture is the small amount of nutritive solution used per unit of planting area or biomass of the cultivated plants, which allows a significant reduction in weight of cultivation devices. The dynamics of mineral absorption by plants have been studied using this method. However, aeroponics cannot be recom-

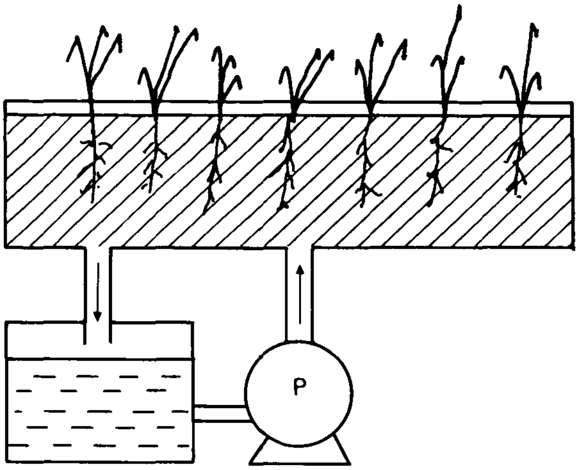

FIGURE 8.—Diagram of a device for the hydroponic growing of plants. P–pump [20].

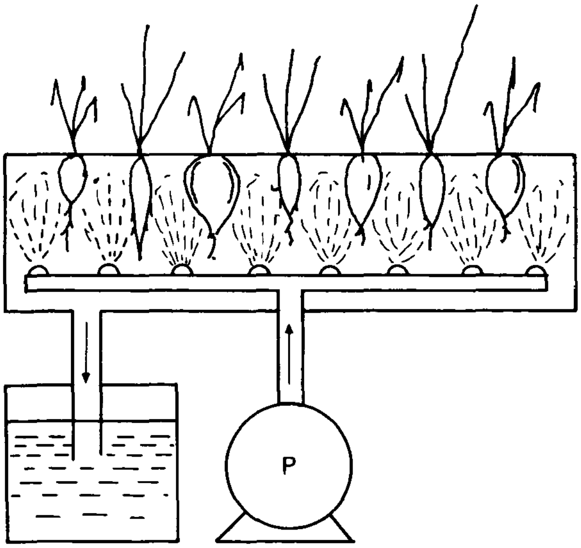

FIGURE 9.—Device for aeroponic growing of plants, P–pump [20].

mended as a method for prolonged culture until clogging in the sprayers has been eliminated. The decrease in volume of the nutritive solution needed in aeroponic devices has the disadvantage of more rapid accumulation of toxic products than when plants are grown on an unchanging medium [140]. Furthermore, the absence of any substrate for the plant root system eliminates normal relationships with rhizospheric microflora, which are intrinsic to these plants under normal soil conditions. Soil is the product of joint activity of plants and microorganisms. Therefore, plant requirements for the soil medium cannot be adequately described by formulas for inorganic nutrient media without allowance for the biotic medium in the root zone. It follows that the microbiologic decomposition of organic waste products, assigned to the mineralization link, may require direct contact with the rhizosphere.

The nonsubstrate cultivation of plants cannot be assumed to serve for tens of generations of self-reproducing populations. Even in excellent hydroponic cultures, plant flowering stops after several life cycles [91]. To obtain plant growth for long periods it may be necessary to use artificial substrates, which could contribute to a more suitable rhizosphere.

The successful completion of the Apollo program made it possible to study substrates from space. Walkenshaw at the Manned Spaceflight Center (Houston, Texas) studied samples of lunar soil collected by the Apollo crew; he established that lunar dust is suitable for cultivating agricultural plants, and assumes that there is a growth stimulator in the lunar dust.[4] Evaluation of the physical characteristics of certain ceramic materials from Earth has revealed the usefulness of vermiculite and cermet as substrates for hydroponics [68], although one difficulty is their chemical activity and high adsorption properties, which contributes to imbalance between the requirements for mineral elements and their availability from the nutrient solution.

The agrochemical properties of cermet were investigated on the basis of its 9-month use in hydroponic devices [110]. The problem of how to balance a nutrient medium has already been discussed for unicellular algae.

The "conveyor belt" approach to continuous cultivation of higher plants is an important feature. A "plant conveyor line" was initially developed to obtain a continuous supply of vitamins from sprouting grain seeds for livestock. Seeds are planted at regular intervals so that mature plants are available for harvest at the same intervals.

Agrotechnical problems. Much recent research in the agrotechnical problems of vegetable plant cultivation with and without substrates has been directed toward determining optimum plant density, the method of preparing seedlings in nonsubstrate devices, and determination of the optimum regime for feeding the nutritive solution to the plants [69, 70, 71, 72]. Table 9 gives a formula for nutrient solutions in hydroponics.

Primary data were obtained on crop size for different plants in hydroponic and aeroponic devices. Table 10 gives data obtained from a large number of experiments in the Institute of Biomedical Problems of the MZ SSSR. It is interesting that the potato crop was obtained without a substrate.

TABLE 9.—*Composition of Nutrient Solutions for Higher Plants*

Component	Amount, g/l				
	1[1]	2[1]	3[2]	4[3]	5[4]
Potassium nitrate	1.10	0.70	1.00		
Calcium nitrate			0.40	1.29	0.43
Ammonium nitrate			0.10		
Potassium phosphate (monosubstituted)			0.25	0.75	0.25
Calcium biphosphate	0.31	0.30			
Potassium sulfate			0.63	0.63	0.10
Calcium sulfate	0.76	0.60			
Magnesium sulfate	0.52	0.54	0.20	0.50	0.17
Ammonium sulfate	0.14	0.12			
Total salts	2.83	2.26	2.58	3.17	0.95

[1] Data from [141].

[2] Recommended by Prof. B. Chesnokov for hydroponic growth of fruit cultures.

[3] As applied in IMBP MZ SSSR for growth of potatoes in substrate hydroponics.

[4] As applied at IMBP MZ SSSR for aeroponic growth of potatoes.

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[4] According to data of the compiler of this chapter, W. L. Jones.

The study by Nilovskaya and Bokovaya [94, 95] of the photosynthetic and respiratory gas exchange of plants, with differing concentrations of oxygen and carbon dioxide in the air, is of great interest. Direct gas exchange between higher plants and the atmosphere makes it unnecessary to concentrate carbon dioxide, which is a problem with an algal reactor [36]. The well-known Warburg effect, a reduction in the photosynthetic rate with increased oxygen, may be of practical importance in the cultivation of plants for regenerating the atmosphere. The data in Table 11 show that this effect varies not only for individual plants, but also with differences in illumination. An increase in light intensity from 100 to 200 W/m^2 decreases the depressive influence of increased oxygen concentrations upon photosynthesis by a factor of 1.5–2. These authors showed that an increase in the oxygen content in the air from 20%–22% to 24%–26% almost doubles the amount of carbon dioxide liberated at night, and increases the proportion of nighttime respiration from 4% to 9% of the apparent photosynthesis during daytime.

Utilization of Waste Products

The direct absorption or use of human waste products by higher plants has not been sufficiently studied. The first studies appear to have been Tsander's experiments on vegetables grown in an artificial substrate of charcoal, using unprocessed human waste products [138]. A few current works represent preliminary studies on the toxicity of mineralization products of organic wastes mineralized differently [3, 140, 153]. One study notes the paradoxical increase in salt tolerance of leafy cabbages when grown on urine mineralization products [140]. The use of urine as a source of nitrogen and other elements is limited by the accumulation of chloride ions not used by plants, creating a problem, as in the cultivation of algae, when recirculation of the nutritive medium is attempted. A closed waste utilization cycle is impossible for higher plants without solving the problem of chlorides in the cycle [84, 105].

Chemoautotrophic organisms. The study of the hydrogen-fixing bacteria, *Hydrogenomonas eutropha*, has received serious attention, particularly by American authors. The results of 3-year studies on the possible use of hydrogen bacteria for regenerating oxygen from carbon dioxide in combination with electrolysis of water were reported at the Sixteenth Congress of the International Astronautical Federation in 1965 [37]. Schematically, these processes take place as:

Bonding of carbon dioxide occurs during heterotrophic synthesis

$$2H_2 + CO_2 \rightarrow (CH_2O) + H_2O \qquad (1)$$

The energy necessary for bacterial synthesis of organic matter is produced by oxidation of hydrogen with the formation of water

$$4H_2 + 2O_2 \rightarrow 4H_2O \qquad (2)$$

TABLE 10.—*Productivity of Certain Plants Under Artificial Light* [1]

Plant	Vegetation period, d	Yield, g/m^2·d					
		Total		Net output		Waste	
		Wet	Dry	Wet	Dry	Wet	Dry
Head cabbage	90	264	24	155	15	109	9
Leaf cabbage	40	412	24	375	21	37	4
Carrot	90	266	34	178	20	88	14
Table beetroot	90	380	48	220	31	160	17
Tomato	90	340	30	220	13	120	17
Radish	40	165	11	150	9	15	2
Potato	90	133	31	111	28	22	3

[1] Data from the Institute of Biomedical Problems, MZ SSSR.

The chemical work of hydrogen bacteria is combined as

$$6H_2+2O_2+CO_2 \rightarrow (CH_2O)+5H_2O \qquad (3)$$

If we add the respiration process in the human organism

$$(CH_2O)+O_2 \rightarrow CO_2+H_2O \qquad (4)$$

The sum of these processes, (3) and (4), is equalized by the electrolysis of water

$$6H_2O \rightarrow 6H_2+3O_2 \qquad (5)$$

The result is a closed cycle system with regard to oxygen, carbon dioxide, and water.

In experiments of Mandel and Shapiro [74], on three generations of rats which received a diet of 27% (by weight) of the bacterial biomass, no changes were observed in the females regarding fertilization, birth, and raising of offspring. However, in later studies [150], it was found that human beings do not tolerate well a biomass of hydrogen-fixing bacteria in their diet. Table 12 gives symptoms and time of onset after intake of 15–26 g of dry hydrogen bacteria by four volunteers. Nearly all experienced dizziness, nausea, vomiting, and diarrhea after each time they ate food which included the bacteria.

Until 1968, a nutritive system based on hydrogen-fixing bacteria was regarded as very promising, but in view of data showing the inapplicability of these bacteria as nutrient products for humans, their use has been questioned. Additional studies are needed to explore the possible use of hydrogen-fixing bacteria as a supplementary food source.

EXPERIMENTAL BLSS MODELS

Experimental modeling is an important stage in BLSS study in order to determine functional characteristics, mechanisms by which stability is maintained, and principles underlying control and regulation. The models must have the maxi-

TABLE 11.—*Photosynthesis and Respiration Rates of Head Cabbage at Various Oxygen Contents in Air* [95] [1]

Oxygen content in air, %	Day of experiment	Absorption of CO_2 in 18 light h, g	Liberation of CO_2 in 6 dark h	
			g	Reabsorption, %
20–22 (Control)	1	13.42	0.61	4.5
	2	14.26	0.62	4.3
	3	13.95	0.62	4.4
	4	14.08	0.45	(2)
	5	13.99	0.59	4.2
	6	14.14	0.67	4.6
	Average	13.97	0.62	4.4
24–26 (Experiment)	7	8.62	0.83	9.6
	8	8.89	0.84	9.4
	9	9.23	0.87	9.4
	10	9.50	0.85	9.0
	11	7.66	0.89	11.6
	12	8.88	0.81	9.1
	13	8.40	0.75	8.9
	Average	8.74	0.83	9.5
Difference		−5.23	+0.21	+5.1

[1] Experimental conditions: planting area 25 dm^2; area of leaves, 62–73 dm^2; intensity of illumination, 100 W/m^2; temperature, 18°–21° C; CO_2 content in the air, 0.3%–0.35%.

[2] No reading on respiration was taken because of sharp decrease in temperature in dark period.

mum amount of closure with respect to material balance, even if difficulties are encountered with weight and energy characteristics, a certain amount of discomfort for humans, and other characteristics important in operational systems. Only with a maximum amount of mass-exchange closure can models illustrate stability, basic functional and operational characteristics, and possible new life-support systems.

Earlier studies on simple models of biologic systems were primarily qualitative, and contained no quantitative information on the metabolic cycle.

The first experiments on the use of algal photosynthesis to provide gas exchange for animals were performed by US researchers, after the flights of the first artificial Earth satellites [14, 24, 26, 84]. At the USAF School of Aviation Medicine in 1961 [9], experiments lasting up to 50 h were performed on monkeys. In 1960–1961, similar experiments lasting more than 170 h were performed on rats and dogs at the Institute of Plant Physiology, USSR Academy of Sciences, and Institute of Biomedical Problems, and two experiments with human beings which lasted about 1 d each [154]. Flat containers were used illuminated by lamps from the outside. The total amount of suspension was about 200 l, with a culture density up to 3 g/l. The process took place in an accumulative culture, with limited illumination. The productivity of the reactors was found to be insufficient to provide human gas exchange. When the sealed cabin was opened, everyone experienced a sharp, unfavorable odor of algae except the test subjects, who concurred in this opinion only after taking several breaths outside the experimental chamber, and then returning to it.

The next experiment using a human subject lasted 56 h, at the Boeing Company Laboratories in 1962 [13]. The experiments were stopped due to insufficient productivity of the photosynthetic reactors, accompanied by accumulation of carbon dioxide in the system and decrease in the oxygen content. However, an important conclusion was that the direct combination of algal photosynthesis with human gas exchange is possible in principle, although many new problems arose indicating that even in such a simple system, the relationships are not as elementary as was first believed.

Thus, in addition to data obtained previously on the liberation of carbon monoxide by *Chlorella* [9, 14, 24, 54, 89, 101], it was found that *Chlorella* may absorb several gas admixtures from the atmosphere, including carbon monoxide [55]. The specific accumulation of CO in a regenerated atmosphere is inversely related to the photosynthetic rate, and thus is indirectly connected with the photosynthetic process. For example, with low productivity of algae (on the average 0.04 $g/l \cdot h^{-1}$), the liberation of carbon monoxide is 2.07 ± 0.5 mg/g of dry algal material. With productivity one order of magnitude greater (0.3 $g/l \cdot h^{-1}$), the amount of carbon monoxide liberated per 1 g of dry algae is one order of magnitude less (0.09 ± 0.02 mg). It is assumed that the phenomenon is analogous to the formation of endogenic carbon monoxide in the human organism. Production during cultivation of algae

TABLE 12.—*Human Response to Ingestion of Autotrophically Grown* Hydrogenomonas eutropha[1]

Test subject	Time of intake, h				Time of first appearance of symptoms				Weight of excrement, g/d
	0830	1230	1730	2130	Dizziness	Nausea	Vomiting	Diarrhea	
A	8.6	17.2			None	1000	1300	1500	Not recorded
B	8.6	6.6			0930	1000	1500	1315	921
C			9.6	5.1	1900	1930	None	2230	423
D			17.2		1930	2030	2100	At night	1265
E [2]					None	None	None	None	0
F [2]					None	None	None	None	277

[1] Data from [150].

[2] Control test subjects.

may be related to oxidation of the tetrapyrrole ring in the chlorophyll molecule [54].

The inverse dependence of carbon monoxide accumulation on the photosynthetic rate was established in later studies [42, 43] (see Fig. 10).

The possibility of prolonged stable cultivation of algae in a closed system (see previous section, DEVELOPMENT OF INDIVIDUAL FUNCTIONAL LINKS IN BLSS) has led to the experimental study of a "man-algal" system, on an improved, methodical basis. A new stage in the study of simple models of biologic systems now includes human beings, and entails gradually increasing complexity in the systems and closure of their mass exchange. The purpose of this modeling is to study interactions building up between the links when operated together, which cannot be achieved by studying the properties of isolated links.

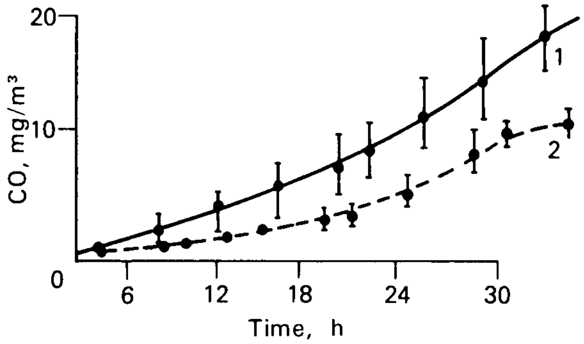

FIGURE 10.—Accumulation of CO in the atmosphere of an algal gas exchanger at different photosynthetic rates: curve 1, 0.5 l CO_2/l suspension · h^{-1}; curve 2, 1.0 l CO_2/l suspension · h^{-1}[43].

Human and *Chlorella* Gas Exchange

The first long experiment of a two-link man-algal system, with a closed gas exchange, lasted 30 days under the leadership of Professor Gitel'zon at the Institute of Physics of the Siberian Division of the USSR Academy of Sciences. It revealed the possibility of prolonged, direct combinations of human and *Chlorella* gas exchange [45]. A 60-day experiment by the same authors, with a three-link system, in which the photoautotrophic link included a hothouse with wheat in addition to *Chlorella*, confirmed these findings [47]. The photosynthetic proportion of wheat plants in the total autotrophic link was about 18%. These experiments also investigated the possibility of direct utilization of urine and waste water in an algal reactor.

The possibility of prolonged introduction of urine into the algal culture, without accumulation of toxic concentrations of sodium chloride, was achieved by a sufficient amount of water flowing through the algal cultivator. The data showed that 5.3 l/d of water were lost from the system, but this loss was compensated by water from sources outside the system [46] The water requirements for feeding algae by photosynthesis equaled 2.3 l/d. Thus, the amount of water passing through the system was 200% more than required. The condensate obtained from the reactor was subjected to purification by an oxidizing-catalytic method. Sanitary-chemical and bacteriologic analyses, as well as toxicologic experiments on animals, established the suitability of the water for human consumption. In the second experiment, the water vapor condensate from the atmosphere of the greenhouse in which the wheat was grown was also used to determine suitability of the water for consumption.

Thus, these experiments show that closing the water cycle in the system studied is possible. The practical implementation is closely related to the degree of system closure for food, and recovery of water from all moisture-containing waste products, including the algal biomass removed from the system which carries water bound in the photosynthetic process. Even though all water losses are reduced to the maximum extent, closure of the water balance is, nevertheless, limited by chemically bound water introduced into the system with the diet. Therefore, the water cycle cannot be closed completely until the system is also closed for food. The degree of closure of the water cycle was studied using a "man-*Chlorella*" system, lasting 15 to 31 days, in which water obtained from the condensate at the algal reactor was the sole source of nutritive water for the test subject [115, 116]. The amount of external water introduced into the diet was decreased to 835 g. This determined water flow through the system, which was 32% of the water required by man (2590 g/d), resulting in water balance closure in the system of 68%. In another experiment (see Table 13, no. 4), the degree of closure increased to 90%.

The regenerated atmosphere of gaseous admixtures was not purified in these experiments, which made it possible to study the dynamics of some of them. In particular, accumulation of carbon monoxide, with subsequent prolonged stabilization at a relatively constant level (Fig. 11), was found in the man-*Chlorella* model. After 14–15 days, a sudden increase in CO level, occurring at the same time as an increase in the acidity of the culture medium in the algal reactor, showed dependence of the equilibrium level on the state of the algal culture. Figure 11 also shows the methane content in the air, which was stabilized after only 11 days. Apparently some mechanism limited the content of this component in the atmosphere.

Ammonia and hydrogen sulfide were not detected in the system throughout the entire experiment, including the last stage when up to 15 g/d of ammonia, obtained by evaporation of urine, were introduced into the air in one of the algal reactors. This may be an indication that an algal system can purify the atmosphere of harmful admixtures. The problem of toxic admixtures in a closed autotrophic-heterotrophic system requires further study to determine the mechanisms by which these substances are liberated and bound by different links.

The satisfactory hermeticity of the system in this experiment enabled the imbalance between the gas exchange of algae and humans to be determined. While there was a gradual increase in carbon dioxide content in the air (periodically removed by adsorbents), the oxygen concentration remained the same. The imbalance was 7.5% of the human gas exchange using a regular diet and a nitrate source of nitrogen for the algae, which corresponded to a total increase in carbon dioxide content of 383 l throughout the experiments.

Urea as the nitrogen source may decrease or eliminate this imbalance. In principle, the independent maintenance of the gas balance is only possible in a system where a human being or any heterotrophic population consumes all of the autotrophic biomass produced in the system [90].

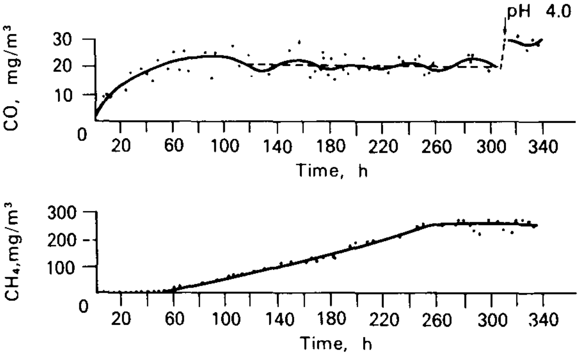

FIGURE 11.—Content of CO (upper curve) and CH_4 (lower curve) in atmosphere of the "man-*Chlorella*" system which is closed with regard to gas exchange [115]. Acidity of culture medium increased at 14–15 d (upper curve).

TABLE 13.—*Comparison of Characteristics of Parameters of Various BLSS Models*

Model	Experiment duration, d T	Characteristic time, d τ	Transition process 3τ	Net time of experiment $T-3\tau$	Net cycles of regeneration $\frac{T-3\tau}{\tau}$	Experiment duration in units of characteristic time $\frac{T}{\tau}$
1[1]	60	17.0	51.0	9	0.5	3.5
2[2]	30	6.7	20.0	10	1.5	4.5
3[3]	15	2.2	6.6	8	3.6	6.8
4[4]	30	2.0	6.0	24	2.0	15.0

[1] "Man-algae-wheat" system [47].
[2] "Man-algae" system [45, 46].
[3] "Man-algae" system [115].
[4] "Man-algae" system [116].

Comparative Evaluation of BLSS Models

Very few studies have been made of complete models of biologic systems, and they deal with only the simplest models having a low degree of closure in the metabolic cycle. Nevertheless, they are of definite interest, because new problems are confronted. We are concerned with the methods and criteria for comparative analysis of models having different functional structures, spatial dimensions, and experimental periods. General prerequisites must be developed, suitable both for experimental models of biologic systems, and the subsequent comparative analysis of their basic parameters.

Closure. The adequate degree of closure in mass exchange has already been discussed. The degree of closure for any substance is established by its rate of consumption in the system (E) and the rate of flow in incomplete closure (e). The system closure coefficient with respect to the given substance (K) is determined by: $K = I - e/E$. If all the basic fluxes of the substance are used, the total degree of material balance closure can be represented.

Closure may be biologic or technologic in character. For example, determination of closure with regard to water will include human water requirements for thirst and in food, as well as loss of water in the photosynthetic process. Water consumption for toilet needs, which may change very greatly and is not strictly a biologic requirement, was not included in calculating the water balance. Thus, characteristics of the strictly biologic cycle in the system can be differentiated from technologic characteristics where water consumption for toilet, household, and other needs is considered.

Cycling rate. Another prerequisite for the development and analysis of biologic system models is assurance of a high specific cycling rate of the basic materials in the system. The initial amounts of circulating material are important in experimental models since a decrease in the amount of a given material will cause an increase in the rate at which it circulates. Thus, sensitivity and informative value of models may be enhanced when their dynamic characteristics are studied.

The unavoidable high rates at which matter circulates in artificial systems decreases the dynamic stability of the system (noted previously) [114]. Nevertheless, the need for the maximum amount of information on regenerating systems in a short time compels a choice of less stable models to provide the most information. The intensification effect arising in such models enables determination of quantitatively minor elements affecting the life cycles, outside the sensitivity of normal research methods, such as phenomena related to the dynamics of trace elements or contaminants in the atmosphere, water, or nutrient solutions.

Time constants. A final prerequisite is determination of the time constants of processes taking place in the models. Attempts to compare structurally different experimental models with respect to absolute time of their existence have been frustrating. Units of time organically related to the properties of the system itself must be used, such as the time in which one cycle of any material is completed. The characteristic time for a system in terms of the material cycle (τ) is determined by the ratio of the amount of material in the system (Q) to the rate at which it is liberated or consumed (q).

For example, the air of a hermetic chamber having a volume of 20 m^3 at normal atmospheric pressure, contains 1000 l of oxygen, which is consumed by man, and must be regenerated at 500 l/d. The characteristic time of the system in terms of the oxygen cycle is 1000:500 or 2 days. This index characterizes the system in terms of the rate at which any material is circulated. A comparison of the characteristic times for basic material flows establishes the paths of the metabolic cycle having the greatest circulation rate and, consequently, the least stability.

Figure 12 shows that because of the closed nature of the system, the replacement of the initial atmosphere by the regenerated atmosphere follows an exponential curve. In practice, the time required to replace the initial atmosphere by approximately 95% is three times greater than the characteristic time of the system. It is only from this moment that the system being studied begins to exist. The process of equilibration taking place earlier makes it impossible to establish the characteristics of the system in terms of the metabolic cycle which may, for example, be accumulating volatile admixtures in the atmosphere.

Consequently, the use of a model with a duration of less than the tripled characteristic time in terms of the basic material flows, is of no scientific interest; a net experiment time less than 50% of its total duration is not economical in labor or amortization of equipment.

Thus, an important property of a model is the characteristic time of the system (τ), which includes the mass of circulating matter and, indirectly, dimensions of the system. From the indices below, derivative indices may be obtained suitable for comparative analysis of the amounts of material provided by models of various bioregenerative systems:

duration of the nonstationary period ($3 \cdot \tau$),
net operational time of the system: ($T - 3\tau$) (total duration of the system operation minus duration of nonstationary period),
quantity of net regeneration cycles of the given material: $(T - 3 \cdot \tau)/\tau$.

These criteria allow comparison of models of biologic systems with different functional structures, masses of circulating material, and spatial characteristics. Three models, with different parameters, each of which supplied gas exchange for one human being, are compared in Table 13. These data were calculated for the oxygen regeneration cycle, and may be evaluated from this point of view only.

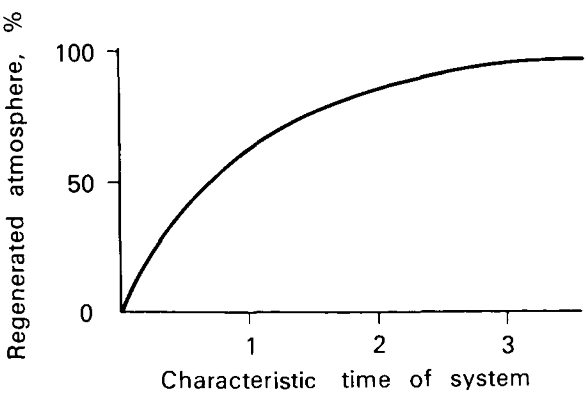

FIGURE 12.—Dynamics of replacement of initial atmosphere by a regenerated atmosphere in a closed system (in units of characteristic time).

The air volume of models 2 and 3 equaled 12 and 5 m^3, respectively. The volume of the first model was calculated indirectly, with an allowance for wheat planting area. The gas exchange of the test subject was calculated from the composition of the assimilated diet, since there was no direct information on these parameters in existing publications. At first glance, a paradoxical conclusion is suggested from the analysis of the data in Table 13: in terms of units of the system's characteristic time, the shortest living model was model 1, which existed for 60 days; longest time of existence was 30 days for model 4. If the unit of effective operation of a system, existing in a specific space with a specific amount of regenerated material, is assumed to be one regeneration cycle of oxygen, then in actuality model 4 performed 24 times more net operational regeneration cycles than model 1 and gave much greater information regarding functional characteristics.

The comparative analysis in Table 13 shows that generalized parameters may be used when comparing models which differ in structural and spatial characteristics. The parameter of characteristic time may be used in a theoretic analysis of biologic system stability by means of mathematical models of material fluxes.

Mathematical Modeling

The study of BLSS requires much time and equipment, which should be alleviated in the future by mathematical modeling. Many data have already been mathematically analyzed, in particular, for evaluation of the effectiveness of algal cultivation, as well as optimization of the parameters of algal cultivators [119, 122, 124, 149]. Most of this summarized material is contained in the study of Smirnov [125].

A much more complex problem is the mathematical modeling of such biologic systems as artificial biogeocenoses. The search for optimum BLSS structures and methods for their control through natural experiments is not realistic in terms of the necessary development time. The studies of Watt, Svirezhev, and Yelizarov [129, 151] shed some light on this problem; they provide a generalization of the great amount of data on mathematical modeling of natural systems (populations and biocenoses). Prior to the creation of natural models, mathematical modeling is the only useful method to analyze stability of biologic systems. The study [129] contains different approaches to this problem based on an analysis of classic models of the Volterra type.

Among the few attempts to model biologic systems based on analysis of material and energy fluxes are the studies of Vinberg, Rubin et al [108, 109, 144, 146]. Mass exchange models may be of interest in analyzing the stability of artificial biologic systems. The limits to stability are determined by the restricted space occupied by the systems and the amount of circulating matter. They have a low damping capacity to fluctuations in the flow of matter. The first stage of this analysis is to clarify and study only those material flows which are limiting paths in the network of material relationships between system components, both biotic and abiotic. For man, the most sensitive biocenotic component in the BLSS, the flow of oxygen and carbon dioxide will be limiting. For plants, the limitation may be water exchange. Water is the mechanism of plant heat transfer with high intensities of light flux in a dense culture. The necessity of modeling human food relationships disappears when establishing the instability of a system based on gas exchanges. The malfunction of a food link manifests itself more slowly than gas exchange malfunction.

One important result of BLSS research is the discovery of the great reliability of biologic systems compared with nonbiologic apparatus. The inadequate reliability of equipment used in the biosystems makes it impossible to establish the limits of reliability for biologic processes. Fears regarding the low genetic stability of rapidly multiplying microorganisms have not been corroborated by many years of using the same strains in the biologic systems studied. The possibility of mutations arising from cultivation with continuous harvesting must be balanced against removing them with the harvested crop. This was shown in a mathematical model and experimentally by Tsoglin, and was confirmed in a study of Shvytov [123].

SUMMARY

The development of biologic life-support systems has yielded certain basic results.

Methods for prolonged, intensive cultivation of unicellular algae in a closed system are well-advanced, which has facilitated creation of experimental models of biologic life-support systems for reclaiming atmosphere, water, and some food.

With regard to the use of higher plants, mineralization methods and recycling of human wastes and other organic waste products are far from complete. A basic problem is the accumulation of chlorides and other components of human excretion, which are not required by plants. A final solution will only be possible when mineralized organic waste products are available for the supply of mineral elements for algae and higher plants. The utilization of waste products for heterotrophic organisms must also be possible.

The additions of heterotrophic links other than human beings has gone no further than preliminary experiments and suggestions for using certain domestic animals and poultry.

It is now possible to study the properties of experimental models of the simplest biologic systems, including man, by making their structure more complex and degree of closure more nearly complete, as additional links in the system are understood.

In future BLSS research, models of entire systems will be studied until an adequately stable structure and degree of closure for the metabolic cycles in the system are obtained.

Some secondary aspects of BLSS are related to their possible use in science and industry.

Economical technologic cultivation of different unicellular algae might be used to produce protein and vitamin products, which could be used in animal husbandry and poultry raising, as well as for partially solving the problem of protein in the human diet. An intensive, readily automated technology for cultivating higher plants may be used to organize year-round industrial production of vegetables near large cities. This technology may have an important influence in developing new types of agriculturally useful plants, where selection time may be reduced by a factor of four or more.

There is no question of the general scientific importance of correctly formulated studies on BLSS. In scientific content, the creation of BLSS as a practical problem is no different than experimental biogeocenology of artificial biogeocenoses. Larger and larger regions of land and water with their agricultural areas, pastures, and fishing and hunting economies are being regarded as such biogeocenoses. Biologic systems, in the sense employed here, represent the limiting cases for such systems, and therefore are acceptable models for a precise quantitative study of processes.

The value of such models for a study of real natural systems may be seen in the example of the accumulation of chlorides in water tanks which receive sewage. This many-year process can be reproduced in a model lasting several weeks.

Experimental ecologic studies of biologic life-support systems with a relatively closed metabolic cycle may give perspective in evaluating the actions of man in the biosphere. The development of biologic life-support systems has been aided by the achievements of other branches of science and industry; there is a basis for assuming that BLSS research will in turn aid other research endeavors.

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Part 3

PROTECTION AGAINST ADVERSE FACTORS OF SPACE FLIGHT

N76-26840

Chapter 11

PROTECTION AGAINST RADIATION (BIOLOGICAL, PHARMACOLOGICAL, CHEMICAL, PHYSICAL)[1]

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Various types of spacecraft in use that are equipped with modern dosimetric apparatus have provided data on radiation around the Earth and in near-Earth space, particularly the composition of the energy spectrum, and spatial and time distribution of cosmic radiation. Analysis of experimental and calculated data has allowed for evaluation of the degree of danger created by primary sources of ionizing radiation in space.

The successful Soviet and US flights have proved clearly that comparatively brief flights, when there are no solar flares, do not present a radiation hazard for spacecrews. However, as flight range and duration increase, the problem of providing radiation protection becomes increasingly important.

In the early 1960s, physicists, astronomers, biologists, and medical specialists developed a special system of protective measures to assure radiation safety for crewmen, which have been implemented in space flights. When this system is used, the peculiarities of radiation must be considered individually for each space flight. Passive shielding only in spacecraft crew compartments (with various structures and shields) cannot provide required radiation protection for extended flights. Problems of physical, chemical, and biological protection for astronauts from penetrating radiation will be discussed in this chapter.[2]

Problems related to physical protection are fairly clear, creating no particular disagreement in principle in the literature. This type of protection has been successfully tested in actual manned flight of Soviet and US spacecraft.

Biological, pharmacological, or chemical protection posed questions that are complex and controversial. Both biological and pharmacochemical methods of protection have proved effective in animal experiments, but no direct proof is available that these methods protect the human from the damaging effects of ionizing radiation. Various factors act on spacecraft and astronauts simultaneously or in sequence during space flight. Another important consideration is the complex composition of cosmic radiation. These factors create difficulties and result in disagreement when attempts are made to apply

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[1] Translation of, Protivoradiatsionnaya Zashchita (Fizicheskaya. Farmako-Khimicheskaya, Biologicheskaya), *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*), Volume III, Part 4, Chapter 1, Moscow, Academy of Sciences USSR, 1973, 98 pages.

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[2] Cosmic radiation has been discussed in detail with an analysis of the radiation situation in Volume I, Part 1, Chapter 2, and in Volume II, Part 3, Chapter 12 of this work.

experimental data to man. Thus, pharmacochemical and biological protection require more detailed analysis.

PHYSICAL PROTECTION

The information in these chapters indicates that for extended, or interplanetary space flights, the radiation factor is a serious threat. In a 3-yr flight, astronauts might receive 350–400 rem of radiation from galactic cosmic radiation (GCR) alone. It has been calculated that the crew of a spacecraft with shielding equivalent, for example, to 1 g/cm^2, spending 20–40 d in the inner radiation belt, would be exposed to a mean tissue dose of 1000-6000 rem. During such long flights, astronauts might be bombarded by proton fluxes from several solar flares [1, 5, 12, 20, 25, 28, 57, 70, 71, 72, 80, 100, 117, 118, 123].

Physical protection is based on the principle of attenuation of the flux of ionizing radiation by absorption as it passes through a mass of some substance. Therefore, the problem of physical protection from radiation is reduced to determination of the most effective lightweight shielding material.

Ideal physical protection from radiation should have the effective density of Earth atmosphere (1000 g/cm^2) and the same magnetic field as that around the Earth at the Equator. However, creation of equivalent protection from radiation in space would require a layer of water approximately 10-m thick, or a lead shield approximately 1-m thick [100]. This magnitude of shielding is impossible since no rocket could lift a spacecraft so equipped [20, 48, 57, 118]. The problem of shielding therefore, must be solved in a complex manner.

Passive Protection

Protection from radiation by a surrounding shield of matter is passive protection. Such shielding of crew space in spacecraft is determined by the physical characteristics of cosmic radiation, flight trajectory, composition of the crew, and the shielding material and criteria used to estimate its effectiveness.

The design of shielding structures against cosmic radiation includes analysis of the proton and spectral composition of corpuscular radiation and its dependence on time and space [48, 70, 123]. This information—plus flight trajectory, time, and launch date—will provide the initial data for an estimate of the radiation danger for a particular flight.

A significant weight saving can be achieved if the shield includes equipment and structural elements of the spacecraft [57, 72, 118]. Consequently, one means of achieving passive shielding is optimal placement of equipment and stores (fuel, food, water, and so forth). Another consists of shielding just the sections in which the astronauts work and rest. Radiation shelters may be used to provide protection from solar flares during long space flights.

The body of the Apollo spacecraft, primarily of aluminum, stainless steel, and phenol-epoxy resins, provides a shield with a density (thickness) of 7.5 g/cm^2. The descent vehicle used to land on other planets, particularly, must be reliably protected. The lunar module of the Apollo spacecraft, however, has a shield with a density of only 1.5 g/cm^2. These thicknesses are not sufficient to provide protection from intensive solar flares [15, 70, 87].

To assure a high degree of radiation protection for the crew against the protons of solar flares and the inner radiation belt around Earth, passive shield thicknesses of 10–40 g/cm^2 are required, depending on the various flight factors [48, 57, 87].

Spacecraft designed for long flights might carry a nuclear reactor as a power source. The primary types of radiation produced by the reactor are fluxes of neutrons of various energy levels and γ-quanta. The problem of protection—to reduce the radiation level to a permissible dose—has been fully solved under Earth-surface conditions.

One of the most important requirements in shielding a nuclear reactor is that the shield be of minimal weight. In planning the shielding, consideration must be given to whether it should be placed immediately around the reactor, around the living and working compartments of the spacecraft, or one part near the reactor and another near the crew quarters. Calculations will show which will give optimal protection [25, 79, 96, 129]. For shadow protection from the reactor, all equipment should be so placed that it serves as an additional radiation shield [42, 100, 118].

Active Protection

Although permissible radiation doses are comparatively high [19, 33, 34, 97], the design weight of passive shielding is also quite high. For a section having a volume of 20–25 m^3, the weight of the shielding minimally must be 10–40 tons [79, 100]. For this reason, scientists have been working to develop principally new types of protection in which magnetic or electrical fields are used to deflect charged particles from the crew quarters (active protection).

Selection of the type of protection is determined by the most important radiation factor for a specific flight. For protection from high-energy protons as produced by solar flares and the inner radiation belt, only magnetic fields can be used. With other types of radiation, such as artificial radiation belts, protection can be provided by electric fields.

One advantage of active protection is the low-level generation of secondary radiation and the significantly lower shield weight [15, 113]. For a 144-m^3 compartment, the weight of a magnetic shield against protons with energies of 1 GeV is approximately 4500 kg; the weight of a passive shield, providing the same level of protection, is 440 000 kg, almost 100 times greater [57, 118]. It should be emphasized that any magnetic shield effective against protons with energies of several hundred megaelectron volts will also be effective for electrons with the same, or lower, energies [118].

According to specialists, it is possible in principle (with today's level of high-voltage and strong magnetic field technology) to produce an active shield which would provide reliable radiation protection for long flights under the most unfavorable conditions. However, difficulties have arisen in developing methods of active shielding, and a number of unsolved problems remain [57, 100, 118], requiring special studies.

PHARMACOCHEMICAL PROTECTION

Status

To find effective pharmacochemical protection from the damaging effects of radiation, more than 15 000[3] different chemical substances, having widely dissimilar physicochemical properties and pharmacological effects, have been tested. They include vitamins, antibiotics, nitrites, cyanides, amino acids, alkaloids, flavonoids, polysaccharides, sulfur-containing substances, analeptics, narcotics, central nervous system stimulants, choline and acridine derivatives, local anesthetics, indolylalkylamines, aminothiols, and the like [2, 3, 4, 6, 40, 41, 58, 66, 69, 74, 75, 76, 89, 97, 101, 126, 130].[4]

As a result of these studies, radiation-protective substances were found which, when given to test animals at a specific time before irradiation, reduce, to some extent, the damaging effects of radiation, favorably influencing the development and course of radiation sickness and increasing the survival rate. In some experiments, several of these preparations have assured 100% survival, while 100% mortality occurred in control groups [2, 74, 76, 97, 126]. Radiation protectors, particularly those containing free sulfhydryl groups [2, 97], are effective not only for mammals, but also for protozoa and other microorganisms, cell cultures, and so forth.

Thus, laboratory experiments have proved the possibility of both increasing and decreasing resistance to radiation by means of chemical substances. Establishment of this fact, which is very important from both a scientific and practical standpoint, must be considered one of the outstanding achievements in radiobiology.

At first, studies in search of radiation-protective, pharmacochemical substances were generally empirical. However, as knowledge was accumulated about the physicochemical processes arising from irradiation of animals, and on the nature of radiation sickness, scientists

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[3] Approximately 11 000 compounds were tested by Plazack et al at the University of Chicago Toxicology Laboratory. The criteria for protection were very strict, and few compounds with protective capacity were found.

[4] Abstracted in *Nuclear Science Abstracts*.

began to base experiments on theoretical assumptions [2, 3, 4, 22, 26, 29, 30, 31, 32, 110, 130].

Mechanism of Protection

With the present concept of the primary mechanisms involved in the biologic effects of ionizing radiation and subsequent pathologic processes, as well as knowledge of the effects of chemical substances [2, 23, 47, 54, 55, 56, 112], it is possible to increase or decrease the radiation resistance with preparations which influence either the primary radiochemical reactions or the protective mechanisms of the organism, or both simultaneously.

It is generally accepted that the radiation protectors act on the primary radiochemical processes initiated by the ionizing radiation [22, 23, 61, 62, 95, 97, 110]. This is indicated by the fact that the great majority of radiation-protective substances known so far have a positive influence only if administered a comparatively short time before irradiation [2, 6, 97, 113, 126, 130].

There are many theories and hypotheses concerning the mechanism of protection, which will not be presented here since they have been described in monographs and special reviews [4, 22, 40, 55, 81, 97, 99, 105, 110, 113, 126, 130]. However, attempts to explain all phenomena by any single mechanism are not justified [22, 92, 93, 97]. The reaction of mammals to irradiation is quite complex, and radiation death results from disruptions in the organism. Therefore, the protective effect of various chemical substances cannot be reduced to any single factor [4, 8, 40, 41, 47, 61, 97, 112]. The absence of reliable data on the mechanism of protection undoubtedly is a hindrance to successful search for effective radiation-protective substances.

Radiation resistance can be increased by pharmacochemical preparations capable of causing oxygen deficiencies in cells and tissues. Morphine depresses the respiratory center; carbon monoxide or aminopropiophenone forms methemoglobin; cyanides block the respiratory enzyme in tissues, decreasing the products of water radiolysis at the moment of irradiation.

The protective mechanism of pharmacochemical radiation protectors may be based on:

Competition for strong oxidizers and free radicals formed as a result of water radiolysis;

Formation of temporary, reversible bonds with sensitive groups in vitally important enzymes or other protein molecules, providing protection from damaging effects at the moment of irradiation;

Formation of strong compounds with heavy metals, resulting in rapid chain oxidation reactions;

Migration of excess energy from macromolecule to radiation protector;

Inhibition of chain oxidation reactions with branching chains, bonding active radicals (formed at the moment of irradiation), and causing a break in the reaction chain;

Absorption of secondary ultraviolet radiation, exciting macromolecules such as nucleic acids;

Increase in stability and mobility of protective mechanisms;

Prevention of disorders in interaction of excitation and inhibition processes in the central nervous system;

Depression of metabolism;

Detoxification or accelerated removal of toxic products from irradiated organism.

There is no single (and could hardly be any natural) chemical preparation having all these properties. Radiation protectors are found among very different classes of chemical compounds and have various protective mechanisms [2, 4, 6, 40, 41, 58, 89, 97, 130].

Classification of Pharmacochemical Protectors

The search for radiation-protective substances continues to be conducted in many directions. More than 1500 substances (the number will increase with each year) have indicated good protective effects in animal experiments. There is, therefore, a need to classify them; however, attempts to produce such classifications have encountered great difficulties [2, 92, 97, 113, 126, 130].

It is impossible to classify radiation protectors according to physical and chemical properties since they belong to widely dissimilar types of chemical compounds. It is impossible to systematize them according to their pharmacologic properties since radiation protectors are found among central nervous system stimulants and narcotics, sympathomimetics and cholinomimetics, and the like. It is also impossible to classify substances according to protective mechanism, owing to insufficiency of scientifically established data. Therefore, no author has yet produced a well-ordered systematization of pharmacochemical protectors.

Apparently, there is more justification for grouping protective substances according to purpose:

1. Those designed as individual chemical protectors against the external effects of penetrating radiation from relatively short-term, high-dose irradiation, as from nuclear blast or solar flare;
2. Those designed as individual pharmacochemical protectors against the external influence of ionizing radiation from extended low-dose irradiation such as long space flights with prolonged exposure to primary cosmic radiation (PCR);
3. Those designed to increase resistance to radiation during x-ray therapy.

Requirements as Protective Substances

The requirements are different for each of the above categories. Particularly rigid standards must be maintained for formulations in Groups 1 and 2. Those preparations have to be self-administered without medical supervision, both on Earth (in case of accident) and during space flight (exposure to solar flares or long flights). After taking the protective substance, the astronaut must be able to continue his work. Group 3 preparations can be prescribed by a doctor or qualified nurse for hospitalized patients, since the route of administration, duration of action, and so forth, are not of such great importance.

A radiation-protective substance designed for spacecrews must meet minimally these requirements:

Sufficient effectiveness without manifest side effects; rapid (within 30 min) and prolonged (at least 2–4 h) effect; at least 5–8 h for Group 2;

Absence of toxicity, or therapeutic factor of at least 3 (dose becomes toxic if multiplied by 3);

Absence of any properties which would even briefly reduce working ability, particularly control skills;

Convenient usage; tablet, capsule, wafer, lozenge, pill, injection (volume not over 2 ml);

No harmful influence with repeated use, no cumulative effect;

Should not reduce resistance to other unfavorable spaceflight factors (acceleration, weightlessness, and the like);

Shelf life of at least 1 yr;

Should not react with diet to enhance radiation effect or decrease drug efficiency on long flights.

In view of these requirements, it is easy to understand why all substances which have produced positive results in animal experiments (particularly with simple biologic forms) cannot be used in medical practice, and especially for protection of cosmonauts. For example, carbon monoxide, sodium cyanide, and potassium cyanide have been found quite effective in experiments on mice and rabbits. However, they are highly poisonous, and cannot be used to prevent radiation damage to man in space flight, or even under terrestrial conditions.

Common Properties of Protective Compounds

The most interesting radiation protectors are the mercaptoalkylamines, indolylalkylamines, aminosulfides, thiourea derivatives, guanidine, and thiazolidines. Many of these have properties in common. They provide protection only when administered a short time before irradiation; after radiation exposure, they either have no positive influence, or make the pathologic process more severe. The protective effect occurs only when taken in large doses, causing significant functional disorders in some organs and body systems. Consequently, after administration of the protective substance, irradiation occurs in an organism with altered metabolism.

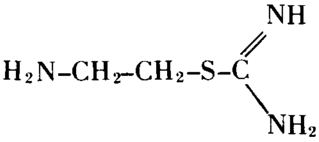
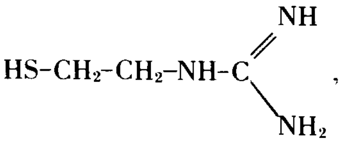
Many radiation protectors have a protective influence in the presence of oxygen, but when the concentration of oxygen is increased, their protective capacity is markedly reduced. Many are rather strong antioxidants. Most have two more significant properties: the ability to penetrate tissue and cell membranes without losing their radiation-protective properties, and the ability to accumulate in radiation-sensitive tissues [2, 4, 69, 92, 97, 113, 126, 130]. The possibility cannot be excluded that these common properties determine the specific activity of radiation protectors.

The terms *protection* and *protective agents* first appeared in radiobiology, 1940–1942 [2, 69, 97], but chemical protection of warm-blooded animals was first achieved in 1949 by Patt, Chapman, and their colleagues [74, 75, 76]. These scientists succeeded in showing that cysteine when administered to animals before irradiation with fatal doses of x-rays, significantly reduced mortality.

Examples of Protective Substances

Cysteine and cystine are amino acids, which are present in hormonal and enzymatic proteins. These compounds participate in the most important metabolic processes, and thus may influence changes in a number of biologic processes and physiologic functions.

Cystine does not protect against ionizing radiation; however, its decarboxylation products provide protection. Decarboxylation products of cysteine and cystine are cysteamine, $HS-CH_2-CH_2-NH_2$ (β-mercaptoethylamine; Becaptan; mercamine), and its disulfide, cystamine, $NH_2-CH_2-CH_2-S-S-CH_2-CH_2-NH_2$ (β,β'-diaminodiethyl disulfide). Both compounds are quite similar in their physicochemical properties to the natural metabolites, cysteine and cystine, which apparently explains the variety of pharmacologic effects of cysteamine and cystamine.

Cysteamine and cystamine are typical aminothiols; their molecules contain both the amino group (NH_2) and the thiol, or sulfhydryl, group ($-SH$). The aminothiols also include AET [S-(2-aminoethyl) isothiuronium; antirad],  $H_2N-CH_2-CH_2-S-C(=NH)NH_2$. This compound is converted in the organism to 2-mercaptoethylguanidine,  $HS-CH_2-CH_2-NH-C(=NH)NH_2$, and is essentially N-substituted cysteamine.

Cysteamine and cystamine were first synthesized in 1889 by the German chemist, Gabriel [27], but for almost 50 years these compounds failed to attract the attention of pharmacologists. Robbers [86] published the first objective experimental data on the pharmacologic characteristics of cystamine in 1937.

In 1951, the well-known Belgian pharmacologist and radiobiologist, Bacq, and his colleagues, first showed that cysteamine and cystamine have manifest radiation-protective effects when administered parenterally, and orally [2, 3, 4]. The dose reduction factor (DRF) is approximately 1.8; e.g., after intraperitoneal injection of 150 mg/kg cysteamine in mice, the radiation dose may be almost doubled without increasing mortality beyond that of the controls [4].

Cysteamine was found to be significantly more effective and less toxic than cysteine. According to the data of Straube and Patt, cysteamine is five times as effective as cysteine in equimolecular doses [105].

Bacq's report on the high protective effect of cysteamine and cystamine attracted the attention of radiobiologists in many countries, and essentially laid the foundation for further systematic studies seeking new protectors. Investigations became more purposeful than before.

The most studied radiation protectors are cysteamine and its derivatives. Therefore, they will be discussed in greater detail, and used to show the status and prospects of pharmacochemical protection against radiation damage.

There is general agreement that the protective effect of cysteamine depends to a great extent on the dose, method and time of administration, and nature of the radiation, as well as the condition of the organism [2, 4, 14, 58, 61, 97, 99], and is most effective when given to animals, intravenously or intraperitoneally in the maximum tolerable dose, 10–15 min before irradiation.

The optimal protective dose of cystamine for animals is 60–180 mg/kg body weight. Thus administered, the survival rate of experimental animals was higher than that of the controls, averaging 55% for mice, 38% for rats, and 67% for dogs.

Cysteamine (mercamine) and cystamine (mercamine disulfide) not only increase the survival rate, but also favorably influence the course of radiation sickness. Clinical symptoms in experimental animals are milder than those of control animals. Leukopenia develops more slowly and does not reach the level observed in controls. Rats tolerate a daily intravenous injection of 33 mg/kg cystamine for 15 d without apparent change in condition, while guinea pigs tolerate a total dose of 693 mg/kg over 11 d. Mice tolerate daily intraperitoneal injections of 150–200 mg/kg cystamine for 10 d without visible signs of poisoning. After long usage of protective doses of either cystamine or cysteamine, no specific changes were observed in the blood, urine, or histology of liver or kidneys.

Investigations in laboratories throughout the world have revealed regularly occurring characteristics (valuable from a scientific aspect), such as the dependence of the radiation-protective effect on the chemical structure of the substance. It has been found that the maximum protective effect of preparations in the aminothiol series (cysteamine and derivatives) is achieved only if the substance contains two functionally active groups in the molecule. One of these must have basic properties, and the other acidic. Active components in the molecular structure of the protective aminothiols, thiazolidines, and thiazolines include the amino- mercapto- and oxy-groups, which should be located at a strictly defined distance from each other. In cystamine, the active components are the sulfhydryl (SH–) and amino (NH_2–) groups. Elimination of one group from the antiradiation substance molecule causes a sharp reduction in protective properties [2, 4, 58, 69, 92, 97, 113].

None of these groups carries the protective properties in itself. Even doubling the groups does not increase the protective effect [2, 95]. For the aminothiol compounds, there is no direct correlation between the number of free sulfhydryl groups and the protective effect [58, 92, 97, 99]. Elongation of the carbon chain by more than 3 atoms of carbon causes a sharp reduction, or complete disappearance, of the antiradiation properties. The amines, as a rule, have more manifest protective properties than the corresponding amino acids [2, 4, 97]. These characteristics of chemical structure are of great significance in the synthesis of new radiation protectors.

Clinical Testing of Radiation Protectors

In addition to cysteamine and cystamine, there are other highly effective radiation protectors: 5-methoxytryptamine (mexamine; 5–MOT), Tsistafos (γ-aminoethylthiophosphoric acid), AET, and others [2, 4, 69, 92, 97, 113, 126, 130]. The good protective effects in animal experiments gave clinical researchers a basis for testing these substances on humans who required radiotherapy for malignant tumors.

In animal experiments, the specific protective effect was generally studied in whole-body irradiation. In human therapy, a comparatively small area of the body is exposed to radiation. Obviously, conditions of general irradiation differ from those of local irradiation. With whole-body radiation of test animals, it is possible to study more precisely and objectively the specific effectiveness of radiation protectors—the survival rate of the animals providing undebatable proof. The possibility also cannot be excluded that the response of the body with malignant neoplasia to both radioprotectors and radiation may differ substantially from the response of a healthy body.

Nevertheless, clinical testing is necessary. It allows tolerable doses to be determined for man, the side effects to be noted, and data to be accumulated on the specific activity of the radiation protector. (Specific activity is judged by the prevention of radiation complications ordinarily arising from radiation therapy.)

Radiation protectors of the aminothiol series were tested on humans in clinics in various countries: Belgium, France, Italy, East and West

Germany, Czechoslovakia, USA, England, USSR, and so forth. Cystamine, in particular, was tested in x-ray therapy, and in the treatment of other pathologic processes. Protectors in the aminothiol series were also given to healthy volunteers. The tests revealed that the aminothiols were effective in eliminating radiation reactions [2, 3, 4, 58, 97].

Bacq and Alexander [3] were among the first to report the testing of cysteamine and cystamine on many patients who received radiation for malignant tumors. The preparations were given after irradiation when signs of radiation sickness developed. According to the authors, after cysteamine or cystamine was administered, the nausea, vomiting, general weakness, diarrhea, colic, and other symptoms of radiation reaction disappeared rapidly in most patients, regardless of the duration of x-ray therapy.

In 1956, Herve [38] reported treating 140 patients with cysteamine salicylate (600 mg orally) and cystamine hydrochloride (200 mg intravenously), for 1–4 d. The author observed good therapeutic effects in 67% of the patients, and a weak therapeutic effect in 16.5%. In another 16.5%, no positive effect was discernible.

The Czechoslovakian investigators, Durkovsky and Sirack-Vesela [21], carefully observed the dynamics of the disappearance of individual symptoms of the radiation syndrome when 200 mg cysteamine hydrochloride were injected 15 min *before* irradiation or during the first hour *after* irradiation (see Table 1). Disappearance of radiation symptoms was observed in 91.7% of the patients injected before irradiation, and in 88% of those injected after irradiation.

Bakhtel' and Sinenko of Leningrad [119] gave their patients cystamine orally, 30–60 min before irradiation each day, or every 1–2 d. Twelve patients were given 0.2 g; 53, 0.4 g; 144, 0.6 g; and 26, 0.8 g. During the entire x-ray therapy, the patients received 8.4–42 g cystamine. No side effects were observed from these doses. (Body surface areas of 48–320 cm^2 were irradiated; a single radiation dose was 200–500 R, the total dose during the course of treatment, 26 000 R.)

Table 2 shows that of the 90 patients in control groups who were not given cystamine before irradiation, 9 patients (10%) could not continue x-ray therapy, while all of the 202 patients who received cystamine completed the course of radiation treatment. Blood transfusions were required by 50 patients (55.5%) in the control groups, but by only 61 of the patients (30.1%) who had been given cystamine. No signs of radiation sickness were observed in 31 of the controls (34.4%), while 141 of the patients (69.8%) receiving cystamine showed no radiation symptoms.

Thus, cystamine significantly (by a factor of more than 2) reduced the percentage of patients developing reactions to irradiation of tumors of the neck, thorax, abdomen, and pelvis. When symptoms did develop, they were milder, and the number of leukocytes, the authors affirm, was less

TABLE 1.—*Disappearance of Radiation Sickness Symptoms with Intravenous Cysteamine Hydrochloride* [21].

Symptoms of radiation sickness	Cysteamine after irradiation			Cysteamine before irradiation		
	Cases, no.	Therapeutic effect		Cases, no.	Therapeutic effect	
		Positive	Negative		Positive	Negative
Anorexia	20	18	2	20	18	2
Nausea	20	18	2	20	19	1
Vomiting	17	17	–	20	20	–
Diarrhea	2	2	–	–	–	–
Headache	3	1	2	11	7	4
Dizziness	6	6	–	1	–	1
Insomnia	4	4	–	3	3	1

markedly reduced than in patients receiving x-ray therapy, without cystamine.

It should also be emphasized that the patients were irradiated with doses which generally cause symptoms of radiation sickness if preventive measures are not taken [38, 49, 119, 120]. According to the data of Kozlova [49], when 12 cm^2 or less of the body was irradiated, 11% of the patients developed clinical symptoms. When the irradiated surface was increased to 50 cm^2, symptoms appeared in 32%; when 106 cm^2, 52%; and 200 cm^2, 100%. In the opinion of several authors [4, 39, 113, 126], cysteamine and cystamine do not change the sensitivity of cancer cells to x-rays.

The information presented above, as an illustration of the clinical use of aminothiols, indicates clearly that radiation protectors of this class of chemical compounds produce definite, positive effects in x-ray radiation therapy. (For further information, consult references [2, 4, 58, 69, 97].)

To summarize the available data on clinical testing of radiation protectors of the aminothiol series, particularly cystamine:

Extremely encouraging results have been produced in clinical testing of cystamine.

Ingestion of 0.2–0.8 g cystamine is satisfactorily tolerated. During radiation therapy, patients have taken as much as 42 g with no observed side effects [58]. In healthy subjects, ingestion of 0.6–0.8 g/d, or three times a day at 6-h intervals, as well as 1 g once in 8–10 d, causes no significant change in sense of well-being or in working ability.

Long-term use of cystamine, in doses up to 0.6 g/d, has no harmful influence on the function of kidneys or gastrointestinal tract.

No cumulative effects are observed when cystamine is taken over a long period.

No contraindications have been established for the use of cystamine.

Cystamine prevents and reduces methemoglobinemia and hemolysis caused by sulfones.

Cystamine prevents benzene leukopenia [4, 58].

Other properties of cystamine have been detected which can be used for treatment of pathologic processes of nonradiation origin.

Cystamine, cysteamine, and AET reduce visible chromosome damage caused by irradiation [2].

Both patients and healthy test subjects do not tolerate AET as well as they do an equal dose of cystamine. Of 98 patients who received 0.8 g AET, 51 (52%) showed side effects, while only 84 (28.7%) of 292 patients who received 0.8-g doses of cystamine showed side effects [58].

According to Zherebchenko [130], Strelkov [109], and other authors [69, 102, 113, 127], 5-methoxytryptamine is similar to cystamine in its radiation-protective effect. Like cystamine, it has a protective in-

TABLE 2.—*Influence of Cystamine on Radiation Sickness Following X-Ray Therapy* [119]

Irradiated area	Patients, no.	Cystamine, g		Treatment interrupted		Blood transfusions		No signs of radiation sickness	
		Maximum one-time dose	Maximum total dose	Patients, no.	%	Patients, no.	%	Patients, no.	%
Thorax	60[1] 130	— 0.8	— 42	4 0	6 0	25 25	48 19	31 105	52 81
Abdomen	30[1] 72	— 0.8	— 32	5 0	16 0	25 36	83 50	0 36	0 50

[1] Control group

fluence when administered both orally and parenterally. In contrast to cystamine, 5-methoxytryptamine has a broader therapeutic latitude in its antiradiation effects.

Radiation-Protective Combinations

Pharmacologists have long known that a single therapeutic substance frequently does not produce the required effect. In some cases, its action is short-lived; in others, it is one-sided or unfavorable effects appear along with the favorable. Frequently, several substances are given simultaneously to strengthen the pharmacologic effect, and to reduce unfavorable side effects. Reinforcement of the effects of medicines, or potentiation, is generally observed only when pharmacologically dissimilar substances are combined, substances individually having different effects. The preparations must have different mechanisms of action [51,64,68,123]. As Kravkov noted [52], some substances, which in themselves have no influence, or which are taken in doses so small as to be ineffective, in combination may significantly alter or strengthen one another's effects.

The complexity of the pathologic processes of radiation sickness, and the number of radiation protectors in various classes of chemical compounds—with different mechanisms of protective action and with clear side effects—prompted scientists to search for effective radiation-protective combinations.

In the USSR, in 1949–1950, this author first established, in principle, the possibility of reducing the toxic effects of protective substances by the combined use of pharmacologic preparations which, when used together, did not reduce, and in many cases slightly increased, their antiradiation properties. Since then, a large number of such formulations have been tested in various laboratories throughout the world [97, 113, 115, 126].

Experimental studies in this author's laboratory—as well as data from the literature—indicate that radiation protectors used in combination have a clearer protective effect, generally, than do any of the substances used separately (see Table 3).

Pharmacologically active substances, e.g., the alkaloids (it is important to note), may reinforce the protective effects of a radiation protector. Although they have no protective properties, they are capable of effecting a favorable change in the reaction of the organism. Apparently, the use of radiation protectors in multicomponent prescriptions makes it possible to reduce the size of the protective dose, decrease side effects and toxicity, and even increase the protective effect [69, 97, 130].

Selection of the proper quantities of components is extremely important because substances in combined use may have different effects, depending on the quantitative relationships in the prescription.

Protection From Proton Bombardment

Inasmuch as protons are the most common type of penetrating radiation to be encountered in space, the question naturally arises as to the effectiveness of known radiation protectors against proton bombardment.

Some investigators believe that pharmacochemical substances effective against x-ray and γ-radiation have no effect against corpuscular radiation, particularly in preventing genetic damage. When such substances are used to provide protection from ionizing radiation, a reduction is observed in their activity against neutron bombardment, and the radiation-protective effect against α-particle bombardment may disappear completely.

In 1961, Yarmonenko et al [127] first showed that in bombardment by protons with energies of 660 MeV, the influence of known radiation-protective substances was as clearly manifested, if not more so, than when irradiation was by x-rays or ^{60}Co γ-rays. These findings were subsequently confirmed by other investigators [89, 95, 97, 102, 115, 116, 126]. The effectiveness of protectors against proton bombardment is shown in Table 4.

Radiation protectors were found to be rather effective in protecting both protozoa and mammals from proton bombardment. With this type of radiation as well, the combined use of protective substances, particularly those with different pharmacologic properties, produces a clearer protective effect than when the substances are used individually.

Flight Factors in Radiation Protection

Cosmic radiation, of course, does not consist solely of protons. In space flight, the astronaut and other biologic forms are subjected to mixed radiation at very high energies which cannot, as yet, be reproduced in the laboratory. Many factors exert their influence in widely differing combinations and sequences. To estimate accurately the biologic effects that may be expected, or the effectiveness of protectors, it is necessary to know the sequence, strength, and duration of the individual factors (including various types of ionizing radiation) as the different areas in space are traversed. As a result of the radiologic heterogeneity of space, the radiation encountered by the astronaut will be distributed unevenly in time. In addition, the nature of the response to radiation (as to therapeutic substances in combinations with certain flight factors) will probably differ. Upon entry into orbit, the response, obviously, will be different than during orbital flight or return to Earth.

Unfortunately, problems of the combined influence of radiation with other flight factors—and particularly the effectiveness of radiation protectors under these conditions—have not been studied in flight, or even in model laboratory experiments. Such studies have only recently been started by scientists in this author's laboratory.

Experiments on mice, rats, and dogs have shown that cysteamine, cystamine, AET, 5-methoxytryptamine, Tsistafos, serotonin, and

TABLE 3.—*Survival Rate of Mice with Combined Use of Radiation Protectors* [126, 130]

Protector	Radiation dose,[1] R	Protector dose, mg/kg	Survival rate, %
Control	800	—	0
5-methoxytryptamine	800	75	16.6
Cysteamine + 5-methoxytryptamine	800	75 + 75	60
AET	850	150	40
Cysteamine	850	150	32
5-methoxytryptamine	850	75	45
Hydroxylamine	850	60	4
5-methoxytryptamine + cysteamine	850	75 + 150	95
Hydroxylamine + AET	850	60 + 150	81
Control	850	—	0
Control	900	—	0
5-methoxytryptamine	900	75	30
Cystamine	900	150	36.3
5-methoxytryptamine + cystamine	900	75 + 150	82
Control	700	—	1.6–8
Tryptamine	700	75	16.6
Cysteamine	700	150	26.6
Tryptamine + cysteamine	700	75 + 150	75
Control	850	—	0
Hydroxylamine	850	60	10
AET	850	150	30
Glutathione	850	900	65
Hydroxylamine + AET	850	60 + 150	90
Hydroxylamine + glutathione	850	60 + 900	45

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[1] Type of radiation not specified.

the like exert their full protective effect under the combined influence of ionizing radiation and dynamic flight factors (Table 5). In some experimental conditions, the effectiveness of protectors may be even greater with the combined action of various factors than against radiation alone.

Some of the most effective protectors have been tested under model radiation conditions, created in a lunar orbital trajectory during solar flares [67, 90, 97]. Survival of animals irradiated under these conditions and treated with protective substances, although slight, was better than that of unprotected controls; however, the mortality of the unprotected controls was only 33%.

The survival rate of animals protected by pharmacochemical preparations under conditions of acute irradiation, and irradiation that would be encountered on a flight to the Moon (combination of fractional radiation with long exposure times), was of the same order of magnitude: 90% and 93.4% for AET, 75% and 96.7% for cystamine, and 65% and 80% for 5-methoxytryptamine.

The clearest radiation-protective effect against acute radiation was observed when AET was used; 5-methoxytryptamine was less effective. This difference in protective influence was observed for the two substances when irradiation was used to model a flight to the Moon.

Preliminary irradiation (60 R) slightly reduced the biologic effects of subsequent irradiation at higher doses and, at the same time, caused an increase in sensitivity to the protective agents. When tolerable doses of AET and cystamine were used under these conditions, approximately 20% of the animals died.

Radiation protectors manifest fully their protective effect when combined with other flight factors (radiation plus acceleration, radiation plus vibration). However, some radiation-protective substances, in optimal protective doses, reduce the resistance of animals to vibration and acceleration [18, 85, 97].

Animal experiments have shown that cystamine, AET, 5-methoxytryptamine, and serotonin definitely reduce resistance to acceleration during the first hours after the preparations are administered. Tolerance of transverse accelerations is determined primarily by compensatory capabilities of the respiratory and cardiovascular systems. Redistribution and deterioration of gas metabolism in the lungs, as well as circulation disruptions in body organs, are accompanied by the development of progressive general hypoxia and a great increase in load on the heart. Under the combined influence of acceleration and radiation protectors, the hypoxic effect is apparently potentiated, causing a

TABLE 4.—*Radiation-Protective Effect of Various Protectors Against γ-Radiation and Proton Bombardment at 600 and 120 MeV* [97]

Protector and dose [1]	^{60}Co γ-Radiation, 850 R		Proton bombardment, 650 MeV dose 1178 rad		Proton bombardment, 120 MeV dose 1200 ± 100 rad	
	Mice, no.	Survival rate at 30th d, %	Mice, no.	Survival rate at 30th d, %	Mice, no.	Survival rate at 30th d, %
Cystamine, 150 mg/kg	40	55	80	51.2	40	60
AET, 150 mg/kg	40	75	60	81.6	40	75
Serotonin, 50 mg/kg	40	60	30	50	40	55
5-methoxytryptamine, 75 mg/kg	40	70	30	70	40	70
Tryptamine, 100 mg/kg	20	40	25	25	–	–
5-oxytryptophan, 250 mg/kg	20	40	20	20	–	–
Radiation control group	40	0	160	1.8	60	3.3
Biologic control group	20	100	60	98.3	20	100

[1] Substances, in 0.2 ml isotonic NaCl solution, injected intraperitoneally 15–30 min before irradiation. Doses are given as the base. Control animals received only 0.2 ml physiological saline solution.

reduction in the resistance of the animals to acceleration.

Data from one experiment will serve as an illustration. Mice were injected intraperitoneally with cystamine dihydrochloride (125–150 mg/kg), AET (150 mg/kg), serotonin creatine sulfate (50 mg/kg), and 5-methoxytryptamine (75 mg/kg), 30 min, 4 h, or 1 d before centrifuging. The animals were subjected to transverse (back-chest) acceleration in a centrifuge with arm length of 4.25 m. The acceleration applied was 44.4 g (1.4 g/s). Centrifuging was repeated three times (5 min each "plateau," with 5-min intervals between centrifugings). The number of animal deaths was noted after each centrifuging.

This experiment showed that the radiation protectors injected 30 min or 4 h before centrifuging reliably reduced resistance to acceleration. The rate of survival of mice given radiation protectors 1 d before centrifuging was almost the same as that of the controls which did not receive the protective substances. The results were approximately the same in experiments with other types of animals.

Colleagues of this author (Vasin and Davydov) clearly showed that accelerations cause an in-

TABLE 5.—*Protective Effect of Cystamine with Combined Exposure to γ-Radiation (Mice—900 R, Rats—800 R), Vibration (70 Hz, 60 Min) and Acceleration 15–20 G, 30 Min)* [97]

Animal and exposure [1]	Animals, no.	Survival rate to 30 d, %
Mice		
Radiation	169	4.1
Vibration	66	100
Vibration + radiation	70	7.1
Cystamine + radiation	60	66.6
Vibration + cystamine + radiation	70	71.4
Biologic control	20	100
Radiation	210	3.3
Acceleration	76	100
Acceleration + radiation	60	11.3
Cystamine + radiation	110	51.8
Acceleration + cystamine + radiation	120	55
Biologic control	25	100
Rats		
Radiation	75	4.0
Acceleration	70	100
Acceleration + radiation	70	5.7
Cystamine + radiation	80	60
Acceleration + cystamine + radiation	86	63.9
Biologic control	20	100
Radiation	150	4.0
Vibration + radiation	60	5.0
Vibration	55	100
Cystamine + radiation	76	47.3
Vibration + cystamine + radiation	80	56.2
Biologic control	20	100

[1] Cystamine injected intraperitoneally 25–30 min before irradiation: mice—150 mg/kg, rats—100 mg/kg, as the base. Vibration and centrifuging performed 30–40 min before irradiation.

crease in sensitivity to cystamine [97]. Thirty minutes after acceleration (10 g for 15 min), they observed a clear increase in the animals' sensitivity to cystamine (LD_{50}=213.8 mg/kg, while in the controls, the LD_{50} = 244.5 mg/kg; $P > 0.001$). After 1 h centrifuging, the sensitivity of mice to cystamine returned to its initial level (LD_{50} = 243.8 mg/kg), and remained practically unchanged for 4 h after exposure to acceleration (LD_{50} = 240 mg/kg).

Consequently, under complex conditions of combined influence of cosmic radiation and other flight factors, apparently many radiation-protective preparations which are effective under ordinary surface conditions cannot be recommended for individual radiation-protective purposes in-flight.

Prospects for Medical Use of Protective Substances

Significant success has been achieved with chemical substances in experimental prevention of radiation damage. However, both researchers and medical specialists are quite dissatisfied with the practical application of these substances.

Several serious, unsolved problems hinder the introduction of radiation protectors in medical practice, and have caused some investigators to state that it is impossible, *in general*, to utilize radiation protectors in medical practice, particularly the aminothiols. Thomson [113] states in his monograph that ". . . in case of an accident at a reactor, or a spaceflight emergency . . . the use of protectors . . . is quite ineffective," and that ". . . the possibility of protection of the crew of a spacecraft using radiation protectors, at least at the present, is unrealistic."

Yarmonenko [126] believes that "the possibility of using chemical substances for protection of man is, as yet, problematical."

Others have negated only the possibility of using the aminothiols for human protection. Strelkov [109] states that the information so far speaks against human protection from ionizing radiation by means of the present sulfur-containing radioprotectors. To provide chemical protection, the aminothiol radioprotectors, at present, must be given in doses equal to those providing a stable protective effect in animals, i.e., 100–150 mg/kg. These exceed by 10–15 times the maximum permissible doses for man, and are lethal. Many authors, however, believe that the possibility of using pharmacochemical substances to protect humans is beyond doubt [2, 4, 58, 69, 92, 97, 130]. Most radiobiologists believe that there is no strict correlation between the toxicity of a preparation and its specific radiation-protective activity, and that either can be arbitrarily reinforced or weakened.

These two statements are important since they inspire confidence in the possibility of preventing, or markedly reducing, the side effects of radiation protectors. However, there is confusion as to what should be considered side effects.

An undesirable side effect has no relation to the specific effect of the pharmacologic substance. Quinacrine hydrochloride has the specific effect of killing malaria parasites. It colors the skin canary yellow, decreases blood pressure, causes ear noise, reduces visual acuity, excites motor activity of the smooth muscles of the uterus, and so forth, but these are considered side effects, since they have no relation to the specific therapeutic effect.

It is possible to be equally clear and definite concerning the specific, and side effects of almost all therapeutic substances. So far, a firm, scientific basis is not available for determining which pharmacologic effects of a radiation protector are the significant, specific factors providing the radiation-protective effect, and which are side effects.

The known radiation protectors are biologically active, causing various pharmacologic effects. Cystamine and cysteamine have a broad spectrum of such effects: they increase the number of catecholamines, and decrease catecholamine sensitivity of the biochemical structures of certain organs and tissues; have a definite glycolytic effect; excite respiration; increase consumption of oxygen by tissues and organs, and increase metabolism; they reduce body temperature, functional activity of the cerebral cortex, blood pressure, methemoglobin, diuresis, and so forth.

There is not sufficient knowledge on which organs, tissues, or body systems a preparation should influence; nor is it known what pharmacologic effects it should cause, to provide protection from radiation. The radiation-protective effect should not be accompanied by marked functional changes causing significant reductions in working ability.

There are certain properties of radiation protectors that should be discussed in greater detail, since they prevent broad use of these substances in medical practice.

The most effective antiradiation substances manifest their protective influence only when given in maximum tolerable doses, causing great functional changes in the organism. The maximum tolerable doses of such preparations for man (dose/kg body weight, or dose/unit body surface) are significantly less than those which have a protective effect in animals and increase the rate of animal survival. Additional increases in the human dose of the radiation protector to the level used in experiments on animals (even the most sensitive animals) are incompatible with survival for man. Thus, the known antiradiation substances cannot be used individually for human protection.

However, a categorical and pessimistic conclusion is premature and not well-founded. The absence of a protective effect (as judged by the survival rate of animals when protectors are used in doses tolerable to man) is not absolute indication that achievement of a protective effect in man is impossible.

Species sensitivity to therapeutic substances, resulting in full manifestation of the pharmacodynamic effects, occurs in various types of animals in response to widely varying doses (dose/kg body weight, or dose/unit body surface). There is also a definite correlation between the maximum tolerable dose of cystamine and the rate of heat production in animals and man: the higher the metabolic rate, the greater the effective dose [97].

Unfortunately, no fully accurate and adequate test has been produced for evaluating the specific activity of a preparation when used in clinical practice on humans. Such a test should correlate well, or at least satisfactorily, with a more reliable indicator—the survival rate in animal experiments. Studies to develop such a test are of primary importance.

Application of Animal Data to Man

Comparison also should be made of the pharmacologic effects observed in various species, given the optimal protective doses of a radiation protector, with the effects produced in man by the dose he is able to tolerate of the same substance. If the pharmacodynamics of the preparation in animals and in man are similar quantitatively and qualitatively, it can be assumed that the dose will provide the necessary protection for man.

The radiation-protective effectiveness of a substance is evaluated in experiments according to the survival rate—an absolutely correct procedure. However, no protector prevents development of the pathologic process. Subjects who received the protector will require subsequent treatment just as the unprotected will.

The effectiveness of therapeutic measures will depend not only on the absorbed radiation dose, but also on the organism's functional state. There is reason to believe that a radiation protector, administered even in small doses (which are ineffective for survival), can create a favorable condition in the organism for subsequent therapy, thus increasing the protector's effectiveness.

It is possible that a prescription specifying combined use of two or three antiradiation substances, particularly those with different mechanisms of action, can reduce the undesirable pharmacologic properties by decreasing the dose required of each substance.

The optimal protective dose is not the same for different species of animals, which is important to remember. The optimal protective dose of cysteamine given parenterally to mice is 150 mg/kg; for rats, 100 mg/kg; for dogs, 50 mg/kg. The protective effect at these dose levels is 25%–100% for mice, 35%–90% for rats, and 50%–95% for dogs, with 95%–100% mortality in the control groups.

The great majority of medicines used in medical practice can be tolerated by man only in doses significantly lower than those tolerated by animals. Hexobarbital soluble (Privenal; Evipan Sodium; hexobarbitone sodium) produces narcosis in man with doses only slightly more than one-tenth the dose required for mice. The dose producing human narcosis does not produce narcosis in any known type of animal. The therapeutic dose of atropine for man is 60–75 times less than that for dogs. The therapeutic dose of strychnine for man is 0.007–0.014 mg/kg; for dogs, it is 0.3 mg/kg.

The tolerable doses of medicines for man generally are 7–12 times less than those for dogs. Approximately the same dosage ratios have been observed for the radiation protectors, particularly cystamine. The tolerable dose of cystamine for man is 20–25 times less than the tolerable dose for mice, 10–15 times less than that for rats, and 7–10 times less than that for dogs [68, 97]. Doses of morphine producing pain relief in animals are significantly greater (50–100 times) than the doses tolerated by man. However, no pharmacologist or clinician would conclude that it is impossible to obtain a therapeutic effect with morphine because human therapeutic doses have no effect on animals.

Data produced in clinical testing during radiation therapy (discussed in detail above) also must not be ignored. In radiation therapy, the patient is irradiated locally, not totally, and the reaction is significantly different from radiation sickness after whole-body irradiation. Intermittent, and particularly local irradiation, of course, does not produce all the syndromes of radiation pathology observed with whole-body irradiation, although many radiation sickness symptoms are displayed after local irradiation. Therefore, the effect of radiation protectors in local irradiation of animals, and in humans subjected to x-ray therapy should also be considered when determining possible chemical protection of man from radiation damage.

The model of radiation sickness is also important in the defense of radiation protectors. Many experimental studies and clinical observations have indicated convincingly that clinically acute radiation sickness follows the same pattern in various species of mammals and has features characteristic of general acute radiation damage. The differences which have been observed in the course of the sickness are probably more quantitative than qualitative [17, 36, 37, 47, 50, 53, 59, 61, 97, 120]. If this is true, then application to man of data on therapeutic or preventive substances produced in animal experiments is fully justified. (Transfer of data would entail risk if the model of radiation sickness in animals were very dissimilar to human radiation sickness.) Therefore, if the substances are protective in experiments on animals of various species, there is no reason to assume that they will be ineffective in man. The effectiveness of various plans for combined therapy, both in animal experiments and in clinical tests on humans (after accidents), showed no significant differences in principle [11, 30, 36, 37, 120].

The general depressive effect of radiation protectors, particularly the aminothiols, must be considered one of their negative properties since it reduces working ability and has a particularly negative influence on acquired professional skills.

Optimal protective doses of a protector (e.g., cystamine) disrupt the process of thermal regulation, so that animals and man tolerate significantly less well high or low temperatures in the surrounding medium. When the ambient temperature is particularly high or low, the toxic effects of radiation protectors are even more strongly manifested. Thus, cystamine and other antiradiation substances reduce resistance to the dynamic factors of flight.

Combined Use of Radiation-Protective Substances

The general depressive effect of radiation protectors can probably be at least sharply reduced, if not completely eliminated, by combined application of protective substances with different pharmacologic properties.

The creation of such radiation-protective prescriptions (radiation protectors and other pharmacologic substances designed to reduce or eliminate the protectors' side effects) is a very difficult and complex task. The effectiveness of such combinations will depend to a great extent on the selection of substances and determination of dosage ratios. The effects of therapeutic substances used in combinations are significantly complicated, since the substances may react with one another, and the products of their interaction may have quite different pharmacodynamics [51, 68]. The strength and nature of the action of pharmacologic substances may change markedly when used together.

Increases in radiation-protective activity or decreases in toxicity, achieved by combined application of protectors, may not always increase a prescription's chances for practical utilization. Cystamine combined with a methemoglobin-forming agent may produce a higher protective effect than either of the two substances used individually. However, the combination will also have even stronger negative side effects.

The scientific value of investigating the combined use of radiation protectors with each other or with other chemical or biological substances which do not in themselves have a radiation-protective effect is beyond doubt. Unfortunately, in most studies the practical application of combined substances which could be solved is missing.

From a practical aspect, it is hardly expedient to combine radiation protectors with substances having a general depressive influence since the radiation protector possesses this negative property. The combination of a protector with transplantation of bone marrow is also of no practical significance.

With optimal protective doses of the indolylalkylamines (particularly 5-methoxytryptamine (mexamine) or serotonin), investigators observed acute hemodynamic disorders, vessel contraction, or manifest hypoxia. These reactions, naturally, do not permit a human being to work over a long period.

The vascular spasm and resulting hypoxia can be eliminated by antagonists of 5-methoxytryptamine and serotonin, which also reduce the protective effect. Tests of other substances to reduce the toxicity of 5-methoxytryptamine have been unsuccessful [130]. Without discussing the experiments in detail, it can be said that the substances were not always wisely chosen, and excessive doses were used [99, 109, 130].

Several investigators [99, 126, 130] believe that experiments with antagonists of 5-methoxytryptamine and serotonin further indicate that hypoxia is the basis of the indolylalklyamines' protective mechanism. However, many data are available which do not agree with this assumption, and cannot be explained by the hypoxia theory. Some derivatives of tryptamine and 5-methoxytryptamine constrict vessels but show no protective effect, e.g., *N*, *N*′-dimethyltryptamine, indopan (α-methyltryptamine), and the like. On the other hand, oxytocin causes almost no hypoxia, yet has a definite protective effect. After administration of 5-methoxytryptamine, a low level of oxygen tension is maintained for 2 h, while the protective effect lasts for less than 1 h. The substance had a protective effect in protozoa experiments.

The data, therefore, indicate that creation of a multicomponent prescription might eliminate, or weaken, the negative effects of 5-methoxytryptamine (hemodynamic disorders, hypoxia), while retaining its radiation-protective effectiveness.

Duration of protective effect. The brevity of the protective effect also must be considered a significant shortcoming of radiation protectors since it makes them difficult to use during prolonged exposure to radiation. This type of exposure is most characteristic in space flight. Two different methods for correcting this shortcoming are theoretically possible. The first entails creation of longer lasting therapeutic forms. (Long-lasting medicines are already used in medical practice.) Sustained release tablets of nitroglycerin (glyceryl trinitrate; Sustac) maintain their therapeutic effect for 10–12 h. One dose of Sustanon-250, a mixture of hormones, maintains its therapeutic effect for approximately 1 month, and there are others, such as the long-acting antibiotics. That there are so few long-lasting therapeutic substances is not as important as the fact that it is possible, in principle, to create a long-lasting protector.

The second method is repeated administration of the protector. During extended irradiation repeated doses, obviously, will be necessary. However, special studies are required to determine optimal doses and optimal intervals between doses.

Protection for Spacecraft Ecologic System

Apparently, higher and lower plants, microorganisms, and other representatives of the animal and plant world will accompany astronauts on long space flights, completing the ecologic system of the spacecraft. Ionizing radiation and other flight factors may produce genetic and cytologic changes which, without proper protection, would lead to disruption of the ecologic balance, creating intolerable conditions for survival of the crew. Studies must be undertaken to develop stable ecologic systems, and radiation-protective chemicals must be found for these other species. It is possible that the requirements for their protection will be somewhat different from those for the crew.

The problem of determining effective chemical substances for protection against radiation damage for the crew and entire biologic complex is not only pressing, but also very complicated, and has been insufficiently studied. The known radiation protectors, unfortunately, are imperfect and cannot be recommended for astronauts as individual means of protection.

To make pharmacochemical protection of man and other biologic species a reality, studies must be continued on a broad scale in a number of areas and should include participation of specialists in various scientific disciplines (pharmacology, chemistry, radiobiology, microbiology, genetics, therapy, and so forth). Research in radiation-protective substances must be continued both to improve known protectors and to synthesize new ones. Particular emphasis should be placed on the necessity of performing laboratory experiments to study protective chemical properties, using models as similar as possible to actual flight conditions, at least for radiation exposure.

Effective protectors must be tested in experiments under the combined influence of radiation and certain other flight factors which can be reproduced in the laboratory; such factors include vibration, acceleration, hypodynamia, and the like. A preparation which is recommended for astronauts must have known pharmacologic characteristics.

In an unfavorable radiation situation (e.g., strong radioactive chromosphere flares on the Sun, extended exposure of the spacecraft or station to the inner radiation belt, or flight through an artificial radiation belt), pharmacochemical protection will be exceptionally important, since physical protection alone is not a reliable safeguard from radiation [12, 20, 48, 70, 80, 100, 103, 104, 117, 118, 123].

BIOLOGIC PROTECTION

Biologic protection, like chemical protection, is achieved by prescribing therapeutic substances. However, these substances, in contrast to chemical radiation protectors, have no specific effect but rather increase general resistance to unfavorable factors, including radiation.

Consequently, the term *biologic protection* is not quite accurate. *Nonspecific pharmacochemical protection* would be more nearly correct, since the substances used for this type of protection increase general resistance to many factors. Protection utilizing radiation protectors, therefore, should be called *specific pharmacochemical protection.*

Adaptogens and Physical Conditioning

Substances capable of causing nonspecific, increased resistance to the effects of many damaging agents have been called adaptogens by Lazarev [60]. The adaptogenic effect can be produced in principle by various therapeutic agents of different origins and mechanisms of action. An adaptogen should be harmless, should have broad therapeutic effects, should cause minimal or no changes in physiological functions, and should manifest its adaptogenic effect only under the proper circumstances [9, 10, 60, 68, 91, 94].

The action of an adaptogen should be nonspecific, i.e., should increase resistance to the harmful influence of a broad range of physical, chemical, and biological factors. The effect of the adaptogen should be stronger, the greater the unfavorable changes produced by these factors, and should have a normalizing influence [9, 10].

Adaptogens, in contrast to radiation protectors, manifest their antiradiation effects only when taken repeatedly for several days or even weeks, before radiation and are effective only against sublethal radiation damage. Preparations are given in doses which, generally, cause no side effects. It is particularly important that increased resistance be realized both in acute and prolonged fractional and chronic irradiation—which has not been achieved with radiation protectors.

Adaptogens facilitate the effectiveness of combined therapy for radiation sickness, also increase the radiation-protective effect of pharmacochemical and local protective measures. There are essentially no contraindications for biologic protective substances; they can be used in almost any situation, including in space.

Among the most effective substances are liquid extracts and tinctures of the thorny eleuthrococcus, ginseng, and Chinese magnolia vine; a vitamin-amino acid complex, consisting of B vitamins (thiamine, riboflavin and vitamin P), ascorbic acid, and tryptophan and histidine; certain microelements, such as calcium and fluorine (particularly in combination with the vitamin-amino acid complex); adenosine triphosphate (ATP); and dibasol (2-benzylbenzimidazole hydrochloride). When these substances are used before irradiation, animals show less hematopoietic and metabolic changes and their chance of survival is increased. For example, when liquid extracts of ginseng root and eleuthrococcus were given for 15 d to mice with acute radiation sickness (from exposure to 560 R), the survival rate of the protected mice was higher than that of controls (by 14% in the ginseng group and by 30% in the eleuthrococcus group), and the mean survival time increased.

Why do adaptogens (regardless of whether they are physical, chemical, or biological in nature) increase resistance to a broad spectrum of unfavorable effects? What is the explanation for adaptogens' widespread influence?

A scientifically well-founded and exhaustive answer to these questions would require special experimental studies. The few available data, particularly on eleuthrococcus and dibasol, indicate that these substances weaken the morphological and biochemical manifestations of the alarm reaction. They help to increase nonspecific resistance under stress and they eliminate, or greatly weaken, the manifestation of unfavorable elements otherwise accompanying resistance. Eleuthrococcus weakens activation of the adrenal cortex, preventing thymic-lymphatic involution and appearance of gastric hemorrhage, indicative of favorable changes in the organism's adaptive activity [9, 10, 88, 90, 91, 97]. Adaptogens increase the area of proliferation of hemopoietic cells and immunologic activity.

Biologic protection also includes measures, such as acclimatization to reduced oxygen content, vaccination, good nutrition, conditioning, physical training, and sports participation. All these undoubtedly increase overall stability. Misuse of alcohol, nicotine, and narcotics exhausts the nervous system and consequently reduces resistance to radiation.

These biologic protective measures can be recommended now for manned space flights. They are particularly suitable for small and moderate doses of radiation, and may have a favorable influence with radiation doses slightly higher than the planned maximum permissible doses.

Bone Marrow Transplantation

Many laboratories throughout the world are studying the possibility of using bone marrow for prevention and treatment of severe radiation damage. The effectiveness of such transplantations has been successfully demonstrated in mice, rats, guinea pigs, rabbits, and hamsters. However, attempts to assure survival of apes and dogs by transplantation of bone marrow after fatal radiation doses have, in most cases, been unsuccessful [4, 15, 44, 113, 115]. More favorable results were obtained with autologous bone marrow transplantation in which samples of bone marrow were taken from dogs and apes before irradiation, stored under proper conditions, then returned before or after irradiation to the same animal. Some investigators have achieved favorable reactions with transplantation of homologous bone marrow in dogs or apes, while other investigators have failed to confirm these positive results.

Bone marrow has also been used in humans to treat acute radiation sickness. Six victims of a reactor accident at the Yugoslavian Nuclear Center were taken the next day to Paris for examination and treatment at the Department of Radiopathology of Curie Institute. Five of the six reacted favorably. However, it is premature to draw any conclusions from these five cases. It is also unclear why, in animal experiments, the effectiveness of bone marrow transplantation is greatly reduced if performed 1–2 d after irradiation, yet the Yugoslavians were given bone marrow intravenously on the 25th d after irradiation. Had they actually received a lethal radiation dose, the Yugoslavians would have died before the 25th d. It is difficult, therefore, to know whether bone marrow transplantation was the reason for their survival. All six were given antibiotics, vitamins, and blood transfusions, and all of these undoubtedly had a favorable influence. According to Thomson [113], homologous bone marrow transplantation may be not only useless, but also even dangerous in humans exposed to sublethal radiation. Extensive data from the literature (see reviews) indicate that the question of using bone marrow (particularly homologous) in the treatment or prevention of radiation damage is far from answered.

Transplantation of autologous bone marrow is a method that apparently can have a favorable effect on humans. However, it has been stated by Professor Thomson [113] that it is hardly practical "for the protection of large groups of people, although it can be useful for small groups subjected to the effects of predefined doses of radiation, for example in space flights. Bone marrow can be taken from each astronaut, stored frozen in glycerin, and reintroduced after irradiation."

The last statement is undoubtedly correct as a generalization. However, at present, it is impossible to state unambiguously and affirmatively that bone marrow transplantation can be used to protect astronauts. Many questions remain unanswered regarding the method and time of storage of the bone marrow, the means and method of its reintroduction in space flight, indications and contraindications for its use, and so forth. Only special, careful, experimental and clinical studies will provide the answers. Without sufficient scientifically well-founded data, practical utilization of bone marrow transplantation for astronauts cannot be considered.

Hypoxia

A shortage of oxygen in the medium surrounding an organism greatly increases its resistance to radiation; this has been experimentally determined with various species of animals. A good protective effect is observed if the oxygen content in the surrounding medium is 7%–10%. Table 6 presents data indicating that animals have survived doses of radiation higher than the usual lethal dose.

The protective effect of hypoxia has been experimentally shown not only with small laboratory animals, but also with dogs, apes, and even humans during radiation therapy of malignant tumors. Careful analysis revealed that in the state of hypoxic hypoxia, both the hematopoietic system and intestines are protected. Radiation protectors are much less effective in protecting the intestinal epithelium.

Animals, especially man, unfortunately can survive only for limited periods with such low oxygen content (10% or less). However, the time which can be spent under conditions of hypoxic hypoxia can be increased by preliminary adaptation to hypoxia, and by administration of medicines. Vasil'yev et al [121] have shown that many substances increase resistance to hypoxia. These include thiamine, riboflavin, pyridoxine, citrin, pantothenic and ascorbic acids, and vitamins B_{12}, B_{15}, and E (individually and in combination); ATP, ACTH, and the adrenal cortex hormones; araloside, γ-aminobutyric acid, chlorpromazine, Aminazine, glutamine, dibasol, and so forth. However, it is not known how most of these subtances influence tolerance to subsequent irradiation.

A preparation needed would increase resistance to hypoxia and retain high radiation-protective effectiveness. However, hypoxia probably can be recommended as protection from ionizing radiation, but only when the radiation dose is extremely powerful and acts over a short period, as when flying through a radioactive cloud.

If hypoxia increases radiation resistance, it follows that an increase in the content of oxygen

TABLE 6.—*Influence of Hypoxia on Survival Rate of Rats Exposed to X-Rays* [113]

Radiation dose, R	Survival rate, %	
	Air	5% Oxygen
600	63	100
800	0	100
1000	9	91
1200	0	81
1400	0	29

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should increase sensitivity to radiation. Some experimental data (unfortunately, not many are available) indicate that in healthy animals, no decrease in radiation resistance was observed with increased oxygen content of the air, unless the animals, during irradiation, were breathing pure oxygen under high pressure (significantly greater than 1 atmosphere). Under these conditions, the toxicity of oxygen is apparently added to the damaging effect of ionizing radiation.

Artificial hypobiosis. Animals are quite resistant during sleep to radiation damage. The same reaction is observed during artificial hypobiosis (as in deep hypothermia). Resistance is increased by 25%–50% not only to radiation, but also to other extreme conditions (acute hypoxia, acceleration, and the like) [63, 73, 114].

The results observed in experiments are very promising, but are still far from practical application in space medicine. To use this method during extended flights, scientists must learn to maintain deep, controlled hypothermia over long periods [73].

LOCAL PROTECTION FROM RADIATION DAMAGE

The possibility of changing the reactions of animals to whole-body irradiation by screening the spleen was first demonstrated in 1949 by Jacobson et al [43, 44]. Since then, a number of reports have been published of experiments in shielding individual organs and body areas during irradiation. In these experiments, scientists studied the peculiarities of damage from penetrating radiation to hematopoietic organs and blood, the significance of the damage to a specific hematopoietic tissue in the development and results of radiation sickness, and the mechanisms of ionizing radiation's damaging effect on the hematopoietic system. Only in the last 10 years have studies in local protection begun to have practical application in space travel.

Animal Experiments

Shielding individual organs or body areas greatly increases resistance to radiation's damaging effects, and the favorable influence of local protection is true for all species of laboratory animals. This has been shown in many studies.

The high survival rate of animals when shielded cannot be explained by the decreased absorbed total radiation dose (Table 7). The spleen of a mouse weighs an average of only 0.1 g (0.005% of total body weight), and can have no practical influence on the total absorbed dose.

In experiments with γ-irradiation of rats (1400 rad), protecting the abdominal area with a shield 4-cm wide decreased the radiation dose by approximately 25%, to 1050 rad, an absolutely fatal dose for unshielded rats. Approximately 90% of the shielded animals survived. These data clearly negate the assumption that the total dose (or total absorbed dose) during shielding is significant for survival.

The protective effect of shielding results from the retention of areas of undamaged tissue in the irradiated organism—tissue located behind the shield at the moment of irradiation. Therefore, this type of protection should not be called local physical protection. Physical protection decreases the radiation dose. Local protection is a variety of biologic protection and is designed not to reduce the total absorbed dose, but to assure the minimal necessary amount of undamaged tissue in radiation-sensitive organs.

Any biologic tissue undamaged by radiation can make the course of radiation sickness less severe. This is true, apparently, only for relatively low doses. With doses causing the death of the majority of animals, shielding the radiation-sensitive organs (particularly bone marrow, spleen, and small intestine) is most effective. The

TABLE 7.—*Survival Rate of White Rats Protected Locally During X-Ray Exposure* [1] [52]

Radiation dose, R	Group	Rats, no.	Survival to 30th d, %
600–613	Unprotected	107	6.5
600–613	Protected	117	68.4
800	Unprotected	17	0
800	Protected	17	63.5

[1] Lead shield placed over upper abdominal area (liver, stomach, and spleen).

abdominal area is approximately twice as sensitive to radiation as other body areas.

In spite of differences observed by various authors, the basic conclusion to be derived from investigations is beyond doubt: shielding individual organs or body areas (Table 8) during whole-body x- or γ-irradiation is an effective method of weakening the radiation reaction, and reducing the frequency of death from large radiation doses.

The entry of man into space has stimulated radiobiologists to turn their attention to cosmic radiation, particularly high-energy protons. Razgovorov, Morozov, Shashkov, Antipov, Dobrov, Konnova, and L'vova first showed that shielding a portion of the body, particularly the abdominal area, is an effective method of protection not only from x-rays and ^{60}Co γ-rays, but also from proton bombardment. Recently, Grigor'yev and colleagues, as well as other investigators, published a series of reports on the effectiveness of local protection of animals against bombardment by high-energy protons [2, 3, 4, 7, 34, 45, 46, 47, 52, 65, 82, 83, 84, 85, 97, 106, 107, 108, 122, 125].

Summary

The effectiveness of local protection has been shown for all species of laboratory animals and various types of ionizing radiation (x-rays, γ-rays, protons, and neutrons).

Shielding a portion of the body, particularly the abdominal area, not only increases animal survival, but also significantly reduces the severity and frequency of appearance of the primary syndromes of radiation damage. Although shielding does not prevent decreases in the primary indexes of peripheral blood during the first 3–5 d after irradiation, nor eliminate reductions in body weight, it significantly decreases the degree of manifestation of such changes and accelerates restoration of the blood indexes [83].

Many studies have shown a significant reduction in depth and manifestation of pathomorphologic changes not only in organs and tissues partially shielded during irradiation, but also in those not shielded (central nervous system, myocardium, retina, testicles, and so forth).

The effectiveness of shielding depends, to a certain extent, on the radiation dose, shield location, area of the shielded surface (mass of tissue shielded), shield thickness which determines the residual dose behind the shield, and other factors.

With radiation doses exceeding the minimal lethal dose, the optimal effect of local protection is observed with combined shielding of the small intestine, and bone marrow. This is best achieved by placing the shield over the upper half of the abdomen [83].

Neither acceleration nor vibration 1 d before, or after irradiation has a negative influence on the effectiveness of shielding [82].

TABLE 8.—*Survival Rate and Change in Leukocyte Count of Dogs with Head and Abdomen Shielded During γ-Irradiation* [83]

Radiation and shielded area	Dogs, no.	Survivors, no.	Leukocytes, thousands					
			Initial	d after irradiation				
				3	7	15	30	60
600 R	6	0	10.3	3.9	0.5	0.18	–	–
600 R; head shielded	7	4	11.8	3.6	0.8	0.5	2.4	7.9
600 R; abdomen shielded; dose beyond shield, 150 R	7	6	11.9	4.7	2.25	2.0	4.9	11.3
600 R; abdomen shielded; dose beyond shield, 300 R	5	4	12.1	3.6	0.95	1.1	3.2	8.4

From a practical standpoint, it is quite important to determine the minimum mass of shielded tissue and the minimum degree of radiation attenuation effected by the shielding material (the residual dose behind the shield). To obtain this information, Razgovorov and Morozov performed special experiments [84] which showed that to achieve a definite protective effect in rats irradiated with 1000–1850 R, a minimum mass (minimum volume) of shielded tissue is required, particularly the intestines and hematopoietic organs. Retention of the normal functioning of these organs is essential for recovery of radiation-damaged organs and tissues. The authors established that with a shield 2-cm wide, the protected mass amounted to 10%–12% of the body weight (approximately 25 g for a 200- to 250-g rat). When the mass of the shielded tissue was 5%–6% of the rat's body weight (the case with a shield 1-cm wide) the area of shielded tissue was insufficient to assure a high survival rate after γ-irradiation in doses greater than 900–1000 R (1.5–2 times the minimum lethal dose).

With the basic shield width of 2 cm protecting 10%–12% of the body mass from doses of 1000–1500 R, a definite increase in animal survival was observed not only when the shield almost completely absorbed the γ-radiation, but also when shielded portions of the body received relatively high radiation doses: up to 100–120 R with a total dose of 1500 R, or up to 230–250 R with a total dose of 1000 R.

The variation in maximum radiation doses (approximately 120–250 R) given shielded tissues, at which the protective effect of shielding could still be observed, is explained by the authors as due to differences in total radiation dose and the consequent severity of damage to unprotected tissues and organs (90% of the entire body mass). With radiation approaching the minimum lethal dose, the high protective effect is retained even when irradiation of the shielded abdominal area is approximately 35% of the total dose.

When the abdominal area of rats was shielded by a steel block 2-cm wide and 15-cm thick, the dose reduction factor (DRF) is approximately 2.4. Most radiation protectors provide a DRF of 1.5–1.7, or less.

Tables 9, 10, and 11 show the dependence of local protection effectiveness on shield width and thickness. The data indicate a high protective effect not only for rodents, but also for dogs. Positive results were also achieved with apes and even humans in radiation therapy.

Shielding tissues of the head or abdomen (10%–15% of the body mass) produces a high protective effect in dogs given otherwise lethal doses of γ-radiation (see Table 12). To achieve this protective effect by shielding the abdomen, the radiation must be reduced by a factor of 3 or 4 by the shield material. The effect is rather high if the radiation dose is reduced to half by the shield. The investigators also had the definite impression that shielding parts of the body during whole-body

TABLE 9.—*Survival Rate of Rats with Abdomen Shielded by Blocks of Various Widths and Constant Thickness of 15 cm During ^{60}Co γ-Irradiation* [84]

Radiation, R	Shield width, cm	Rats, no.	Survival rate, %
1000	0	95	3.2 ± 1.8
	6	30	100.0
	4	30	96.7 ± 3.3 [1]
	3	36	97.2 ± 2.8 [1]
	2	30	83.3 ± 6.8 [1]
	1	42	90.5 ± 4.5 [1]
1200	0	12	0
	4	12	100.0
	2	24	95.8 ± 4.1
	1	18	33.3 ± 11.1
1500	0	12	0
	4	12	100.0
	3	17	82.4 ± 9.2
	2	17	82.4 ± 9.2
	1	18	11.1 ± 7.4
1600	0	12	0
	3	29	82.8 ± 7.0
	2	30	70 ± 8.4
	1	30	0
1800	2	18	27.8 ± 10.6
1950	2	18	0

[1] Reliability of difference from control, $p > 0.001$.

γ-irradiation, in greater than the minimum lethal dose, was even more effective in dogs than in rats. When the head was shielded, the survival rate for dogs was appriximately 60%, while that for rats was approximately 30%.

TABLE 10.—*Survival Rate of Rats with Abdomen Shielded by Blocks of Various Widths and Thicknesses During* ^{60}Co *γ-Irradiation* [84]

Radiation, R	Shield dimensions, cm		Rats, no.	Survival rate, %
	Width	Thickness		
1000	1	0	95	3.2 ± 1.8
		3	24	8.3 ± 5.6
		5	24	20.8 ± 8.3[1]
		10	24	29.2 ± 9.3[1]
		15	42	90.5 ± 4.5[1]
	2	3	48	14.6 ± 5.1[1]
		5	42	88.1 ± 5.0[1]
		10	42	92.9 ± 4.0[1]
		15	30	83.3 ± 6.8[1]
1500	2	5	24	8.3 ± 5.6
		10	18	50.0 ± 11.8[1]
		15	17	82.4 ± 9.2[1]

[1] Reliability of difference from control, $p > 0.05$.

The investigations of Strelin et al [106, 107, 108] are particularly worthy of attention, as are those of several other authors [34, 45]. In these studies of local protection against extended, chronic, fractional irradiation, shielding proved to be effective. Strelin et al irradiated mice with 40 R/d, at 5 R/min. Half of the mice were unshielded, while the other half wore protective lead sleeves 3-mm thick around one shin. In the unprotected group, deaths began to occur after 35 d, when the total radiation dose reached 1240 R. All of the animals had died by the 73rd day after a total dose of 2520 R. In the shielded group, the first death occurred when the total dose reached 2720 R. The last animal died only after 135 d, with a total dose of 4640 R. In a separate series of experiments, the mice with shielded legs were not irradiated after the last control animal died on the 73rd day. The shielded mice survived. Strelin and colleagues believe the protective effect of shielding during chronic irradiation to be significantly higher than for acute, one-time irradiation.

In low-dose, chronic irradiation, pharmacochemical protectors are not only ineffective, but also are even harmful, since extended use of the substances (over 15 d) may cause toxic effects and even intensify the radiation reaction.

TABLE 11.—*Residual Dose Beyond Shields and Survival Rate of Rats with Abdomen Shielded During* ^{60}Co *γ-Irradiation* [84]

Radiation, R	Shield dimensions, cm		Survival rate, %	Residual dose beyond shield	
	Width	Thickness		% Total radiation dose	Approximate value, R
1000	1	3	8.3 ± 5.6	40.0	400.0
		5	20.8 ± 8.3	22.9	230.0
		10	29.2 ± 9.3	8.1	80.0
		15	90.5 ± 4.5	3.5	35.0
	2	3	14.6 ± 5.1	40.0	400.0
		5	88.1 ± 5.0	22.9	230.0
		10	92.9 ± 4.0	8.1	80.0
		15	83.3 ± 6.8	3.5	35.0
1000	2	5	8.3 ± 5.6	22.9	350.0
		10	50.0 ± 11.8	8.1	120.0
		15	82.4 ± 9.2	3.5	50.0–55.0

Local protection has also been found effective for small doses of radiation. In experiments on guinea pigs and rats, Vasin and Razgovorov [122] showed that with low-dose radiation (100–200 R), the postradiation reduction of chromosome disorders is higher, when organs in the abdomen are shielded. Three days after irradiation of guinea pigs (100 R) and rats (200 R) with abdomen shielded, the percentage of chromosome disorders in bone marrow cells fell within the norm. With doses one-half as great but without local shielding, the number of chromosome disorders was higher than those of the controls.

Shielding the abdomen or head during irradiation significantly accelerates the recuperative process. The half-recovery period for shielded animals is 2–3 times shorter than that for animals irradiated without shielding.

COMBINED USE OF LOCAL PROTECTION AND PHARMACOCHEMICAL SUBSTANCES

Several reports have been published in recent years on the combined application of local shielding and medicines, primarily radiation protectors. Most of these reports clearly show that the specific effectiveness of aminothiol and indolylalkylamine radiation protectors is significantly increased when a portion of the body is shielded during irradiation. The increased effectiveness of radiation protectors, in animals exposed to lethal radiation, is particularly clear when shields are used in combination with smaller than usual doses of these substances (Tables 13, 14, and 15).

Radiation protectors in combination with local shielding have a more clearly expressed effect than either type of protection used alone, which is shown in these tables. It is also particularly important that combined protection allows the dosage of protective substances for animals to be decreased by a factor of 2–4, and the weight and size of the shield also to be decreased. Some reports have indicated that local shielding increases the therapeutic effectiveness of hematopoietic preparations and antibiotics.

There is no need for further proof that studies of the combined application of local shielding and radiation protectors as well as other therapeutic measures administered after shielding are not only of great scientific interest, but also of great practical value.

TABLE 12.—*Survival Rate of Dogs with Head or Abdomen Shielded During γ-Irradiation* [83]

Radiation, R	Degree of attenuation of dose and dose beyond shield	Group no. and location of shield	Dogs, no.		Survival rate, %	Mean survival time of dogs that died, d	Radiation sickness, degree of severity [1]		
			Total	Survived			I	II	III
500	500	1, control radiation	7	0	0	15.7	–	–	7
600	600	2, control radiation	6	0	0	13.7	–	–	6
	$\frac{4.1}{150}$	3, head shielded	7	4	57.0	20.3	–	4	3
	$\frac{4.1}{150}$	4, abdomen shielded	7	6	86.0	33	6	1	–
	$\frac{3.0}{200}$	5, abdomen shielded	5	4	80.0	10	2	2	1
	$\frac{2.0}{300}$	6, abdomen shielded	5	4	80.0	18	2	1	2

[1] I = slight, II = moderate, III = severe.

Experimental data indicate that local shielding can be used today in spacecraft, orbital stations, and other flight vehicles as one method of active antiradiation protection of the crew. It can be used with both low and high radiation doses, delivered at low and high rates. There are no contraindications.

The leading role in the introduction of local shielding in aviation and space medicine must belong not to radiobiologists and medical specialists, but to design engineers. It is essential to bear in mind that shields, belts, or helmets will only be effective against lethal radiation doses (400–600 rem for man) if they shield a minimum of 10%–15% of the body mass and reduce the radiation dose by a factor of 3 or 4. Of course, shields, belts, or helmets should not prevent astronauts from performing their necessary duties nor cause serious injury.

With lethal radiation doses, it is extremely important to shield the radiation-sensitive organs, particularly the bone marrow, spleen, and small intestine. This can be achieved most successfully by shielding the upper abdomen. With nonlethal doses or combined protection (local plus pharmacochemical), the volume of shielded body mass may be less, and the residual dose beyond the shield may be greater.

When partial, as well as whole-body shielding is used, it should be remembered that some radiations may interact with the shielding material and produce secondary radiation; therefore, the shielding may not be only ineffective, but also even harmful.

The high effectiveness of local shielding does not mean that it is unique among methods of active protection, or that it should be compared to biological or pharmacochemical protection. These measures should supplement one another.

SUMMARY

Radiation safety can be provided by a combination of measures. They include evaluation of protective properties of the shell and shields of a planned spacecraft; development of a system of on-board and individual dosimetry for the astronauts; performance of biologic dosimetry of cosmic radiation during each flight; and operation of the flight radiation-safety service, commencing as the spacecraft is prepared for launch, and continuing throughout flight (prediction of space radiation, indication of ionizing radiation along proposed flight path, special observation of solar activity, and so forth).

Medical-hygienic measures include local, biological, and pharmacochemical preventive procedures, as well as treatment of radiation damage.

This combination of measures has been used

TABLE 13.—*Influence of Shielding and Protectors on Survival Rate of Irradiated*[1] *Rats* [7]

Protector	Dose, mg/kg	Rats, no.	Survival to d after radiation			Survival rate to d 30, %
			6	12	30	
Control radiation	–	31	8	0	0	0
Cystamine [2]	100	43	37	6	5	12
5-methoxytryptamine [2]	30	35	20	8	4	12
Shield [3]	–	40	28	11	7	18
Shield + 5-methoxytryptamine	30	35	33	28	25	70
Shield + cystamine	100	44	44	34	33	75

[1] X-rays, 900 R.

[2] Protective substances given intraperitoneally 10 min before irradiation.

[3] Shin shielded with lead plate 5-mm thick.

in varying degrees during all manned Soviet and US space flights. However, all the flights have been relatively brief, and have occurred under favorable radiation conditions. Data on radiation safety for previous space flights can be found in the literature. Radiation hazards in future space flights will be quite different.

THERAPY FOR SPACEFLIGHT RADIATION DAMAGE

Pharmacochemical, biological, and local protection (partial shielding of individual radiation-sensitive organs) can greatly reduce the damaging influence of radiation, decrease the severity of radiation sickness, and save lives. None of these methods can completely prevent development of the pathologic process resulting from exposure to penetrating radiation. Therefore, anyone subjected to radiation (particularly during long flights, solar flares, and long periods spent in the natural and artificial radiation belts of Earth) will require treatment regardless of the protective measures used. The effectiveness of the therapy, however, will be greater for those who have had protection.

Since no single, specific method of treating radiation sickness exists (nor is one likely to be found), combined therapy must be used [2, 13, 16, 30, 36, 37, 42, 50, 77, 78, 113].

The principles upon which any given plan of combined therapy are based are determined by the present concept of the primary pathogenic mechanisms operative in the development of radiation sickness, and by the extent of individual symptoms. Therefore, therapeutic measures must be directed primarily toward helping the patient to survive the initial reaction, supplementing and restoring the disrupted activity of hematopoietic organs, and preventing or treating infectious complications and hemorrhaging. Combined therapy should also include symptomatic treatment

TABLE 14.—*Survival Rate of Irradiated*[1] *Rats Protected by Combined Use of Shielding and Cystamine or Cystamine plus AET* [85]

Type of protection	Rats, no.	Survival rate		Mean survival time of rats that died, d
		Absolute	%	
Control radiation	138	1	0.7 ± 0.7	8.1 ± 0.2
Abdomen shielded [2]	137	37	27.0 ± 3.8	12.9 ± 0.5
Cystamine + AET (50 mg/kg each)	17	12	70.6 ± 11.1	21.2 ± 3.3
Cystamine + AET (50 mg/kg each) + shielded abdomen	21	20	95.2 ± 4.7 [3]	12.0
Cystamine + AET (25 mg/kg each)	48	3	6.3 ± 3.5	10.2 ± 0.6
Cystamine + AET (25 mg/kg each) + shielded abdomen	48	29	60.4 ± 7.1 [4]	18.6 ± 1.4
Cystamine (50 mg/kg)	60	2	3.3 ± 2.3	10.3 ± 0.5
Cystamine (50 mg/kg) + shielded abdomen	60	38	63.3 ± 6.2 [4]	15.7 ± 1.5
Cystamine (25 mg/kg)	113	3	2.7 ± 1.5	9.5 ± 0.3
Cystamine (25 mg/kg) + shielded abdomen	120	59	49.1 ± 4.6	12.9 ± 0.6

[1] γ-Radiation, 1000 rad.

[2] Shield 2-cm wide, 3-cm thick.

[3] Difference statistically reliable only for abdomen shielding.

[4] Difference statistically reliable for abdomen shielding and for protective substances in same dose.

directed toward maintaining and improving the functioning of all organs and systems damaged in any way during acute radiation sickness.

Treatment given during the initial reaction can be reduced to measures which decrease the extent of the dyspeptic syndrome. These may include administration of antihistamines and antinauseants, as well as multivitamins. There are no effective substances as yet to halt destruction of hematopoietic tissue or assure more rapid development of the tissue's recuperative processes.

Transplantation of autologous or homologous bone marrow, use of DNA and RNA preparations, and transfusion of formed elements of the peripheral blood are impossible under space conditions, even if the crew includes a doctor. Nor can it be stated yet with certainty that these methods should be used, even on the Earth, as a part of the combined therapy for radiation sickness.

Complications developing from infections can be serious in radiation sickness, and are one of the primary causes of death. Broad-spectrum antibiotics, used in large doses, are effective in combating such complications, as many experimental studies and clinical observations have proved [36]. To prevent secondary infection of an irradiated crewmember, it is necessary to isolate him as fully as possible from the rest of the crew.

Sulfanilamide compounds, such as phthalylsulfathiazole, are good for suppression of still-inactive, endogenous, gastrointestinal microflora. There is no unanimous opinion as to the indications for antibacterial therapy in acute radiation sickness, nor when such therapy should be started. Some authors recommend that antibiotics be administered as soon as possible; others recommend that antibiotics be taken only after the number of leukocytes in the peripheral blood drops to 1000 or less.

Hemorrhaging is treated with substances that decrease the permeability of the vascular wall and influence individual phases of blood coagulation. Patients are given ascorbic acid, calcium chloride and calcium gluconate, rutin, citrin, serotonin perparations, fibrinogen, and ϵ-aminocaproic acid. According to the observations of

TABLE 15. —*Survival Rate of γ-Irradiated Rats Protected by Combined Use of Shielding and Cystamine or 5-Methoxytryptamine* [85]

Radiation and dose rate	Type of protection	Animals, no.	Survival rate		Mean survival time of rats that died, d
			Absolute	%	
1000 R 10.7–13.5 R/min	Control radiation	72	0	0	8.2 ± 0.3
	Abdomen shielded	66	20	30.3 ± 5.7	13.4 ± 0.8
	Head shielded	29	3		
	Cystamine (50 mg/kg)	60	2	3.3 ± 2.3	10.3 ± 0.5
	Cystamine (50 mg/kg) + abdomen shielded	30	24	80.0 ± 7.34	14.2 ± 2.7
	Cystamine (50 mg/kg) + head shielded	39	32	82.1 ± 6.1 [1]	15.7 ± 3.2
925–945 R 33.7–38.8 R/min	Control radiation	60	0	0	5.7 ± 0.3
	Abdomen shielded	48	8	16.7 ± 5.4	14.1 ± 1.0
	Head shielded	48	6	12.5 ± 4.8	6.2 ± 0.7
	Cystamine (25 mg/kg)	36	0	0	8.8 ± 0.4
	Cystamine (25 mg/kg) + abdomen shielded	36	17	47.2 ± 8.3 [1]	13.4 ± 1.3
	Cystamine (25 mg/kg) + head shielded	36	16	44.4 ± 8.3 [1]	10.8 ± 1.5
	5-methoxytryptamine (5–6 mg/kg)	54	2	3.7 ± 2.6	8.8 ± 0.6
	5-methoxytryptamine (5–6 mg/kg) + head shielded	52	19	36.5 ± 6.7 [2]	10.0 ± 1.2
	5-methoxytryptamine (5–6 mg/kg) + abdomen shielded	60	46	76.5 ± 5.5 [2]	16.3 ± 1.8

[1] Difference statistically reliable for cystamine and shielding of head or abdomen.

[2] Difference statistically reliable for 5-methoxytryptamine and shielding of head or abdomen.

clinicians, ε-aminocaproic acid is the most effective of these substances.

Daily scheduling of therapy and complete nutrition are vital in the treatment of radiation sickness. The food should be appetizing and rich in protein, with proper distribution of the primary ingredients. For severely ill patients, it is particularly important that aseptic conditions be maintained, that the skin and mucous membranes be well-cared for, and that the ordinary hygienic procedures be carefully performed.

Data from experiments in which large laboratory animals (dogs and apes) were used indicate that even a very simple plan of combined therapy—consisting of antibiotics and multivitamins, with proper care and nutrition—has a good therapeutic effect. The survival rate of treated animals, after irradiation at LD 75%–90% is 40%–55% higher than that of the controls.

The extent of treatment which can be given during flight depends largely on the availability of a doctor. If there is no physician among the crew, the best that can be hoped for is qualified first aid (self and mutual). The astronauts, using well-defined instructions, can apply a simple plan of combined therapy, consisting of the use of vitamins and antibacterial substances, particularly if these do not require parenteral injection.

If there is a doctor in the crew, the use of combined therapeutic measures, particularly a relatively simplified plan, is quite possible. However, the antiradiation substances included in the onboard medical kit must be tested during flight preparations on the ground. Many of the preparations may cause allergic reactions of varying severity, and it is quite difficult to cope with an allergic reaction in space.

In view of the continuing progress of pharmacotherapy (the development of new transfusion preparations, antibacterial and other substances, and new methods of application), it is hardly wise to make specific recommendations or give instructions for treatment of acute radiation sickness. This author, therefore, has limited himself to a presentation of general principles. Specific preparations and instructions for their application can lose their practical significance quite rapidly, while general principles will scarcely change significantly in the next 5–6 years.

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Chapter 12

MEDICAL CARE OF SPACECREWS (MEDICAL CARE, EQUIPMENT, AND PROPHYLAXIS)[1]

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The dispensable lower half of the first lunar landing craft bears an inscribed plaque which declares for ages to come, that in A.D. July 1969, men from the planet Earth first set foot upon the Moon. The plaque is a testament to human vision, daring, and determination. Enormous numbers of people in the United States and throughout the world made possible that historic mission as well as those which preceded and followed it. The first lunar landing was the 33rd in a series of manned space flights that began when cosmonaut Yuri Gagarin first demonstrated that humans could survive and function in space. Before any of those who flew were committed to spaceflight missions, and before future personnel can be committed to similar or more extensive missions, their physical well-being must be insured. Those who are implementing the science of aerospace medicine are responsible for providing these guarantees.

Aerospace medicine is principally preventive medicine. Its practitioners must anticipate, insofar as possible, every physiologic consequence of exposure to the spaceflight environment. They must prevent those physiologic problems which can be anticipated and treat any that arise. Such a program is broad in scope, involving preflight, in-flight, and postflight phases. While it may not always be possible to prevent every illness or injury to space crewmen, any which occur must be viewed by aerospace medicine practitioners as failures in preventive medicine. Such failures may then be precluded in future spaceflight by a failure-analysis approach, such as that employed by engineers in analyzing the structural or performance failures of spacecraft and spacecraft systems.

This chapter reviews current thinking in both the US and USSR regarding therapeutic and prophylactic treatment of spacecrews.

A definition of the aim and purpose of aerospace medical prophylaxis and treatment in the Soviet Union was provided by Terent'yev and Krupina [37] which expresses equally well the US concept of the science. They suggest that prophylaxis and treatment must involve a system of procedures directed at preserving the health of spacecrews and maintaining their work ability at a high level. The preventive aspects of such a program must preclude illness, trauma, toxic hazards, and radiation damage, as well as other functional disturbances that might be produced by spaceflight factors. The program must provide for timely diagnosis of disorders in spacecrews and effective treatment required by

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[1] The contributions of the Soviet authors V. G. Terent'yev and T. N. Krupina are gratefully acknowledged as are those of C. A. Jernigan, W. J. Frome, and B. C. Wooley. These authors prepared preliminary materials on which the current chapter was based in part.

a crew during flight preparation, during the flight itself, and after return to Earth. The same authors described steps in a comprehensive medical prophylactic program for spaceflight application as follows:

- Preflight procedures
  - discovery of latent illnesses and insufficiencies of compensatory mechanisms in the human organism during selection and preparation for flight;
  - preflight sanitation, execution of quarantine or observational and other antiepidemic measures;
  - preventive operational interventions;
  - determination of individual sensitivity to medicines.
- In-flight procedures
  - prophylactic, diagnostic, and medical procedures aboard the spacecraft during flight;
  - preparation for and execution of evacuation to Earth;
  - execution of medical procedures designed to increase resistance of the human organism to the effects of flight factors during launching and landing (splashdown).
- Postflight procedures
  - medical observation and medical assistance to the crewmembers after the flight;
  - organization and execution of quarantine and observational procedures after flights to other planets;
  - medical observation of crewmen and developing measures for rapid readaptation of crewmembers postflight.

This chapter will discuss problems and procedures relevant to treatment and prevention of the physiologic problems of spacecrews in each of these phases of a spaceflight program.

PREFLIGHT PROCEDURES

The procedures performed preflight have insured improved performance of flight tasks and, with rare exceptions, have prevented the outbreak of illness in-flight. This outcome has been, in part, the result of medical screening and selection programs designed to provide physically competent crews and determine their sensitivity to medications. Observation and semi-isolation programs have also helped to detect any latent ailments that might produce frank symptoms in-flight and limit the chance of preflight infection. During this period, also, efforts have been made recently to insure sufficiently high levels of dietary potassium to preclude potassium deficit and its consequences in-flight. Finally, a training course for US astronauts acquaints them with spaceflight stresses and their effects on the human organism so that crewmen may recognize any abnormalities in their health status and understand therapeutic measures which may be prescribed in-flight.

Medical Screening/Selection

The best medical care is preventive care. Perhaps this is more true for a select group such as astronauts than for most other groups. Good preventive care in a group chosen for a particular job begins with medical selection. Standards for astronauts are intended to identify:

1. Individuals physically capable of performing astronaut duties, specifically those who possess the necessary physical and psychomotor capabilities and who are not subject to incapacitating physiologic disturbances when exposed to various spaceflight stresses.
2. Individuals free of underlying physical defects or disease processes that could shorten their useful careers.

The original Project Mercury astronauts were carefully preselected from some 500 military test pilots. Of this original group, 33 were selected for detailed evaluation after screening their careers, medical records, and interviews. The 33 candidates were then examined in a $7\frac{1}{2}$-d protocol at the Lovelace Foundation Clinic at Albuquerque, N. Mex. This very detailed examination included history taking (both aviation and medical), laboratory tests, physical and radiographic examinations, and physical competence and ventilatory efficiency tests. After completion of these tests, the candidates reported to the US Air Force Research and Development Command's Aerospace Medical Laboratory at Wright-Patterson Air Force Base, Ohio, for stress testing.

Stress tolerances were determined for thermal flux, acceleration forces, low barometric pressure, pressure-suit protection, isolation, and confinement. Seven astronauts were selected from the 33 candidates.

Two of these seven men subsequently developed significant medical problems. Shortly after selection, one had recurrent atrial fibrillation and was, at that time, disqualified for space flight. The second man successfully completed the first US manned suborbital ballistic flight, but was later disqualified for 5 years because of onset of Ménière's disease. His first labyrinthine symptoms occurred 3 years after the suborbital flight. However, no evidence indicates that spaceflight exposure contributed in any way to development of the syndrome. The Ménière's symptomatology was relieved by an endolymphatic shunt procedure, and the astronaut later successfully completed a lunar exploration mission. While more extensive cardiac function data might have detected the first problem prior to selection, not enough is understood about the development of Ménière's disease to postulate any selection techniques which would have predicted this problem.

Subsequent groups of US astronauts have been selected by techniques which varied only slightly from those applied to the first seven. The standards used closely approximated US Air Force Flying Class I Standards, except in the selection of scientist-astronauts, where it was necessary to relax the visual standards to qualify a sufficient number of candidates. Examinations have been performed at the US Air Force School of Aerospace Medicine, Brooks AFB, Tex., with findings later evaluated by the NASA Manned Spacecraft Medical Directorate. Between 1959 and 1967, 225 astronaut candidates were examined and 66 selected. Table 1 lists the disqualifying diagnoses.

Components of the examination used in medical selection of the group of astronauts chosen in 1967 were:

1. Medical history and review of systems
2. Physical examination
3. Electrocardiographic examinations, including routine ECG studies at rest, during hyperventilation, carotid massage, and breath-holding; a double Master's exercise-tolerance test, cold pressor test, and precordial map
4. Treadmill exercise-tolerance test
5. Vectorcardiographic study
6. Phonocardiographic study
7. Tilt-table studies
8. Pulmonary function studies
9. Radiographic studies, including cholecystograms, upper GI series, lumbosacral spine, chest, cervical spine, and skull films
10. Body-composition study, using tritium dilution
11. Laboratory examinations including complete hematology workup, urinalysis, serologic test, glucose-tolerance test, acid alkaline phosphatase, BUN, sodium, potassium, bicarbonate, chloride, calcium, phosphorus, magnesium, uric acid, bilirubin (direct and indirect), thymol turbidity, cephalin flocculation, SGOT, SGPT, total protein with albumin and globulin, separate determinations of α_1-, α_2-, β-, and γ-globulins, protein-bound iodine, creatinine, cholesterol, total lipids and phospholipids, hydroxyproline, and RBC intracellular sodium and potassium. Stool specimens were examined for occult blood and microscopically for ova and parasites. A urine culture for bacterial growth was made, and a 24-h specimen analyzed for 17-ketosteroids and 17-hydroxycorticosteroids
12. Detailed examination of sinuses, larynx, and eustachian tubes
13. Vestibular studies
14. Diagnostic hearing tests
15. Visual fields and special eye examinations
16. General surgical evaluation
17. Proctosigmoidoscopy
18. Dental examination
19. Neurological examination
20. Psychologic summary, including Wechsler Adult Intelligence Test, Bender Visual-Motor Gestalt Test, Rorschach Test, Thematic Apperception Test, Draw-A-Person Test, Gordon Personal Profile, Edwards' Personal Preference Schedule, Miller Analogies Test, and Performance Testing [35, 42]
21. Electroencephalographic (EEG) studies
22. Centrifuge testing

Only one astronaut from the five groups selected after the Mercury program has been permanently disqualified because of physical problems. This individual developed aspirin asthma which progressed to moderately severe pulmonary disability. Temporary disqualifying conditions will be discussed in later sections.

In the Soviet Union, cosmonaut selection is in three stages: initial ambulatory selection; stationary examination[2] in specialized medical areas; and screening during the first months of professional activity [7]. The first stage involves

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[2] A term meaning the subject is at rest.

identifying those who have definite contraindications for flight. In the initial examination, the dropout rate is high. The main reasons for failure are ailments of the otolaryngological organs, as well as internal diseases, primarily neurocirculatory dystonia and vestibular-vegetative instability.

A stationary medical examination provides a very careful, complex examination for latent pathology. In this stage, the principal causes for failure are: ailments of internal organs (about half the unsuccessful candidates), vestibular-vegetative instability, ailments of otolaryngologic organs, anomalies of development, and degenerative changes in the spine.

In the ambulatory examination, the dropout rate due to vestibular disturbances decreases considerably. To study the barofunction[3] of the ear, Soviet investigators have widely used a simulated "descent from high altitude" in a pressure chamber.

Professional cosmonaut activity is reported to cause functional changes in some individuals. About 10% have been pronounced unsuitable at this stage of the selection process [7].

Health Stabilization

Preflight exposure to communicable disease, with subsequent development of symptoms inflight, has been recognized as potentially hazardous from the beginning of the US space program. Total isolation of flightcrews prior to launch has indisputable advantages, but has been rejected because of operational difficulties: flightcrews are required to be in contact with great numbers of people and move from place to place during the last few weeks of training for space flight. However, physiologic problems of operational significance noted during the preflight period for missions of Apollo 9 and 13 made it apparent that some preflight health-stabilization program was imperative.

The purpose of the Flight Crew Health-Stabilization Program is to minimize or eliminate adverse alterations in the health of flightcrews during the immediate preflight, flight, and postflight periods. The elements of the program are shown in Figure 1. Each component warrants discussion in terms of its use in Apollo and subsequent missions.

TABLE 1.—*Disqualifying Diagnoses Among Astronaut Candidates, 1959–1967* (*N* =*225*)

Diagnosis	No. cases
Visual system	
Blepharitis	1
Cataracts	1
Defective color vision	1
Glaucoma suspected	3
Miscellaneous abnormalities	16
GI disorders	
Duodenal ulcer	3
Diverticulitis of colon	1
Rectal bleeding	1
Rectal polyps	2
Genitourinary disorders	
Bladder neck contracture	1
Renal calculus	3
Pyelonephrosis	1
Hydronephrosis	1
Prostatitis, chronic	1
Testicular prosthesis, air-containing	1
Pyuria	1
Ear, Nose, and Throat	
Sinusitis, chronic	11
Tonsillitis, chronic	2
Recurrent URI	1
Allergic rhinitis	1
Hearing loss	1
Acoustic nerve degeneration	1
Hernias	8
Hypercholesteremia	1
Abnormal glucose-tolerance test	3
Hyperparathyroidism	1
Asthma	1
Migraine	5
Polyps of gallbladder	1
Cholelithiasis	1
Splenomegaly	1
Chronic liver disease	1
Lymphoma	1
Neoplasm of duodenum	1
Polio residual	1
Traumatic amputation, terminal phalanx, thumb	1
ECG abnormality	2
Aortic valvular insufficiency	2
Chronic periodontal disease	1
Psychiatric unsuitability	5
Abnormal EEG	1
Epilepsy	1

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[3] The capacity to equilibrate the pressure on both sides of the tympanic membrane: a test for permeability of the eustachian tubes.

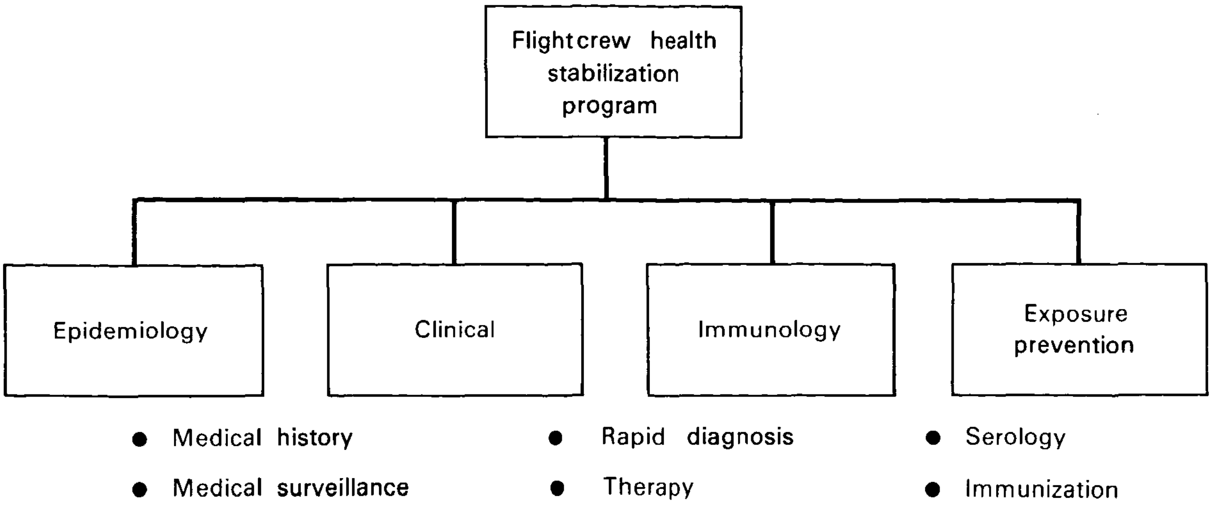

FIGURE 1.—Flightcrew health stabilization program.

Clinical medicine. Since it is critical that all astronauts be maintained in good health, a clinical medicine program is provided for US crewmembers and their families. This health program is initiated immediately upon selection of flight crewmembers and continues as long as they are on flight status. It provides both routine and emergency physical examinations. Rapid diagnosis and prompt effective treatment of any disease in crewmembers or their families are provided. Complete virologic, bacteriologic, immunologic, serologic, and biochemical studies at the NASA Lyndon B. Johnson Space Center are available.

Immunology. Ideally, crewmembers and their families would be immunized against all disease agents; however, the number of diseases for which there are satisfactory immunizations is extremely limited. Indeed, immunizations are not available for the most likely illnesses—viral and bacterial infections of the upper respiratory and GI tracts. The immunizations listed in Table 2 are those currently administered. These were selected after careful review of all known immunizations by NASA medical personnel and a microbiology advisory committee of the National Academy of Sciences. Other immunizations were excluded due to: (1) questionable effectiveness; (2) traumatic side effects; and (3) low probability of exposure. Serologic tests are conducted to determine immunity levels prior to immunizations. Tuberculin skin tests are given and serologic tests are performed for tetanus, syphilis, typhoid, mumps, polio, rubella, rubeola, and yellow fever.

Exposure Prevention

Prevention of exposure to disease is the most important aspect of a successful preventive medicine program. If exposure to infectious diseases is not minimized or eliminated, the program will not be successful, regardless of the effectiveness of all other aspects combined.

TABLE 2.—*Immunization Requirements*

Disease	Astronaut	Astronauts' children[1]
Diphtheria	Req.	Req.
Pertussis		Req.
Tetanus	Req.	Req.
Typhoid	Req.	
Influenza	Req.	
Mumps	Conditionally req.[2]	Req.
Polio	Req.	Req.
Rubella	Conditionally req.	Req.
Rubeola	Conditionally req.	Req.
Smallpox	Req.	Req.
Yellow fever	Req.	

[1] Astronauts' children received additional immunization only as indicated for diseases endemic to specific travel areas and as recommended by US Public Health Service/American Public Health Association for their age group.

[2] Immunize if no serologic response.

Diseases can be transmitted by fomites (contaminated inanimate objects), contaminated consumables (e.g., air, food, and water), and personal contacts. Fomites are probably the least important source of infectious diseases. Nevertheless, precautions are taken, such as separate headsets and microphones for crewmembers. Contaminated consumables pose a greater threat. To prevent transmission of an infectious disease through the air, a closely controlled living environment is provided during the prelaunch period.

All areas where crewmembers reside or work are equipped with ultrahigh efficiency bacterial filters in all air supply ducts. This precludes exposure to microbial agents from adjacent, nonmedically controlled areas and individuals. Air-conditioning systems are also balanced to provide positive air pressure in areas inhabited by crewmembers, relative to areas outside. Air leakage around windows, doors, floors, walls, and ceilings is directed outward rather than inward toward crewmembers.

The food which will eventually be consumed by flight crewmembers is a source of potentially infectious microorganisms. As a precaution, no set or publicized pattern of food procurement is established. Food procurement is supervised by members of the medical team. Portions of each food lot are subjected to microbiologic evaluations, and all food preparation areas are inspected daily for cleanliness. Drinking water sources are limited to drinking fountains provided in quarters and working areas. Water samples are taken daily from all areas visited by crewmembers and subjected to microbiologic evaluations.

The most important means of preventing exposure of the crew to infectious disease is to minimize personal contacts during the critical 21-day preflight period. Areas which may be visited by crewmembers are strictly limited and the number of individuals who may have contact with crewmembers is limited to slightly over 100 with mission-related responsibilities. A medical surveillance program of primary contacts insures that those who do have contact with the flight crewmembers present a low probability of disease transmission. Crewmembers are also isolated from potentially infected carriers such as transient populations (launch-site visitors), high-incidence groups (children), and uncontrolled contacts (maintenance and other personnel about whom no medical information is known). Launch-site visitors from throughout the US and from many foreign nations carry microflora significantly different from those to which the astronauts are normally exposed. Since children are the most common carriers and transmitters of upper respiratory and GI infections, astronauts are isolated from their children. The need for this measure was borne out by epidemiologic data obtained during initial implementation of the health-stabilization program in support of the Apollo 14 mission.

An exposure-prevention program may be implemented in several ways. Building facilities to house crews and primary contacts for the prelaunch period, or modifying existing ones, are effective approaches, but prohibitive economically. The solution adopted now provides for strict isolation of flight crewmembers (both prime and backup) in crew quarters, and limiting their contacts to medically approved individuals. Such individuals are permitted to maintain residence at home, but their health status is constantly monitored to minimize the possibility of their exposing flight crewmembers to infectious diseases. This monitoring of primary contacts led to the epidemiologic surveillance program.

Epidemiologic Surveillance

The medical surveillance program, which is initiated 3 months prior to launch, begins with compiling medical histories and other critical information from each primary contact. Each one is then subjected to an extensive physical examination about 60 days prior to launch, and microbiologic samples identify carriers. Based on this information, certain individuals are medically approved for access to flight crewmembers during the 21-day prelaunch period.

Each primary contact and all his family are subjected to medical surveillance during the F–21 prelaunch period. Primary contacts are instructed to report to the medical examination facility whenever they or any of their family become ill or have been exposed to infectious diseases. Reports of illness are also obtained from all schools attended by children of astronauts or primary contacts. Daily school reports provide data on all student absences, including children of crewmembers or primary contacts. (Approximately 30% of the illnesses in primary contacts have occurred previously in one or more members of their families.) Daily reports from public health authorities in the launch site area also determine trends and incidence of specific diseases within the population where primary contacts may be exposed.

A computerized data-processing system has been developed to maintain complete and up-to-date records on all crewmembers, primary contacts, and their families. The system links the medical laboratories at NASA Lyndon B. Johnson Space Center in Houston, Tex., with the Medical Surveillance Office at the Cape Kennedy launch site. With this system, medical information on any individual can be made available immediately. This program was first implemented in support of the Apollo 14 mission and has operated successfully since. As missions become longer and infectious disease poses a greater threat, a stricter isolation program may be needed.

To prevent respiratory and adenoviral diseases, the Soviets have found it adequate to limit service personnel contact with cosmonauts to 1 week prior to flight, perform daily examinations, relieve of their responsibilities those who become ill or appear to be becoming ill, use protective measures, and constantly disinfect the area [37].

Preflight Medical Examinations

Physical examinations of flight crewmembers conducted in the month prior to launch are intended to detect any medical problems preflight that might require remedial or preventive intervention and provide a baseline for postflight comparison. The physical examination profile for the crew of Apollo 14 is representative of the preflight physical examination format used in the US space program:

> Preliminary examination at F − 27 d. Interval history, vital signs, and general physical examination.
>
> Interim examination at F − 15 d. General physical, vital signs, and dental examination.
>
> Comprehensive examination at F − 5 d. Interval history. Detailed physical examination to include height and weight, audiometry, near and distant visual acuity, near point accommodation, visual fields, standard 12-lead ECG, chest x-ray, rectal examination, detailed neurologic examination, and photographs of significant skin areas.
>
> Cursory examination at F − 4 to F − 0 d. Brief physical examination and history, daily vital signs (weight on F − 0).

The preliminary physical examination, which was conducted 27 d prior to flight for the Apollo 14 crew, must be performed not before 30 days and not after 21 days prior to lift-off, to permit time for evaluation, and to take preventive or remedial measures for any new health problems. A comprehensive examination is performed within 5 d of launch to document accurately the physical status of each crewmember at mission onset. The final examination prior to flight includes recording weights and vital signs under standardized conditions to provide a reliable basis for postflight comparisons.

Dietary Potassium Control

Another preflight measure, adopted after the observation of cardiac arrhythmias in the Apollo 15 crew, is the strict control of preflight diet to insure a sufficiently high potassium intake. A diet high in potassium provides that no crewmember begins his mission with a potassium deficit, a precautionary measure first taken during the Apollo 16 mission when such diets were provided for 72 h prior to launch. Potassium supplements are also taken in-flight (105 meq versus a normal of 70 in the command module diet, and 135 meq in the lunar module diet). These procedures, coupled with improved work-rest schedules, seemed to prevent a recurrence of the cardiac arrhythmias in the Apollo 16 crew which were experienced in the Apollo 15 crew. Similar measures used for Apollo 17 crewmen were not equally successful in preventing potassium deficits but the physiologic problems attributed to these deficits did not recur.

Table 3 lists preflight medical problems noted in conjunction with the Apollo missions, including etiology, where identifiable, and the number of occurrences of each symptom or finding.

Medication Sensitivity Testing

Medication sensitivity testing is to determine the response of flight crewmembers to each item in the medical kit carried aboard, to preclude allergic reactions and other undesirable side effects. Each US crewmember is tested under controlled conditions. (The medical kit is described in the section where in-flight items and procedures are discussed.) After a physician takes a medical history concerning every crewmember's experience with each medication under test, and it has been determined that (1) no adverse reaction has been experienced, and (2) there is no evidence of impaired health at the time of testing, the medication is administered to the astronaut-subject. The crewmember is observed by the physician for an appropriate period following administration of the medication, and is queried about subjective responses. If positive subjective findings are reported, the test is either repeated with a double-blind placebo method, or an appropriate drug is substituted for which no undesirable side effects have been reported. Individuals are also tested for any allergic reaction to the biosensor electrode paste.

Soviet cosmonauts are tested similarly for medicinal sensitivity. Parin et al [28] recommended that the individual's sensitivity to medication be determined both during rest and with flight factor simulation, in order to study the effects of medications during changes in the organism's reactivity. They further suggest that when some medicine is necessary in-flight, it is most advantageous for the cosmonaut to test his ability to withstand the preparation, by taking only one-fifth or one-fourth of the full dose. If no exaggerated or paradoxical reaction is observed after 30–45 min, the cosmonaut can consider it safe to take the full dose. If he has an allergic reaction, appropriate medicine must be provided in the kit to overcome these complications; the cosmonaut must be able to identify these medicines and use them correctly. Finally, Parin and colleagues note, when assembling medicine chests, it should be taken into account that there will be changes in the organism's reactivity to medicines, as a result of certain flight factors.

Table 4 shows drug administration and observation constraints applied in the US space program. All medications used are treated in a similar fashion.

Medical Training

A space crewman must understand the interaction of spaceflight stresses and their effects on the human organism, and how the body adapts to spaceflight effects, to be properly equipped for his job. The crewman should also be able to recognize any abnormalities in his health status and be aware of therapeutic measures prescribed for in-flight problems.

In 1970, Yaroshenko and Terent'yev [43] stated that medical preparation of cosmonauts must include sufficient training for necessary medical self-help. This training should include the necessary minimum knowledge of anatomic and physiologic matters, difficulties and ailments that may arise on long space flights as well as their differential diagnoses, and (as noted previously) the effects of available medications onboard.

Medical training for US Gemini and Apollo crews began shortly after selection of spacecrews, with classes on spaceflight physiology and therapeutics. The curriculum studied by the astronauts selected in 1967 illustrates the scope of this training program; it encompassed 16 h instruction provided by experts in each area.

> *Cardiovascular system.* Brief outline of anatomy and physiology, methods of observing and monitoring cardiac activity, system response to acceleration, weightlessness, work and other stresses, functional testing such as tilt-table, lower body negative pressure (LBNP), bicycle, treadmill systems.
>
> *Pulmonary system.* Brief outline of anatomy and physiology, pulmonary function, gas exchange, problems related to hypo- and hyperbaric environments, physiologic limits of spacecraft atmospheres, contemplated atmospheres for future vehicles, respiratory response to acceleration, weightlessness, and

work, physical conditioning and testing, respiratory capacity.

Hematology and laboratory medicine. Review of Mercury and Gemini findings involving blood elements and chemistries, review of present programs scheduled for Apollo and Skylab programs, illustration of the need to establish good baseline data, controls and possible expansion of the present program.

Human engineering and human factors as applied to Apollo programs. Familiarization with pressurized full pressure suit operations in both lunar module and with simulated lunar surface activities; practice with lunar surface tools and stowage equipment; $^1/_6$-G familiarization sessions in KC–135 aircraft flights.

Role of psychiatry in crew selection. Crew and dependents support, personal considerations of long-term confinement, group dynamics, and responses to various stresses encountered in-flight and on the ground.

Description of vestibular apparatus. Its function, equilibrium, and testing thereof; response of vestibular system to acceleration, weightlessness; flight experiments in Gemini; and planning for Apollo and Skylab programs.

Visual apparatus. Brief description of anatomy and physiology, relationships to other sensory organs, effects of acceleration and weightlessness on eye and visual system, problems in space, such as light, ultraviolet, trauma, high closing speeds, and depth perception without reference points.

Refresher courses are required of each astronaut every third year in the technical and practical aspects of altitude physiology and medical aspects of survival. Before each mission, a detailed medical briefing provides a review of the medical experiments and procedures to be performed before, during, and after a given mission; medical kit items and their use; and reporting and consulting procedures for the in-flight period.

The US Skylab crews were the best medically trained of any US spacecrews. Astronauts received intensive medical training (at Sheppard Air Force Base, Texas) which was to prepare them to observe symptoms, take histories, and treat medical problems in consultation with ground-based physicians. The training was, in a sense, an abbreviated version of that given medical students. Instruction in diseases of skin, eye, and head, and in cardiovascular, pulmonary, abdominal, and musculoskeletal systems, was provided by physicians specialized in each given area. By using checklists, astronauts were able to treat physical problems as simple as athlete's foot or as complex as tracheotomy. The latter procedure has been simplified by an instrument that makes an incision and inserts a tracheotomy button in one step. Special instruction was also provided in dental equipment and oral surgery. Crews were trained in such procedures as catheterization of the urinary bladder, nasogastric intubation, splinting, and bandaging.

The more complicated procedures, for example, catheterization, were under the direction of ground-based physicians. Simpler procedures were conducted by astronauts on their initiative without help from the ground. The training schedule was intensive, with all aspects covered in a 3-day program.

Ongoing Medical Care

Space crewmen retained on flying status after selection assumes great importance for a number of reasons; not least is the amount of money invested in training such individuals. Consequently, comprehensive health care is presently provided all US astronauts and their families through a preventive, diagnostic, and therapeutic program managed by the NASA Lyndon B. Johnson Space Center, Flight Medicine Branch, aided by many civilian and military consultants. Care of the family by the same physicians tending the astronauts provides an understanding of the total milieu in which the astronaut lives and functions.

Astronauts are encouraged to report all illnesses and injuries for evaluation and treatment. Once a year, during their birthday month, they are given a thorough physical examination whether or not on active duty. Astronauts form a unique group; they have been exposed to environmental factors never before experienced by man, and others to which men have been exposed but not in the same combination or sequence. They present an opportunity for

TABLE 3.—*Preflight Medical Problems in Apollo Mission Crews*

Symptons, findings	Etiology	No. occurrences
Abrasions	Sensor attachment, pressure suit	2
Blister, left toe	Undetermined	1
Callouses, scapulae and iliac crests	Pressure suit	1
Caries, dental		1
Cellulitis, hand	Laceration	1
Conjunctival injection	Dry air of suited EVA practice	1
	Undetermined	2
Dermatitis, face, scalp,	Seborrhea	2
circumanal	Pressure suit	1
Dermatophytosis, feet	Undetermined	2
Folliculitis, abdomen	Undetermined	1
Furunculosis	Undetermined	2
Gastroenteritis	Undetermined	4
	Salmonellosis (walnut meats)	2
	Viral infection	1
Gingival burn	Ingestion of hot food	1
Hematoma, iliac crests	Pressure suit	1
upper arms	Pressure suit	1
legs	Surfboard	1
Inflammation, medial canthus, right eye	Undetermined	1
Influenza syndrome with secondary gastroenteritis	Undetermined	2
	Viral	1
Keratitic plaque	Undetermined	1
Lesion, right buccal mucosa	Cheek biting	1
	Herpes	1
Lymphoid hyperplasia, posterior pharynx	Probable viral syndrome	3
Micropyuria	*Haemophilus*	2
	Undetermined	2
Facial redness, swelling	Undetermined	4
Papules/pustules	Mosquito bites, torso & legs	5
Paronychia	Bacterial infection	1
Pharyngitis	Undetermined	1
	Viral	2
Pulpitis, tooth no. 31	Previous restoration and caries	1
Prostatitis		1
Tinea cruris	Undetermined	1
pedis	Undetermined	1
Tympanic membrane infection	Viral syndrome	1
Rash, facial	Seborrhea	2
Rhinitis	Probably viral	1
Rhinitis and pharyngitis	Herpes simplex	2
Ringworm, arm	*Microsporum canis*	1
Strep throat	β-hemolytic streptococcus	1
Sunburn, face & torso		2
Ulcer, aphthous	Undetermined	2
Urinary infection, mild	Undetermined	5
	Viral	3

TABLE 4.—*Typical Pharmacological Agent Administration and Observation Constraints*

Item	Route of administration	Frequency of observation by physician	Constraints
Demerol	IM 1/4 dose (25 mg)	0–15 min; 2nd h; 4th h	No flying, driving, or other hazardous pursuit for 8 h
Scopolamine and Dexedrine	0.3 mg (scopolamine) and Oral 5.0 mg (Dexedrine)	1 h and 4 h or immediately upon development of any reaction	Not within 4–6 h planned sleep
Darvon	Oral (6 mg)	One time within 4 h or immediately on development of any reaction	No flying or driving within 6 h
A.S.A.	Oral (300 mg)	One time within 4 h or immediately on development of any reaction	None
Tetracycline	Oral (250 mg)	Within 4 h or immediately on development of any reaction	Not within 24 h of stool collection for microbiology
Marezine	Oral (50 mg)	Within 4 h or immediately on development of any reaction	No flying or driving for 8 h
Ophthaine	Topical	On application	None
Ponaris	Topical	On application	None
Mylicon	Oral	Within 4 h	None
Afrin	Topical	(1) On application (2) 8–12 h or immediately on development of any reaction	None
Electrode paste	Topical	At 48 and 72 h after application	None
Ampicillin	Oral (250 mg)	0–15 min; within 4 h or immediately on development of any reaction	Not within 24 h stool collection for microbiology
Actifed	Oral (60 mg)	One time within 4 h or immediately on development of any reaction	No flying or driving for 8 h
Lomotil	Oral	One time within 4–8 h or immediately on development of any reaction	None
Dexedrine	Oral (5 mg)	2nd h, 4th h, or immediately on development of any reaction	Not within 4–6 h before planned sleep; heart rate to be recorded
Skin cream	Topical	Within 4–6 h or immediately on development of any reaction	None
Methylcellulose eye drops	Topical	On application	None
Neosporin ointment	Topical	On application	None

longitudinal study that must not be bypassed. The components of the annual examination are:

- History, including:
  - Review of medical record
  - Interval history (questionnaire completed by patient and reviewed with him by examining physician)
  - Updating of case index, family history, and immunity index
- Physical examination by a physician, including tonometry performed annually and sigmoidoscopy biannually from ages 35 to 40, and annually thereafter
- Optometric examination
- Audiometry
- Chest and abdomen radiographic examination
- Laboratory examinations, including
  - Urinalysis
  - Hematology
  - Biochemistry
  - Immunology
- Cardiovascular examination, including standard 12-lead ECG, Master's Two-Step and Orthostatic Tolerance Tests
- Cardiopulmonary evaluation, including pulmonary function test
- Dental examination and prophylaxis
- Tuberculin skin test
- Physician critique, findings, and recommendations for treatment or preventive measures.

These periodic medical examinations are valuable for:

> Early detection of disease processes in order that timely corrective action may be taken, longitudinal evaluation of the spaceflight program effects on man, and evaluation of preventive medicine program now in use.

Significant problems detected in annual physical examinations and those brought to the attention of the flight surgeon between such examinations are listed in Tables 5–11.

Dental disease is fundamentally microbiologic in origin, so that part of the dental care program is directed toward studies of oral tissue response in both humans and primates to simulated spacecraft environments. Attention is also directed to the influence of the oral microbial population on general health, either directly or via cross-contamination and to the effect of fluorides (currently used for resistance to dental caries) on bone metabolism and disease. Individuals are barred entry into the US astronaut corps who have severe periodontal diseases or use prostheses which, if lost or broken, would not permit clear enunciation or adequate mastication.

Prediction of Medical Problems

In a comprehensive medical care program for spacecrews, an essential part is reliable prediction of types of medical and psychological problems that might occur in-flight, and severity of reactions to be expected. Efforts have been made to clarify these issues from the inception of the space program in both the US and USSR. Predictive data have been derived from many sources: the general population; small, isolated groups in the Arctic, Antarctic, and aboard submarines; subjects under simulated spaceflight conditions on Earth; and individuals engaged in actual space flight. Although certain factors of the spaceflight environment, for example, acceleration, radiation, and weightlessness, are difficult if not impossible to simulate on Earth,

TABLE 5.—*Infectious Diseases*

Infection	No. cases
Upper respiratory infections	133
Influenza syndrome or viremia	33
Pneumonia	7
Sinusitis	19
Otitis media	1
Otitis externa	6
Gastroenteritis	29
Genitourinary	30
Skin, bacterial	9
Superficial fungal[1]	20
Conjunctivitis	3
Blepharitis	1
Chalazion	3
Herpes zoster	1
Herpes hominis, recurrent	1
Cellulitis and lymphangitis	1
Rubella	1
Tuberculin skin-test conversion[1]	2
Total	300

[1] Detected at annual physical examination.

certain other factors of that environment can be realistically paralleled. Included are prolonged neuropsychiatric stress; deterioration of hygienic conditions; relative hypokinesia, isolation, and sensory deprivation. Under combinations of these conditions, subjects in Earth-based tests have exhibited numerous changes which proved similar in kind, if not in degree, to those noted in spacecrews engaged in the relatively brief space missions accomplished so far. The principal changes noted involve the neuromuscular [5, 21] and cardiovascular systems [4, 7, 8, 31], and alterations in human microflora [4, 15, 23, 30]. Neuropsychic disturbances and reactions observed in individuals in a state of hypokinesia for long periods (tests as long as 100 d in the Soviet Union [1, 14, 22, 38]) have no parallel so far in space flight, but may be important in long-term missions.

Soviet investigators have developed mathematical predictions of in-flight illness based on the types of data described above; they report that these predictors have been essentially verified during long-term experiments, and, to some extent, by short-term space flights [37, 43]. Similar analyses on the likelihood of dental problems predicted by US scientists indicate that dental problems, serious enough to compromise a crewman's efficiency, can be expected every 9000 man-days. Minor problems that would cause minimal inconvenience to the afflicted crewman can be anticipated every 1500 man-days.

Both US and Soviet scientists agree that data for prediction must be considered preliminary and be further refined. A problem compounds the difficulty of predicting spaceflight illness: the possibility that interaction of spaceflight stresses may produce disorders previously unknown. Moreover, unknown space-related factors may further complicate this problem. Efforts are being made to quantify the risks of illness involved in space flight

TABLE 6.—*Neoplasia*

Neoplasm	No. cases
Basal-cell carcinoma	2
Epithelioma	2
Polyp, colon	1
Adenoma, thyroid	1
Fibroma	1
Squamous papilloma, eyelid[1]	1
Total	8

[1] Not detected during annual physical examination.

TABLE 7.—*Hereditary and Metabolic Diseases*

Disease	No. cases
Plasma thromboplastin antecedent deficiency	1
Gout	1
Abnormal glucose tolerance	2
Hypercholesterolemia	1
Hyperlipemia	1
Total	6

TABLE 8.—*Degenerative Disorders*

Disorder	No. cases
Hearing loss	6
Presbyopia	6
Lenticular opacities	3
Vertebral degenerative changes	4
Cervical spondylosis, Brown-Sequard syndrome[1]	1
Degenerative disk disease, early	1
Atrial fibrillation	1
Total	22

[1] Not detected during annual physical examination.

TABLE 9.—*Allergy Problems*

Allergy	No. cases
Angioneurotic edema	1
Urticaria	7
Aspirin asthma	1
Hypersensitivity, ant bite	1
Allergic vasculitis and synovitis	1
Contact dermatitis	3
Drug rash	2
Total	16

NOTE: One individual has had four episodes of urticaria. He is the same individual who manifested hypersensitivity to ant bites and who developed a synovitis and skin lesion of the elbow diagnosed by biopsy as representing allergic vasculitis.

and define the need for, and development of, the indicated in-flight treatment capability.

IN-FLIGHT PROCEDURES

The in-flight phase of prophylaxis and therapeutics has involved long-distance diagnoses (made possible by biotelemetry) and on-board treatment with the appropriate medical kit items. This treatment has been carried out by spacecrews under the direction of ground-based physicians, with the exception of one Soviet flight and the US Skylab program, each of which included a physician-astronaut.

Monitoring

When the US space program began, it was a new notion to obtain continuous physiological data by instrumenting the human operator. No sufficiently reliable ready-made items were available. Since then, sophisticated and highly reliable biotelemetry devices have been developed in both the US and the USSR. Table 12 lists the principal devices to provide comprehensive monitoring of biomedical status. Electrocardiographic equipment, for example, permitted real-time monitoring of cardiac arrhythmias noted in an Apollo 15 crewmember. Small segments of these recordings are illustrated in Figure 2. In this case, fortunately, no pharmacologic intervention was required. Should it be needed, lidocaine and atropine injectors are available as well as procainamide capsules to be prescribed by the ground-based physician in charge.

In-flight Medications

The earliest data on the use of medications in the weightless state were obtained during flights aboard aircraft flying Keplerian trajectories [45]. During these tests it was established that intake of oral medications was not impeded if given in tablet form, in special tubes packed in foil. Glass ampules cannot be used for ordinary injections; medicines in solution must be contained in cartridge-type syringes or injectors [44]. Droplets, suppositories, solutions, tinctures, decoctions, and powders (according to Saksonov et al [32]) must not be included in the medical kit. The same authors suggest that the most convenient and suitable forms for medications in space travel are dragees, pills, capsules, tablets, and hypodermic syringes.

Planning the volume of medical equipment on-board must, of course, be based on data con-

TABLE 10.—*Traumatic Injuries*

Trauma	No. cases
Muscle strain	9
Sprains	9
Torn meniscus (knee)	2
Fractures	11
Dislocation (shoulder and phalanges)	2
Lacerations	10
Bursitis or synovitis (elbow)	2
Burns	3
Contusions	3
Eye injuries	9
Dysbarism	
Bends	2
Tympanic membrane	1
Barotitis	4
Dog bite	1
Peripheral compression neuropathy	1
Concussive labyrinthitis	1
Laryngitis (excessive speaking)	1
Total	71

TABLE 11.—*Miscellaneous Problems of Medical Significance*

Problem	No. cases
Cholecystitis or cholelithiasis[1]	2
Hernia[1]	2
Sperm granuloma	1
Hemorrhoids, symptomatic	5
Possible renal calculus[1]	1
Ménière's syndrome	1
Thrombophlebitis	1
Migraine equivalent	1
Congestive prostatitis	2
Rectal fissure	1
Abdominal pain, unknown etiology, severe	1
Total	18

[1] Detected by annual physical examination. Cholecystitis and cholelithiasis corrected by cholecystectomy prior to astronaut participation in flight. Hernia also surgically repaired preflight. Renal calculus diagnosis not confirmed; case being followed.

cerning the types of disorders anticipated and the possibility of medical manipulation (examination, establishment of diagnosis, and medical procedures) in the weightless state [32].

The initial philosophy regarding medications in space flight was to provide them only for medical emergencies. Additional experience and confidence gained thereby have permitted some relaxation of this philosophy so that certain medicines are now routinely prescribed whenever a need is indicated. For example, sleep medications are prescribed for both US and Soviet crews when adequate rest is not obtainable and sound sleep is important.

Medical kits in the US space program. Medical kits carried aboard US spacecraft have varied relative to mission duration and prior experience. In the first four Mercury missions, drugs carried were: an anodyne, an antimotion sickness drug (both in automatic injectors making possible self-administration through the pressure suit), a stimulant, and a vasoconstrictor for shock treatment. In later missions, only the antimotion sickness drug and anodyne (Demerol) were stowed. For the last Mercury flight, tablets of dextroamphetamine sulfate, an antimotion sickness drug, and an antihistamine tablet were placed in both the suit pocket and survival kit. The only medication used was dextroamphetamine sulfate, with one tablet taken on instruction from the medical monitor at about 33 h into the 34½-h flight, prior to initiation of the retrofire sequence, to relieve fatigue.

The zero-G environment and requirement to wear gloves necessitated development of special packaging for tablets. The pill case developed consisted of an aluminum container lined with Velcro and having a Velcro top flap that could be lifted easily from either end with a gloved hand. The tablets were broken and placed in

TABLE 12.—*In-Flight Biomedical and Performance Measures*

Parameter measured	Techniques employed	
	American missions	Soviet missions
Cardiac activity and circulation	2-lead ECG with synchronous phonocardiography, vectorcardiography, cardiotachography, blood pressure—pressure cuffs and automatic measurement of tones, leg plethysmography during LBNP tests, venous compliance	Continuous 1-lead ECG, periodic 12-lead ECG, seismocardiography (myocardial contractility), kinetocardiography, blood pressure-pressure cuffs, tachooscillography and other measurements, sphygmography, rheoencephalography and cardiac output (Bremser-Ranke)
Hematology	Hemoglobinometry, venous blood collection with separation and preservation	
Respiration	Impedance pneumography, spirometry, gas exchange	Perimetric pneumography, pulmonary volumes, gas exchange
CNS, sensory function and performance	EEG, sleep analysis with EOG, voice communication, vestibular tests in rotating chair, overall task performance, otolith test goggles, rod and sphere (for spatial orientation)	EEG, EOG, voice communication, vestibular tests, psychophysiological tests, overall task performance
Metabolism	Body mass measurement, biosampling, bicycle ergometry, metabolic analyzer (O_2 consumption, CO_2 production), body temperature (ear probe)	Biosampling

capsules which were then sewn with a single thread to the Velcro flap. As the flap was lifted back, the individual capsule could be easily bitten off and ingested [3].

A number of investigators predicted that for missions appreciably longer than the Mercury flights, man would require drugs to help him cope with the spaceflight environment. Sedation prior to launch and stimulation prior to reentry had been mentioned. In the absence of truly definitive information to the contrary, a drug kit containing these items and others was made available for in-flight prescription for Project Gemini missions. It has been previously noted that crews were pretested for each drug. Aspirin and APCs (a combination of aspirin, phenacetin, and caffeine) were used in-flight for occasional mild headache and for relief of muscular discomfort prior to sleep. Dextroamphetamine sulfate was used on several occasions by fatigued Gemini crewmen prior to reentry. A decongestant relieved nasal congestion and reduced the need for frequent clearing of the ears prior to reentry. An anti-motion sickness medication was taken in one instance prior to reentry to minimize motion sickness in the capsule after splashdown in a heavy sea. An inhibitor of gastrointestinal motility was prescribed on occasion for limiting in-flight defecation. No difficulty was experienced in the use of any of these medications. Gemini medical kit items are listed in Table 13.

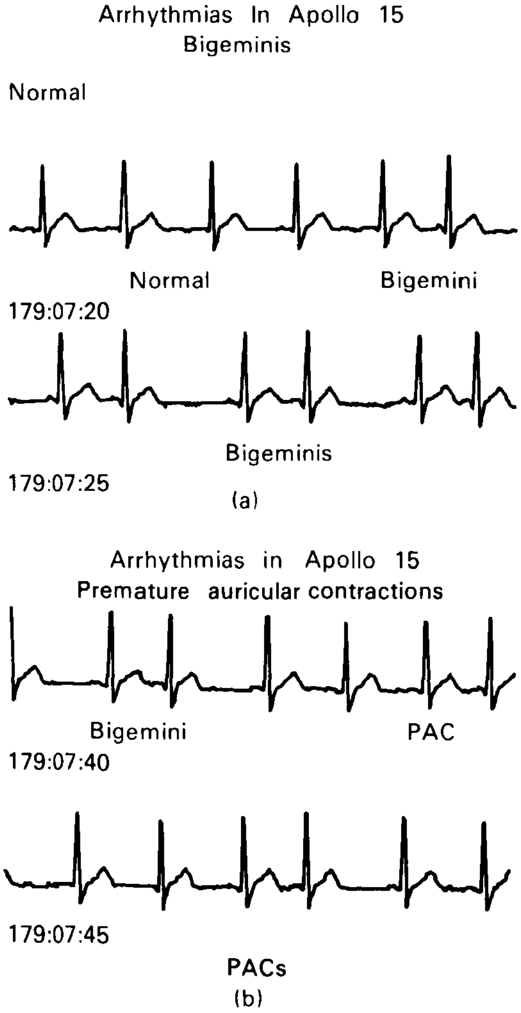

FIGURE 2.—Electrocardiographic trace of arrhythmias in an Apollo 15 crewmember [5].

The Apollo medical kit contained a greater variety of drugs than the Gemini kit. Certain drugs were replaced by more effective ones and others were added as needed. The addition of sleeping medication has already been noted. After cardiac arrhythmias were experienced by two Apollo 15 crewmen, antiarrhythmic drugs were included in the medical kit (lidocaine and procainamide). These medications and other additions and deletions to the medical kits of both Apollo and Skylab missions are indicated in Tables 14 and 15.

Medical kits in the Soviet space program. Special medicine chests installed aboard Soviet spacecraft contain radioprotective substances, stimulants for the central nervous system (CNS), analgesics, and other preparations. All flights thus far have been under favorable radiation conditions, so that there were no direct medical indications for use of radioprotective drugs [33]. Medications listed in Table 16 were in the Soyuz 11/Salyut 1 medical kit with directions for use. Saksonov et al [32] note that while there has been as yet "essentially no direct medical indication that medicines should be used in-flight, on longer missions the need for medication will surely develop."

A medicine chest for space flights lasting more than 2 weeks must include medicine, bandages, several instruments, and medical tools required for sampling urine and gases, providing for skin care, and so on. In addition to the chemical radioprotective substances already mentioned, the medicines should include materials for treating radiation burns, cardiovascular and gastrointestinal problems, antimicrobials and antiviral substances (e.g., antibiotics and sulfamide preparations), analgesics, soporifics, sedatives, tranquilizers, antiallergic preparations, preparations for stimulating and activating the nervous system, substances for combating hemorrhage and shock, means of treating motion sickness, materials for treating fatigue and preventing nausea, preparations for preventing coughing, protecting the skin, vitamins, methods of preventing muscle asthenia, supplies for assistance in problems affecting the eyes and teeth, and antiseptics [37].

Kotsyurba suggests that medical preparations be sterilized prior to the flight using radioactive radiation [16]. Semeykina [34] recommends testing medicine storage techniques. Such tests would provide data concerning durability of tablets, particularly under the stress of vibration and overloads.

A brief survey of studies on problems of space pharmacology and pharmacy shows that work on solving the problems facing space medicine is still far from complete and many more pertinent studies are needed [37].

Selection of medications. Medical kit selections should include preparations that can be used for a variety of purposes and be the most effective. Preparations that reduce the individual's resistance to flight factors must be excluded. For example, most tranquilizers produce a less-than-normal state in the individual, with unpredictable mental attitudes, and may alter judgment and orientation to reality. Some of these drugs also reduce tolerance to several types of stresses, including altitude and acceleration [3]. Another medication that had received consideration, 9-alpha-fluorohydrocortisone, is very effective in maintaining fluid balance [36], but has the undesirable side effect of accelerating potassium loss. It is obviously desirable to find and include in medical kits pharmacologic preparations that reduce the organism's sensitivity to unfavorable spaceflight factors, but in no way compromise other areas of physiologic, psychologic, or psychomotor performance.

Certain pharmacologic preparations have unfavorable effects on the ability of the organism to withstand spaceflight factors. Cystamine may increase sensitivity to rolling movement and high temperatures [25]; cystamine, aminoethylisothiuronium, and serotonin may depress the organism's resistance to radial acceleration. Injections of cystamine reduced the resistance of mice to physical stress [18].

The negative effect on the vestibular apparatus from streptomycin has been noted [26]; this antibiotic also increases hemorrhagic phenomena and leukopenia in acute radiation disease [29]. Saksonov et al [33] suggest that aspirin, pyramidone, and salicylate, which sensitize the organism to ionizing radiation, not be used in spaceflight.

Certain preparations have a distorted effect under special conditions. For example, after irradiation of animals, corazole produced a toxic

TABLE 13.—*Gemini 7 In-Flight Medical and Accessory Kits*

Medication	Dose and form	Label	Quantity
Cyclizine HCl	50-mg tablets	Motion sickness	8
d-Amphetamine sulfate	5-mg tablets	Stimulant	8
APC (aspirin, phenacetin, and caffeine)	Tablets	APC	16
Meperidine HCl	100-mg tablets	Pain	4
Triprolidine HCl	2.5-mg tablets	Decongestant	16
Pseudoephedrine HCl	60-mg tablets	Decongestant	16
Diphenoxylate HCl	2.5-mg tablets	Diarrhea	16
Tetracycline HCl	250-mg film-coated tablet	Antibiotic	16
Methyl cellulose solution	15-cc in squeeze-dropper bottle	Eyedrops	1
Parenteral cyclizine	45 mg (0.9 cc in injector)	Motion sickness	2
Parenteral meperidine HCl	90 mg (0.9 cc in injector)	Pain	2

TABLE 14.—*Medications in Apollo and Skylab Medical Kits*

Item	Command module kit											
	7 Stowed/ used	8 Stowed/ used	9 Stowed/ used	10 Stowed/ used	11 Stowed/ used	12 Stowed/ used	13 Stowed/ used	14 Stowed/ used	15 Stowed/ used	16 Stowed/ used	17 Stowed/ used	Skylab stowed/ mission
Methylcellulose eye drops (1/4%)	2/1	2/2	2/0	0/0	0/0	0/0	0/0	2/0	1/0	2/0	1/0	2
Methylcellulose eye drops (1%)	0/0	0/0	1/0	2/0	2/0	2/0	2/0	0/0	0/0	0/0	0/0	0
Tetrahydrozoline HCl (Visine)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1/1	0
Compress—bandage	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2/0	2
Band-Aids	12/2	12/0	12/0	12/0	12/0	12/0	12/0	12/0	0/0	12/0	12/0	12
Antibiotic ointment	1/1	1/0	1/0	1/0	1/0	2/0	2/0	2/0	2/0	2/1	2/1	2
Skin cream	1/0	1/1	1/1	1/0	1/0	1/0	1/0	1/0	1/0	1/1	1/0	1
Demerol injectors (90 mg)	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	6/0	6/0	6
Marezine injectors	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	3/0	0/0	0/0	0
Marezine tablets (50 mg)	24/3	24/1	24/4	12/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0
Dexedrine tablets (5 mg)	12/1	12/0	12/0	12/0	12/0	12/0	12/1	12/0	12/0	12/0	12/0	12
Darvon caps. (60 mg)	12/2	18/0	18/0	18/0	18/0	18/0	18/0	18/0	18/0	18/0	18/0	15
Actifed tablets (60 mg)	24/24	60/0	60/12	60/2	60/0	60/18	60/0	60/0	60/0	60/0	60/1	30
Lomotil tablets	24/8	24/3	24/1	24/13	24/2	24/0	24/1	24/0	24/0	24/0	48/5	24
Nasal emollient	0/0	2/1	2/1	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1/0	1
Aspirin tablets (0.3 g)	72/48	72/8	72/2	72/16	72/Unk	72/6	72/30	72/0	72/0	72/0	72/0	60
Tetracycline (250 mg)	24/0	24/0	24/0	15/0	0/0	0/0	0/0	0/0	60/0	60/0	60/0	60
Ampicillin	0/0	60/0	60/0	45/0	45/0	60/0	60/0	60/0	60/0	60/0	60/0	30
Seconal capsules (100 mg)	0/0	21/1	21/10	21/0	60/0	21/6	21/0	0/0	21/0	21/3	21/16	15
Seconal capsules (50 mg)	0/0	12/7	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0
Nose drops (Afrin)	0/0	3/0	3/1	3/0	3/0	3/1	2/1	2/1	3/0	3/0	3/3	3
Benadryl (50 mg)	0/0	8/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0
Tylenol (325 mg)	0/0	14/7	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0
Bacitracin eye ointment	0/0	0/0	1/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0
Scopolamine (0.3 mg)—Dexedrine (5 mg) caps.	0/0	0/0	0/0	0/0	12/6	12/0	12/2	12/0	12/0	12/0	12/1	24
Mylicon tablets	0/0	0/0	0/0	0/0	20/0	40/0	40/0	40/0	40/0	0/0	0/0	0
Ophthaine	0/0	0/0	0/0	0/0	0/0	0/0	1/0	1/0	1/0	1/0	1/0	1
Multivitamins	0/0	0/0	0/0	0/0	0/0	0/0	0/0	20/0	0/0	0/0	0/0	0
Ophthalmic ointment (idoxuridine)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	1
Acetazolamide tablets (250 mg)	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	20
Lip balm	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	3
Pronestyl	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	80/0	80/0	80
Lidocaine	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	12/0	12/0	12
Atropine	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	12/0	12/0	12
Mycolog cream	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	0/0	2

effect instead of stimulation [13]; a distorted effect of pituitrin action has also been noted in prolonged hypokinesia in humans [20]. Paradoxical reactions can and do occur in humans even without superimposition of special stresses. Benzedrine, which stimulates the CNS in most individuals, depresses it in others. During the action of overloads, an injection of epinephrine increases, then decreases, the pressor effect. During overloads too, vasoconstrictors (epinephrine and norepinephrine) and vasodilators (nitroglycerine and papaverine) produce a longer effect on blood pressure [27] than under normal conditions.

Several Soviet authors [28] have suggested that vasodilators with brief action (nitroglycerine and isadrine) should be administered periodically for training the baroreceptors of the vessels in a state of weightlessness. This proposal is, however, under dispute.

TABLE 15.—*Lunar Module Medical Kit*

Lunar module kit (Apollo 17)	
Item	Quantity
Medical package assembly	
Rucksack	1
Stimulant pills (Dexedrine)	4
Pain pills (Darvon)	4
Decongestant pills (Actifed)	8
Diarrhea pills (Lomotil)	12
Aspirin	12
Band-Aids	6
Compress bandages	2
Eye drops (methylcellulose)	1
Antibiotic ointment (Neosporin)	1
Sleeping pills (Seconal)	6
Anesthetic eye drops	1
Nose drops (Afrin)	1
UCTA[1] roll-on cuffs	6
Pronestyl	12
Injectable drug kit	
Injectable drug kit rucksack	1
Lidocaine (cardiac)	8
Atropine (cardiac)	4
Demerol (pain)	2
CSM[2] auxiliary kit	
CSM auxiliary drug kit rucksack	1
Pronestyl (cardiac)	80
Lidocaine (cardiac)	12
Atropine (cardiac)	12
Demerol (pain)	6

[1] Urine Collective Transport Assembly.

[2] Command Service Module.

During flight, there may be a reduction in the effectiveness of stimulating preparations and an increase in the activity of preparations that inhibit CNS function.

Soviet space medical experts endorse the use of soporifics; Krupina et al [19] feel these medications are absolutely necessary in flight, especially for insomnia. They caution against the use of meprobamate, however, since it produces an undesirable weakening effect on the muscles. Some of the soporifics (e.g., phenobarbital) should not be used in space flight because of the extreme length of sleep they induce (up to 12 h) and the pronounced posthypnotic and other side effects [28]. Other soporifics (e.g., chloral hydrate) produce hypotensive effects.

For prophylaxis of muscular atrophy and stimulation of the neuromuscular periphery, the Soviets recommend that the food ration include alpha-tocopherol and pantothenic acid [26].

To insure prolonged prophylaxis of vestibular disturbances, a combination of drugs has been used successfully by US crews. Dexedrine-scopolamine has proven more effective than various drugs used alone. Parin [28] suggests that the combination of scopolamine-Dexedrine not be repeatedly used because of undesirable side effects (dryness of mouth, disruption of accommodation, and insomnia).

Finding effective methods of protection against radiation damage to the crew and the entire biocomplex during space flights is a timely and very complex problem [37]. Of the radioprotective chemicals known at present, some (mercamine hydrochloride, mercamine salicylate, mercamine disulfide, aminoethylisothiuronium) have proven highly effective for humans in clinical tests [33]. However, while considerable work is ongoing in this area, no available drug is wholly acceptable. The energy sinks (e.g., sulfhydryl drugs) have proven toxic in doses large enough to afford protection [3]. Furthermore, almost nothing is known about chemical protection against radiation under spaceflight conditions. On long space flights, the doses of cosmic radiation may exceed permissible limits for man. Some Soviet authors [10] feel the use of cystamine and strychnine is justified in this case. Such drugs are believed too toxic for consideration in the US program.

Diagnosis and Treatment

Diagnosis of medical status on space missions has been made possible through information provided with biotelemetry devices and through voice communication between spacecrews and ground-based medical personnel. During one flight of the Voskhod spacecraft, a physician in the crew made it possible to expand the range of medical tests and measure arterial pressure, gas exchange, and so forth [27]. The first US Skylab crew included a physician.

Medical problems in-flight during the US Apollo missions are enumerated in Table 17, which also indicates the etiology of each disorder, where identifiable, and number of occurrences.

The need for clinical medical care in-flight becomes more pronounced as mission durations increase. For long-term missions, it is desirable to have a physician crewmember on-board and include diagnostic machinery among spacecraft systems. Should surgical intervention be required and mission profile preclude returning a stricken crewmember to Earth for treatment, the presence of a physician becomes imperative.

In the US, efforts are underway to develop an integrated medical/behavioral laboratory measurement system to provide clinical medical support for spacecrews. In the Soviet Union, the possibility of performing in-flight surgery has been tested aboard aircraft in Keplerian parabolas. In these studies, special transparent containers were used to perform surgical operations on rabbits, notably laparotomy, under local anesthetic (the preferred approach in zero-G) [44].

TABLE 16.—*Medical Kit—Soyuz 11/Salyut 1* [11]

Drug Types	Indications	Drug Items
Radioprotective	Command from the ground	Ambratine, vitamin complex
Analgesic	Headache, toothache, muscular ache	Analgin
	Severe pain	Promedol
	Very severe pain	Promedol-injector (command from the ground)
Sedative	Irritability, alarm, fear	Trioxazine
	Dreams, hallucinations, excitement, vomiting	Etapersaine
	Insomnia	Barbamyl
	Cough	Codeine
Antimicrobial	Inflammatory processes with high temperature	Oletetrin
	The same and GI disturbances	Madribon
Cardiac	Substernal heartache	Nitroglycerin
Antiallergic	Nettle rash, edema	Dimedrol
Gastrointestinal	Diarrhea	Opium
	Constipation	Isaphenin
	Pyrosis	Mint tablets
	Stomach pain	Bellalgin
	Flatulence	Carbolen
Antivomiting	Nausea and vomiting	Plavefin
	In the absence of Plavefin effect	Antropin injector (command from the ground)
Tonic	Fatigue, performance decline	Caffeine
	Severe fatigue, performance decline	Caffeine injector (command from the ground)
	Sharp decline of the mental and physical performance	Phenamine
	Decline of the cardiac and respiratory activity	Cordiamine injector
First-aid	Traumatic inflammation of mucous membranes	Tetracycline ointment
	Burns, erosion	Antiburning plaster
	Nasal and otic hemorrhages	Hemostatic sponge swabs
	Bandages	Band-Aids
	Various injuries	Bandage

While cutting the mesentry of the small intestine was accompanied by vigorous blood flow, the blood did not spurt out and scatter into the atmosphere, but flowed around the injured vessels in the form of puddles. Greater care must be taken when arterial blood flow is expected because, as might be anticipated, droplets form and tend to scatter. Contamination of the cabin atmosphere can be prevented when cutting tissues rich in blood by applying clamps beforehand and using cloth dressings. Should it be necessary to open the abdomen, incisions should be made in stages, limiting the length of the cut, since there is a tendency toward increased eventration of the intestine [37]. On the positive side, the eventration eliminates the need for retractors. Such work has established the possibility of performing surgery under conditions of weightlessness.

Any present discussion of the finer points of surgical intervention is of little more than academic interest, since there is no pressing need in the near future for such procedures. Rescue vehicles such as the US space shuttle will be available to remove seriously ill persons from space vehicles. Problems related to surgery in weightlessness will have to be resolved for planetary missions which preclude returning a crewmember to Earth.

Most emergency dental problems will be treated symptomatically until more sophisticated treatment capabilities become available. The on-board medical kit includes analgesics and antibiotics which can be used if necessary. Future spacecrews, in absolute necessity, will be able to extract teeth. The medical training program for Skylab crews, described earlier,

TABLE 17—*In-Flight Medical Problems in Apollo Crews*

Symptom/finding	Etiology	No. cases
Barotitis	Barotrauma	1
Cardiac arrhythmias	Undetermined, possibly linked with potassium deficit	2
Eye irritation	Spacecraft atmosphere	4
	Fiberglass	1
Dehydration (Apollo–13)	Reduced water intake during emergency	2
Flatulence	Undetermined	3
Genitourinary infection and prostatic congestion	*Pseudomonas aeruginosa*	1
Headache	Spacecraft environment	1
Head cold	Undetermined	3
Nasal stuffiness	Zero-gravity	2
Pharyngitis	Undetermined	1
Rhinitis	Oxygen, low relative humidity	2
Respiratory irritation	Fiberglass	1
Rash		
facial, recurrent	Contact dermatitis	1
inguinal	Prolonged wearing of urine-collection device (Apollo 13)	1
Skin irritation	Biosensor sites	11
	Fiberglass	2
	Undetermined	1
Seborrhea	Activated by spacecraft environment	2
Shoulder strain	Lunar core drilling	1
Subungual hemorrhages	Glove fit	5
Stomach awareness	Labyrinthine	6
Nausea, vomiting	Labyrinthine	1
	Undetermined (possibly virus-related)	1
Stomatitis	Aphthous ulcers	1
Urethral meatal excoriation (Apollo 13)	Prolonged wearing of urine-collection device	2
Urinary tract infection		1

includes dental training to enable crews to treat basic dental problems under the direction of the ground-based medical team. An in-flight program of oral hygiene is also observed to avoid dental problems wherever possible.

Preventive Medicine

In the relatively brief space missions so far, it has become apparent that a program of preventive medicine in-flight is needed and probably will be expanded as mission lengths increase. Exercise, ideally using a device such as the bicycle ergometer, is helpful in safeguarding the cardiovascular system. Exercise alone, however, is not effective in combating cardiovascular deconditioning [5] and other hypodynamic disturbances [20]. It may be helpful adjunctive therapy if the technique employed raises the heart rate above 120 beats/min. Dietary potassium supplements, mentioned earlier, appear helpful in preventing cardiac arrhythmias. For longer missions, other techniques may be required.

Application of gradient positive pressure by means of a pressure garment has been investigated in both the US and USSR. The technique, known as lower body negative pressure (LBNP), is also being examined for longer flights; it develops longitudinal G-tolerance, i.e., ability to withstand blood shifts and insure adequate venous return to the heart. The potential efficacy of LBNP application for perhaps a week prior to reentry is being investigated. Preliminary results appear promising, but establishment of a suitable LBNP profile for spaceflight application awaits further data. Some of these data have been provided by the LBNP experiment in the US Skylab program. Provision of positive pressure by the application of an antihypotension garment has been investigated in conjunction with the Apollo 17 mission.

Efforts were made to counteract the effects of zero gravity on the circulatory system in the Soyuz 11 crew by a complex of techniques which included use of a treadmill device, a gravity suit, and medication. In-flight testing indicated adequate adaptive capability of the cardiovascular system, although a possible decline in orthostatic tolerance was suggested by LBNP measures. Nevertheless, it was believed that readaptation for the Soyuz 11/Salyut 1 crew could have been less difficult than it had been for the Soyuz 9 cosmonauts, possibly as a result of the preventive measures [11].

Bed rest studies suggest that orally administered calcium and phosphate are more effective than exercise (no effect) or longitudinal compression (limited effect) for preventing mineral loss from the bones. The period of efficacy, however, was limited to 10 weeks in a 4-month study.[3] Mineral loss was principally from weight-bearing bones, and was recoverable in the posttest period.

In prolonged weightlessness, stabilization of mineral balance may occur. Calcium balance appears to normalize after some years in paralytics [12]. Nevertheless, bed rest data indicate the requirement for high calcium and phosphate intake during long space flights. Soviet scientists have noted that calculations based on mechanical correction of calcium deficit by means of its exogenic introduction under conditions of prolonged weightlessness are inadequate. Panov and Lobzin [26] discuss only attempts at finding a method of regulation (possibly hormonal) of mineral metabolism disturbances in general.

Future crews may be more prone to vestibular disturbances than past crews. Consequently, the possibility of preadapting vestibular responses to the effects of zero gravity is being studied. Studies conducted in slow rotation rooms are expected to demonstrate the feasibility of preadaptation [2].

Terent'yev and Krupina [37] point out various techniques being investigated in the USSR for increasing man's resistance to various spaceflight factors. Trainers and physical exercise techniques have been developed, and the possible use of pharmacologic preparations is under study.

POSTFLIGHT PROCEDURES

Spacecrews are closely observed by medical personnel and extensive tests are performed as soon as possible after the spaceflight mission, usually within the first few hours postflight, and for several weeks thereafter. A comprehensive physical examination is performed, as soon as

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[3] Hulley et al., unpublished data.

possible after recovery of the spacecrew, so that physiological signs with a rapidly changing time course may be detected and documented. Examination is made of:

head
neck
eyes
nose, mouth, throat
lymphatics
lungs
heart
vascular response
abdominal area
genitalia
rectum
skin
extremities
mental status

In addition to the physical examination, laboratory studies are done:

urine culture and sensitivity
complete blood count
urinalysis
serum electrolytes

Functional, orthostatic tolerance, and exercise tolerance tests are also accomplished.

Postflight Findings and Their Implications

The systems which exhibit *principal* change after space flight are:

cardiovascular/hemodynamic
musculoskeletal
endocrine, fluid, electrolyte
microfloral
vestibular

Postflight heart rates have been elevated in most space crewmen (in-flight they tend to stabilize at lower levels), and normalization is inhibited. Recent studies also reveal a decreased cardiac silhouette in both US astronauts [5] and Soviet cosmonauts [24]. Blood pressure is labile and orthostatic stability is decreased. Exercise tolerance is reduced. These changes are, however, all reversible within a relatively brief period postflight.

Musculoskeletal changes, small but detectable, have often been noted in US and Soviet crews, as well as slightly reduced bone optical density and negative nitrogen balances. Bone findings, however, have not been demonstrated by all methods employed. Decreases have been found in the volume of both calf and thigh. In the Apollo 16 crew, decreased limb size persisted beyond 1 week postflight. In the Soyuz 9 crew, muscular pain was reported as well as measurable alterations in gait [5, 9].

Significant changes have been noted in total exchangeable potassium in the US Apollo 15 and 17 crews. Table 18 indicates the percentage change, showing wide individual variation. Other electrolyte and hormone changes noted were consistent with the pattern of rapid recovery of in-flight weight loss immediately postflight.

Microbiological studies during the Apollo mission series indicate that growth of opportunistic organisms is favored in spaceflight environment [6]. Soyuz 9 cosmonauts also exhibited microfloral shifts with a number of organisms less resistant to antibiotics postflight [15]. The etiology of these changes is unclear, and factors other than weightlessness, e.g., confinement, may be involved. These changes are in contrast to the findings of earlier, very brief space flights where no significant changes were seen in immunological reactivity [17, 39–41]. Table 19 lists the microflora of possible significance identified postflight in Apollo spacecrews.

The net microbiological changes may be summarized as:

anaerobic bacteria decreased in number
aerobic bacteria increased in number and type
microorganisms were isolated at more body sites
organisms tended to spread across crewmembers (especially *Staphylococcus aureus*) fungal isolates decreased in number
higher carrier states for mycoplasma were indicated.

Through the Apollo program, vestibular-related difficulties have not been reported by US crews, either in the severity or with the consistency of those reported by Soviet cosmonauts. Gemini crewmembers reported no vestibular-related difficulties. Some Apollo crewmen reported problems that might be related to the vestibular system, but these were all reversible, subsiding after 2–5 d into any given flight. In future missions, when spacecrews will be drawn from broader populations including many without any aviation experience, the incidence of vestibular symptomatology may increase [5]. The clinical medical problems of Apollo crews are listed in Table 20.

The implications of cardiovascular changes were discussed in conjunction with in-flight therapeutic procedures, as was the "treatment" for calcium loss. A further point regarding calcium depletion from the bones is that the apparent loss of bone minerals is relatively slight. It is also possible that there may be a stabilization of this mechanism.

The question of readaptation after long flights obviously becomes more serious. A schedule of physical stresses may be necessary, to be imposed carefully, stepwise, after prolonged space flight. Microbiological changes noted, for example, should pose no real problem for the returning space traveler, provided he is gradually reexposed to Earth microflora.

In the conquest of space, one of the most important problems is that of insuring the medical safety of space crewmen. Management of the principal problems has only begun. Longer duration flights may pose problems not yet encountered or anticipated; many problems are being predicted on the basis of ground-based, simulated spaceflight experiments. This testing and controlled in-flight testing should yield extremely valuable information in the design of medical support programs and systems to enable man's safe travel into space on missions that could conceivably last for several years or more.

TABLE 18.—*Percent Change in Total Body Exchangeable Potassium Determined by ^{42}K Studies in Apollo 15, 16, and 17 (Premission vs Postmission)*

Mission	% Change
Apollo 15	
CDR	− 7.4
LMP	+ 3.2
CMP	− 6.0
Apollo 16	
CDR	− 7.9
LMP	+ 6.1
CMP	− 4.8
Apollo 17	
CDR	− 4.2
LMP	+ 4.5
CMP	− 6.9

TABLE 19.—*Microflora of Possible Medical Importance Identified Postflight in Apollo Crews*

Staphylococcus aureus	*Moraxella* sp
epidermis	*Corynebacterium* sp
faecalis	*Enterobacter aerogenes*
Klebsiella aerobacter	*Haemophilus parahaemolyticus*
enterobacter	*Herella vaginicola*
pneumoniae	*Escherichia coli*
Proteus mirabilis	
Pseudomonas aeruginosa	β-Streptococcus
Serratia sp	Mycoplasma
Mima polymorpha	*Candida albicans*

TABLE 20.—*Postflight Medical Problems in Apollo Missions*[1]

Symptoms/findings	Etiology
Aerotitis media	Postdescent
Folliculitis, moderate, right anterior chest	
Gastroenteritis	Possible food poisoning
Herpes simplex, lip	Herpes simplex
Influenza syndrome	Influenza B Undetermined Influenza A_2
Laceration	Blunt trauma
Nasal discharge, unilateral	Undetermined
Papular lesions, parasacral, multiple (no pustules)	Undetermined
Prostatic congestion, slight	Undetermined
Pulpitis, tooth No. 7	Caries and previous restoration
Pustules, back and eyelids, left eye	Bacterial
Rhinitis, pharyngitis	Influenza B β-Streptococcus, not group A
Sinusitis	Postcongestive
Strain, ligament, right shoulder	Lunar core drilling
Urinary infection	*Pseudomonas*
Vestibular dysfunction, prolonged (7 d) mild (head-down feeling)	Unknown

[1] One instance of each symptom found with the exception of prostatitis, of which there were two cases.

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Chapter 13

DESCENT AND LANDING OF SPACECREWS AND SURVIVAL IN AN UNPOPULATED AREA[1]

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The principal problems in the reentry and landing phases of manned space flight, from a medical vantage point, are associated with acceleration forces experienced by astronauts as the spacecraft reenters the Earth's atmosphere and at the moment of impact. After safe descent and landing, the primary requirement is to insure safety of the crew until recovery. Spacecraft and their crews have been recovered quickly on land (USSR) or sea (USA) in the vast majority of cases, but it is conceivable that this period could be extended by difficulties with the spacecraft manual landing systems, breach in radio communications, inclement weather or heavy seas at the time of splashdown, or inaccessible landing sites.

The physiologic effects of accelerative forces depend on a number of factors, including magnitude, direction, duration, and other variables surrounding the exposure. In regard to acceleration forces in the final phases of manned space flight, this chapter will be confined to specific medical and physiologic experience gained in spaceflight programs of the US and USSR. The application of such knowledge to future programs will also be discussed. Survival in the postlanding period will be treated in the context of rather extensive research which was conducted to define and solve problems likely to be experienced during a post-spaceflight survival sequence. Finally, a brief description will be given of the survival provisions currently made for spacecrews.

CONSIDERATIONS ON ACCELERATION

Project Mercury was the first series of US manned space flights, consisting of 25 major flight tests. Six of these flights were manned, the last four of which were orbital; they provided the highest G-loads in descent and landing in the US manned spacecraft program. The Mercury spacecraft were equipped with a contoured couch specially designed to provide maximum comfort and protection during reentry and landing. In the Gemini capsule, the support and restraint system was more conventional and the reentry forces lower than those experienced in the Mercury program. Reentry forces experienced by Apollo crews depended upon the mission, more extreme following a lunar than an Earth orbital mission. Lunar mission reentry accelerations approximately equalled those experienced during Gemini missions.

In these manned spaceflights and Skylab Earth orbital flights, the most recent phase of the US

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spaceflight program, reentry and landing acceleration forces are directed in the transverse ($+G_x$ or eyeballs-in) direction. However, future programs incorporating reusable boosters and orbiting spacecraft may impose positive accelerations ($+G_z$ or eyeballs-down) on the crew and passengers. Data on reentry and landing accelerations in Mercury, Gemini, Apollo, and Soviet programs will be reviewed in sections to follow, with results of recent studies directed toward problems of physiologic tolerance to positive acceleration vectors expected in future programs.

Mercury Project

The majority of acceleration and impact studies conducted in the 1950s were not directed specifically toward answering questions concerning manned space flight. However, information derived from these studies was usefully applied to the Mercury program. A review of acceleration physiology which summarized work up to the time of the Mercury flights was prepared by Gauer and Zuidema in 1961 [11].

Extensive studies of physiologic tolerance to acceleration and impact were conducted at the Aeromedical Field Laboratory, Holloman Air Force Base, N. Mex.; Aeromedical Laboratory at Wright-Patterson Air Force Base, Ohio; and at the US Navy's Aviation Medical Acceleration Laboratory, Johnsville, Pa. [27, 28, 35, 36, 37] These studies identified the need for increasing human tolerance to deceleration and impact forces that could occur in space flight, particularly in the event of aborted reentry and landing. Numerous protective methods were examined and evaluated. The fiberglass-contoured couch developed at the Langley Aeronautical Laboratory, Virginia, was one device that provided necessary G protection as well as the required characteristics of smallness, lightness, and sturdiness. In studies of the couch and various body angles in relation to transverse acceleration loads conducted at the Aviation Medical Acceleration Laboratory, two subjects successfully tolerated $20+G_x$, one for a period of 6 s [29]. This G-load was far higher than the expected nominal reentry for the Mercury spacecraft, although an aborted reentry using the Mercury escape system could subject the astronaut to a $20+G_x$ reentry acceleration load. The Mercury escape system consisted of a solid propellant escape rocket mounted on top of a tower attached to the spacecraft. In an aborted stage, the escape rocket was designed to lift the spacecraft sufficiently high to allow deployment of a parachute.

During training sessions at the US Navy's Johnsville centrifuge, the Mercury astronauts completed mission acceleration profiles ranging from 8 to $18+G_x$ with no adverse effects. These runs included a 259-mm Hg, 100-percent oxygen atmosphere in the gondola, and simulated flights were made with and without the pressure suit inflated. During training sessions, the astronauts learned breathing and straining techniques to increase tolerance at the higher G levels [25].

Impact problems identified early in the Mercury program were alleviated by employing a fiberglass fabric bag which attenuated the landing impact forces by forming an air cushion between the spacecraft structure and the deployed ablation shield. Water-landing impact forces were reduced from approximately 50 G to 15 G by this method.

The first US manned space flight, a suborbital flight, was made by astronaut Alan B. Shepard, Jr., May 5, 1961. The acceleration profile, shown in Figure 1, indicates a maximum load of $11.0+G_x$ reached during reentry. Landing impact forces were not measured but were estimated at 12 to 14 G [18]. There were no adverse physiologic effects resulting from reentry and landing. Table 1 summarizes Mercury project missions and shows the maximum G-level reached during reentry on each of the manned flights.

The success of the Mercury project and the early Vostok flights provided assurance that man could function in space, and withstand the physiologic stresses of reentry and landing following short periods in weightless environments. In the six Mercury flights, astronauts were capable of normal physiologic function and performance during reentry. Vibration and noise levels were well-tolerated. There was no disorientation or nausea associated with reentry or landing. Heat loads, while uncomfortable on occasion, were no problem during spacecraft reentry. The peak heart rate during reentry occurred immediately after reaching peak reentry acceleration, or on drogue parachute deployment, ranging from 104–184 beats/min [3].

Gemini Project

Project Gemini spacecraft systems provided for controlled reentry of the spacecraft to a specific landing area. Table 2 briefly summarizes the 10 Gemini manned missions and lists the maximum G-load experienced during each reentry.

The original objectives for Gemini spacecraft called for land landings; however, when problems in the development of the land landing system threatened to delay the overall program, the backup water landing system was substituted. This system utilized a 2.4-m diameter drogue parachute followed by a 5.5-m diam pilot parachute and a 25.6-m diam ring-sail main parachute. After deploying the main parachute and attaining nominal velocity, the spacecraft was repositioned by rotating from a vertical position to a 35° nose-up position for landing. This attitude with respect to the water resulted in landing impact forces well below the maximum tolerated by crew and spacecraft in earlier test sessions.

The landing impact did, however, vary from a very soft landing to a heavy shock. The variation resulted primarily from oscillation of the spacecraft and the particular point of oscillation when the spacecraft touched down. The wind, size, and

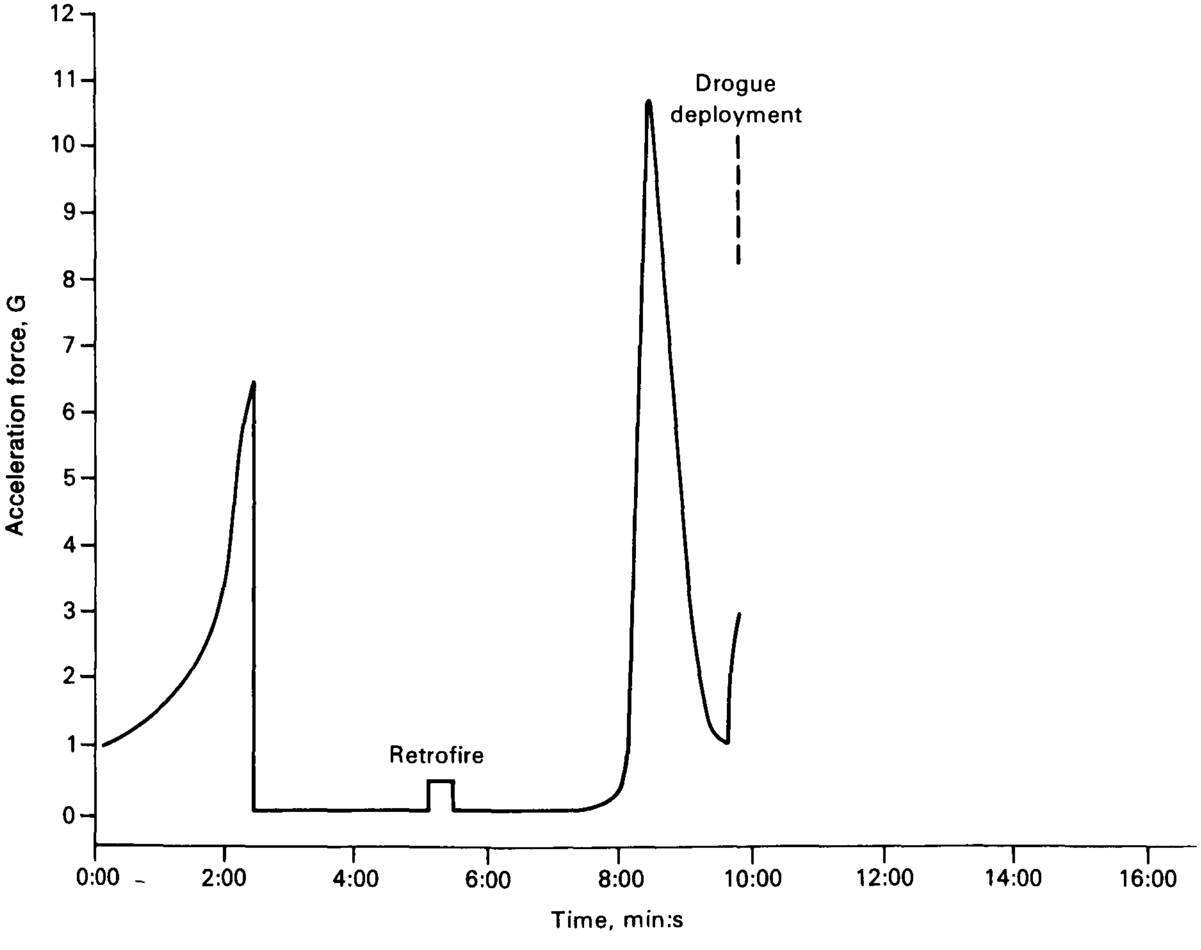

FIGURE 1.—Lift-off and reentry profile—Mercury.

part of the waves contacted contributed to the impact, although even the most severe landing did not affect crew performance.

The Gemini spacecraft was provided with ejection seats as an emergency escape system in the event of a launch vehicle failure, and as a backup landing system if the main parachute failed. If the spacecraft reentered over land, the ejection seats would become the primary landing system.

Figure 2 presents the reentry profile of Gemini 4. The reentry acceleration level of $7.7+G_x$ was the highest experienced by any crew in the Gemini project, although well below the $11.1 +G_x$ of MR-4 and far lower than the G levels willingly tolerated in centrifuge training sessions.

Many in the project were concerned that the long periods of weightlessness prior to the deceleration stress of reentry would result in a decreased tolerance to G-loading. An increased G sensitivity was noted by all three long-duration mission crews, each feeling that they were under a load of several Gs when, in fact, they were just beginning reentry. However, at peak G-load, the sensation was the same as in centrifuge simulations.

Peak heart rates during reentry ranged from 90–180 beats/min and appeared to be somewhat higher for longer-duration missions' reentry. However, no cardiovascular problems were observed during any Gemini reentry [4].

The objective of the Gemini to provide controlled reentry in a specific landing area was attained with an impressive degree of accuracy. Table 3 shows the landing accuracy of each Gemini mission.

The medical knowledge gained in Project Gemini and the Voskhod missions not only showed that man could successfully live in space, but also could accomplish the tasks necessary for a lunar mission.

TABLE 1.—*Mercury Manned Space Flights*

Flight	Crew	Launch	Duration (h:min:s)	Maximum G
MR 3	Shepard	5/5/61	0:15:28	11.0
MR 4	Grissom	7/21/61	0:15:37	11.1
MA 6	Glenn	2/20/62	4:55:23	7.7
MA 7	Carpenter	5/24/62	4:56:05	7.8
MA 8	Schirra	10/3/62	9:13:11	8.1
MA 9	Cooper	5/15/63	34:19:49	7.6

Apollo Program

Reentry G levels for Apollo missions in Table 4 show that acceleration levels for Earth orbital missions, Apollo 7 and 9, were about one-half those of lunar missions. Neither reentry mode results in any medically significant physiologic stress. The greater reentry lift capability of the Apollo spacecraft over its predecessors accounts for the much lower acceleration forces. Acceleration levels of an Earth orbital and lunar mission reentry are presented in Figures 3 and 4.

While nominal reentry G levels have been well-tolerated by the crew and pose no severe constraints on crew performance, an aborted Apollo launch could result in G_x acceleration levels as high as 16.2 G with an oscillating 1/2 Hz component ranging from $-1\ G_z$ to $+3.2\ G_z$. Such aborted acceleration levels could be endured, in all probability, without injury by crewmembers

TABLE 2.—*Gemini Manned Space Flights*

Flight	Crew	Launch	Duration	Reentry maximum G
G 3	Grissom, Young	3/23/65	4:52:31	4.3
G 4	McDivitt, White	6/3/65	97:56:12	7.7
G 5	Cooper, Conrad	8/21/65	190:55:14	6.4
G 7	Borman, Lovell	12/4/65	330:35:01	4.8
G 6A	Schirra, Stafford	12/15/65	25:51:24	4.5
G 8	Armstrong Scott	3/16/66	10:41:26	5.3
G 9A	Stafford, Cernan	6/3/66	72:20:50	5.5
G 10	Young, Collins	7/18/66	70:46:39	6.1
G 11	Conrad, Gordon	9/12/66	71:17:08	6.2
G 12	Lovell, Aldrin	11/11/66	94:34:31	6.4

with experience in acceleration tests and protected by the Apollo couch and restraint system. It is very doubtful, however, that spacecraft control tasks could be adequately performed under such conditions and, for this reason, crew tasks have been minimized during aborted reentry. The Apollo spacecraft aborted escape system is similar to that used in the Mercury program—an escape rocket separated from the attached spacecraft by a tower. The rocket lifts the Command Module (CM) from the booster and high enough for parachute deployment.

The condition of the astronaut at the time of reentry is another factor in evaluating physiologic effects of reentry. Crewmembers are exposed to many stresses during a mission, including weightlessness, confinement, dehydration, changing illumination, 100-percent oxygen (259 mm Hg) atmosphere (US flights), vibration, and fatigue. Acceleration tolerance appears so far to be unimpaired by spaceflight factors. However, the cardiovascular and musculoskeletal changes associated primarily with weightlessness could conceivably influence acceleration tolerance following long-duration missions.

The Apollo spacecraft landing system employs three parachutes and the repositioned command module system used in the Gemini program. On a nominal landing, the spacecraft enters the water at a 27.5° angle. The most severe impact experienced in an Apollo space flight was with Apollo 12. It was estimated that the CM entered the water at a 20°–22° angle, producing a 15-G impact [2]. This entry angle resulted when

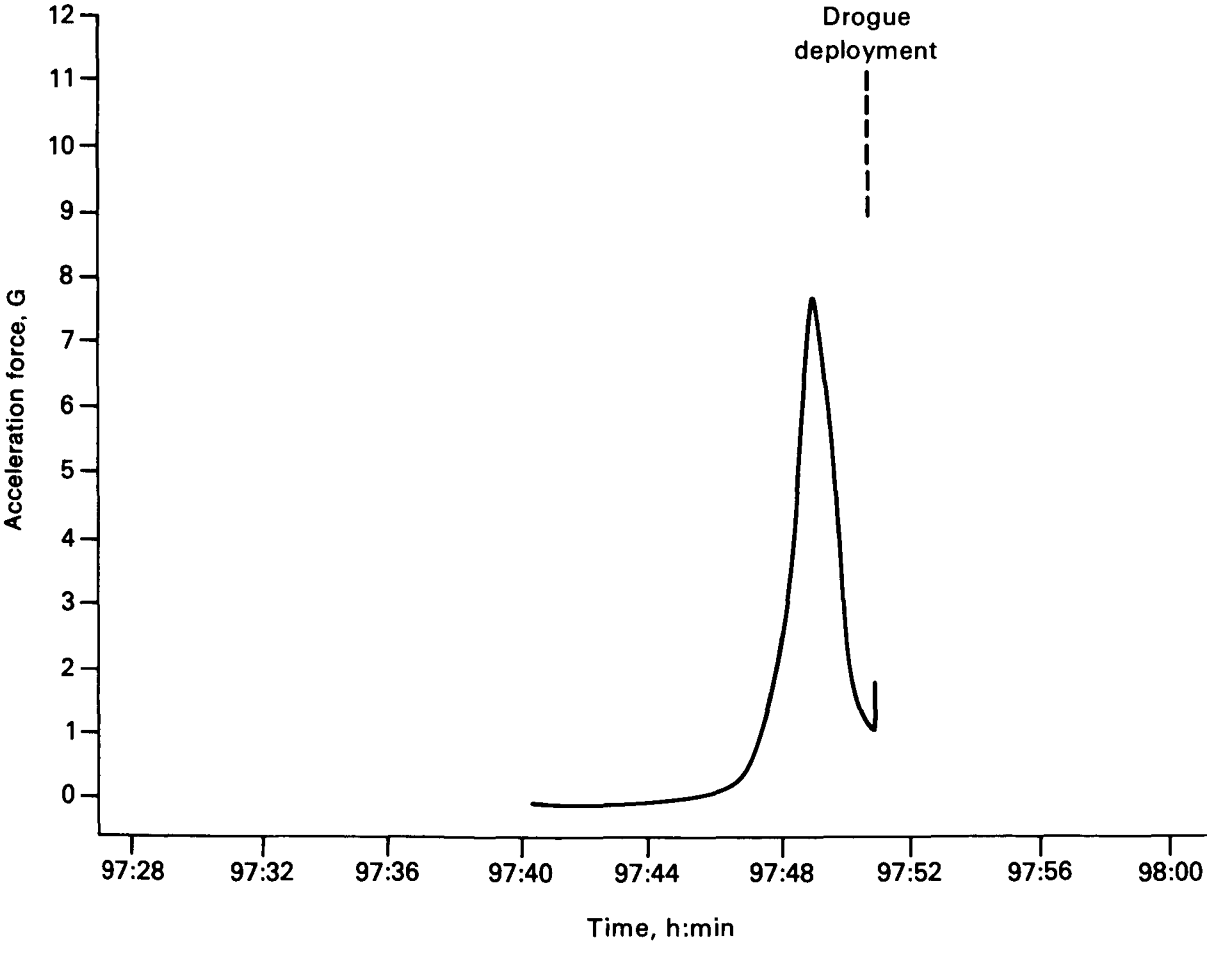

FIGURE 2.—Reentry profile—Gemini 4.

TABLE 3.—*Landing Accuracy*
(Naut mi/km from Projected Landing Point)

Flight	Coordinates		Accuracy	
	Latitude	Longitude	Naut mi	km
G 3	22°26′N	70°51′W	60	111.2
G 4	27°44′N	74°11′W	44	81.5
G 5	29°44′N	69°45′W	91	168.6
G 6A	23°35′N	67°50′W	7	12.9
G 7	25°25′01″N	70°06′07″W	6.4	11.9
G 8	25°13′08″N	136°E	1.1	2
G 9A	27°52′N	75°00′04″W	0.38	0.7
G 10	26°44′07″N	71°57′W	3.4	6.3
G 11	24°15′04″N	70°W	2.65	4.9
G 12	24°35′N	69°57′W	2.6	4.8

the wind caused the spacecraft to swing and meet the wave slope at a more normal angle. On impact, a camera detached from the mounting bracket and struck a crewman over the right eyebrow. The astronaut lost consciousness for approximately 5 s and a 2-cm laceration was sutured following retrieval. The injury healed normally. While the 15-G impact of Apollo 12 was described as very hard by the crewmen, no other physical difficulties were experienced.

Apollo landing impact studies involving 288 human tests were conducted on a linear decelerating device at Holloman Air Force Base [8], using impact forces up to 30 Gs at various selected body orientations. Although significant effects

TABLE 4.—*Apollo Manned Space Flights*

Flight	Crew	Launch	Duration (h:min:s)	Reentry maximum G
Apollo 7	Schirra, Eisele, Cunningham	10/11/68	260:09:45	3.33
Apollo 8	Borman, Lovell, Anders	12/21/68	147:00:11	6.84
Apollo 9	McDivitt, Scott, Schweickart	3/3/69	241:00:54	3.35
Apollo 10	Stafford, Young, Cernan	5/18/69	192:03:23	6.78
Apollo 11	Armstrong, Aldrin, Collins	7/16/69	195:18:35	6.56
Apollo 12	Conrad, Bean, Gordon	11/14/69	244:36:25	6.57
Apollo 13	Lovell, Haise, Swigert	4/11/70	142:54:41	5.56
Apollo 14	Shepard, Roosa, Mitchell	1/31/71	216:02:00	6.76
Apollo 15	Scott, Worden, Irwin	7/26/71	295:07:34	6.23
Apollo 16	Young, Mattingly, Duke	4/16/72	290:32:16	7.19
Apollo 17	Cernan, Evans, Schmitt	12/6/72	301:52	N/A

on the neurologic, cardiorespiratory, and musculoskeletal systems were recorded, no significant incapacitation or undue pain resulted. Snyder provided an excellent review of human impact tolerance in 1970 [26].

Skylab Program

A space laboratory was launched following the Apollo lunar landing program; it was visited by three-man crews on three separate occasions. This project, the Skylab program, had a primary objective to perform a series of medical experiments to evaluate man's physiologic responses to long-duration space flight. The first mission of the Skylab program was planned for up to 28 d; the second and third missions were planned for 56 d and lasted for 59 and 84 d respectively. Apollo Command Modules served as spacecraft for reaching, and returning from, the orbiting laboratory. Therefore, no acceleration or impact problems were expected in this program other than those associated directly with increasing the time spent in space prior to reentry and landing.

The Skylab program extended man's sojourn in the weightless environment significantly beyond any previous mission flown. The medical evaluations made during this period provided immediate and continuing information relating to each astronaut's physical well-being. The greatly increased volume of the laboratory over previous spacecraft also permitted greater movement and exercise capabilities, allowing for more normal daily living patterns.

Space Shuttle Program

The Space Shuttle program introduces a significant change in previous spacecraft reentry procedures. This spacecraft will be designed to enter the Earth's atmosphere in a reentry mode

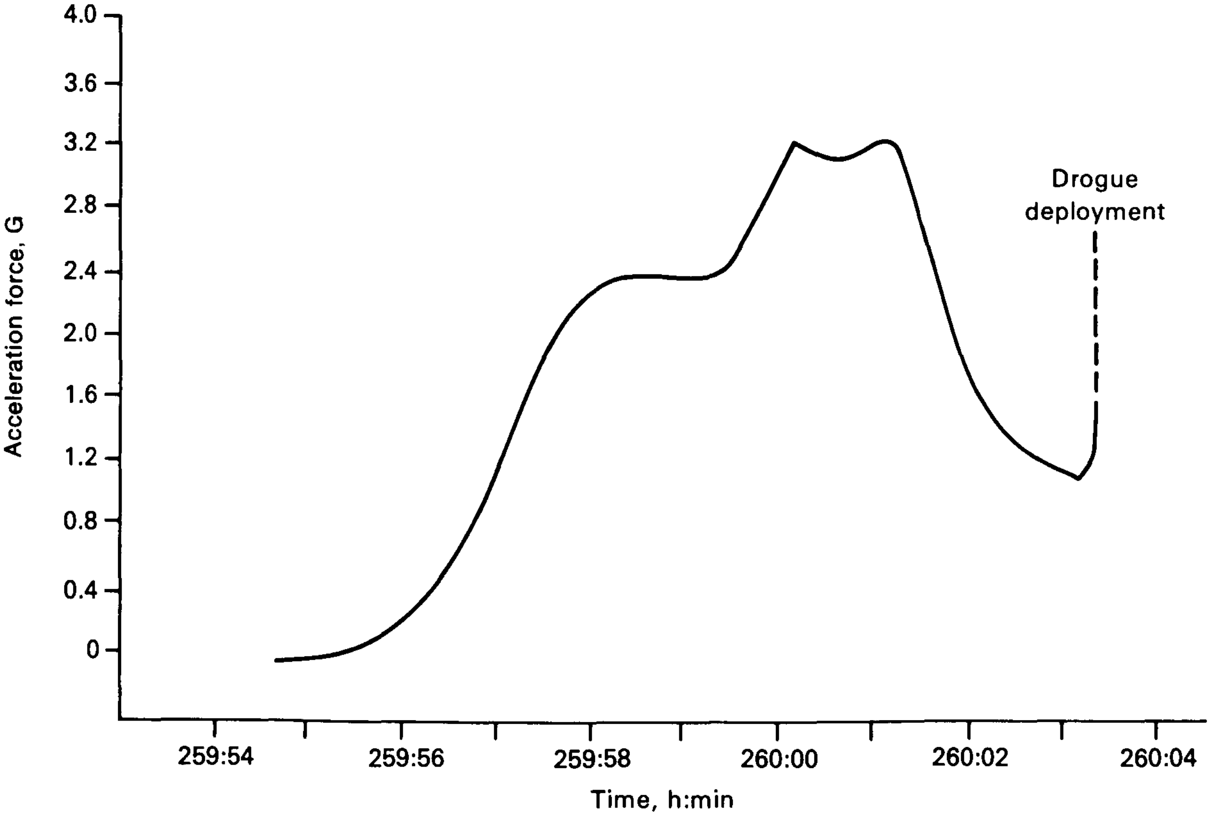

FIGURE 3. – Reentry profile – Apollo 7 (Earth-orbital mission).

that will impose upon the pilot and passengers a $+G_z$ acceleration vector. Trajectory analyses indicate nominal reentry acceleration G-levels that are within the tolerance of qualified flight personnel. It is important, however, to investigate these acceleration levels with regard to previous exposure to a weightless environment, and to identify tolerance thresholds in order to establish realistic emergency limits.

A study was conducted at the Manned Spacecraft Center, Houston, Tex., in 1970, to assess the physiologic effects of $+G_z$ acceleration following 1 and 7 d bed rest employed as a weightlessness analog. In this study, nine healthy (USAF Class III Flying Physical [1]) male subjects ranging from ages 20 to 36 were exposed to + 2.5, +3.0, +3.5, +4.0 and 4.5 G_z for 370 s or until an established end point was reached. The end point was loss of peripheral vision, central light dimming, and a verbal request from the subject to terminate the centrifuge run. After establishing a tolerance level in baseline runs, the subjects were bed-rested for 24 h to simulate 1 day in space, and exposed to the same centrifuge protocol as before bed rest. After a 4-d ambulatory recovery period, the subjects had bed rest for 7 d and were again centrifuged. All subjects were experienced participants in centrifuge tests.

The centrifuge profile consisted of a 0.03-G/s ramp to the $+2.5$-G_z to $+4.5$-G_z level which was maintained for 370 s or until the physiologic end point was reached. The downramp was also 0.03 G/s and included a +2.5 G_z spike occurring during 30 s which represents a maneuver following reentry to place the spacecraft in the normal flying position. The visual end point was measured using a standard light bar with green peripheral lights and a red central light. The green lights were 61 cm apart, and the distance from the headrest plane to the light bar was 81.3 cm. The bed rest episodes were conducted in the Crew Reception Area of the Lunar Receiving Laboratory (LRL). Strict bed rest was observed and, insofar as possible, a subject was

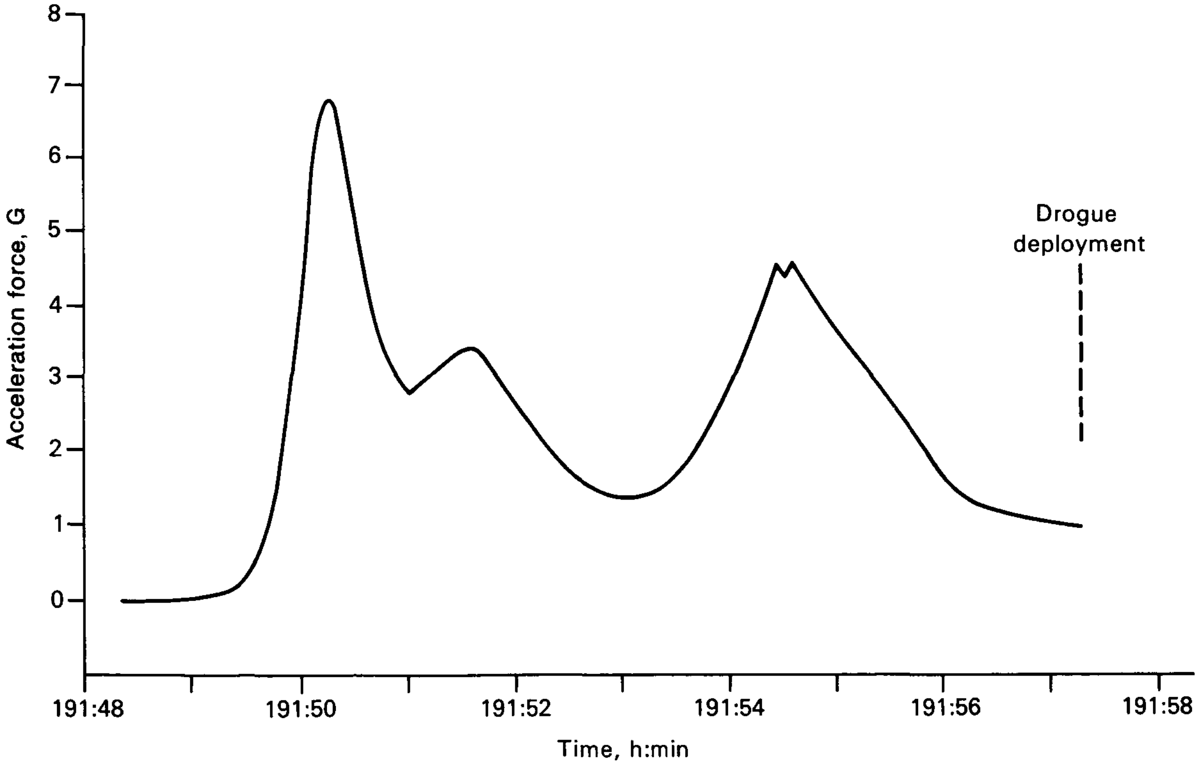

FIGURE 4. — Reentry profile — Apollo 10 (Lunar mission).

required to remain on his side, abdomen, or back with elbows on the bed or at the sides for the entire bed rest period.

Subjects were transported on a stretcher from the bed to the 15.2-m radius centrifuge at the Manned Spacecraft Center (MSC) Flight Acceleration Facility, and inserted into the gondola in a horizontal position. Each subject was then adjusted to a supine seated position, with the head pointing toward the center of the axis of rotation. The centrifuge gimbal was locked in place so that the subject remained in a $+1\ G_x$ environment during the entire centrifuge period. The resulting hypothetical angle of the inertial vector changed from 21.8° at $+2.5\ G_z$ to 12.5° at $+4.5\ G_z$.

During centrifugation, respiration rate was measured by an impedance pneumograph and ECG was measured from sternal and biaxillary sensors. Subjects were instructed not to use straining or breathing techniques to resist the acceleration since the runs were designed to test acceleration effects with the subject relaxed. No G-protection devices were used in this investigation.

In the baseline run, all subjects completed the $+2.5\ G_z$ profile; eight, the $+3.0\ G_z$; four, the $+3.5\ G_z$; two, the $+4.0\ G_z$; and two, the $+4.5\ G_z$. After 24 h bed rest, all completed the $+2.5\ G_z$ profile; seven, the $+3.0\ G_z$; four, the $+3.5\ G_z$; one, the $+4.0\ G_z$; and one, the $+4.5\ G_z$. After 7 d bed rest, seven completed the $+2.5\ G_z$ profile; five, the $+3.0\ G_z$; two, the $+3.5\ G_z$; one, the $+4.0\ G_z$; and none, the $+4.5\ G_z$. Not only did the $+G_z$ tolerance level decrease following 7 d bed rest, but all subjects reported a more rapid loss of vision. Tables 5, 6, and 7 show the time in seconds each subject remained at the various G-levels prior to terminating the centrifuge run. The average time for all subjects at $+2.5\ G_z$ during the baseline run, the post 24-hour bed rest run, and the post 7-day bed rest run was 370 s, 370 s, and 312 s, respectively. The average time for all subjects at $+4.5\ G_z$ with the same pretreatment was 103 s, 51 s, and 17 s, respectively.

The results of this study indicate that bed rest has a significant effect upon tolerance to $+G_z$ acceleration. Because it is believed that bed rest is a realistic analog of weightlessness, further

TABLE 5.—*Subject Reaction at Peak G Before Any Bed Rest* (Baseline)

Subject	1	2	3	4	5	6	7	8	9
$+G_z$–Level	Time, s at peak G								
2.5	370	370	370	370	370	370	370	370	370
3.0	370	370	370	370	250	370	370	370	370
3.5	370	3.3 G_z[1]	370	370	3.4 G_z[1]	370	320	370	370
4.0	370			3.7 G_z[1]		285	12	370	370
4.5	370					68		370	110

[1] G-level on up-ramp at which subject reached visual end point and run was terminated.

TABLE 6.—*Subject Reaction at Peak G After 1-Day Bed Rest*

Subject	1	2	3	4	5	6	7	8	9
$+G_z$–Level	Time, s at peak G								
2.5	370	370	370	370	370	370	370	370	370
3.0	370	189	370	370	12	370	370	370	370
3.5	370	1	3.25 G_z[1]	1		215	370	370	370
4.0	370					48	165	370	85
4.5	370						7	75	13

[1] G-level on up-ramp at which subject reached visual end point and run was terminated.

bed rest studies, planned and ongoing, are being employed to evaluate the effectiveness of various protection measures for increasing $+G_z$ tolerance following deconditioning. A more extensive study conducted for the NASA Ames Research Center [13] tested male volunteers in an experimental protocol employing one possible space shuttle acceleration profile, acceleration stresses of 2 to 4 G ($+G_z$) for periods up to 700 s.

The male volunteers were in the 24- to 27-year-old age range. The experimental protocol consisted of five phases: a 14-d ambulatory period, a 15-d bed rest period, a 14-d recovery period, a second 15-d bed rest period, and a second 14-d recovery period. While at bed rest, unrestricted movement was allowed in the horizontal plane, but arm movement was limited to forearm raising with elbows on bed. The protocol was:

1. Daily measurement of vital signs, determinations of body weight on a metabolic balance, oral food intake, and urine output.
2. Urine collection and analysis for sodium, potassium, and creatinine.
3. Blood chemistry and hematology studies.
4. Isotopic volume studies.
5. Tilt-table studies.
6. Lower body negative pressure studies.
7. Exercise studies, performed after recovery after tilt-table studies during all phases of the test.
8. Centrifuge studies, performed before the start of the test and during the recovery phase 24 h following the tilt or LBNP and exercise studies.
9. Metabolic dietetic program. All subjects on special diet prior to and during test.

The Ames Research Center study successfully documented and quantified a "bed rest effect" by metabolic studies and cardiovascular stress tests and evaluated the influence of bed rest on high $+G_z$ tolerance with and without the use of a G-suit. The metabolic studies, including fluid and electrolyte balance results, demonstrate a lower orthostatic tolerance following bed rest. A lower calculated maximum oxygen uptake from exercise studies following bed rest denotes deterioration in cardiovascular performance.

The centrifuge studies demonstrated decreased tolerance to high levels of $+G_z$ acceleration. However, the use of a G-suit dramatically offset the decreased tolerance. In some cases, the use of such a garment gave the subject a post-bed rest $+G_z$ tolerance equal to that during the ambulatory control and recovery period. The extent of protection provided by the G-suit appears to be related to the quality of the fit. Other studies have demonstrated that subjects whose G-suits fit best, fitting almost to the point of discomfort at 1 G had the most satisfactory $+G_z$ tolerance [19, 23].

These studies, coupled with limited in-flight experience with antihypotensive garments, suggest that such garments may be a beneficial countermeasure to provide increased reentry acceleration tolerance in individuals exposed to prolonged space flight.

Another study conducted at the Ames Research Center in 1973 investigated the effects of acceleration forces on females participating in a bed rest/acceleration tolerance study. These US Air Force flight nurses, participating in a 5-week program, were subjected to 2 weeks of complete bed rest and exposed to a maximum of +3 G_z

TABLE 7.—*Subject Reaction at Peak G After 7-Day Bed Rest*

Subject	1	2	3	4	5	6	7	8	9
$+G_z$–Level	Time, s at peak G								
2.5	370	35	370	370	185	370	370	370	370
3.0	370	7	1	228	1	370	370	370	370
3.5	370			75		142	250	370	217
4.0	370			2		27	100	20	2.886G_z[1]
4.5	156					1	1	3.56 G_z[1]	

[1] G-level on up-ramp at which subject reached visual end point and run was terminated.

before and after bed rest. Maximum oxygen uptake and lower body negative pressure tests were also performed.

Data from this study are not yet fully analyzed. Preliminary results indicate an acceleration toleration degradation of about 50% in the test subjects. Antihypotensive garments were not used in this study. Finally, the results do not suggest that there is necessarily any limitation to the inclusion of women participants, particularly women scientific investigators, in the Space Shuttle program.

Potentially promising countermeasures to increase acceleration tolerance have been reported by many investigators. In the US space program at present, the most serious consideration is given to G-suits and the application of lower body negative pressure in the final days of orbital space flight [7]. The efficacy of these two methods should be supported by data yielded by the Skylab program.

Vostok, Voskod, and Soyuz Flight Programs

Prior to participation in space flight missions, Soviet cosmonauts, like US astronauts, are exposed to acceleration forces as great as, and greater than, they may experience in actual space flight. According to statements by a majority of cosmonauts, accelerations were endured with far more difficulty during the reentry phase of Vostok, Voskhod, and Soyuz space flights than accelerations of the same magnitude during centrifuge training [31]. The pulse rate for some cosmonauts during these periods reached 168–190 beats/min. These values, too, were higher than those noted during similar accelerations in centrifuge rotation. Most cosmonauts experienced short-duration visual blackouts during the landing segment of flight, which were not observed in centrifuge training.

Accelerations were not well-tolerated when the length of Soviet spaceflight missions increased. After 1 day of spaceflight exposure, heart rates were 10 beats above centrifuge training levels; after 3- and 4-d flights, heart rates were 30–32 beats/min higher; and after 5 d, these values reached the maximum of 62 beats/min above those recorded during centrifuge testing in one cosmonaut. These findings caused concern regarding the effects of long-term space flight on man's ability to tolerate reentry acceleration forces. Consequently, laboratory experiments examined the effects of simulated weightlessness on acceleration tolerance.

Twenty-one subjects were exposed to G_x accelerations on a centrifuge before and after hypokinesia in the form of strict bed rest for up to 20 days. Following the 20 days of hypokinesia, tolerance for the same acceleration force (in this case, 7 G) was decreased from a control value of 4–5 min to 4–6 s. Systolic blood pressure was also elevated during the action of acceleration after hypokinesia; it was increased by 70%–85% compared with 54%–60% in control experiments. A significant decrease in visual acuity was noted in the subjects along with blurred vision and visual blackout after hypokinesia at lower acceleration levels, compared with the controls.

On the basis of this experiment and similar studies,[2] various approaches were considered by Soviet scientists to increase the resistance of cosmonauts to the effects of acceleration after prolonged weightlessness. Measures which are used include properly selected physical exercises, pharmacologic preparations (including combinations of strychnine nitrate, caffeine, and phenamine), application of lower body negative pressure in flight, and the use of anti-G suits [14, 31].

PROTECTING THE LIVES OF SPACECREWS IN THE LANDING PHASE

Spacecraft landing is accomplished with accuracy (already described). However, in the most accurate of landings, the crew is not safe from the possibility of medical mishaps until successful conclusion of the recovery sequence, which is no simple matter in water landings. The history of on-target or near-target landings notwithstanding, the possibility still exists, however slight, that failure in one of numerous systems could require crews to make emergency escapes

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[2] Details on acceleration studies are in Volume II, Part 2, Chapter 5 of this publication.

or landings in any region of the globe. For this possibility, escape and survival equipment is provided in Soviet and US spacecraft.

Research programs are ongoing to define physiologic limits, and optimum protective devices and procedures, for survival situations possible after aborted landings, as added insurance for the safety of spacecrews. Again, it should be stressed that a long-term survival situation is extremely unlikely. In US naval experience with recovery of downed aviators, the longest time recorded until rescue, in the last several years, has been 24 h 45 min. With the highly organized, worldwide communication network monitoring the progress of the final stages of a space mission, it can be expected that rescue of spacecrews will always be accomplished at least as efficiently as the rescue of military aviators.

The rapid rescue of spacecrews may be more difficult, perhaps, when spacecraft make hard, land landings. Should a space capsule land off-target and in the open sea, it will take longer to recover the crew, but it should be no more difficult to locate them. With the use of modern rescue ships and aircraft and their strategic placement, any delays would likely be brief. Landing off-target on land, on the other hand, could complicate considerably the location and rescue process.

Experiments have shown that men can live under the most severe conditions, but those who are unaccustomed to climatic extremes may be significantly less able to tolerate these extremes than acclimatized individuals. It is important, therefore, to know the limits of physiologic and psychologic stability for the unacclimatized individual subjected to environmental extremes, so that training and equipment are the most effective for sustaining life in spacecraft emergencies.

The most reliable information concerning survival can be gained from studies of man under real-world conditions, equipped as he would be in a genuine survival situation. Research is ongoing to further understand environmental effects on the human body in the "survival" situation and the special problems posed by various survival scenarios where spacecrews could conceivably find themselves. These situations include survival in the desert, in the tropical ocean zones, and in the Arctic regions.

Long-Term Survival

Spacecrews can conceivably be faced with the prospect of long-term survival in arctic, tropical, or desert climates. The problems associated with each are unique. Protection from environmental extremes, principally by means of clothing, shelter, and maintenance of adequate water and food intake, may be crucial with the relative importance of these factors shifting with the survival scenario. For example, the most important protective measures will be: in the desert, against injury from the Sun and acquiring water; in the Arctic, contending with cold; in jungles, efforts directed primarily toward prevention of tropical diseases [32].

Arctic Survival

Cold is the greatest danger to which man is subjected in the Arctic [32]. A crew that has landed in the Arctic region must create protection against exposure to low temperatures and prevent supercooling and frostbite; first and foremost, this involves construction of temporary refuges from materials at hand. Such refuges are easily constructed in forested regions from tree trunks and branches, whereas in the tundra and on drifting floes, snow is good construction material. Burrows and caves can be excavated from large snowdrifts, and igloos can be constructed from snow blocks. Animal fat and dry moss can be used for heating a dwelling in unforested regions. Along the seacoast, one can generally find driftwood for fuel.

The essence of danger in exposing flesh to wind under cold conditions is illustrated by the well-known "windchill chart," shown in Figure 5. The chart indicates that under strong wind conditions, a survivor's exposed flesh may be in danger of frostbite at temperatures of the order of $-12.22°$ C (10° F).

It is particularly important to protect the extremities against cold; under its influence, body temperature initially changes insignificantly. At the same time, the temperature of the ex-

Estimated wind speed		Actual thermometer reading																							
	°F	50		40.0		30.0		20.0		10.0		0		− 10.0		− 20		− 30.0		− 40		− 50		− 60	
	°C	10		4.5		− 1.1		− 6.7		− 12.2		− 17.5		− 23.3		− 29		− 34.5		− 40		− 46		− 51	
		Equivalent temperature																							
mi/h	km/h	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
calm		50	10.0	40	4.5	30	− 1.1	20	− 6.7	10	− 12.2	0	17.5	− 10	− 23.3	− 20	− 29.0	− 30	− 34.5	− 40	− 40.0	− 50	− 46.0	− 60	− 51.0
5	8.05	48	8.9	37	2.8	27	− 2.8	16	− 8.9	6	− 14.4	− 5	− 20.5	− 15	− 26.1	− 26	− 32.2	− 36	− 37.8	− 47	− 43.9	− 57	− 49.4	− 68	− 55.6
10	16.1	40	4.5	28	− 2.2	16	− 8.9	4	− 15.6	− 9	− 22.8	− 21	− 29.4	− 33	− 36.1	− 46	− 43.2	− 58	− 50.0	− 70	− 56.7	− 83	− 63.4	− 95	− 70.6
15	24.1	36	2.2	22	− 5.6	9	− 12.8	− 5	− 20.5	− 18	− 27.8	− 36	− 37.8	− 45	− 42.8	− 58	− 50.0	− 72	− 57.8	− 85	− 65.0	− 99	− 72.8	− 112	− 80.0
20	32.2	32	0	18	− 7.8	4	− 15.6	− 10	− 23.3	− 25	− 31.8	− 39	− 39.4	− 53	− 47.2	− 67	− 55.0	− 82	− 63.3	− 96	− 71.1	− 110	− 78.9	− 124	− 86.7
25	40.2	30	− 1.1	16	− 8.9	0	− 17.5	− 15	− 26.1	− 29	− 33.8	− 44	− 42.2	− 59	− 50.6	− 74	− 58.9	− 88	− 66.7	− 104	− 75.6	− 118	− 83.3	− 133	− 91.7
30	48.3	28	− 2.2	13	− 10.6	− 2	− 19.0	− 18	− 27.8	− 33	− 36.1	− 48	− 44.4	− 63	− 52.8	− 79	− 61.7	− 94	− 70.0	− 109	− 78.3	− 125	− 87.2	− 140	− 95.6
35	56.3	27	− 2.8	11	− 11.7	− 4	− 20.0	− 20	− 28.9	− 35	− 37.2	− 49	− 45.0	− 67	− 55.0	− 82	− 63.3	− 98	− 72.2	− 113	− 80.6	− 129	− 89.4	− 145	− 98.3
40	64.4	26	− 3.3	10	− 12.2	− 6	− 21.1	− 21	− 29.4	− 37	− 38.5	− 53	− 47.2	− 69	− 56.1	− 85	− 65.0	− 100	− 73.3	− 116	− 82.2	− 132	− 91.1	− 148	− 100.0
(Wind speeds greater than 64.4 km/h (40 mi/h) have little additional effect)		Little danger (for properly clothed person)								Increasing danger				Great danger											
										Danger from freezing of exposed flesh															
Trenchfoot and immersion foot may occur at any point on this chart																									

FIGURE 5.—Windchill chart.

tremities decreases by −7.7° to −6.6° C (18°–20° F), circulation decreases appreciably, sensation is lost, and finally frostbite occurs at temperatures below the freezing point. Superficial frostbite is common on face, hands, and feet. Frostbite is the result of crystallization of tissue water in the skin and adjacent tissues. The depth and severity of the injury is a function of the temperature, the chill factor, and duration of exposure. Exposure of the extremities, usually feet, to wet conditions at temperatures above freezing for hours or days can result in damage to nerves, muscles, and blood vessels, commonly known as trenchfoot or immersion foot. Immobility of the extremity aggravates and predisposes toward the condition. The onset of frostbite is signaled by sudden blanching of the skin on nose, ears, or cheeks, which may be subjectively noted as a momentary tingling. Numbness of face, hands, or feet in severe cold is the beginning of frostbite. Particular care should be taken not to allow hands to become wet with kerosene, gasoline, alcohol, or other fluids which freeze below 0° C (32° F), which quickly causes frostbite and freezing. Footgear must be roomy to permit easy movement of toes for continous flexion and extension to increase circulation, which delays frostbite and freezing.

Clothing is of great importance at subarctic and arctic temperatures. The primary function of protective clothing is to insure adequate ventilation for the escape of both insensible and sensible perspiration and provide an insulating zone of dead air space around the body. This zone must be compartmentalized in sufficiently small pockets so that currents of air will not be set up by movements of the body, dispersing heat [9].

Dry, multilayered clothing has excellent heat insulating properties, but insulation is lost rapidly as clothing becomes wet. Caution must be exercised to avoid profuse sweating, since during later periods of diminished activity, there is excessive heat loss when the vaporized perspiration condenses on the cold outer cloth, permitting direct heat transfer by conduction. Because retention of vaporized perspiration in clothing diminishes the effect of the sweat mechanism in cooling the skin surface, increased production of perspiration ensues and a potentially dangerous situation develops.

Man's energy expenditures at rest under arctic conditions rarely exceed the usual expenditures; that is, those observed in the middle latitudes. However, performing physical work in heavy clothing or in a deep snow cover, while impeding movement, greatly increases energy expenditures. Therefore, an individual may find that he is wearing more insulation than needed during work and less than needed at rest. To reduce sweating and moistening the inner layers of clothing, some clothing may be removed and cuffs and collars unbuttoned when performing physical work.

Frostbite injuries should be treated immediately to prevent progression to freezing injury. Various parts of the body that are frostbitten may be treated by using other parts to warm the affected area. Frostbite should never be treated by rubbing with, or without, snow or slush. Although frostbitten tissues swell and blister, similar to burned tissues, the tissues should not be treated with ointment as with burns. Later, when the frostbitten area begins to peel, as sunburned skin does, any bland lanolin-based ointment will allay discomfort. Frostbitten body parts should not be warmed directly near fire since the injured tissue may be further damaged by the heat. The proper treatment is to melt snow or ice in a suitable container and immerse the injured part in tepid water. Quick thaw has proved clinically successful for ultimate recovery of freezing injuries. Water temperatures of 40° to 43° C are required.

Snow blindness is another physiological problem encountered in the Arctic, which results from burning the mucous membrane of the eyes by ultraviolet light reflected from the snow. The disorder follows an acute course, accompanied by marked pain, flow of tears, photophobia, and, with lack of adherence to precautionary measures, can be repeated many times. It is extremely important to realize that snow blindness can occur on cloudy as well as sunny days. The most reliable protection is afforded by light-filter eyeglasses or a mask or bandage with thin slits for the eyes.

Sufficient water can be obtained in the Arctic without any special problems since ice and snow are abundant. Spacecrews are provided with rations (to be described) to satisfy nutritional requirements should they be forced down in a remote region, and fish can serve as a supplement if needed.

Survival in Desert and Tropical Climates

The high temperatures and solar radiation in the desert exert an extremely unfavorable effect on the human body. Under these conditions, man receives up to 1256 J/h (300 cal/h) or more of exogenous heat. At temperatures greater than 33° C there is virtually no heat transfer by convection and radiation. Consequently, under desert conditions the body's normal heat balance is maintained by sweating.

Water losses with perspiration at rest at an air temperature of 37.8° C (100° F) are up to 300 g/h. The losses increase considerably (up to 1 l or more) during physical work and when moving on sun-parched ground. As a result, during the day the body can lose from 4 to 8 to 10 l of fluid during heavy work. With adequate water consumption the body can contend successfully with a thermal load without a water deficit. However, with a small water supply and no natural water sources, it is not possible to compensate for water losses. Sooner or later this will result in dehydration. The rate at which this occurs may vary, but it will govern the duration of man's survival in the desert.

The process of dehydration creates thirst, which is first manifested by a conscious stress, which later becomes overwhelming. After prolonged water deprivation, the urge to drink may not be sufficient to maintain hydration in hot climates. Unabated water loss soon leads to physical and mental deterioration. Death ensues in a matter of hours in a highly unfavorable environment. Under ideal conditions, man can survive for as long as 14 d without water [22]. Figure 6 illustrates the symptoms which accompany dehydration.

The energies of a space crewman downed in the desert must be directed, on the one hand, to creating protection against exposure to exogenous heat (erecting improvised tents, wearing clothing), if he is to survive, and, on the other hand, to reducing body heat production. His water intake will play an extremely important role.

With a single intake of 1 l of water, a considerable part (371±207 ml) is eliminated by the kidneys [16]. However, if this same quantity of water is ingested in 83 ml portions, the renal losses will be only 82±29 ml; that is, when drinking small quantities, the body uses almost all the ingested water in perspiration.

The effects of hot, dry desertlike conditions were observed in another study conducted in the Soviet Union in 1969. Subjects were exposed to temperatures of 46° to 48° C (114.8° to 118.4° F) in the shade and provided with low calorie (900 kcal) diets. The water consumption was limited, amounting to 1–2.5 l/d [34].

The best way to conserve water, in the desert, is to control sweating. Figure 7 shows sweating rates for various activities performed in the desert at an air temperature of 38° C (100° F) dry bulb [24]. The advantages of sitting quietly in the shade in the daytime and doing any necessary walking at night are made clear from these data.

Limited water supplies should be rationed and sipped four to eight times a day. Since eating hastens dehydration (digestion requires water which forms urine to remove waste products), a normal amount of food should not be eaten unless the water ration is 1.9 to 2.8 l daily. Preference should probably be given to carbohydrate, if there is a choice in food selection. Water should be purified before drinking by boiling or with water purification tablets or a small amount of an iodine solution, provided in survival kits.

In the tropics, besides the problems of obtaining sufficient food and water, conserving energy and minimizing water loss (a less severe problem with tropical humidity), the problem of protection from insects and predators must also be dealt with. For maximum protection against insects and pests, many of which carry disease, clothing that covers the entire body should be worn at all times, especially at night.

The smallest scratch can cause serious infection within hours; all scratches require immediate first aid. Skin exposure should be minimized by tucking trouser cuffs into the tops of boots. Sleeves should be rolled down. Both clothing,

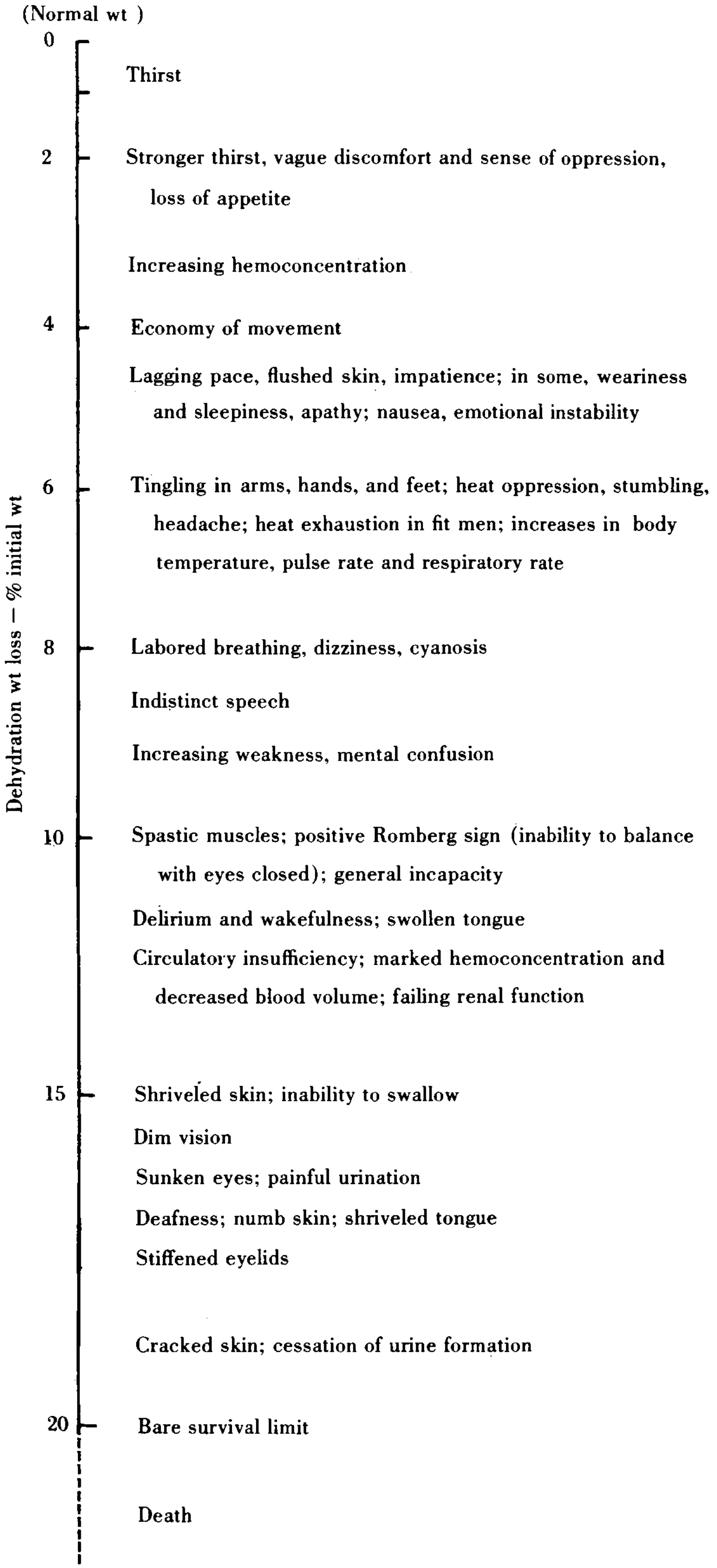

FIGURE 6.—Signs and symptoms of dehydration. (Based on data of [14]; in [37])

which should be removed in the morning, and the skin should be inspected for evidence of ticks, chiggers, insects, leeches, or other vermin. Clothing worn loosely will help keep the body cool; trapped air makes good insulation. In open country or in high grass, a neck cloth should be worn or a head covering improvised for protection from the Sun and/or dust. In the desert clothing provides protection against sunburn, heat, sand, and insects, conserves sweat, and delays dehydration.

Survival in the Tropical Zone of the Ocean

The tropical zone of the ocean is characterized by high air temperatures combined with considerable moisture content. This combination causes functional shifts in a number of body systems, especially in the heat regulating system. Intensive sweating leads to the body's loss of a great quantity of fluid which carries the threat of exhaustion by dehydration.

Dehydration can occur rapidly while awaiting rescue on the open sea. The rapid rolling motion of the sea can produce severe seasickness. Accidental ingestion of petroleum products on the water surface or of seawater will aggravate vomiting, with resulting great water losses. Should this condition be accompanied by diarrhea, the resulting dehydration could become a matter of grave concern in a very short time.

Ewing and Millington [11] suggest procedures which can minimize loss of body water through sweat production and insensible water diffusion through the skin. Since such loss is directly related to skin temperature, the skin must be kept cool if the loss is to be minimized. The procedures include:

1. Erecting a barrier between the Sun and the body such as a parachute cloth parasol or awning.
2. Avoiding unnecessary exercise and, thus, increased skin blood flow and sweat production.
3. Directing any breezes to the skin.
4. Keeping clothes dampened with sea water to increase evaporative cooling from other than body water.
5. Occasionally immersing the body completely in the sea. Caution should be observed here, however, since a weakened man might not be able to reboard the liferaft.

The effectiveness of moistening clothes and remaining in the shade as a means of minimizing water loss has been demonstrated in a number of studies [33, 34]. When nude subjects were exposed to the Sun at temperatures of 45° to 50° C (113° to 122° F) water losses of 350 to 600 g/h were noted. Moistening the clothes reduced this to 100 to 150 g/h and remaining under an improvised tent reduced the loss to 200 to 300 g/h.

Since survival at sea may depend on conservation of body water, great care must be exercised in developing the appropriate "water management program." Drinking seawater can produce fatal results. Seawater can be recommended only in small quantities *after* it has been diluted with three to six parts of fresh water, and then only for the replacement of salts lost through seasickness and induced vomiting [21]. Seawater introduces a hypertonic solution into the circulation, causes intracellular water to move into the extracellular space, and thus throws a load on the kidneys to remove the excessive water. While the increased electrolyte is partially removed by renal filtration, the body experiences a net gain in electrolytes which causes constant cellular space dehydration which must eventually cause death [11]. In addition to its basic dehydrating effect, drinking seawater also is likely to lead to intestinal discomfort followed by diarrhea. If large amounts are ingested, mental disturbances can follow.

Urine should not be drunk, however desperate the circumstances. Drinking urine accelerates intracellular dehydration by introducing excessive electrolytes into the body water which simply accelerates the dehydration process.

Finally, the survivor in the open sea must not be overzealous in conserving water supplies. The longer an individual remains reasonably fit, the better his chances of survival. Simply put, it is better to drink a cupful of water for 10 d and be relatively fit when the water is gone, than it is to ration it to a couple of teaspoons per day and die of dehydration at the end of 1 week, with some water supplies remaining.

Water supplies can be supplemented by precipitation (rain, dew), by fluid squeezed from the flesh of fish which have been caught, and by employing special chemical and solar distillation apparatus for freshening seawater.

Food supplies in the survival kit can be supplemented with fish. But, again, great caution must be exercised because in the tropical zone, there are many poisonous fish. One must avoid eating flesh of fish with a bright color, unusual spherical configuration, or with spines or growths on the skin. Regardless of the external appearance of the fish, it is recommended that the milk, eggs, and liver not be consumed.

Sharks constitute another serious danger for persons in a lifeboat or on a raft in the tropical zone. During one US Project Gemini mission, sharks were seen swimming in the vicinity of the space capsule, and the shark repellant used in this instance was not particularly effective. No truly reliable means have been developed for protection against sea predators with great aggressiveness and voracity. Although sharks usually do not attack boats, it is recommended,

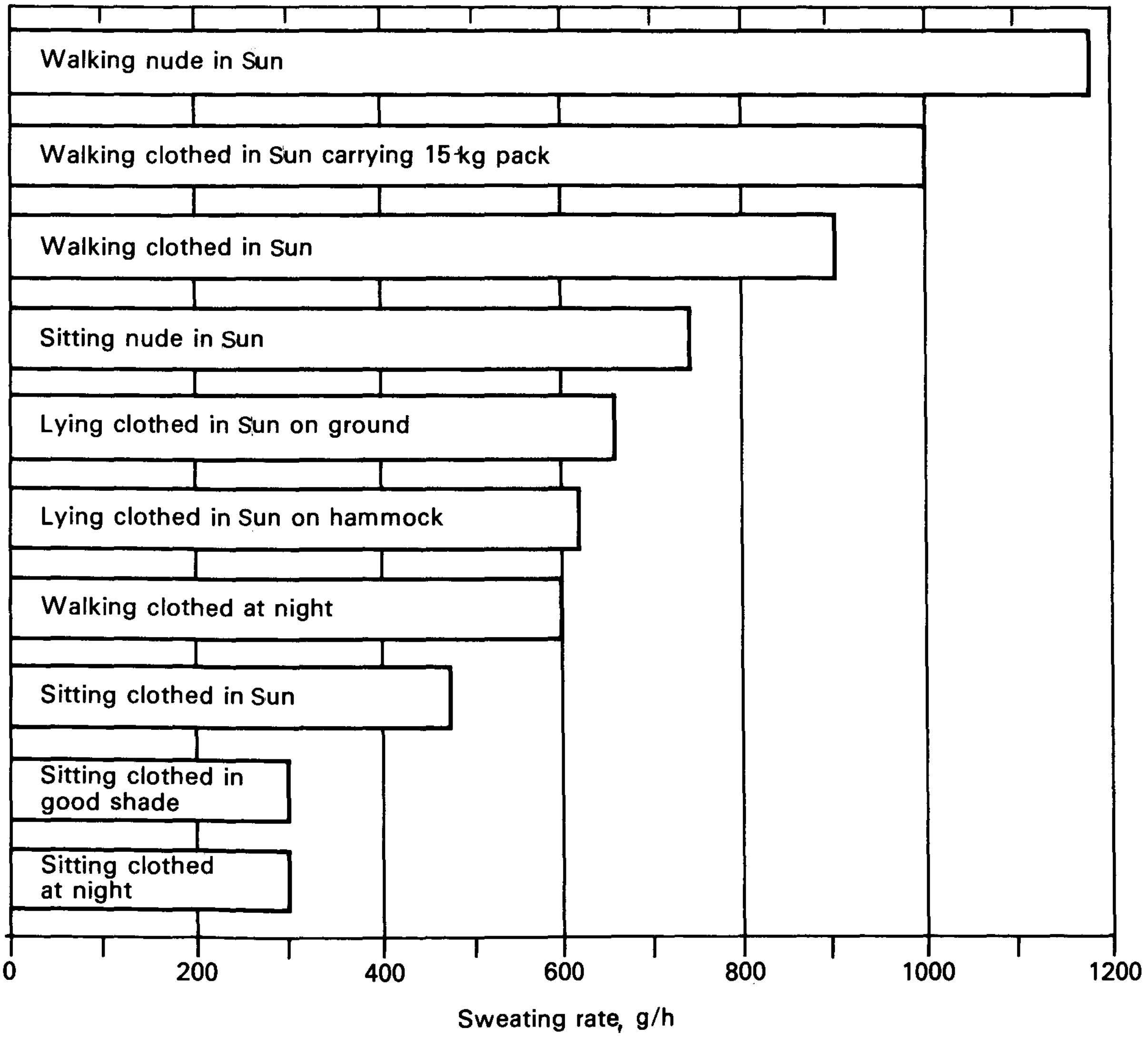

FIGURE 7.—Sweating rates shown for various activities in the desert at an air temperature of 38° C (100° F) dry bulb [24].

nevertheless, that no actions be taken which could incite their attack. For example, when sharks appear near a boat, fishing should stop at once, and wastes must not be thrown into the water.

Survival Rations and Survival Kits

Optimum food rations for survival situations has been the subject of a considerable amount of study, but again, it should be stressed that the type of food carried is probably of little importance since man can easily survive for a day or two without food until he is rescued, and it is unlikely that the time needed to rescue a spacecrew will exceed this period. Still, since a long-term survival situation is theoretically possible, a short discussion of the rationale on which emergency rations have been developed is included here.

While food is rarely the most critical factor in survival, it can play a key part. Food must provide calories sufficient for basal metabolism and for the increased metabolic load associated with physical exertion and exposure to a cold survival situation. The precise caloric requirement depends chiefly on the amount of muscular work performed and the temperature at which the work is done. It may range from 1000 cal/d for a sedentary individual to as much as 7000 cal/d for a man in northern latitudes doing extremely hard work. Figure 8 illustrates the effect of ambient temperatures on caloric intake.

Only in very long-term survival is maintenance of adequate dietary protein critical. As a rule, the emergency food ration is made of high-calorie products which can be used either after cooking or in the dry form. However, the shortage of space in the survival kit container makes it necessary to use preserved products which have maximum caloric content with minimum weight and volume. Some investigators feel that the emergency food ration must strictly maintain the ratio between the basic nutrient substances [10], but this point of view is not generally accepted. Others proceed on the basis that a stay under survival conditions is relatively short, and therefore an increase in the caloric content of the ration is more important than strict observation of the ratios between the food components: fats, proteins, and carbohydrates.

The view concerning the principles of the emergency food ration makeup was supported by successfully testing a ration which was intended for regions with a cold climate. In this ration (compared with the regular ration), by reducing the carbohydrates from 711.4 to 627.7 g, the amount of protein was increased from 141.1 to 184.5 g and fats from 179.8 to 279.8 g. This made it possible to increase the caloric content of the ration from 4654.0 to 5930.0 kcal. In a laboratory test, one group of individuals was fed the experimental ration and the others received a regular ration for 7 d. Results showed that the average weight loss of subjects fed the experimental ration was 1.2–2.9 kg while subjects in the second group lost 1.9–3.5 kg. Despite the increased content of fat and protein in the ration, none of the subjects showed any indications of disturbances of fat and protein metabolism, indicated by data from laboratory studies of urine and blood. Those who had eaten the experimental ration showed a decrease in the amount of total nitrogen excreted in the urine [30].

The developers of other emergency rations have given preference to carbohydrate products.

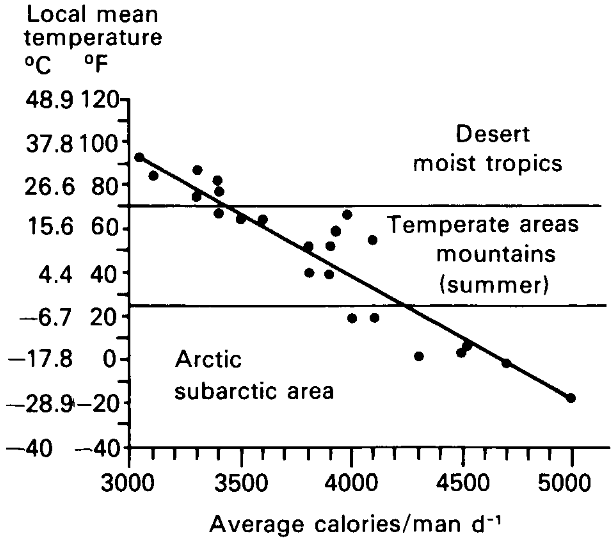

FIGURE 8—Voluntary caloric intake, North American troops. (Averages are for 50 or more men with abundant food supplies in different parts of the world.)

During subcaloric nutrition, the energy consumption of the organism is made up through the deposits of fat. The use of endogenic fat is accompanied by formation of unoxidized products (acetone, β-oxyoleic acid). For more complete utilization of endogenic fat, it is necessary to have an additional amount of readily assimilated carbohydrates, no less than 60–70 g/d [20]. These data were used as the basis for developing a diet proposed by Komarevtsev, Pobol', and Kumanichkin [17].

This experimental diet, intended for survival at sea, was composed of sugar and vitaminized candy drops. To test the ration, 16 sailors spent 4 d in inflated rafts at air temperatures of 14–19° C with a water temperature of 15° C. On the first day, the subjects did not receive any food. Beginning the second day, the crew of the first raft was given the experimental ration, consisting of 50 g sugar and 100 g candy containing 225 mg of vitamin C, 5 mg of vitamin B_1, 5 mg of vitamin B_2, 2.5 mg of vitamin B_6, 10 mg of vitamin PP, 25 mg of folic acid, 25 mg of pantothenic acid and 10 mg of para-aminobenzoic acid. The caloric content of the ration was 600 kcal. The sailors aboard the second raft received 150 g candy made from maltose. The subjects aboard the third raft were fed concentrates, bread, butter, and received 1700 kcal/d. The water ration for all three groups was limited to 0.5 l/d. Medical examination of the subjects involved checking the cardiovascular and respiratory systems, in conjunction with a number of analyses aimed at determining the urinary content of total nitrogen, vitamins, amino acids, oxygen, chlorides, creatinine, and acetone.

Results of examinations after the experiment showed that the sailors on the first raft had the most significant weight losses, i.e., those who had been fed the experimental ration; the average weight loss was 4.5 kg. The sailors on the second raft lost an average of 3.7 kg. The subjects who had been fed a ration with relatively high caloric content lost an average of 0.5 kg. Those who had been on the experimental diet showed more pronounced decrease in the amount of nitrogen, amino acids, and total urinary nitrogen, indicating better retention of proteins by the organism. All showed an improved vitamin supply, as a result of active administration of vitamins. Hence, this ration was found to be the best for conditions of independent existence aboard liferafts at sea.

Survival kits provided to Soviet cosmonauts were typified by the Vostok survival kits which included a radio with a range of several thousand km, day/night signals for alerting recovery helicopters, a portable stove with solid fuel, windproof and waterproof matches, a specially designed navigation sensor and small-scale map, water for several days and chemical purifiers, rubber one-man rafts with automatic inflation capability, medicines, slings, and similar items for first aid, and lightweight, high-calorie food.

US Apollo astronauts carried these survival items: survival lights, desalting kit, sunglasses, radio beacon, spare radio beacon battery and spacecraft connector cable, survival knife, water container, sun lotion, utility knife, survival blankets and utility netting, a three-man survival raft with carbon dioxide inflators, a sea anchor, sea dye markers, sun bonnets, a mooring lanyard, mainlines and attachment brackets. This survival kit was designed to provide a 48-h postlanding (water or land) survival capability for three men between 40° north and south latitude. Food was also provided for emergency use.

In conclusion, it should be stressed that provisions to help the astronaut or cosmonaut through a survival situation will be effective *only* if they are appropriately used. Survival training is, therefore, an important phase of astronaut/cosmonaut preparation. Part of this training should be devoted toward indoctrination in "survival mentality;" perhaps the key ingredient in the survival scenario is the survivor's mental attitude. Depression, monotony, physical and mental fatigue are to be expected and must be coped with. An attitude of "never-give-in" optimism may be crucial to the successful conclusion of a long-term survival situation.

Recovery Techniques

Since the downed astronaut or cosmonaut will, in all likelihood, be rescued very quickly, his knowledge of rescue techniques may be even more important than his knowledge of using survival kit items.

FIGURE 9.—Billy Pugh rescue net.

Egress from space capsules in heavy seas is not a simple task, particularly for an astronaut who may be weakened from exposure to weightlessness. This procedure becomes further complicated if seasickness supervenes. Capsule egress, like all other aspects of spaceflight missions, is practiced prior to flight by spacecrews in the open sea. During such training, astronauts are instructed, among other things, in the proper way to inflate individual flotation gear. Flotation gear is provided since a space suit may tear during capsule egress, fill with water, and cause the wearer to sink rapidly.

During capsule egress, another problem is the possibility of entanglement in the shroudlines of the capsule parachutes. Ideally, shroudlines are automatically guillotined, and parachutes sink rapidly to pose no threat to the crew leaving the capsule. If the guillotine mechanism is ineffective, care must be taken by both rescue personnel and spacecrews to avoid entanglement. Survival knives provided in the survival kit may be used by the astronaut to cut shroudlines, if the spacecraft lands out of range of recovery vehicles and personnel.

As soon as capsule egress has been accomplished in normal operations where swimmers are present to assist the crew, transfer of the individual from the capsule to the liferaft is next. Here again, great care must be exercised because the astronaut may be in a deconditioned, weakened state. It is imperative and standard practice in transfer in the US program for a swimmer to be on either side of the astronaut to assist him into the liferaft. The same caution must be exercised when transferring the individual from the liferaft to the helicopter rescue device, the Billy Pugh net.

The Billy Pugh net is the latest of a number of devices for spacecraft recovery operations. Early in the US space program, rescue seats and rescue slings (commonly known as horse collars) were used. The Billy Pugh net, shown in Figure 9, is superior to either of the earlier rescue devices for spacecrew recovery operations. There are several reasons. It is sufficiently large to permit two men to be lifted out of the water simultaneously if desired. Its principal advantage is that it eliminates the danger of a rescuee's falling during the recovery operation. Unlike many other helicopter rescue devices, the Billy Pugh net is a nonconductor of static electricity, eliminating one further potential problem.

Summary

The American projects Mercury, Gemini, Apollo, and Skylab, and the Soviet Vostok, Voskhod, Soyuz, and Salyut programs have demonstrated that reentry and landing of spacecraft, both on land and at sea, pose no significant medical problems for crews. The absence of specific difficulties during these operations is attributable to the design of spacecraft systems and the training of both spacecrews and recovery teams. On the basis of ground-based testing it is believed that there is low probability of injury during an aborted reentry and landing. Nevertheless, the problems which might be encountered after such a landing continue to be assessed by both the US and the USSR so that optimum equipment and training can be provided for all future missions, and survival of crews insured.

When future programs extend the duration of space missions, attendant stresses, particularly weightlessness exposure, could conceivably influence the physiological and medical aspects of reentry and landing. These stresses are being carefully assessed and the necessary counter measures evaluated and designed, for future missions, which was also done for the earlier space flights.

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Chapter 14

PROTECTION OF CREWS OF SPACECRAFT AND SPACE STATIONS[1]

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The history of manned space flights dates from slightly more than 10 years. Along with glorious and thrilling achievements, sad pages have already been written. The tragic events of the Apollo 204 fire, and the Soyuz 1 and Soyuz 11 disasters have demonstrated the real threat of serious accidents in space flight, so that development and use of effective measures to rescue crewmembers in spacecraft accidents are urgently needed.

Implementation of rescue work in space is a multifaceted, difficult problem. Because of great expense and the need to encompass almost the entire Earth, atmosphere, and space, certain aspects can be implemented only within the framework of international collaboration [11, 19]. The Soviet-American agreement on cooperation in the exploration and use of outer space for peaceful purposes (May 24, 1972), which provides for joint development of rescue measures for astronauts, is a vivid example of common interests in space cooperation.

This chapter presents a survey of research on life support for astronauts in emergency situations during flight when depressurization of the spacecraft cabin, fire, and failure of air regeneration and conditioning systems of manned compartments occur.

Other emergency situations and their consequences—accidents at launch, insertion into orbit, descent, splashdown, and landing stages, and depletion or failure of on-board and emergency water and food supplies, radiation damage, serious illness of crewmembers, and the like—are discussed in corresponding chapters of this work.

The rapidity and sharply pronounced deleterious effects of these emergencies require immediate control measures on-board the spacecraft or orbital station when the disaster occurs. In these cases, it is impossible to use assistance from another spacecraft or special rescue system, such as space shuttle, space tug, or lunar orbiting vehicle for emergency rescue (LOVER) [25, 31]. The time required just for maneuvers in approaching and docking with the spacecraft in trouble is greater than the time available for rescue work on-board. For this

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[1] Translation of, Obespecheniye Zhizni i Zdorov'ya Ekipazhey Kosmicheskikh Korabley i Stantsiy v Avariynykh Situatsiyakh, *Osnovy Kosmicheskoy Biologii i Meditsiny* (*Foundations of Space Biology and Medicine*), Volume III, Part 4, Chapter 14, Academy of Sciences USSR, Moscow. 1973, 64 pp.

Experimental data of Soviet and American scientists have been used in preparing this chapter, and papers have been cited which were presented at international symposia on space rescue work. The compilations of Charles A. Berry, USA, and A. I. Shaposhnikov, USSR, are gratefully acknowledged.

reason, primary attention is focused here on the effectiveness of on-board rescue resources: life-support system (LSS), full and partial pressure space suits, and pressurized compartments.

CREW PROTECTION AGAINST SPACECRAFT DEPRESSURIZATION

The problem of assuring safety of space flights was not entirely solved with implementation of the concepts of Tsiolkovskiy—the creation of a pressurized cabin with artificial atmosphere to protect cosmonauts from the vacuum of space [59]. The possibility of depressurization with subsequent decompression constitutes a potential danger in space for any sealed structure under excessive pressure.

Depressurization of the cabin can occur if its walls are damaged by meteorites, impact with other spacecraft or parts of previously launched spacecraft, and as a result of failure in operation of pressure regulators and valves during docking and undocking or in a hard landing on the Moon or planets without atmospheres [9, 10, 24]. Depressurization will probably increase with increased duration and distance of space flights, enlargement of orbital stations (especially of interplanetary craft), as well as an increase in their number in space. Furthermore, there may be deliberate depressurization of a spacecraft for extinguishing a fire or for rapid removal of toxic substances from a manned compartment [9, 30].

Loss of vital cabin atmosphere is the immediate and, to the crew, most hazardous consequence of depressurization; the drop in total pressure results in decompression, and oxygen partial pressure decrease results in hypoxia. When there are critical levels of decompression and drop in Po_2, serious, fatal pathologic states develop in the unprotected organism: oxygen starvation of body tissues (acute hypoxic hypoxia), decompression sickness, and tissue emphysema (ebullism). Explosive decompression, which occurs within fractions of a second, also poses the possibility of internal and external trauma. Internal trauma is caused by rapid increase of excess pressure due to expansion of gases in gas-containing cavities and organs whose walls are resilient and elastic when external pressure drops. This is associated with hyperdistention and rupture of tissues and vessels with all their aftereffects.

Damage can occur in the lungs, which are distinguished by their fine structure, large air content, and connection with the atmosphere through a complex system of air pathways. Rupture of lung tissue occurs from rapid distention of the lungs by more than two or three times and an increase in excess intrapulmonary pressure to 80 mm Hg or more. When there is great accumulation of gases in the gastrointestinal tract, explosive decompression may also lead to trauma of the crewmembers' abdominal organs.

External trauma during decompression is related to rapid movement of the astronaut near the decompression site caused by the flow of air, and blows he sustains from solid and sharp protruding parts of the cabin equipment. Furthermore, trauma can be sustained by loose objects moving about rapidly in the sudden flow of air. Weightlessness enhances these movements and can cause trauma when a spacecraft cabin is depressurized. The pathogenesis and clinical syndromes of disturbances during decompression are discussed in detail in Volume II, Part 1, Chapter 1. However, only matters pertaining to protection and rescue of the crew in case of cabin depressurization will be discussed here.

Life-Support Systems (LSS)

Life-support resources which can be used in extremely rarefied atmosphere and for protection in space are: emergency systems with a reserve of air and oxygen, full-pressure suits, and pressurized capsules or compartments (pressurized structures). In depressurization of the spacecraft cabin, these life-support resources give reliable protection from the traumatizing effect of explosive decompression and compensate for the shortage or total absence of oxygen and pressure.

An important factor in determining the choice of protective and rescue devices for a spacecraft crew undergoing decompression, especially if explosive, is the time in which it is possible to effect either their own rescue or rescue by other crewmembers [9, 27, 57].

The time available for independent rescue depends entirely on the time of active "useful" consciousness, which is the interval from the moment of decompression to marked impairment of fitness ("time of useful consciousness" (TUC) [9, 10], or "reserve time" [57]).

Data from numerous studies to determine TUC during rapid decompression at an altitude equivalent in pathologic effect to the vacuum of space are cited in the comprehensive surveys by von Beckh [9, 10]. TUC in human beings averages 12 s, ranging from 10 to 15 s (Fig. 1). The gas composition of the environment (pure oxygen or air) prior to decompression does not have a discernible effect on the duration of TUC at high altitudes.

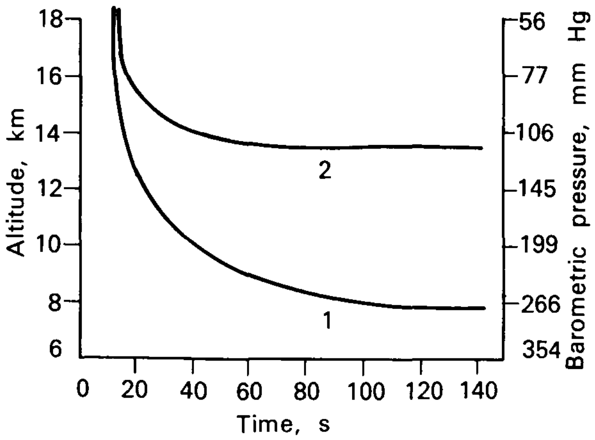

FIGURE 1.—"Time of useful consciousness" (TUC) at different altitudes when breathing air and oxygen following rapid (< 1 s) decompression from sea level [17]. Curve 1, breathing air; curve 2, breathing oxygen.

It is unlikely that in such a short period, under the exceptionally hostile conditions of space vacuum accompanied by severe emotional stress in the emergency situation, the cosmonaut will be able to take effective rescue measures (put on protective clothing, move to the pressurized compartment, correct cabin damage). Under such conditions, independent rescue is feasible in practice only if additional life-support measures can be activated automatically when cabin pressure drops.

Emergency air supply. In the satellite spacecraft Vostok, the emergency air supply system was turned on automatically when cabin pressure dropped to 530±30 mm Hg (altitude of about 3000 m). With a further pressure drop to 430±30 mm Hg (4500 m), there was automatic delivery of oxygen, accompanied simultaneously by a flashing signal to close the pressure suit helmet. The oxygen regulator of the full-pressure suit was set to deliver a gas mixture to the helmet at a rate of 40 l/min with increase in percentile content of oxygen as the cabin pressure decreased. At a cabin altitude of over 9000 m, pure oxygen was delivered to the helmet, and pressure of 0.4–0.28 absolute atmosphere (ata) was maintained [54, 60].

The emergency system in the command module of the Apollo spacecraft can maintain a pressure of 170 mm Hg for 5 min for a hole up to 13 mm in diameter in the spacecraft skin. This is enough time for astronauts to don full-pressure suits [29, 54, 61].

Another independent protective measure from cabin depressurization is either constant use of the pressure suit throughout the flight or donning it prior to the most important stages (launch, docking and undocking, Moon landings, intentional depressurization).

Full-pressure suits. Full-pressure suits, which automatically provide vital parameters of the atmosphere and normal physiologic conditions for respiration and hemodynamics during decompression [27, 45, 61], are at present the most effective individual protective outfit for space flight. Full-pressure suits allow human beings to be exposed to atmospheric rarefaction [5, 26, 27] for many hours and even many days by maintaining the required excess pressure level and Po_2 in the inspired air, and appropriate conditioning of air within the suit. This is also confirmed by experiments in which the subjects in full-pressure suits under excess pressure of 300 mm Hg remained in a low pressure chamber at a pressure of 5–6 mm Hg (altitude of 35 km) for 7 d 17 h [26]. These investigations demonstrated in principle the feasibility of 7-d life support for a cosmonaut using a full-pressure suit for his own rescue in emergency decompression of a spacecraft cabin.

Significant experiments involving extravehicular activity (EVA) of cosmonauts in full-pressure suits in space, especially on the Moon, demonstrate convincingly the high degree of effectiveness of the full-pressure suit not only as reliable protection but also for performing intensive work under the stress conditions of space vacuum [52, 54]. There is no doubt that the cosmonaut, wearing a full-pressure suit, can perform specific acts to save not only himself, but also other crewmembers if the cabin is depressurized. Detailed information about full-pressure suits is given in Part 1, Chapter 7, of this volume.

Partial-pressure suits. The partial-pressure suit (PPS) may also be used to protect cosmonauts from decompression. The chief elements of the PPS are: pressure helmet, altitude pressure suit, and oxygen breathing equipment. The PPS provides poorer physiologic conditions for respiration and hemodynamics than full-pressure suits because of the deficient design of the system for compensating excess intrapulmonary pressure. This applies to outfits with a mechanical capstan tension system for the suit shell, which exerts uneven counter-pressure on the body, limits the respiratory excursions of the chest, and elicits local skin injuries and pain. As a result, a man can wear a PPS from 10 min to several hours, depending on its construction, in an extremely rarefied atmosphere [36, 60, 61]. Outfits which allow prolonged stays at high altitudes are those in which the mechanical system of counter-pressure on the body is supplemented or replaced by a pneumomechanic system: bladders connected to the pressure helmet and usually placed in the region of the trunk and proximal parts of the extremities [61] (Fig. 2).

At the same time PPS outfits are smaller and weigh less than full-pressure suits, allow better mobility, and do not require constant ventilation, especially at high altitudes, where heat transfer occurs through vacuum evaporation of sweat from the body surface [20]. These operational advantages make PPS outfits tentatively advisable as emergency rescue aids in short space flights, where the duration of protective action after decompression of the cabin amounts to minutes or a few hours.

This assumption has also had experimental confirmation [21, 37, 38]; subjects, wearing PPS outfits with a pneumomechanic counter-pressure system, remained in a hypobaric chamber for 2–4 h at altitudes equivalent (according to pathologic effects) to space altitudes (35–40 km) after both controlled and explosive decompression (380 mm Hg in 0.2 s). The subjects periodically performed work of moderate intensity (climbing a ladder) for 10–20 min/h. The pressure level maintained in the suit (170–180 mm Hg) provided adequate oxygenation of blood. To prevent altitude decompression sickness, preliminary denitrogenation was performed, or pressure in

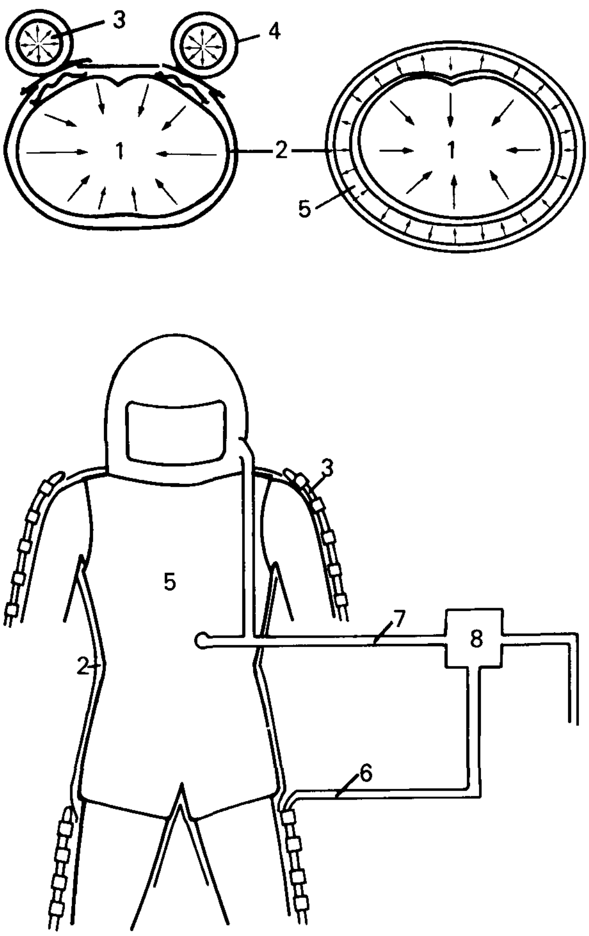

FIGURE 2.—High-altitude outfit (partial pressure suit) with a mechanical (top left), pneumomechanical (top right), and combined (bottom) systems of excess intrapulmonary pressure compensation [6]. 1. trunk of body; 2, suit covering; 3, tension [capstan] device chamber; 4, tape; 5, respiration compensating chamber; 6, 7, O_2 delivery hoses to chambers and pressure helmet; 8, oxygen regulator.

the suit was raised to 260 mm Hg during the first hour of exposure to high altitude. Successful performance in most of these tests indicated the high effectiveness of this life-support aid under simulated accidental depressurization of an aircraft cabin.

Combined use of a full-pressure suit and PPS outfit during space flights is also under consideration [51]. The PPS is used as a relatively convenient emergency aid that does not tire the cosmonaut throughout flight in a pressurized cabin and for the first few minutes after its depressurization. For a subsequent prolonged stay under vacuum conditions and for the performance of rescue work, the cosmonaut should move to the pressurized compartment and change into the full-pressure suit. Wearing the full-pressure suit, he initiates the necessary measures to rescue the other crewmembers, restore cabin pressure, and complete the flight.

The feasibility and desirability of using PPS outfits as rescue aids in prolonged space flights require special investigation. There is reason to believe that the physiologic effectiveness of PPS outfits for emergency depressurization of the spacecraft will be diminished under these conditions because of: (1) deterioration of respiratory tolerance under excess pressure caused by diminished functional reserves of the cardiovascular system during prolonged weightlessness [12], and (2) poorer compensation of excess suit pressure caused by decreased perimeters of the trunk and extremities resulting from body weight loss (dehydration, muscular atrophy, diminished fat depots). These factors must be considered when using PPS outfits with a mechanical system for compensation of excess intrapulmonary pressure in long-duration space flights.

Total Rescue Time

Full-pressure suits, and the most effective PPS outfits can be used by cosmonauts not only for their own protection but also to rescue other crewmembers in case of accidental depressurization of the spacecraft cabin. Under such conditions, it is extremely important to know the critical time during which the main physiologic functions are preserved and independent recovery is possible, i.e., the critical time available for recompression. The period from the moment of decompression until the possible spontaneous recovery of physiologic functions suppressed under vacuum conditions, is called "total rescue time" [9] or survival time [34]. In experiments on animals, this interval is defined as the period from the start of decompression to total respiratory arrest. As applied to accidents in space, "total rescue time" includes "time of independent rescue" or "time of useful consciousness" and "time of rescue by others" [11].

Surveys by von Beckh [9, 11] provide experimental data obtained during simulation of damage to the full-pressure suit in space or depressurization of a manned spacecraft compartment.

Experiments with chimpanzees [32] were especially interesting; animals trained in certain behavioral skills were exposed to decompression in 0.8 s from an altitude of 10.6 km to 46 km after 4 h denitrogenation (respiration of 100% O_2). Exposure to the final altitude for 5 s to 4 min was followed by recompression in an oxygen environment to 10.6 km. The period in which developed behavioral skills in the chimpanzees were preserved, comparable to the "time of useful consciousness" in human beings, averaged 12 s. If the animals remained at the final altitude for no more than 180 s, they made an independent recovery of all recorded physiologic indices 4 h after recompression and, particularly important, recovery of the entire set of behavioral reactions, although the period of total inhibition of these reactions had lasted 20–30 min.

On the basis of these investigations, and allowing for the development of a "safety reserve," the author estimates that the "total rescue time" during decompression in space constitutes 120–150 s. This means that in depressurization of the spacecraft or damage to the pressure suit, the cosmonaut should enter the pressurized compartment within no more than 120–150 s and submit to recompression up to the maximum possible on-board pressure with mandatory normal oxygen supply. If these conditions are met, recovery of vital activity and work capacity can be expected.

It is difficult to assess the validity of experiment results on chimpanzees as extrapolated to man; but it is not reasonable to expect a longer "survival time" for human beings under these exceptionally extreme conditions. There could only be a question of reducing the time required to protect and rescue crewmembers who have suffered decompression in space.

Chimpanzees were exposed to decompression after prolonged denitrogenation in an oxygen environment under Earth-normal and low pressure. Other investigators [34, 36], using dogs as test animals, where decompression was conducted without prior denitrogenation, found a considerably shorter "survival time," 50–66 s. These data indicate that life support during accidental decompression in space requires further study on both theoretical and practical levels. Questions to be solved pertain to the significance of gas composition and atmospheric pressure in the cabin prior to decompression, as well as species-specific distinctions of the organism in survival under such conditions.

Multicompartment Spacecraft

The foregoing indicates that if there is accidental depressurization of a spacecraft, or if there has been damage to the full-pressure suit in space, a cosmonaut in the cabin without a protective outfit can be rescued only by other crewmembers wearing such an outfit and using on-board life-support systems. The rescue systems should provide for rapid movement of the victim to the pressurized compartment as well as immediate recompression and restoration of normal oxygen supply.

Such requirements are met by the proposed two- or multicompartment design for spacecraft and orbital stations [10]. The author proposes a sequence of rescue operations in case of decompression (Fig. 3).

In a routine flight, the station crew is in compartments "1" and "2," wearing full-pressure suits throughout the flight. In sudden depressurization, for example, of compartment "1" (Fig. 3) at the top left, the hatch cover "6" is shut by the stream of air escaping from the formed opening. The crew in compartment "2" will be safe. The crewmember on duty in compartment "1" rapidly evacuates the victims to lock "3," and together with the crew of compartment "2" performs recompression and other measures to revive them; measures are then instituted to correct damage to the compartment.

If compartment "2" is depressurized, rescue operations will be carried out by the member on duty in this compartment along with the crew of compartment "1" (Fig. 3, top middle).

In depressurization of lock "3" (which is unlikely), hatch covers "5" and "6" will close, and the crews in compartments "1" and "2" will be separated (Fig. 3, top right). Another lock (tunnel, "4") with three hatches and manually operated covers "7," "8," "9" (Fig. 3, bottom) is provided for communication. Lock "4" can also be used to assist a crewmember who happens to be in lock "3" at the time of decompression.

The proposed two- or multicompartment construction of orbital stations would be useful for purposes other than saving the lives of cos-

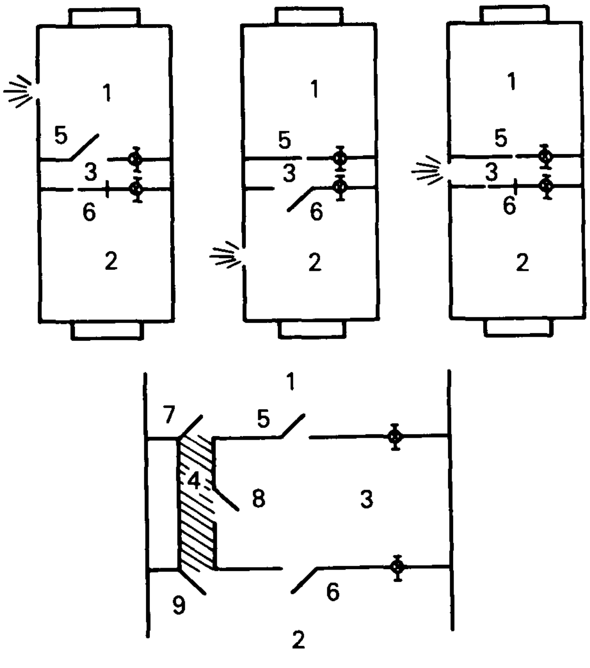

FIGURE 3.—Spacecraft and orbital station cabins showing pressurized compartments in case of decompression [9] (see text).

monauts under spacecraft depressurization. It would be possible to perform controlled decompression to extinguish a fire or remove toxic substances from the cabin atmosphere. It would be easy to equip the lock to administer in-flight hyperbaric oxygen therapy to decompression victims or as a shelter in case of radiation hazard.

The use of a "minishelter" is proposed to protect and save cosmonauts if damage to full-pressure suits occurs while working at a distance from a station on the Moon or planets without atmosphere. The minishelter would consist of a readily transported pressurized structure with a lock, which should be located close to where the cosmonaut is working and would provide for recompression until "total rescue time" had elapsed.

Resuscitation Techniques

In group space flights which include a physician, it will be possible to use effective resuscitation measures in addition to recompression for victims of spacecraft decompression [34]. In experiments by Sirotinin et al [55, 56], dogs were revived by extracorporeal circulation after 10–18 min of clinical death from decompression (rapid "ascent" to an altitude of 18–20 km with exposure up to 5 min). In another study, total recovery of physiologic functions and behavioral reactions of dogs was obtained by a set of resuscitative measures after 7-min exposure to an altitude of 15 km [33]. The "survival time" of dogs under analogous altitude conditions but without resuscitation after recompression is 60–66 s [34, 36].

Consequently, in the event of decompression, survival time can be extended by adding to the natural functional reserves of the body various techniques of resuscitation. However, effective use of these measures is also limited as to time, due to development of irreversible hypoxic changes, especially in the central nervous system, which is the reason for the interval from decompression to development of irreversible tissue damage being called "possible resuscitation time" [17, 34]. The duration of this period will depend partly on the effectiveness of resuscitation measures and to a larger extent on the functional state of the body and its vital systems: respiration, circulation, central nervous system.

Hence, the important practical conclusion is that by improving resuscitation techniques and selectively altering the state of the body at different structural and functional levels, the appearance of irreversible changes apparently can be postponed and ultimately this means greater chances of rescuing the victims of decompression. The development of technical resuscitation devices to compensate adequately for impaired or extinct vital functions is necessary, as well as ways and means to increase the body's resistance to the effects of decompression in space.

Investigations in development of resuscitation devices [55] have only begun, but more studies have been devoted to increasing resistance of man and animals to decompression damage: high-altitude (mountain) and pressure-chamber acclimatization [6, 8], cooling [34], anesthesia [34], and administration of agents aiding tissue respiration and production of energy in the mitochondria [42]. Although positive results have been obtained, their potential application in actual space flight is still open to question.

Data on rescue measures in accidental depressurization of a spacecraft, in Table 1, show that a spacecrew does not have much choice of rescue aids when there is disaster in space involving decompression. This is attributable both to the rapid development of serious disturbances in the body and to the limited number of protective devices developed so far. Many theoretical aspects of life support under these conditions have not yet been investigated. For example, the question of "survival time" and "resuscitation time" during decompression is far from clear, as well as the influence of prolonged weightlessness on these intervals. At the same time, these data must be considered when substantiating the choice and use of cosmonaut protective and rescue devices in accidental depressurization of the spacecraft. Resuscitation devices should meet the main requirement of recompression and reoxygenation before "time of useful consciousness" or, as a last resort, "survival time" has elapsed.

Recompression and Reoxygenation

It is difficult to overestimate the significance of immediate recompression and reoxygenation in resuscitation of cosmonauts who have suffered depressurization. By this means, oxygen deprivation in the body's vital systems and organs is corrected, the consequences of embolism and blockage of the cardiovascular system by gas and vapor bubbles are arrested, pathologic effects from distended and displaced gas-containing organs are avoided, and serious complications of acute hypoxia (edema of the brain and lungs, myocardial disturbances, and posthypoxic encephalopathy) are prevented. Recompression is also a critical and immediate resuscitation measure in which pressure rise is equivalent to artificial inspiration, especially in the absence of spontaneous respiration [17, 34].

If respiration is not restored spontaneously or remains irregular for several minutes after recompression and reoxygenation, artificial respiration by any available means should be used: periodic alteration of pressure in the full-pressure suit or pressurized compartment, mouth-to-mouth respiration, external cardiac massage, or respiration under alternating excess pressure. Even if cardiac activity is negligible, dilated pupils react poorly to light, and breathing has stopped [17, 34], resuscitation measures should be administered. If a doctor is on-board, other resuscitation measures and symptomatic treatment (intubation, intravenous injection of fast-acting cardiac agents, extracorporeal circulation, hypothermia, hyperbaric oxygen therapy) may be administered.

Depending upon the duration and severity of disturbances to vital functions during decompression, resuscitation measures may result either in rapid, stable recovery of consciousness, or the victim may remain unconscious. If there is continued unconsciousness or secondary impairment of consciousness after it appears to be restored, prognosis is poor, and indicates irreversible hypoxic brain damage due to the effect of low Po_2 during decompression and posthypoxic cerebral edema. In this case, effective dehydration as well as symptomatic and maintenance therapy, should be administered [17].

Exposure to Decompression

A cosmonaut exposed to decompression, even though moderate and with totally successful resuscitation measures, should abstain at first from intensive mental and, especially, physical activity. His productivity will be low because of a pronounced decrease in work capacity; exposure to additional load could cause functional disturbances, for example, posthypoxic encephalopathy [17].

Crew rescue under explosive decompression occurring within less than a second, the most dangerous kind of spacecraft depressurization, has been discussed. The data for justification of emergency measures are also suitable for

TABLE 1.—*Rescue and Protective Measures for Cosmonauts in Rapid Depressurization of Spacecraft Cabin*

Rescuer	Available resources	Time, s	Limitation criteria	Terminology
Victim, independently	LSS, full-pressure suits, PPS	10–15	Retention of consciousness and work capacity	"Reserve time," "time of useful consciousness"
Other crewmembers	LSS, full-pressure suits, PPS, pressurized compartments	120–150	Retention of vital functions	"Total rescue time," "survival time"
Cosmonaut-physician	Same as above + resuscitation measures	150 (up to 7 min for animals)	Irreversible structural damage	"Resuscitation t

decompression occurring in several seconds. In the more likely cases of smooth, slow decompression from a small decompression opening, in which air leakage from the cabin (pressure suit) is compensated for by emergency air (oxygen) reserves in the LSS, or deliberate depressurization, the chances of rescue are greater. This is attributable to two circumstances.

Time intervals limiting man's survival in an extremely rarefied environment are extended. Sergiyenko [53], in experiments with different decompression rates, showed that as decompression slows down, retention time of work capacity increased. With "ascent" in a low pressure chamber at 0.1 m/s, the retention time of work capacity averaged 13 h 21 min; at 2 m/s, 53 min; and at 25 m/s, 6 min 30 s.

During slow decompression, the technical means available for rescue are broader. With a reserve retention time of work capacity numbering minutes and even hours rather than seconds, the cosmonaut can take steps to correct the defect in the cabin or don a protective outfit, move to a pressurized compartment, and call another spacecraft or special rescue device for help.

After rapid depressurization, only cosmonauts wearing proper outfits and who have not suffered from decompression can perform rescue work. Under such conditions, help from another spacecraft can be used only in the second phase of rescue work, after the victims have been moved to the pressurized compartment, and recompression and reoxygenation including (if necessary) resuscitation, have been carried out. Of course, the complex, urgent steps required on-board the spacecraft, with the accident, considerably complicate rescue of the crew if the manned compartment is depressurized.

FIRE CONTROL MEASURES

Fire, another hazard on-board spacecraft, if intense and extensive, will of course, cause rapid death of the crew and destruction of the spacecraft. Even moderate, localized fire can cause marked, prolonged impairment of health and work capacity of cosmonauts, as well as damage to spacecraft equipment, which could preclude continuation of the flight and make rescue difficult.

Despite development of multiple preventive and protective measures, the potential danger of fire prevails. This is caused by highly combustible materials (solid, liquid, vapor, and gaseous) onboard spacecraft, and potentially flammable, ignitable sources (failure of electric equipment and sources of increased heat production, injury to containers with highly active chemicals, oxidizer (oxygen) sources). The limited size of compartments and especially the high oxygen level in the spacecraft cabin atmosphere can cause fire to spread and intensify combustion. Thus, in an environment of pure oxygen, the flame-spreading rate in the combustion of many of the hydrocarbons is greater by several factors than in air [28, 49].

In gas environments with high oxygen content and increased quantity of combustible material, there is a greater probability of ignition, and a higher rate of energy liberation.

A fire in pressurized chambers with increased oxygen partial pressures is characterized by an exponential increase in flame-spreading rate and can therefore assume dangerous dimensions within a very short time, even though a relatively small quantity of combustible material and oxygen is present [1, 3].

The lack of natural convection under weightlessness conditions retards combustion. However, forced convection when the spacecraft's ventilation systems are operating would counteract this effect [49].

Fire may develop on-board a spacecraft in near-Earth orbit and, especially, during interplanetary flight, due to perforation of cabin walls by meteorites. Although the probability of such a contingency is small, data indicate that a spherical body 3 m in diameter with aluminum walls 0.03-cm thickness would be perforated by a meteorite every 2.3 years, on the average [17]. In long-duration space flights, the probability of meteorite hazard would acquire significance for flight safety.

The danger from fire to life and health of the spacecrew is primarily due to thermal burns by flames, toxic gases, hot air, and heated objects. During weightlessness, in limited cabin space, there would be rapid accumulation of melted and heated liquid, solid, and gaseous products of combustion, which could induce fatal lesions through the respiratory tract. Increased pressure in the cabin during a fire, especially if there are explosions, could lead to impairment of pressurization with ensuing dangerous consequences to the crew: acute hypoxia, decompression disorders, explosive decompression. If the spacecraft were perforated by a meteorite, injury could come from the flash of light and shock wave resulting from explosive oxidation in the cabin's atmosphere of melted and evaporated particles from the meteorite and spacecraft skin [17]. Contact with fire-damaged electrical wiring and equipment and with chemicals toxic to the body and respiratory tract caused by damaged containers could lead to electrotrauma and electric and chemical burns and aggravate the damage from fire.

The adverse environment of space flight limits the use of Earth-based devices for fire control and rescue work in space. The high speed of such a catastrophe precludes help from another spacecraft. At the same time, because of weight and dimension limitations, as well as toxicologic restrictions, the choice of on-board fire control aids is markedly narrowed.

Preventive Fire Safety Measures

Preventive fire safety measures against the extreme danger of a fire on-board a spacecraft are imperative. They include primarily a gas atmosphere in the cabin as safe as possible from fire and explosion, or replacement with a safer atmosphere during the most critical stages of the flight. An example is the choice of atmosphere on the US Apollo spacecraft. During ground tests, launches, and insertion into orbit, a two-gas atmosphere, nitrogen (40%) and oxygen (60%), is used in the cabin instead of pure oxygen. During this time, astronauts use the independent life-support system of the pressure suits for respiration and denitrogenation. In orbit, the oxygen-nitrogen mixture in the cabin is replaced with oxygen at a pressure of 260 mm Hg [2, 30]. In Soviet spacecraft, an atmosphere close in gas composition and pressure to that of Earth is maintained at all phases of the flight, and is advantageous for fire safety.

An equally important fire-control safety measure is the choice, construction, and placement of materials used in cosmonauts' outfits and in the interior and equipment of the spacecraft cabin. Combustible materials are replaced with nonflammable, fireproof material. For example, the latest pressure suits for Apollo spacecraft astronauts are made with noncombustible "Beta" fiberglass instead of nylon, which would help spread flames under specific conditions. Instead of a separate heat-protective suit, a permanently attached lining has been developed which has increased considerably the fire-resistant qualities of the entire pressure suit [30]. If use of combustible material is unavoidable, it should be shielded, coated with fireproof material, or placed between fireproof materials to prevent the spread of flames [2, 14, 28].

To eliminate the causes of ignitable and inflammable loci, strict inspection of the quality and working order of on-board electric equipment is necessary, including proper functioning of all parts of elements and units in the heat-regulating systems and their resistance to different types of damage.

In working out effective and high-speed aids to control fire under different environmental conditions, investigators found the time available to rescue cosmonauts from the moment of appearance of flames ("survival time") fluctuates over a broad range, from 50–100 ms to 10–20 s (Fig. 4). For this reason, the following are general requirements for fire control devices at all phases of flight: immediate detection of fire sources, rapid localization of such sources, and effective extinction. The actual fire control measures may vary, depending on the time and conditions under which the fire started.

Fire-Extinguishing Systems

When fire occurs during launch or testing, all fire-extinguishing devices and systems available on the launching pad and on-board, including individual fire extinguishers, are used. Special rescue services equipped with emergency rescue equipment should be created and an effective system must be developed for rendering first aid to crewmembers. There should be regular instruction for personnel of the emergency rescue service with simulation of spacecraft fires, using life-size mockups [3, 17].

If fire occurs on-board during launch or at the start of insertion into orbit, the cosmonauts could also be rescued by the emergency rescue system, which ejects the crew compartment up and to one side of the carrier rocket [27]. At the reentry stage, the spacecraft could be abandoned by ejection, although this possibility is limited by air-velocity pressure. Without protective devices (full-pressure suit, capsule), man can withstand an ejection velocity pressure head of no more than 4000–5000 kg/m^2, with a full-pressure suit, no more than 8000 kg/m^2 [27, 29]. Use of rescue capsules [29] is the most effective means of life support and safe return of spacecraft crews in fire during descent.

If fire occurs during orbital flight, the most effective means of extinguishing it is probably depressurization of the cabin. Prior to depressurization, the crew should don full-pressure suits or seek shelter in a pressurized compartment before the flames spread throughout the spacecraft [17, 48]. Such a method of extinguishing a fire constitutes a rare example of using one of the extreme space factors, deep vacuum, to save human life.

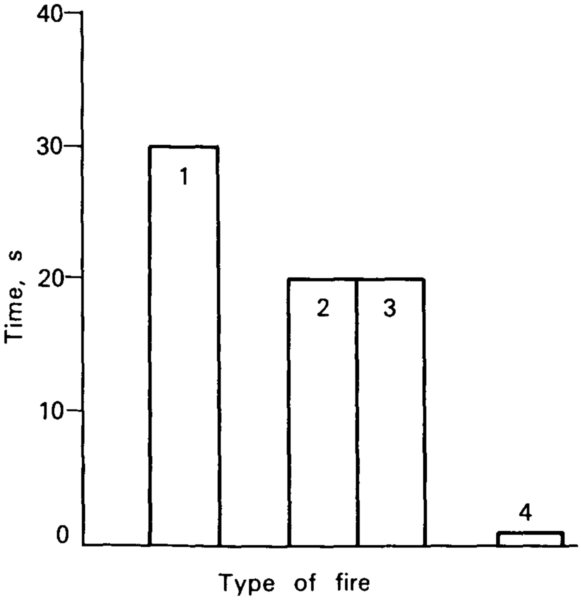

FIGURE 4.—"Survival time" from data on fires on-board aircraft, spacecraft, and experimental chambers. 1, on aircraft; 2, in the Apollo cabin (O_2, 100%; 3.5 · 10^2 g/cm^2, 5 psi) during ground tests; 3, in a hypobaric chamber (O_2 100%; 4.9 · 10^2 g/cm^2, 7 psi) at Brooks Air Force Base, USA; and 4, aircraft fuel tank explosions [14].

Compression of the cabin with inert gas (preferably nitrogen) with simultaneous disconnection of oxygen supply sources is another means of extinguishing or localizing fire on-board a spacecraft. In this case, the crewmembers should wear full-pressure suits or masks, and breathe oxygen from emergency sources [17].

Resuscitation and Medical Aid

Immediately after the fire is extinguished, resuscitation measures for victims may be required. By this time, elimination of health dangers from depressurization, accumulation of toxic combustion products and chemically active residues of fire-extinguishing agents should have been achieved, the latter by stepped-up operation of ventilation systems, which may have been switched off to prevent convective spreading of fire.

The diversity and difference in degree of fire damage during space flight make it difficult to establish a general method of rescue and aid suitable in all eventualities. Rescue measures should be undertaken according to type and severity of injury and capability of the crew to render medical aid with the limited means on-board [17].

Help should first be given to individuals sustaining not only burns but also injuries from explosive decompression, explosion, electric discharge, and injury to respiratory organs. The methods have already been discussed: recompression and reoxygenation, breathing oxygen under ordinary and excess pressure, artificial respiration, and hyperbaric oxygen therapy. General supportive and symptomatic treatment follows control of these critical conditions.

Discussion of specific medical measures, for example, treatment of types and severity of burns and their complications, is not feasible in this survey. This information is available in the comprehensive monograph by Busby [17] dealing with clinical medical problems related to various accidents in space, including fires. The author correctly notes that when treating burns during space flights at present and in the foreseeable future, it is impossible to duplicate entirely methods tested on Earth.

Surgical treatment of burns, including subsequent skin transplants which are established procedures on Earth, would be difficult in the small, restricted compartments of spacecraft. In the open method of treatment, for instance, and during application of dressings, weightless solid and liquid particles discharged from the burned surface would spread throughout the cabin, presenting a serious danger of injury and infection to the respiratory tracts of the entire crew. Vomitus, often observed among burn victims with paresis and obstruction of the intestine, would be equally dangerous for the same reason. However, pollution and contamination of the cabin's atmosphere can be prevented by "suction" devices. Dressings of the cuff, sleeve, and trouser-leg type that can be applied rapidly and changed easily, should be used to cover burned surfaces. Such dressings can also be used to immobilize the burned part of the body in a physiologic position [17].

Special in-depth studies should be undertaken concerning other aspects of burn treatment and concomitant complications: treatment of combined dehydration of the organism (from burns and weightlessness), effectiveness of vasoconstrictive agents, oxygen therapy, respiration under excess pressure in lung involvement, and air embolism of pulmonary vessels. Experiments with animals in space flights which are being conducted in an international flight safety program may provide data to answer these questions.

During the second rescue stage after extinguishment of an extensive fire, elimination of its most dangerous consequences, and controlling critical conditions in individual crewmembers, effective treatment of victims often may need to be administered on Earth. Consequently, the space flight would have to be terminated and the crew returned to Earth either in their own spacecraft or in a special rescue craft.

PROCEDURES DURING FAILURE IN AIR REGENERATION AND CONDITIONING SYSTEMS

Failure of air regeneration and conditioning systems on-board spacecraft may be caused by different accident situations. There may be partial or combined disruption of preset gas composition of the artificial atmosphere (drop in oxygen partial pressure and increase in carbon dioxide content) and change in temperature conditions, usually manifest as a temperature increase in the cabin. Protective measures should be directed toward preventing pronounced hypoxia, hypercapnic syndrome, and overheating of crewmembers. Prompt detection of the causes of faulty operation of life-support systems is important.

A subject, after special instruction, can recognize a hypoxic state in himself [16] if oxygen deficiency is prolonged during wakefulness, and if he does no work, and concentrates on changes in well-being during the experiment. In actual flight, during both sleep and active work periods, this capacity will not be fulfilled, and the onset of dangerous signs of oxygen deficiency will be unnoticed by the cosmonaut. In group flight, however, external signs of hypoxic hypoxia—euphoria, stupor, inadequate behavior, cyanosis—can be detected by other crewmembers, especially when specifically trained in this area.

Permissible Po_2 Level

The development of technical aids for use on-board spacecraft to signal when parameters of Po_2 and total pressure exceed the permissible range should be emphasized [29, 64]. Diagnostic machines can be used to signal impairment of life-support systems according to changes in indices of the chief physiologic functions and oxygen conditions of the organism [39], rather than to physical parameters.

If an irreversible Po_2 drop in the cabin's atmosphere below the permissible level occurs, steps must be taken either to restore oxygen supply or for rescue. In a two-gas atmosphere with a pressure of 0.6–1.0 atm, the permissible PO_2 level at which minimal work capacity is retained is considered to be 110–120 mm Hg. If P_{O_2} drops to 90–100 mm Hg, immediate steps must be taken to prevent serious consequences of hypoxic hypoxia [29, 40, 64].

If we know the ventilated volume of a spacecraft cabin and the quantity of O_2 consumed by the organism (20–150 l/h varying from negligible to very intensive physical loads), the time available to the crew before P_{O_2} drops below critical levels can be determined quite accurately. Before each flight, it would be useful to prepare the data of mockup tests in the form of a table or graph showing O_2 decrease rate in the cabin's atmosphere as a function of its useful volume, degree of damage to the regeneration system, and intensity of the workload. All other conditions being equal, the larger the ventilated volume of the cabin, the greater the reserve of time for repair work or completion of the flight [29, 64].

If it is impossible to repair the regeneration system within this time, the flight should be terminated and expenditure of oxygen in the subsystems, the emergency systems, and pressure suits or other personal protective outfits should be minimized. This is precisely what the American astronauts of Apollo 13 did. After one of the main oxygen units failed, they switched to oxygen supplies from the lunar module. Although oxygen reserves in the module were planned for brief support of only two people while working on the Moon, conservation measures enabled oxygen to be supplied to the three astronauts for the time needed for their safe return to Earth [5]. This was a brave and wise step for the astronauts to take.

In addition to using independent, emergency oxygen reserves when P_{O_2} drops in the cabin's atmosphere, some authors suggest that the body's resistance to the effect of hypoxia be increased by adding carbon dioxide to the inhaled air [40]. In lengthy tests (48 h), it was shown that a drop of P_{O_2} to 110–120 mm Hg in the atmosphere of a cabin mockup was better tolerated by subjects if the P_{CO_2} was increased to 10–15 mm Hg; if $P_{O_2}=90–100$ mm Hg, P_{CO_2} was increased to 15–18 mm Hg, and if $P_O=65$ mm Hg, P_{CO_2} was increased to 20–25 mm Hg. These observations were made in a two-gas oxygen-nitrogen artificial atmosphere at a pressure of 760 mm Hg. No doubt, when using a single gas oxygen atmosphere in a cabin with low pressure, as well as in cases of prolonged weightlessness, the effect of adding CO_2 can be different. This interesting question invites further study. It would be tempting to use this end product of metabolism, which is to be removed from the cabin's atmosphere, to optimize the gas environment or, more precisely, to improve cosmonauts' tolerance in this emergency situation. This becomes more important when there is damage to the air regeneration system and a drop in oxygen content, because there is often an accompanying accumulation of carbon dioxide.

Hypoxia

The most effective means of life support under these conditions will always be restoration of adequate oxygen supply to the organism by any or all means available on-board the spacecraft. During serious stages of hypoxia (loss of consciousness, respiratory arrest, severe hemodynamic disturbances, neurologic symptoms), resuscitation should be administered, as after accidental decompression.

Depending upon the duration and severity of hypoxia, after reoxygenation the victims either immediately regain consciousness or remain unconscious with impairment of motor functions, vomiting and seizures and sometimes intermittent periods of lucidity. Such pathologic phenomena are related to reversible or permanent hypoxic brain damage as a result of both the primary effect of low P_{O_2} in the atmosphere and development of cerebral edema, which aggravates tissue hypoxia. Busby recommends that the most vigorous steps be taken to prevent and treat posthypoxic edema of the brain: dehydration agents (mannitol, dextran, glucose), hypothermia using the heat-regulating system of the full-pressure suit, as well as sedatives and tranquilizers to alleviate the effects of mental, motor, and automatic disturbances [17].

A cosmonaut suffering from hypoxia may perform acts dangerous to himself and other crewmembers, even after regaining consciousness. For this reason, until there is total recovery, he should be carefully observed by crewmembers and he should have complete rest. Of course, all this will make it more difficult for the crew to carry out the chief program of the flight.

At the beginning of therapeutic reoxygenation, the possibility of "posthypoxic oxygen paradox," a brief 15–30 s deterioration of well-being and general state to the extent of unconsciousness and seizures similar to an epileptic attack, should be considered. This condition is dangerous because of possible trauma, and develops more often when starting to breathe pure oxygen after the prolonged effect of pronounced hypoxia, although pathogenesis of this phenomenon has not been elucidated definitively. Individual predisposition in some persons has been established and a stereotype of pathologic reactions in an individual has been formulated. Individuals with particularly severe manifestations of the posthypoxic oxygen paradox can therefore be excluded in the selection and training of cosmonauts [17].

Hypercapnia

Hypercapnia is another potential hazard for the cosmonaut in flight: increased level of CO_2 in the lungs, blood, and tissues resulting in physiologic reactions, pathologic disturbances, and impaired work capacity. Hypercapnia develops when there is a rise in carbon dioxide in the cabin's atmosphere or pressure helmet caused by partial or complete failure of the LSS to absorb CO_2. An excess of CO_2 in the cabin could be provided by the flight program to conserve weight, size, and energy supply of the LSS, intensify regeneration of oxygen, prevent hypocapnia, or attenuate the deleterious effect of cosmic radiation [17, 63].

Rise of CO_2 to a toxic level (more than 1% or 7.5 mm Hg) may occur within several minutes or hours, depending upon the ventilated volume of the full-pressure suit and cabin, degree of damage to the LSS, and quantity of carbon dioxide produced by the crew, resulting in acute hypercapnia. Prolonged exposure for days, weeks, and months to a moderately high CO_2 level in the atmosphere leads to chronic hypercapnia.

According to estimates, the toxic CO_2 level in the pressure helmet will be reached within 1 to 2 min after the CO_2 absorption system package breaks down in the space suit while an astronaut is working on the Moon. In the Apollo spacecraft cabin, with three astronauts performing their usual work, this would happen more than 7 h after total failure of the LSS. In both instances, acute hypercapnia could develop. During long-duration flights, less serious malfunctions in the CO_2 absorption system could cause chronic hypercapnia [17].

Figure 5 illustrates the dynamics of CO_2 accumulation in a pressurized chamber as a function of its volume, time of exposure, and an individual's activity in a simulated complete failure of the CO_2 absorption system [58]. It would be advisable to chart similar data for each flight, showing actual ventilated volumes in

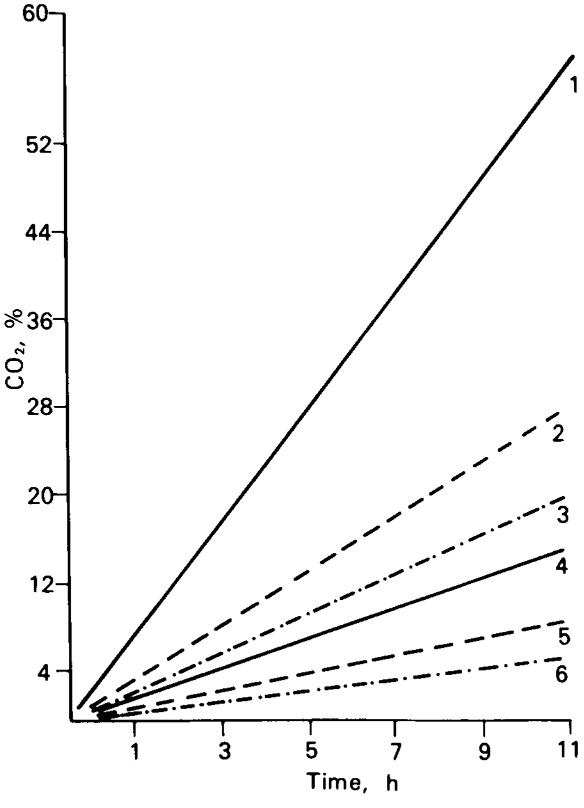

FIGURE 5.—Rate of CO_2 accumulation in different-sized pressurized chambers; at rest, curves 4, 5, 6; moderate muscular work, curves 1, 2, 3; curves 1 and 4, 1 m^3/person; curves 2 and 5, 2 m^3/person; curves 3 and 6, 3 m^3/person [58].

spacecraft cabins and degree of LSS malfunction. These graphs would be helpful in rapid initiation of effective rescue measures when emergency situations occur in actual flight.

Hypercapnia, even when moderate, deteriorates the well-being and general condition of an individual, and depletes the reserves of vital functions. Human behavior becomes inadequate, mental and especially physical work capacity diminishes, and there is a decrease in resistance to stress factors: acceleration, orthostasis, overheating, hyperoxia, and decompression [41, 44, 47, 58, 63].

The "reverse" effect of carbon dioxide can cause possible serious complications from hypercapnia in space flight. Switching from a hypercapnic to a normal gas mixture for respiration, or to air or oxygen, often causes hypercapnic disturbances in the organism to persist or even intensify, or new symptoms of carbon dioxide poisoning appear. Such a condition could last for minutes, hours, and sometimes days after restoration of normal gas composition of inhaled air.

Permissible CO_2 Level

From literature surveys dealing with the effects of CO_2 on the organism, it may be concluded that increase of CO_2 in inhaled air to 0.8%–1% does not elicit disturbances of physiologic functions nor decrease work capacity in either acute or chronic exposure. The cosmonaut does not experience discomfort from this CO_2 level in the pressure helmet and will be able to perform intensive physical work. Thus, a CO_2 content of 0.8%–1% (6–7.5 mm Hg) can be considered the permissible level in the cabin and pressure helmet for brief or prolonged exposure [50, 58, 63].

Permissible levels of higher CO_2 concentrations should be determined taking into consideration the duration of exposure and intensity of work. If the cosmonaut is to work for several hours in the pressure suit, the CO_2 level in the pressure helmet should not exceed 2% (15 mm Hg). There will be complaints of dyspnea and fatigue when this CO_2 level is reached, but the work will be properly performed.

When light work is performed periodically in a spacecraft cabin, the cosmonaut can cope with his assignment for several hours after CO_2 rises to 3% (22.5 mm Hg), although he will manifest pronounced dyspnea and headache, which might persist as an aftereffect.

Signs of chronic hypercapnia develop during a long stay in an atmosphere high in CO_2 content, 0.9%–2.9%. Under these conditions, changes are noted in electrolyte and acid-base balance, physiologic functions, and depletion of functional reserves as demonstrated by load tests.

Clear signs of chronic hypercapnia appear when CO_2 rises to 3% or more, even without special tests [17, 50]. After brief exposure and intensive physical load or prolonged exposure with periodic performance of light work, a rise of CO_2 in the pressure helmet or cabin to 3% or more, must be interpreted as a serious emergency situation requiring immediate correction.

Unlike oxygen deficiency in hypoxia, hypercapnia can be established not only by instrument readings and CO_2 analyzers, but also by subjective and clinical signs. The appearance of dyspnea, especially at rest, nausea and vomiting, fatigue during work, headaches, vertigo, impaired vision, cyanosis of the face, and profuse perspiration, indicate acute carbon dioxide poisoning, even without laboratory tests. Chronic hypercapnia is characterized by phasic changes in psychomotor activity (excitation alternating with depression), which are manifested in behavior during both mental and muscular work. Headaches, fatigue, nausea, and vomiting are less pronounced. Persistent hypotension is often observed. Disturbances in electrolyte and acid-base balance, as well as intensive function of the adrenal cortex, are demonstrable only by biochemical methods.

Auxiliary CO_2 Absorption Systems

No specific methods have yet been developed to treat hypercapnic acidosis or to increase resistance to high concentrations of CO_2. For this reason, when the regeneration system malfunctions, speedy restoration of normal gas composition of inhaled air would constitute the most effective help for the cosmonaut. If malfunctions in the main regeneration system cannot be corrected, subsystems and emergency systems, as well as emergency oxygen reserves on-board or in pressure suits should be used. Air free of CO_2 can be delivered directly to the mask or mouthpiece rather than the cabin atmosphere as a conservation measure.

Effective use of auxiliary CO_2 absorption systems in which there is excessive accumulation of CO_2 in the cabin environment was demonstrated by Apollo 13 astronauts. After the main oxygen units malfunctioned, the astronauts switched to the regeneration system of the lunar module. After 26 h 30 min of flight with altered utilization of the LSS, the CO_2 content in the cabin atmosphere reached 15 mm Hg, or 6% of a cabin pressure of about 250 mm Hg. This happened because the cartridge with the CO_2 absorber in the module was designed for two rather than three people and for a shorter time. To remove the danger of hypercapnia, the blower in the lunar module cabin was attached with hoses to the absorber in the LSS in the main unit of the spacecraft, allowing lowering of CO_2 to 5 mm Hg and safe completion of the flight [5].

The cosmonaut can isolate himself from the hypercapnic environment of the cabin by closing the visor in the pressure helmet of his space suit. The US astronaut, L. G. Cooper, used this procedure in the Mercury 4 flight. When the CO_2 analyzer showed a CO_2 rise in the cabin to 3.5–5 mm Hg during the last two orbits, the astronaut shut his pressure helmet and turned on the emergency oxygen supply system of the space suit for 30 s. He continued to breathe oxygen from the pressure suit LSS, which had a normal CO_2 content until the flight was completed [43]. Thus, for the first time, it was proven in practice that hypercapnia can be prevented during space flight by using on-board devices. This example shows the desirability of determining the time at which the CO_2 danger level indicator shows when CO_2 level constitutes up to 1% of the air. Advance signaling of the danger of hypercapnia allows the cosmonaut to take preventive measures in good time.

Normalization of the gas composition of inhaled air does not always curb hypercapnia rapidly; quite frequently hypercapnia is even intensified due to the "reverse" effect of CO_2. Some authors have observed a beneficial effect following hypercapnia when respiration was switched to an oxygen-nitrogen mixture with O_2 increased to 40%, rather than air or pure oxygen [58]. This effect was noted in tests at barometric pressure of 760 mm Hg. Investigations were not made at lower cabin pressure.

In case of persistent nausea, headache, and fatigue, symptomatic and maintenance therapy using analgesics, tranquilizers, and sedatives is indicated.

Overheating

Malfunction of the air-conditioning temperature control system of the cabin and pressure suit may bring about danger of overheating. Continuous production of endogenous body heat (100 to 500 kcal/h at rest and during intensive work), and the presence of energy units in the cabin having a heat emission problem would facilitate accumulation of heat and impair thermal balance.

Overheating may be manifested differently when working in space, ranging from negligible discomfort from heat to pronounced clinical signs. Thus, in the case of considerable exogenous heatloads and intensive work by cosmonauts who are not physically sturdy or adapted to heat exposure, thermal collapse may occur from abrupt impairment of blood supply to the brain brought about by persistent dilatation of peripheral vessels. The decrease in circulating blood volume and disturbances in the cardiovascular system during prolonged weightlessness, coupled with G-loads during deceleration and landing of a spacecraft, will provoke this condition [12]. If there are local and general circulatory disturbances, prolonged exposure to high temperatures and increased humidity may lead to irritation, maceration and infection of the skin, impairment of fluid (dehydration) and salt metabolism, and development of "heat prostration." In serious cases of overheating, fatal heatstrokes are often observed.

The maximum external and internal heatload tolerance is excessive heat accumulation of 1.43 kcal/kg, or about 100 kcal for an adult male weighing 70 kg [35]. When converted to body surface area, the range of heatload tolerance constitutes 60–63 kcal/m^2 [23]. With increase in heatload intensity and simultaneous decrease in exposure to tolerable heat, the maximum heat level increases. Thus, with a heat accumulation rate of 0.3–1.8 kcal/m^2 min, tolerable heat accumulation increases from 50–75 kcal/m^2; during physical work in which accumulation rate ranges from 0.45–1.79 kcal/m^2, maximum heat accumulation increases from 51–86 kcal/m^2 [23]. At critical levels of overheating, rectal temperature rises to more than 38° C, and mean weighted skin temperature registers more than 36.6° C.

In order to evaluate objectively the body's thermal state in these emergency situations, forecast its reserve capabilities, and initiate effective protective measures, as much information as possible about the hygienic parameters of the environment and state of the cosmonaut's physiologic functions should be used. Data on ventilated volume, temperature, pressure, and humidity in the cabin or space suit, as well as information on the dynamics of pulse and respiration rate, arterial pressure, and skin and body temperature are necessary. The heat sensations of the cosmonaut and assessment of his own and environmental heat conditions should also be considered. By comparing such data with estimated and experimentally substantiated forecasts of variants of thermal balance disturbances in man, timely steps can be taken to prevent serious consequences of overheating and aid completion of the flight without detriment to the cosmonaut's health.

Means tested on Earth should be used to protect the cosmonaut in-flight from excessive thermal loads and consequences of overheating: effective systems of regulating heat in the cabin and space suit, as well as provision for adequate exogenous conditions for water and salt balance in the body [17].

If the body is in danger of overheating due to failure of the air-conditioning systems, an emergency procedure can be taken by reducing heat and removing perspiration with a suction pump [20, 62]. Automatic removal of body-surface sweat (by suction) is achieved in a pressure (altitude-compensating) suit and pressure helmet without additional devices. It is only necessary to lower the cabin pressure to or below the level of saturating-vapor pressure at skin temperature, or less than 40 mm Hg. As a result of vacuum boiling and evaporation of perspiration under these conditions, the skin temperature drops, the flow of heat from the skin increases, and the individual experiences coolness or even cold sensations [20, 62]. According to altitude chamber experiments, thermal balance of the body can be maintained for a long time merely by means of vacuum evaporation of perspiration at altitudes up to 35 km at rest and 150–300 kcal/h when performing physical work involving energy expenditure [20].

Vacuum evaporation of perspiration can be used in space flight to maintain thermal homeostasis only in a physiologically effective space suit providing for adequate intrapulmonary pressure and counter pressure to the body, and preventing oxygen deficiency and decompression disorders. An effective pneumomechanical system to compensate for high pressure [61] is suitable for such purposes. A pressure suit equipped with a special device for vacuum evaporation of perspiration is even more effective for life support [13]. The device consists of a chamber filled with hygroscopic material connected, when necessary, to a vacuum and located on the body surface (on the undergarments). Its walls are made of material permeable to water but not gas. Perspiration from overheating enters the chamber, which, when connected to the vacuum of space, results in evaporation of perspiration, cooling its walls, as well as the undergarment and skin under it. However, there are still many problems to solve before such a pressure suit can be used in space flights [13].

Preliminary acclimatization of the cosmonaut on the ground to increased thermal loads has been suggested to prevent overheating [7, 17]. The effectiveness of acclimatization has been shown to increase with combined heat and muscular work, or hypoxic hypoxia, i.e., when there is a combination of specific and nonspecific acclimatization [6, 17]. The brief period of increased thermal resistance (1–2 months) prompts some authors to recommend that acclimatization acquired on Earth be maintained in space flight. The thermal regulating system of the space suit has been suggested for this purpose as well as periodic intensive exercise [17]. Prolongation of heat acclimatization will become acceptable in long space flights when conditions causing overheating of cosmonauts will be probable or even inevitable. However, the effect on the cosmonaut of acclimatization to heat during prolonged weightlessness requires in-depth investigation.

Overheating in space flights appears to be a danger for the foreseeable future, and effective means of controlling the consequences of heat stress on-board the spacecraft in emergency situations are required. Maximum use should be made of experience in treating overheating on the ground. The overheated cosmonaut should have complete rest in a cool "area," i.e., cabin, special pressurized compartment, or pressure suit with an operational thermoregulation system. When necessary, the fluid and salt loss from the body should be replaced. These measures may be sufficient to curb most of the overheating syndromes [17]. However, in heatstroke, more vigorous, specific treatment may be required: measured hypothermia, intravenous infusion of fluids, oxygen therapy, and symptomatic treatment [17]. These measures can be performed successfully if there is also a cosmonaut-physician among the spacecraft crew.

Overcooling

Cooling is less probable than overheating when air-conditioning systems malfunction in space flight. The crew is quite well-protected from excessive heat loss in the cabin. Convective and conductive heat transfer is entirely ruled out in the vacuum of space, and radiative heat transfer is hindered by insulated cabin walls. Furthermore, when the cabin temperature drops below comfort level, the cosmonauts can put on thermal clothing or resort to muscular exercise for protection against the cold.

There are some situations in which overcooling could develop: working in a pressure suit in space, on the shaded side of the spacecraft, or on the lunar surface in shaded places. Immobility, prolonged contact with the cold surface of the spacecraft or lunar soil, increased humidity in the space suit, compression of the insulating liner of the pressure suit, as well as excessive operation of the space suit thermoregulation system with moderate heat production would lead to increased heat loss by the body. In these improbable cases, there may be both generalized cooling of the body and local cooling causing injury to specific parts of the body to the extent of frostbite [17].

Elimination or reduction of these factors will constitute the prophylactic measure against cooling. The schedule for a cosmonaut in a full-pressure suit in space, on the shaded side of the spacecraft, or on areas of the Moon and planets not exposed to the Sun, should provide for active muscular exercise; intake of food high in proteins and carbohydrates for dynamic increase in metabolism; efficient limitation of heat removal by the full-pressure suit thermoregulation system; avoidance of motionless, fixed position; and others [17].

The principles of aid to cosmonauts with frostbite and overcooling are similar to those on the ground: rapid heating of frostbitten parts with heating pads and warm objects, and gradual heating of the victim at a cabin or space suit temperature of about 23° C in the case of general cooling. After warming, the frostbitten areas, which usually have incurred impaired circulation and diminished pain sensitivity, should be carefully protected from trauma and infection. In general, hypothermia, the possibility of shock from rapid warming [17] should be noted. The most effective treatment of local frostbite can be administered on Earth where both surgical and physiotherapeutic procedures can be fully used [17].

RESCUE OF SPACECRAFT CREWS

The foregoing discussion of life support for spacecraft crews during cabin depressurization, fire, and failure of the air-conditioning and regeneration systems suggests general approaches to the medical problems in these emergency spaceflight situations. The first rescue stage consists of prompt measures to eliminate life-threatening consequences of the accidents: cabin pressurization, extinguishing fire, restoring the atmosphere, and speedy correction of the victims' critical condition by resuscitation, recompression, reoxygenation, and artificial respiration. These and other emergency rescue operations are performed by the crew independently, using only limited available facilities in the cabin and on-board, which are not always effective enough.

In the second stage of emergency measures, the program for continuation of the flight must be determined. If consequences of the accident are negligible and correctable, and the health and work capacity of the cosmonauts completely restored, or their functions temporarily performed by other crewmembers, the flight can be continued as planned or, more likely, shortened. In pronounced impairment of the cosmonauts' health, considerable damage to the spacecraft, or total depletion or damage to regular and emergency LSS reserves, it would be impossible to continue the flight.

In these cases, variants of terminating the flight are possible. If the control and landing systems are in good order, the crew could return to Earth in the spacecraft. Under more critical conditions, rescue would be feasible only with the help of another spacecraft or special rescue device. The rescue crew, after docking with the damaged spacecraft, would render aid to the victims and return them to Earth.

In future space flights, the functions of rescue space vehicles will probably be more complex and diverse. The crew will be able to repair the stricken spacecraft, supplement spent LSS resources, and bring replacement cosmonauts. Such complex rescue measures will be feasible only through international collaboration between governments engaged in space exploration. Steps were taken in developing collaboration between the USSR and the USA when planning the joint flight of the Soviet Soyuz and the American Apollo spacecraft. One of the objectives of this flight was to work out rescue measures for cosmonauts in space flight [18, 22, 46].

The joint flight of Soyuz and Apollo spacecraft will undoubtedly stimulate theoretical research and practical solutions to spaceflight safety problems. Joint rescue measures will probably include: international standardization of docking and transfer device components, first aid to crew accident victims, more similar gas composition of the spacecraft atmosphere, and a standard space distress signal. It will then become possible to rescue crews of damaged spacecraft promptly. If an accident in the infinite expanse of space should occur on a spacecraft belonging to one country, necessary assistance may be given by spacecraft of another country [11, 18, 46], just as any ship that is nearby hastens to respond to the SOS of a ship in trouble in the stormy ocean.

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Part 4

SELECTION AND TRAINING OF ASTRONAUTS

N76-26844

Chapter 15

SELECTION OF ASTRONAUTS AND COSMONAUTS[1]

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Many problems related to the conquest of space, even prior to the first orbital flight, required solution. One extremely complex and responsible task which arose was selecting persons medically fit for this new type of activity. This chapter describes the process by which the USA and USSR selected astronauts and cosmonauts for early manned space flights.

Each country followed similar philosophy and methodology independently in choosing both pilot-astronauts and scientist-astronauts [2, 3]. Soviet scientists carried out more extensive animal research as a precursor to manned space flight than did scientists in the US, where policy was directed primarily toward observing man in space flight, step by step, on an incremental basis [8].

The first step in both countries was to find certain systems already approved for medical selection of persons working under conditions approximating as nearly as possible those in space flight. The medical selection system already used in aviation medicine was most suitable for this purpose; hence, the well-developed and approved system of medical selection and examination of flight personnel became the basis for medical selection of candidates for spacecrew duty. In early selection programs, both countries turned to experienced military pilots accustomed to quick decisionmaking, already physically fit for high-altitude, high-speed flight at the threshold of space; they then began selection processes for scientific investigators as part of the spacecrew. As subsequent evidence accumulated on the influence of spaceflight factors on the human organism, the system of medical selection of astronauts was improved and modified, acquiring an independent trend.

In little more than a decade, each nation had so progressed that astronaut crews could look forward to a mutual, cooperative space mission

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[1] Many interested and dedicated people helped to compile the scientific literature for this chapter; the authors are particularly indebted to Dr. T. N. Krupina of the USSR and Drs. Jack Bollerud and A. H. Schwichtenberg of the USA.

in the mid-seventies (1975). This meant that each nation had followed a philosophy of choosing types of individuals who could function both individually and as team members.

SELECTION CRITERIA FOR US ASTRONAUTS

In this review of US astronaut selection, details of time and place are given chronologically to indicate the frequent simultaneous complex decisions, procedures, and logistics involved in selection [17]. For project Mercury, the Space Task Group (STG) of the National Aeronautics and Space Administration (NASA) and a Special Committee on Life Sciences at NASA headquarters clarified crew selection procedures, with the major burden undertaken by the life sciences part of the STG working group in the field.

The initial concepts developed during the summer of 1958 followed the thinking of scientifically oriented planners; later, the views of operationally oriented flight surgeons prevailed as a pragmatic necessity [1, 2, 3]. Earth-orbital flight was but a step beyond high-altitude, high-speed flight already tested [46]; space technology, a few short steps beyond the most advanced US military experimental aircraft which had already taken man to the threshold of space [27, 42].

The main criteria for selection of astronauts centered around recruiting individuals already best qualified professionally and physically [31]. The medical and related examinations assured that, insofar as the medical state of the art permitted, individuals with the best likelihood of continuing good physical and mental health would be selected.

The first step was preparation of a "duties analysis" to: (1) survive; (2) perform; (3) serve as backup for automatic controls and instrumentation; (4) serve as scientific observer; and (5) serve as engineering observer and, as true test pilot, to improve the flight system and its components.

Qualification requirements included demonstrated environmental stress capability, toughness, and resilience; motor skill; perceptual skill; education (engineering or scientific degree because of the technical nature of the job); and height no greater than 177.5 cm (5 ft 11 in) (dimensions of the Mercury space capsule as conceived on the drawing board were severely restricted). The age maximum was arbitrarily set at 35 years, pending further study.

Assistance to the newly created agency (NASA) in the selection of astronauts was provided by the Department of Defense which assigned aerospace medical specialists to the STG in September 1958. These aeromedical officers became deeply involved in the day-to-day planning of astronaut roles and functions as well as development of further selection criteria for project Mercury [12, 14, 27].

NASA headquarters and STG planners also jointly explored professions most likely to furnish the individuals best qualified to serve as astronauts: aircraft pilots [44], balloonists, submariners, deep sea divers (particularly scuba divers), mountain climbers [40], Arctic and Antarctic explorers, flight surgeons, and scientists that included physicists, astronomers, and meteorologists. In late December 1958, however, the White House issued verbal instructions that only active military test pilots were to be used as astronauts in project Mercury.

Early implementation of project Mercury required that the selection of astronauts be limited to individuals who had already demonstrated that they could, on the basis of temperament, health, training, and experience, accomplish the proposed Mercury mission: to demonstrate the feasibility of manned orbital flight and assure space operational reliability of Mercury spacecraft, its systems, subsystems, and other components as well as the rocket propulsion systems. To meet the requirements for scientific observation on these early flights, it was concluded that intensive instruction of the astronauts prior to actual space flight would provide sufficiently reasonable competence to meet immediate needs [42].

The US Air Force (USAF) and the aeromedical community at large had already concluded that man could physiologically withstand Earth-orbital travel if technology could provide sufficient life-support equipment [7, 23, 31, 33, 35]. The principal unknown factor was the possible adverse effect of weightlessness, which could be determined only in actual flight since it was not possible, except for a few seconds, to simulate this condition [6, 21, 29].

The decision to utilize only military test pilots proved fortuitous, from the medical viewpoint. The combined records of the military services provided the Astronaut Selection Team with information on both the medical status of the candidate from the time of initial application for military service, and a medical history spanning his entire life [4, 10, 11, 15, 23]. The service record also provided a summary of the fitness or officer effectiveness report [5], regularly completed on all officers in the military services. The records indicated combat experience, awards and decorations, and a summary of educational history, information that was valuable in assessing the total personality of the individual [34].

The 35-year age limit was found to be too restrictive, so it was changed to 39 years. A total of 510 complete service records available to the selection committee included Army pilots who had completed one of the military test pilot courses and Marine test pilots [27].

The Astronaut Selection Team considered the total flying time, total testing experience [10, 11, 15, 16], ratings by representatives of test pilot schools, and the age and number of children of the potential candidates. The selection committee attempted to assess those who theoretically appeared best qualified [26] as well as those who would most likely volunteer for the program. Of the 510 candidates' records reviewed, 110 were found to be fully qualified on the basis of preestablished criteria: 58 Air Force, 47 Navy, and 5 Marine test pilots. These 110 were divided into three groups for interviews according to general qualifications obtained from the records.

Astronaut selection and training for the United States manned spaceflight program, for the next 10 years, generally paralleled military pilot selection and training. The future scientific nature of the NASA mission, however, soon required additional criteria to qualify potential scientist-astronauts [27].

Physiologic criteria for selection of military pilots had been under constant study since 1915–1920, and had been modified continuously to meet changing stresses and environmental hazards resulting from advancing aircraft technology [28]. From this substantial experience came the medical standards for military flyers that were used by US Armed Forces and exemplified by the Air Force Medical Standards [1, 2]. For the selection of Mercury astronauts, NASA used Class I military medical standards for flight training, augmented by special tests (to be described later in this chapter). As spaceflight experience increased, NASA relaxed the standards slightly in order to accept otherwise qualified candidates who could meet Class II or III military medical standards for flying [1].

The rationale underlying the selection process, as crystallized by the NASA Astronaut Selection Team in early 1959, remained the basis for present and future astronaut selection, whether pilot or scientist. Selection, for example, was not based on whether a candidate was qualified, but whether, among an already qualified group, he was the best qualified for the unique mission ahead.

Even to be considered was itself an honor. In age range, the choice was between younger individuals in the mid-twenties with less experience, education, training, background, and maturity, and about whom comparatively little was known, or those who were approximately 10 years older. The older group was chosen, even though it was recognized that they would provide fewer years of operational usefulness [26, 31, 44].

Another consideration in the selection process was the time element which involved realistic scheduling to meet operational requirements. Selection procedures, including even the criteria to some extent, were tailored to the Mercury program time schedule [37]. Thus, it was decided that the selection process must begin in early January 1959 and be completed by the end of March 1959 [27].

The first group of 35 potential candidates reported on February 2, 1959, to attend briefings by NASA personnel [12]. The presentations stressed that participation beyond this briefing was to be completely voluntary. A battery of written tests was given to the candidates to measure general intelligence and aptitude for engineering and mathematics, which included Miller's Analogy Test (graduate school level), Minnesota Engineering Analogy Test, and the Doppelt Mathematical Analogy Test. Finally, the volunteer completed a biographical inventory developed by NASA for selecting scientific and research personnel. Each applicant had four interviews, the most important of which was a joint technical interview by senior management. The candidates were also interviewed by each of two US Air Force psychiatrists covering their program and relationships with their families and other associates. Thirteen traits were evaluated individually by each psychiatrist on scales from 1 to 9, and a combined rating derived by a joint conference was reported to the committee.

In the final interview, flight surgeons reviewed the Armed Services Medical Record of each candidate. The medical officer sought to amplify the information on any background history medical item of interest and to elicit further medical information. At the end of the second week, 32 individuals had been selected for continued screening; all of them were exceptionally highly qualified individuals professionally, and from this group 5 to 12 candidates were to be selected [10, 27].

First Astronaut Group

The next two phases of the medical evaluation were carried out at the Lovelace Foundation for Medical Research and Education and Lovelace Clinic in Albuquerque, New Mexico, and at the Aerospace Medical Research Laboratories (AMRL), Wright-Patterson Air Force Base, Ohio. Evaluation for all candidates included: history—aviation and medical; physical examination; laboratory tests; radiographic examinations; physical competence and ventilatory efficiency tests; personality evaluation; and final evaluation [30].

A program of tests at AMRL to assist in selecting pilots for certain special projects, including possible space flight, had been under development for several years. The program evolved into a series of physiological and biochemical tests to be integrated into a stress test program [47]. Facilities included a human centrifuge, extremely low pressure chambers, thermal exposure chambers, C–131 and KC–135 aircraft modified to fly Keplerian trajectories safely for weightlessness studies, tumbling turntable, and an anechoic chamber. The stress test profile was designed to simulate all aspects of the stresses anticipated, insofar as practicable, during the actual Mercury project.

Additional information was derived from observation of candidates during acceleration, pressure suit testing, cold pressor testing, and in isolation. The accumulated impressions of trained observers were intended to guarantee highly reliable maturity in those recommended to continue with the Mercury program. All of the candidates chosen as Mercury astronauts received a rating of outstanding by the committee.

There were six astronaut selection programs in the first decade of the US manned space flight program [25, 30, 42]. The first, undertaken jointly by NASA headquarters and the STG, was, in effect, a pilot study from the medical viewpoint. The astronauts selected formed the first reservoir of astronaut skill in the US and provided the nucleus for successive early manned flight programs. Selection programs during the 1960s included four for pilot astronauts, and anticipating the time when diverse skills would be needed, two scientist-astronaut groups.

Great effort was expended to assure that the Mercury astronaut team could meet professional, physiologic, and psychologic demands of the first manned orbital flight—demands that could not be completely assessed until demonstrated in actual flight [23, 35]. This difficult task was completed in an effective and altogether exemplarly manner, and the Mercury mission successfully accomplished. Yet no program of such magnitude and with so many unknown factors could be without shortcomings, and constructive criticism was expected. Changes in future selection procedures were inevitable.

The President's decision to use only applicants who were graduates of a military test pilot school, currently on duty as test pilots, proved to be sound and vital to mission success. Nevertheless, many individuals may have been bypassed who doubtless could have become astronauts, given time and opportunity. Such opportunities were later provided, although the same selection procedures were continued. Astronaut-pilot selection was broadened to include qualified test pilots from within NASA and from industry.

Dynamic physiologic testing, or stress testing, was a relatively new concept and only limited information was available [33, 39, 47]. Its value in a predictive sense and as an aid to selection was consequently limited. After the first pilot-astronaut selection program, therefore, the expert consensus was that while stress tests at the Aerospace Medical Research Laboratories had produced useful medical information, they were not worth the effort, with certain exceptions such as exercise tolerance [25].

Medical evaluations, including stress tests, were accepted as necessary and meaningful by astronaut candidates; however, there was an undercurrent of dissatisfaction with the number of tests requiring blood and other biologic samples [30, 31]. Medical authorities recognized, therefore, that schedules should be improved to eliminate unnecessary repetition of procedures. In contrast to necessary clinical and physiologic evaluations, astronaut pilot candidates showed considerably less general acceptance of psychologic testing. Consequently, greater care in choosing experienced, skillful interviewers was needed.

On the other hand, the role of psychologic testing and psychiatric interviewing in nonpilot astronaut selection was generally recognized by these candidates as meaningful, necessary, and therefore acceptable.

Looking to the future, another factor for consideration was the need to gear selection programs closely within the framework of mission scheduling as the various phases of the national space program progressed. More frequent selection programs, accepting relatively few astronauts, were considered preferable rather than less frequent selection programs, bringing in larger numbers of astronauts at one time. One advantage was individualized training and more rapid assimilation into the astronaut community. Professional and medical selection criteria, consistent with the most recent space operational experience were assured, and the range of talents and training of the astronaut group would be augmented.

Changing requirements for astronaut selection were anticipated as the size of spacecraft and duration of space missions increased, and as scientific and related space tasks became more diverse and specialized [12, 14]. For example, Mercury astronauts were programed to carry through one-man missions only. During these pioneering missions, the greatest possible demands were made upon the individual as pilot or operator of the spacecraft, as scientific observer, as experimenter, and as subject. The astronaut was dependent upon his own resources, training, and multiple capabilities to resolve in-flight problems as they arose. During Gemini flights, test-pilot astronauts encountered longer flights, the need for coordinating the activities of two individuals, extravehicular (EVA) operations, and the necessity for getting along with each other for up to 2 weeks in confined quarters. More extensive scientific observations required the two Gemini astronauts to act as scientific observers and experimenters, and thus expansion of academic subjects to be mastered [22].

In the Apollo project, a third member chosen for scientific background, although possessing less pilot experience, had to be fully qualified to manage the operation of either the spacecraft or the Lunar Module (LM).

Meanwhile, to improve logistic efficiency, medical evaluations were made at a single facility. The USAF Aerospace Medical Center at Brooks Air Force Base, Texas, was well-suited for this purpose, particularly as plans moved forward to build the new NASA Manned Spacecraft Center (MSC) (later named the NASA Lyndon B. Johnson Space Center) at nearby Houston, Texas, and to transfer STG functions from Langley Research Center, Hampton, Virginia.

Finally, another change for future programs was for veteran astronauts of Mercury flights to serve on the MSC selection board, thus enhancing understanding of mission requirements and the type of individual best suited to carry out the mission. The stage was set for future astronaut selection procedures, both pilot and astronaut scientist [42].

Pilot-Astronaut Selection Program 1962–67

There would be many basic similarities between both astronaut-pilot selection programs and the scientist-astronaut selection programs carried out by NASA Manned Spacecraft Center in Houston, and the first astronaut selection program at Langley. Experience and lessons from project Mercury would be applied to subsequent procedures which were simplified and integrated even more closely with various elements and phases of the increasingly complex manned space program.

Astronaut Donald K. Slayton, the Director of Flight Crew Operations, was assigned the key position in astronaut selection and training and would also head the Astronaut Selection Board. Charles A. Berry, M.D., left the USAF to become the first permanent civilian Director of Medical Operations at the MSC, responsible for shaping the future course of medical and related qualifications of pilot-astronauts and later scientist-astronaut candidates. Medical factors were integrated into the team evaluation effort. By early 1962, the modus operandi was set for five subsequent astronaut selection programs [25].

Specific tests and criteria for the medical evaluation were selected by the NASA MSC staff and the USAF Aerospace Medical Center at Brooks AFB. The US Air Force recognized that flight research activities, which included manned space flight, posed new and increasingly stringent demands upon man's tolerance. It had early developed a comprehensive biomedical evaluation program to identify candidates with the greatest potential to complete training and participate productively over a long period. This biomedical evaluation was of great importance in the US astronaut selection program.

The main elements of the medical evaluation, which Lamb [26] describes in four parts, are summarized in the following pages. In the first part, for the detection of significant diseases or abnormalities, the evaluation was sufficiently comprehensive to discern abnormalities often not apparent from history and physical examination alone, such as evidence of renal stones, silent gallbladder stones, peptic ulcer, evidence of convulsive focus in the brain, dental apical abscesses, rectal polyps, diabetes, and many other abnormalities which could interfere with success in prolonged participation in space missions.

The second category concerned predisposition to disease or to limited performance capability even though, as isolated phenomena, they did not permit diagnosis of disease or abnormality; for example, obesity, and persons with borderline glucose tolerance tests [25, 36].

The third area was concerned with complex evaluation of mental and character dynamics: the candidate's motivation, intellectual ability, learning aptitude, emotional adaptability, and maturity.

The fourth part emphasized physiologic capacity under different loads and stresses, including tests during maximum exertion, use of the tilt table for evaluating autonomic control of the cardiovascular system, and physiologic stresses such as hyperventilation and breath-holding combined with orthostatic influences. Clearly, this dynamic approach was significantly distinct from the usual clinical situation in which the individual is studied in the resting state.

Aeromedical Evaluation

Aeromedical history. To insure comprehensive coverage, a carefully designed, detailed questionnaire encompassing all essential medical specialties and suitable for automatic data processing was completed by each candidate. It provided a uniform medical history which was a valuable supplement to the information obtained directly by examining physicians.

Physical examination. A group of highly trained clinical specialists conducted a physical examination, which comprised, along with all standard procedures, proctoscopy and rectosigmoidoscopy. Careful dental examination and a complete series of dental radiographs were included.

Laboratory examination. A typical series of clinical laboratory procedures on fasting blood and a urinalysis were performed. In addition, a 2-h glucose tolerance test was administered to all candidates.

Radiology examination. The comprehensive diagnostic radiologic examination consisted of:

1. Skull—lateral, posterior-anterior, occipital, and base views; for the paranasal sinuses, an upright view.
2. Chest—posterior-anterior and left lateral projections; separate views of the thoracic spine were not routinely done.
3. Spine—lateral and anterior-posterior views of the lumbosacral spine and pelvis were obtained in conjunction with the cholecystogram; oblique views of the spine were not routinely made.
4. Abdomen—a survey of the abdomen was done in all cases.
5. Gallbladder—cholecystography was carried out 14 h following oral administration of contrast material. Localization of the gallbladder was accomplished on lumbosacral spine views; in most cases, only one additional view, either in the oblique or upright position was needed. This examination did not routinely include a fatty meal or other stimulus with subsequent gallbladder visualization.
6. Upper gastrointestinal tract—fluoroscopic examination of the esophagus, stomach, and duodenum was performed during administration of a barium meal. Special attention was given to eliciting the presence of hiatus hernia or gastroesophageal reflux. During fluoroscopy, four spot views centered over the first part of the duodenum were obtained; following fluoroscopy, a posterior-anterior view of the abdomen and two right anterior oblique views of the stomach were made. Delayed films were omitted from these examinations.
7. Colon—only those with proctoscopic evidence of disease received barium enemas. In such cases, there had been proctoscopic visualization of polyps.

Otorhinolaryngology evaluation. The ear, nose, and throat examination which included vestibular and audiometric testing was considerably more detailed and comprehensive than the routine evaluation. Additional procedures helped to provide a reliable basis for comparison of candidates and to establish sound selection criteria in the final medical recommendation process.

Ophthalmology evaluation. The eye examination allowed a great deal of flexibility to accomplish these functions:

1. Ruling out active subclinical disease processes.
2. Ruling out early asymptomatic dystrophic diseases and glaucomas.
3. Ruling out present and predictable incapacity from "normal" causes, such as hyperopia and heterophoria.
4. Establishing current visual capabilities of each candidate at normal light levels and extremes of illumination.
5. Establishing baseline data for followup.

Neurologic evaluation. One hour was devoted to each candidate for detailed neurologic history and examination which were recorded on a standard form along with results of visual fields, audiograms, and caloric tests. Electroencephalograms using monopolar and bipolar techniques were obtained on all astronaut candidates. The total recording time for the resting record was about 20 min. Additional tracings were obtained during and after 5 min of hyperventilation, photic stimulation, carotid sinus stimulation, carotid artery compression, the Weber maneuver, and inhalation for 4 min of 93% nitrogen mixed with 7% oxygen.

Psychiatric and psychologic evaluation. Details of this part of the evaluation are presented in the final part of this section (SELECTION CRITERIA FOR US ASTRONAUTS).

Pulmonary evaluation. Pulmonary function studies mainly emphasized maximal breathing and vital capacities.

Cardiovascular evaluation. Each candidate received a comprehensive cardiovascular history and physical examination by an internist [33]. Significant physical findings were rarely noted other than occasional moderate obesity. Functional murmurs and other physiologic variations were sometimes noted on cardiac auscultation. Particular attention was given to blood pressure determinations since moderate elevations may predispose to subsequent disease.

Procedures included in the cardiovascular evaluation were:

1. The cold pressor test. This was performed in the standard manner. After immersion of the hand in ice water, individuals having a rise in diastolic pressure less than 10 mm Hg were classified as hyporeactors; those with a rise between 10 and 20 mm Hg, normal reactors; and those with a rise exceeding 20 mm Hg, vascular hyperreactors.

2. Plethysmography, using an impedance plethysmograph, primarily tested characteristics of the curves and documented normal bilateral equal pulsations for subsequent comparative data.

3. Phonocardiography. A standard twin-beam phonocardiographic instrument was used to record inspiration, expiration, and midinspiration at standard valvular areas. In a highly selected group without clinical evidence of valvular or other forms of cardiovascular disease, the phonocardiogram was used primarily to establish baseline interval values by simultaneously recording one lead of the electrocardiogram with the mechanical events. Where there was a question of significant cardiac murmur, the auscultation was carefully carried out in a soundproof room.

4. Ballistocardiography. A simple ballistocardiographic procedure was carried out with simultaneous recording of electrocardiogram, phonocardiogram, and respiration. This provided information related to cardiovascular function and established normal values for an apparently healthy population.

5. Valsalva. Each subject in the standard Valsalva procedure took a very deep breath and bore down firmly against the closed glottis as long as possible. The electrocardiogram was recorded throughout this procedure and blood pressure determinations were obtained at regular intervals by the ordinary manual method. Integrity of reflex control of the circulatory system and identification of significant cardiac arrhythmias, occurring occasionally during such a procedure, were indicated by this test.

6. Electrocardiogram. A standard 12-lead electrocardiogram was recorded for all subjects.

7. Precordial map. A precordial map was done on each subject beginning with the 2nd right intercostal space and extending as low as the 6th right intercostal space. The carefully constructed map identified early in the program those individuals with R′ waves and other minor electrocardiographic variations which may be recorded from time to time as related to electrode position. It provided a more adequate baseline for comparison of the chest leads in subsequent examinations.

8. Vectorcardiography. An electrically balanced bipolar vectorcardiographic reference system was used. In addition to obtaining photographic representation of frontal, sagittal and transverse planes, vector components were recorded on magnetic tape for subsequent analysis by analog computer from which linear vectorcardiograms were obtained. The electrically balanced reference system permitted more adequate evaluation of minor electrocardiographic variations, such as Q–3 patterns. Three-dimensional representation permitted subsequent analysis of electrocardiographic variations associated with position or variabilities of the QRS in flight.

9. Master's exercise tolerance test. A double Master's exercise tolerance test was performed in a standard manner. Only significant plateau ST segment depression, 2 min after exercise, was considered a positive criterion.

10. Special electrocardiographic studies. Each candidate had an electrocardiogram during a series of physiologic maneuvers: in the sitting position, during maximum breath-holding, carotid sinus massage, simple standing for orthostasis, hyperventilation followed by maximum breath-holding, and while seated, breathing 100% oxygen for 10 min at a regulator setting of 43 000 m (approximately 11 mm Hg). These physiologic maneuvers demonstrated dynamic variability and provided a definitive basis to evaluate minor electrocardiographic variations, such as nonspecific T-wave changes and cardiac arrhythmias. Some of the same stresses were used during tilt table studies and their repetition without the tilt table indicated the influence of the tilt table. ECG variations produced with these stresses were not given the same significance as those observed in the resting baseline ECG. The influence of the autonomic control of the cardiac rhythm and ECG patterns is so significantly altered during

stresses that their direct application to clinical diagnosis must be regarded with skepticism. They usually demonstrated individual physiologic variations.

11. Tilt table studies were conducted on an especially designed tilt table capable of rapid changes of position and rotation through 360° in which the subject's feet were suspended so that they could not support the body. The tilt table assessed the adequacy of circulatory adaptive mechanisms, chiefly autonomic control, to minor simple changes in G-stresses. The tests used about 20 min of orthostasis, and by gradual addition of stresses to the initial orthostatic stress, accumulative factors tending to decrease cerebral blood flow were initiated. The most common ECG changes in healthy individuals during tilt table procedures were physiologic T-wave variations induced either by orthostatic stresses or by a combination of orthostatic and ventilatory maneuvers. These variations were so frequent that they were the rule rather than the exception. Displacement of the cardiac pacemaker from the sinus node to an atrial position was also observed frequently. Tilt table stress tests were primarily used to study adaptive responses; individuals who showed unusual susceptibility to minimal stresses by losing consciousness were less desirable as candidates for space pilot programs.

12. Lean body mass was determined for each candidate [26].

13. Blood volume determination used the ^{131}I method; Lugol's solution was given the day prior to testing.

14. Maximum oxygen consumption [4] was measured during maximum physical exertion. The subject walked on a constant treadmill at 10 m/min (3.3 mph) while the treadmill grade gradually increased. When the heart rate reached 180 beats/min, it was assumed that the subject was nearing maximum exertion. He could continue if not unduly fatigued, quitting at any time. If the systolic pressure exceeded 240 mm Hg or the diastolic pressure exceeded 140 mm Hg, the test was terminated. It was also terminated immediately if the pulse rate began to drop or there was significant drop in blood pressure.

The maximum oxygen consumption test appears to be an effective procedure for measuring general physical fitness and endurance; an individual would probably not achieve top values within the first quartile without very competent coronary blood flow. This test alone, however, particularly in the medium ranges of values, cannot completely exclude underlying coronary artery disease since individuals with known coronary artery disease are capable of performing an appreciable quantity of work. Individuals with values in the high normal group generally show medical and physical features attributed to robust good health. Factors other than coronary artery disease may limit maximum oxygen consumption, including a left-to-right shunt mechanism or other forms of cardiac disease. It should be possible, however, on the basis of pulmonary function tests compared with ventilation required during maximum exertion to differentiate between limitations in exercise caused by pulmonary and cardiovascular factors. Unusually low values suggest more searching clinical evaluation. Individuals with possible pathologic findings who had lower values of maximum oxygen consumption were classified as clinical vascular hyperreactors, labile hypertension, or essential hypertension [5].

The procedures which have been described were generally followed in subsequent evaluations, with appropriate modifications in the light of growing experience. Candidates were listed in order of preference according to the best medical estimates and predictions on maintenance of high health levels over a prolonged period. Allowance was made for age and experience of the pilot or astronaut-scientist candidate. An individual who had been medically disqualified was in no instance selected by the board.

Scientist-Astronaut Selection Programs 1965–67

Procedures for the two scientist-astronaut selection programs in 1965 and 1967 varied only slightly from those for pilots. A public announcement by NASA invited interested scientists to apply. The National Research Council (NRC) was designated to determine scientific professional competence and qualifications. Dr. Berry and his staff screened medical examination forms for disqualifying defects and the candidate was dropped from consideration if definite disqualifying defects were found. A medical examination was then given at the USAF Aerospace Medical Center, and later the candidate appeared before the Astronaut Selection Board.

Because in-depth medical information about the first group of scientist-astronaut candidates was lacking, medical evaluation again included multiple forms of stress-testing at Wright-Patterson AFB. The medical member of the NASA Astronaut Selection Board, however, came to the same conclusion as with the pilot-astronauts: that in terms of medical results such testing was unwarranted for scientist-astronaut applicants. Thus, for the second time, NASA concluded that extensive environmental stress-testing was unnecessary for astronaut candidates, although certain types of physiologic stress tests were retained, such as maximum physical exertion/maximum oxygen consumption, and postural tests of autonomic circulatory stability.

The scientist-astronaut candidate group was composed of 84 young men from the national scientific community, whose previous medical examinations had varied widely in periodicity and depth, and whose mean age was 32 years. In comparison with military test pilot-astronaut candidates (111 candidates with the same mean age of 32 years), the very high incidence of medical abnormalities was of such significance in the scientist group that it warranted reservations about their selection. Seven candidates had a history of notable medical problems; physical examinations revealed several cases of strabismus, myopia, nasal polyps, obstructive nasal septal deviation, indirect inguinal hernia, and varicose veins. The military candidates possessed no comparable abnormalities, as might have been expected from those who had to meet rigid medical standards for flying.

Psychiatric and Psychological Evaluation

Distinct differences between scientist-astronaut and pilot-astronaut candidates were elicited by psychiatric evaluation. Aside from military test pilots who had undergone some psychiatric screening prior to assignment to Aerospace Research Pilots School, comparatively few candidates of either group had ever been exposed to psychiatric or psychologic testing procedures. Test pilots showed significant differences in greater self-confidence and increased maturity. For example, the vast body of psychiatric evidence and operational experience indicates that the most satisfactory performances emanate from the physically healthy male who is intelligent, emotionally mature, and basically independent yet able to form strong group identifications, working comfortably and cooperatively toward common goals. He is realistic not only in program motivation and self-evaluation, but also in his appraisal of program risks and rewards; he possesses high self-esteem, based upon realistic self-evaluation, and has little difficulty with impulsivity [34, 36].

The initial psychiatric interview was standard, involving acquisition of background information covering the individual's entire lifespan, and lasted from 1 to 4 h, depending upon complexity of personality structure and life history complications. A battery of psychological tests, usually requiring a minimum of 8 h, was divided into two categories: tests assessing intellectual abilities, and those which revealed personality structure and motivational drives. Psychiatric interviews and projective psychologic testing combined with the individual's history offer the most reliable measure of personality integration and stability at present. Individual traits become less important than their total integration into a cohesive, stable personality. Classification, based upon numerical scores were: "unqualified," "qualified with major reservation," "qualified without major reservation," and "exceptionally well-qualified." For a selected group of men of such high achievement, however, the "unqualified" category was rarely used.

A notable background difference between pilot and scientist groups involved past exposure to physical stress. All pilots had considerable flying experience, and most were test pilots; most had faced demanding situations involving acute physical threat. Such "testing" experiences, however, had not been experienced by the majority of scientist candidates. Their objective and subjective responses to such unfamiliar evaluation procedures as centrifugation, biaxial vestibular stimulation, and monitored ride in F–100 aircraft were therefore of great interest when related to available psychiatric information.

Because military achievers and nonmilitary scientists presented a heterogeneous group in origin and interest in scientific research, interesting methodological problems of assessment resulted. The military candidates were atypical of average service pilots in their strong motivation to obtain advanced professional degrees and interest in pursuing careers. On the other hand, while interested in flying, the nonmilitary scientist group was for the most part nonpilots; as scientists, they were usually educated to doctorate level in a specific discipline. Motivated to conduct research in their major field within the NASA structure, they hoped to become active crewmembers aboard a space vehicle. Thus, there were distinct differences between the military and academic structures within which each group had flowered and they contributed a different frame of reference toward the total effort.

Psychologic testing followed proven clinical psychologic evaluation procedures utilizing a basic standard test battery augmented by additional pertinent tests. A unique facet of this assessment was that it concerned "normal" individuals, i.e., normal in the sense that significant psychopathology was an uncommon finding.

Wechsler Adult Intelligence Scale. The mean intellectual level of candidates, using the Wechsler Adult Intelligence Scale (WAIS), was generally over two standard deviations above the mean for the general population; there was little difference between military and civilian populations. The inclusion of several candidates whose measured intelligence quotients were not in the same superior to very superior range, but who had, nevertheless, achieved sufficient success within their fields to warrant preselection from the large pool of available volunteers, might raise speculation on the meaning of intelligence and its utilization in such an assessment program.

Three specialized tests were utilized to obtain an estimate of the individual's level in verbal, mathematical, and engineering areas, measuring past learning and indicating breadth of knowledge. In general, the civilian group scored consistently higher on these three special tests.

Protocols in astronaut selections were being obtained similar to those of earlier studies. For the most part, the records of the military group reflected good ego strength, practicality, common sense, ability to organize effectively, adequate controls, emphasis upon responsiveness, and emotional interaction with the environment. Individuals appeared to be action-oriented, taking pride in mastering their respective areas of training and their emotional lives. They were productive and creative, with their imagination reality-oriented and perceptually appropriate.

Rorschach Test. Some individuals tended toward more concrete, engineering perception, and in the Rorschach test, for instance, tended to emphasize form characteristics; their movement responses were the popular ones along with a controlled use of color without undue inflexibility or rigidity. They had learned through training and experience to deal with life in a practical, form-oriented manner, with appropriate emotion utilized in a somewhat distant fashion. These men were not robots; they were highly achievement-oriented, goal-directed individuals whose lifestyle, as reflected by test protocols, was expressed by logical positivism, subtle humor, and warm, empathic feelings for others, with well-defined lines of degree and involvement.

Others, although they had similar training and experience, were more creative, introspective, and cognitively oriented. In contrast to the "engineer," they responded with greater openness to Rorschach stimuli. Their perceptive and emotional processes were harmonious, permitting greater latitude in their response process. They ranged broadly through the stimulus material, building elements into well-organized wholes, permitting themselves the luxury of an incongruous percept while recognizing it as such, with the freedom to let it come into being. They reflected self-confidence and a sureness in their ability to succeed in whatever they undertook. There were potential conflicts; the creative, ingenious, self-actualized individual could pose a problem for an action-oriented, engineer type, and vice versa.

Civilian candidates in the Rorschach protocols manifested greater variability and to some extent were more likely to deviate from the usual patterns than did the military group. The number of responses tended to be greater, and whole responses and content categories greater and more varied. They tended to be impatient with routine procedures and to enjoy the challenge presented by Rorschach and the Thematic Apperception Tests (TAT). Surprisingly, they tended to express their aggressive feelings more openly than did the military group. They were inclined to pursue a course of action to its completion. There were few major differences on the TAT between military and civilian groups.

Candidates who gave evidence of being comfortable with themselves tended to reflect a pervasive, subtle sense of humor which was not manifested in a hostile way but rather in a playful, almost boyish delight.

In summary, the astronaut volunteer was found, upon extensive physical and psychologic evaluation, to be a very healthy specimen. He was physically strong and resilient, and of superior intellectual endowment. A well-organized, pragmatic, concretely oriented, aggressive (in the nonhostile sense) man of action, he tended to handle sensitive interpersonal relationships rather distantly. He derived major professional satisfaction from mastery and competence in increasingly complex flying vehicles and technical pursuits. His confidence came from realistic assessment of his own capabilities, although he generally invested little time in introspection.

SELECTION CRITERIA FOR SOVIET COSMONAUTS

Early in the USSR manned spaceflight program, it was recognized that flight in space is accompanied by exposure to acceleration, vibration, noise, weightlessness, long-term isolation, relative hypodynamia, disorder of the diurnal rhythm, and other factors. Since experimentation by direct human participation was not practical during this early period, the only other possibility (correct as it turned out) of carrying out in-depth clinical and physiologic investigation was to use a broad complex of load tests to estimate the somatic and functional capacities of candidates. Many years of experience in medical and flight expertise contributed to the solution of this problem.

The first cosmonauts were selected from flight personnel. It was assumed that the first cosmonauts should have, in addition to good health, strong will, rapid reactions, and the capacity to make and execute decisions rapidly in unexpected situations. They had to be familiar with flight conditions and the effect of conditions similar to those which might be encountered in space flight. It was highly probable that persons with these qualities could be found among flight personnel.

The complexity of spaceflight conditions, testing of space equipment, and conduct of scientific investigations required that cosmonaut investigators with high scientific qualifications be included in the spacecrew. Thus, it became necessary to modify certain criteria established for the first cosmonauts in evaluating the health of selected candidates, as well as to verify problems pertaining to selection, and particularly to training of cosmonauts and investigators.

Medical selection of cosmonaut investigators took into account characteristics of age and deficient level of physical training, as well as their professional value as highly qualified specialists [24, 49].

In selecting cosmonaut investigators, the difference in the medical evaluation was in the interpretation of data on the candidates' functional reserves, and in improved prophylactic measures for optimal medical support. It was also important to have a thorough knowledge of any peculiarities in reactions which could unfavorably affect the performance of the spacecraft crewmember. Consequently, because of the professional value of the cosmonaut investigators and their range of duties in flight, certain deviations in health condition could be permitted in their training.

Subsequent preflight analysis of data elicited at all stages of selection and data furnished by clinicians, physiologists, and psychologists provided a basis for recommending candidates who were best prepared and most resistant to spaceflight influences so as to predict adequate tolerance for successful completion of the flight. In the mean-time, changes in certain organs and systems of the human body during various tests remained under careful observation in all stages of training and in space flight with the view toward further improving the system of selection and training. A continuing search is underway for active prophylactic measures and more rational health indices for using such measures prior to flight, during flight, and in the period of restoration of functions disturbed in space flight.

The starting point in the formulation of the Soviet system of medical selection of cosmonauts was the concept that selection is a continuous process. The system developed for selecting cosmonauts was planned for several interrelated stages of examination and selection: (1) under ambulatory conditions, (2) under clinical conditions, and (3) in the training process.

The ambulatory stage was directed toward revealing clear pathology and functional disorders absolutely contraindicating admission to space flight.

Clinical and Psychological Evaluation

Selection under clinical conditions was planned to reveal concealed pathology, initial preclinical forms of diseases, changes in functional conditions of the organs and systems of the human body, and to determine functional body reserves.

The preliminary program of clinical examination consisted of:

1. Aeromedical and other clinical specialty examinations of the same scope and variety as for flight personnel, with health standards identical to those for flying school candidates.
2. After successful completion of the first stage, tests revealing functional reserve capacities, i.e., load tests specifically designed for cosmonaut activity (centrifuge, vestibular tests), and nonspecific load tests (tests with physical load), were administered. In addition, supplementary clinical examination was directed toward revealing possible latent pathology.

Psychological examination, a significant part of medical selection, was designed to reveal characterological facets of personality in order to predict behavioral and emotional reactions under stress conditions. Experimental psychologic investigations, using individual and group methods, were conducted to estimate interactions of persons in group activity. The data were to be used subsequently in assigning crewmembers to spacecraft according to their compatibility.

Examination and Selection in Training

After passing successfully through all selection stages and demonstrating good resistance to load functional tests, candidates who were recognized as suitable for space flight were sent to the Cosmonaut Training Center for specific flight training. The primary role of this training was to increase resistance of the human body, develop adaptive reactions to the effect of specific spaceflight factors, and acquire the necessary working skills to control spacecraft systems and instruments.

Significant numbers of cosmonaut candidates in all selection stages were rejected for health defects during all selection stages, but particularly in the clinical evaluation. In various years, from 25% to 50% of candidates who had gone through the initial selection process were rejected, primarily for functional disorders and diseases of the internal organs. Moreover, candidates with diseases of the eye, nose, and throat; anomalies of development or degenerative changes of the spine; or vestibulovegetative instability were judged unsuitable.

Rejection in the second stage diminished in recent years, due to a stricter preliminary examination, and to the application at this stage of new methods of investigation. For example, the replacement of standard vestibular tests with a new test to determine the effect of cumulative vestibular stimuli by Coriolis acceleration has significantly decreased rejection of candidates for vestibular disorders [9, 32, 50].

Soviet data and investigations of scientists of other countries show that in weightlessness and under conditions of limited movement in space flight, characteristic changes in the human body are disorders of water, electrolyte, and hormonal balance, and vascular tonus, as well as decreased tolerance for physical stress and radial accelerations.

In a prolonged state of weightlessness, a number of disorders of the cardiovascular system may develop. Emotional stress, which is natural in space flight, is also significant as are stress reactions arising from cosmonaut activity, particularly during long space expeditions. All this required certain corrections in the methodology of medical selection based upon analysis of results of clinical and physiologic investigations in a state of rest and during physical tests under conditions simulating space flight. Such a clinico-physiologic approach enabled more active estimation of functional capacities, range of resistance to extremal factors, and determination of compensator adaptive mechanisms.

The experience acquired in actual space flights, in addition to knowledge obtained from terrestrial investigations, made it possible to lay the groundwork and systematize criteria for expert medical estimation of health and physical standards for cosmonauts in training for space flights. The best diagnostic approaches were determined in regard to the most frequently encountered and isolated pathologic conditions and to limited and latent forms of illness and disorders revealed by cosmonaut candidates. The latter pose great difficulty in interpretation in regard to the tasks of selection.

Endocrine System

Endocrine disorders are known to cause functional deficiency of the cardiovascular system under stress conditions. Therefore, diagnosis of latent endocrine deficiency, specifically determination of hyper- or hypofunction of the endocrine glands, even without pronounced signs of disorders, casts serious doubt upon the candidate's suitability to participate in long-term space flight. For example, a disorder of the lipid metabolism of endocrine origin must be viewed as a contraindication for long-term space flight. Obese persons cannot be considered promising candidates for cosmonaut activity, primarily because they are subject to early atherosclerosis. Underweight persons are also undesirable since they are more subject to decrease of working capacity resulting from loss of fluid under unfavorable conditions aboard spacecraft.

Orthostatic Stability

Loss of fluid and other disorders of water and electrolyte balance are among the main etiologic causes for decrease in orthostatic stability.

According to Vasil'yev and Kotovskaya [43], and Gazenko and Gyurdzhian [20], a limiting factor in adaptation to weightlessness is decreased orthostatic stability, specifically related to change in afferentation as the result of significant decrease in hydrostatic blood pressure under these conditions. Redistribution of blood in the central and peripheral regions of the body causes decrease in the volume of circulating blood.

Disorders of water-salt metabolism related to hypodynamia and weightlessness can lead to formation of stones in the urinary system according to clinical data. One study reported renal complications in 15 of 44 patients (35%) following long-term limited movement. An increased excretion of phosphorus in 12 men led to formation of phosphate stones which was related to decreased muscular activity.

Persons with a history of renal colic, gallbladder disease, hematuria of unknown etiology, hyperphosphatemia, oxaluria, or goiter—conditions favoring formation of stones—should not, of course, be accepted for space flight. In addition to the usual clinical methods, including intravenous pyelography, other methods of revealing latent forms of kidney stone illness were used to check the "provocative" effect of such flight factors as radial accelerations and vibrations. Urinalysis before and after such exposures enabled detection of latently occurring forms of urolithiasis. Further searches are necessary for methods of determining predisposition to kidney stone illness.

Cardiovascular System

The effect of prolonged immobility and weightlessness on the functional character of the cardiovascular system justifies careful study of the resistance of the human body to stress factors, particularly among persons having cardiovascular abnormalities. Disorders of the nervous and circulatory systems which can appear in space flight also include dysfunctions of the conduction system of the heart, and are important considerations in cosmonaut selection. The basic criteria in determining suitability of candidates with cardiac rhythm disorders are the frequency, localization, and nature of appearance of the extrasystole. Overstimulation of the parasympathetic innervation of the heart plays a large role in the occurrence of extrasystole. Extrasystole related to an increase in the tonus of the vagus nerve usually appears when the myocardium is in good functional condition and most frequently is of left ventricular origin, and has no particular influence on circulation.

Extrasystoles are usually encountered in a state of rest with diminished pulse, and are scattered. Persons having such extrasystoles endure functional load tests well. Extrasystoles usually disappear under the influence of atropine or physical loads, an indication of their functional character. The most significant of various types of extrasystoles are those of the atrium and A–V node. Clinical observations of atrial extrasystoles generally show significant morphologic changes in the atria [19]. A–V node premature contractions give even more reason to assume damage to the myocardium. It should be taken into account that atrial and A–V nodal extrasystoles are frequently percursors of paroxysmal tachycardia and atrial flutter [19, 38].

Multifocal and runs of extrasystoles as well as stress extrasystoles usually appear as the result of inflammatory and atherosclerotic damage to the myocardium and can lead to disorders of circulation, while frequent A–V nodal extrasystoles can lead to retrograde conduction to the atria. Candidates with such forms of extrasystoles should not be considered suitable for cosmonaut selection. Persons with various disorders of the conductive system of the myocardium were also observed; if they had retarded atrioventricular conductivity in the P–Q interval of up to 0.22 s, they were considered suitable when the standing orthostatic test showed conductivity was not retarded even more and when the duration of conductivity did not shorten with atropine and physical exercise. Nor was extension of the Q–S interval to 0.11 s in persons with good tolerance during load tests a basis for rejection.

Decrease in arterial blood pressure resulting from decreased vascular tonus is observed in connection with loss of catecholamines and aldosterone during hypokinesis and in weightlessness. This leads to the threat of orthostatic hypotension. As a result, persons with stable orthostatic hypotension below 100/55 mm Hg were not admitted to the space program. Constant arterial pressure, which periodically decreases, was evaluated individually, taking into account results of tests under stress conditions. Persons with hypotony and predisposition to collapse reactions under stress conditions are unquestionably unsuitable for space flight.

Persons inclined to hypertensive reactions require careful differentiation. Subjects in whom high arterial pressures are recorded first under clinical conditions are occasionally encountered; these cases can be explained by the influence of the emotional factor. A persistent tendency toward such hypertensive reactions in a candidate should be cause for rejection. This is necessary not only because cosmonaut activity is laden with emotional influences and phychologic stress which may result in development of disorders of vascular tone, but also because of the predictive significance of frequent increases in arterial pressure above the norm in the development of subsequent hypertensive disease. Candidates in whom disorders of the heart valves and other pronounced pathologic conditions were found were recognized as unsuitable.

Load Tests

Accumulated data on the effect of space flight on man and experimental studies of individual flight factors made it possible to detect changes in various systems and organs. In clinically healthy persons, functional limits differ individually and characterize tolerance to flight conditions. Consequently, suitability of a particular candidate for space flight is determined by complex evaluation of his state of health according to the results of clinical investigations and by the way functional load tests are tolerated.

According to Vyadro [45] and others, and

Krupina et al [24], the most informative tests are physical load, orthostatic, hypoxic, and thermal tests. The future value of these methods will increase with unification of the evaluation system and the competence of comparing terrestrial data with the stress effects in space flight. Accumulated experience permits the hypothesis that certain health deviations in cosmonauts may not deter even long-term flights if, in functional load tests and certain flight simulations, adaptive disorders do not develop.

Gastrointestinal System

Gastrointestinal pathology is important among latent forms of diseases of the internal organs. Ulcer and cholecystitis are potentially dangerous diseases, unquestionably incompatible with cosmonaut activity. In a number of cases, they occur asymptomatically, revealed only in the form of decrease in resistance to the effect of functional load tests and specifically to such conditions as hypoxia and vestibular stresses. For this reason, great emphasis was placed on diagnosing diseases of the gastrointestinal tract at the clinical stage of selection. In addition to a more careful and goal-directed study of an individual's medical history along with widely used methods of clinical diagnosis, investigations were conducted toward expanding diagnostic possibilities of revealing preclinical forms of gastrointestinal diseases [18, 45].

Spinal Column

A great variety of surgical diseases require expert, individualized evaluation, among which are degenerative and dystrophic changes of the spine. Evaluation by x-ray is undoubtedly indicated since an overwhelming majority of cases occur asymptomatically, evincing neither pain nor significant disability of the spinal column.

The condition of static and dynamic function of the spinal column was considered very significant during clinical evaluation of degenerative and dystrophic diseases of the spine. In candidates recognized as suitable, such clinical data served as additional indices of overall physical conditioning; consequently, during subsequent dynamic observations, the data could be used to evaluate suitability of the system of special physical training. Wide use was made of goniometry in the selection process to record objectively not only configuration but also amplitude of movements in various regions of the spinal column. Goniometric measurements revealed a limited backward inclination of the trunk, an important clinical sign, among a number of candidates with deforming spondylitis and osteochondrosis. Expert judgment on the significance of such findings took into account the character of the upcoming spaceflight activity, degree of morphologic changes in the spinal column, and its functional ability. Caution was necessary inasmuch as in these processes, compensation of function is extremely unstable and easily disrupted, particularly in training on a large scale with various exercises such as parachute jumps and physical exercises.

Vestibular-Autonomic System

Correct evaluation of the complex system of "analyzers" (special senses developed in the process of human evolution), particularly vestibular, visual, and kinesthetic, is a primary physiologic consideration for long-term flights [48]. As a result of specific spaceflight conditions (weightlessness, G-forces, and so forth), the normal function of certain sensory and regulatory systems can be disrupted, causing development of various disorders, among the most unfavorable of which are disturbances of the vestibulovegetative system (vestibular-autonomic nervous system effects). In consequence, development of a methodology for vestibular selection was emphasized.

Many authors do not share the viewpoint that there is a direct relationship between resistance of the vestibular apparatus to the effect of adequate stimuli under terrestrial conditions and tolerance to space flight. However, assuming such a direct relationship and considering the experiences of all test flights in the Vostok, Voskhod, and Soyuz spacecraft, it is clear that persons naturally resistant to the cumulative effect of adequate stimuli as well as those trained to the appropriate complex of vestibular factors can endure space flight and rapidly adapt to weightlessness without autonomic system disorders.

Conclusions from these observations formed the basis of a system of vestibular selection criteria and demonstrated the expediency of specially preparing cosmonauts by active and passive training of the vestibular system. Vestibulometric methods were developed for selection and training, based on the complex effect of Coriolis accelerations and linear accelerations (Khilov swings); also procedures for applying optokinetic stimuli in combination with loads on the statokinetic system by balancing on a measured variable nonstable fulcrum. The vestibular aspects of cosmonaut selection and training will continue to be important in future plans for long-term space flights, particularly when spacecraft are designed for artificial gravity.

Selection Criteria for Prolonged Space Flight

Orbital flight experience has shown that the system chosen for selecting cosmonauts for short-term flights has been fully justified. The methodology of selecting the first cosmonauts was developed from vast medical and aviation expertise, fundamental investigations carried out by specialists in aviation medicine supplemented by observations and experiments of clinicians, and experience gained in actual manned space flights.

Although certain medical standards for selecting cosmonauts were reevaluated and modified for the scientist-cosmonauts, as advocated by Soviet scientists, this tendency will not likely be extended to candidates selected for long-term space flights. The long-term effects of flight factors, an expanded range of duties which will be assumed by all crewmembers, and the need for interreplaceability of cosmonauts during flights will require stricter selection criteria in the somatic and psychologic spheres. Improvement in determining functional capacities of persons selected for prolonged space expeditions will be needed.

In proportion to the increase in duration of space flights, other specialists besides pilots will undoubtedly be needed, such as navigators, engineers, physicians, biologists, astronomers, geophysicists. Thus, development of new medical and psychologic selection methods, and improvement in the system as a whole will be required. Moreover, with the goal of preserving the health of cosmonauts and maintaining a high level of functional capacities, it will become necessary during general training to have systematic medical control in which functional reserves and adaptive reactions can be estimated—data which determine the tasks of the next selection stage. Skills in overcoming difficulties of new cosmonaut activity will become intimately intertwined with the development of resistance to spaceflight factors. A careful analysis of the illness rates and physicians' consultations for persons passing through the training cycle has been made during the training period. This analysis, compared with data from a control group, specifically showed that illnesses among cosmonauts do not reveal nosological forms of disease which could be attributed to occupational hazards in the training system.

In conculsion, the system of selecting astronauts and cosmonauts will be constantly improved, taking into account flight peculiarities, modern achievements of general medicine, space medicine, and the general level of the biologic sciences. It should be possible not only to predict the tolerance of crews to conditions in space flight, but also to provide for their high working capacity, successful completion of the flight, and safe return to Earth.

For this purpose, undiminished effort by the scientific and medical communities will be required in the study of conditions of long-term space flight and the influence of spaceflight factors on the human body.

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Chapter 16

TRAINING OF COSMONAUTS AND ASTRONAUTS[1]

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The biomedical and preflight training of spacecraft crews is discussed in this chapter, which is based on a survey of scientific and technical literature in the US and USSR. Similar methods of training and conditioning were developed in both nations, using the experience gained from high-velocity and high-altitude aircraft flights. In each country, available data were extrapolated to successive longer term flights, the possible human reactions were predicted, and theoretic models of human adaptation to the new environment of space were built. Actual spaceflight experience also provided scientists and specialists with ever-increasing data from which the state of human health in space could be predicted and life-support measures for missions of increasing duration developed [4].

Biomedical training of Soviet cosmonauts and American astronauts is a dynamic process which increases resistance to spaceflight factors such as noise, vibration, weightlessness, acceleration, vestibular stimuli, and peculiarities of the flight and spacecraft conditions, e. g., isolation, artificial atmosphere, peculiarities of nourishment, the unique psychologic background, and neuroemotional stress.

Environmental control and life-support systems protect the crew from outer space factors as well as from noise, vibration, and others, eliminating the need for medical, biologic, and psychologic conditioning for these factors [16, 32]. However, special conditioning for increasing resistance to acceleration effects, and particularly to weightlessness, is obligatory. The biomedical training program of Soviet cosmonauts, for example, emphasized certain one-time factors to study individual human capacities and reserve capacities. These included 10-day trials in the soundproof chamber and trial runs in the thermal chamber. The conditioning program in both countries required flying in aircraft, including flights in the Keplerian parabola, rotation in the centrifuge, vestibular conditioning, plus general physiologic training and combined investigation-training in the spacecraft simulators.

The special training programs include the goals and tasks of space experiments as well as characteristics and physical condition of the parti-

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cipants and the possible forms of their activity during various stages of the space flight. The training programs provided for regular and repeated exposure to spaceflight factors, gradually increasing the intensity of the stimuli. Individual characteristics of the spacecrew members were taken into account in determining the optimal loads and intervals between series of conditioning sessions.

BIOMEDICAL TRAINING

Soviet cosmonaut training for the first flights included trials in the silence (soundproof) chamber. The goal of a long-term test in the silence chamber was "a study of the state of the neuropsychological sphere and the physiological reactions, determination of the human capacity exactly to accomplish tasks within the framework dictated by the activity." During these trials, both isolation and conditions of relative hypodynamia were provided. The cosmonauts lived and worked according to an altered work-rest schedule corresponding to realistic conditions of space flight; a complex method for recording the medical and biologic information was devised, which made it possible to conduct experimental psychologic investigations.

Soviet authors [14, 15, 34, 35, 36] cite experimental data on the functional changes among certain cosmonauts during the experiments in the silence chamber. All subjects had a high level of emotional-psychologic stability and adaptive capacities. Time in the chamber was not uniform; for example, V. V. Tereshkova spent 7 days there, while V. G. Bykovskiy spent 10 days. These differences were the result of a number of circumstances, including the proposed duration of the space flight.

In these investigations, special sets of physical exercises were tested and proved effective. A series of special devices and procedures was suggested; these included the bicycle ergometer, rubber expanders, and the system of inertial and isometric exercises [2]. These devices, tested during nine long-term experiments, proved effective in preventing the undesirable consequences of hypokinesis, and were recommended for use during an actual space flight.

The first groups of cosmonauts and astronauts received special conditioning in thermal chambers, the purpose of which was twofold:

to increase resistance to temperature (a rise in temperature in spacecraft cabins was considered a probable emergency situation)
to determine individual reaction to a set thermal load.

As a result of the investigations, Soviet authors [1] recommended exposure to a temperature of 60° C, as a functional heat test for undressed subjects. Thermal conditioning was used in the US only for the initial group of astronauts.

Primary attention was paid to conditioning to weightlessness—the principal unknown factor of space flight which could not be duplicated except for short periods during an aircraft flight along a Keplerian trajectory. Use of these flights for conditioning was studied in the US and USSR [47] in the late 1950s. These investigations proved that the human reaction to short-term (several tens of seconds) weightlessness is individual and all subjects could be classified according to their feeling and behavior in weightlessness as persons who (1) felt good, (2) experienced illusory sensations that disappeared after 12–15 exposures, and (3) developed immediate discomfort and adapted with difficulty. With repeated parabolic flights, most persons with a lower tolerance to weightlessness adapted gradually, which was highly significant.

The investigations of Kitayev-Smyk [17], Kolosov [18], and Kopanev et al [19] demonstrated that statokinetic disorders in flight personnel were less pronounced and disappeared more rapidly during repeated exposure than among nonflying personnel. For example, sensory disorders among flight personnel vanished completely after 12 exposures to weightlessness; among nonflying personnel more than 30 repetitions were necessary.

Adaptation

The possibility of adaptation to short-term weightlessness was the basis for conditioning cosmonauts and astronauts in aircraft in parabolic flights. Conditioning was carried out both with the trainees secured in their work places, and drifting free in the cabins of large aircraft. Soviet and US scientists were fully aware of the differences between physiologic reactions to short-term and prolonged weightlessness: the first affects primarily the vestibular apparatus and neuroemotional sphere; the second affects the cardiovascular system and metabolic processes. Nevertheless, parabolic flights made it possible not only to estimate predisposition to vestibulovegetative disorders, but also to lessen unfavorable reactions by conditioning [44, 46].

As experience in manned space flights increased, the primary purpose of parabolic flights in aircraft changed to the character of test flights for certain assemblies and systems whose working capacity in weightlessness was doubtful as well as to training sessions to develop human skills in carrying out certain operations in weightlessness.

To insure physiologic adaptation to the effect of transverse accelerations during space flight, the training system of both cosmonauts and astronauts included familiarization and conditioning runs in the centrifuge [21, 24, 26, 27, 28, 29, 30, 31]. During centrifugal rotations, individual resistance to accelerations of varying intensity was determined and measures were taken to increase this resistance. Both cosmonauts and astronauts considered preflight conditioning on the centrifuge a valuable part of their training. General strengthening of the body as well as development of skills in voluntary tensing of leg muscles, abdominal press, and abdominal and thoracic types of breathing significantly increased resistance to acceleration.

Observations of reactions during the action of G-forces formed the basis for development of the conditioning system. As an example of the magnitude of forces experienced, the Soviet cosmonauts were subjected to transverse acceleration of 7, 9, and 10 G. Stepantsov and Yeremin [38] showed conditioning in the centrifuge to be particularly effective in those cases when the original tolerance to acceleration was low. Most effective were conditioning regimes based on the principle of a gradual increase in load with simultaneous increase of the intervals between rotations on the centrifuge.

Conditioning

The cosmonauts were first to encounter vestibulovegetative disorders (motion sickness). The symptoms of motion sickness were observed in the pilot of the Vostok 2 spacecraft, G. S. Titov. Thus, the Soviet program of biomedical training placed great importance on vestibular conditioning. The special programs of conditioning, which were always strictly individualized, included active and passive methods. Methods of active conditioning involved physical exercises, including exercises on gymnastic devices. Passive conditioning did not require activity on the part of the person being conditioned, and consisted of swinging on simple and quadrasupport swings, rotation on special devices, and so forth [33]. Vestibular conditioning proved effective in preventing gastrointestinal symptoms of motion sickness (success in 50% of the cases), and slightly effective when there were nervous and cardiovascular symptoms. Naturally, when conducting the conditioning exercises the individual characteristics of the person being conditioned must be taken into account.

In the conditioning programs of both countries, physical training was emphasized as a nonspecific method for increasing resistance to the effects of most spaceflight factors [4, 9, 21]. The program for physical training of cosmonauts included both group exercises and individual training taking into account personal characteristics and interests. Similarly, in the US, each astronaut developed an exercise program he considered appropriate from ground-based experiments and mission experiences. Water skiing, jogging, and other exercises were used. Various swimming methods, especially the crawl, with rotation about the longitudinal body axis, were proposed for increasing vestibular and statokinetic tolerance.

As spacecraft development and navigation progressed, spacecraft crews began to include specialists in science and engineering, each with specific tasks. Gurovskiy et al [15] point out that the preflight training of scientist-cosmonauts differed from that of pilots. Health requirements were eased, permitting lowered physical conditioning and an older age. Thus, for example, improving qualities of spatial orientation such as the capacity to observe moving points for orientation is particularly important for the spacecraft commander, but not necessarily of primary significance for other crewmembers. Tolerance for dynamic flight factors (weightlessness and G-forces), however, should be high among all crewmembers.

The first stage of training scientist-cosmonauts in the USSR was carried out without interruption in their basic work, as for example, a physician in the clinic or institute, or an engineer or astronomer in his department. At this stage, emphasis was on physical conditioning, vestibular conditioning, and living at moderately high altitudes in the mountains. Acclimatization to moderately high altitudes was shown to increase resistance to acceleration and hypoxia, and it increased physical work capacity. Moreover, a stay in the mountains is convenient for psychologic training of the crews for actions under complex conditions and for checking their personal qualities. Only after this did the scientist-cosmonauts proceed to conditioning as part of the crew, which was conducted with persons freed of their primary professional duties [14].

COSMONAUT TRAINING

Training facilities differ greatly in regard to their purpose, tasks which can be performed in them, effectiveness, and design. All training facilities can be divided into simulators and facilities for training spacecrews for spaceflight conditions, and simulators for developing professional skills in controlling the spacecraft and its systems. There can also be combined simulators for professional activity training in combination with conditioning the body for extreme flight factors.

The first group, for training crews for spaceflight conditions, includes simulators and facilities for physical and special training such as centrifuges, gymnastic facilities, batut (a device similar to a trampoline), treadmills, landing simulators, and aircraft, as well as environmental simulators such as pressure chambers, silence chambers, and aircraft for parabolic flights. The second group, for controlling spacecraft and its systems, includes simulators for developing professional control skills such as navigation, communication, approach and docking, landing, and life-support system simulators. In the third group, the complex simulator combines in itself many individual simulators of both groups.

Training in spacecraft control for the first group of cosmonauts was carried out on a simulator which provided development and reinforcement of skills in manual orientation and manual spacecraft descent. It included an optical orientator, a course, pitch, and yaw control, engine controls, planetarium, various flight instruments, a computer for navigation, a flight dynamics computer, trajectory, kinematics, and engine regulators, and a simulator control panel.

Such a system of control simulators can be used for training in spacecraft of any type; it enables the individual to work on the Earth on a real-time scale and to simulate the actual parameters of movement of the spacecraft with respect to the Earth and the other planets. Naturally, the instruments used in such devices vary according to their degree of perfection [37].

The Soyuz and Salyut programs also provided training sessions on special simulators for the development of skills in docking spacecraft in space. They were based on the actual approach of two spacecraft models whose movements were controlled by the cosmonaut. An optical system was used to relay movements to the indicators (the "Volga" simulator) and television screens.

Training of cosmonauts (and astronauts) in control of the spacecraft and its systems developed skills of basic operations to the point of automatism. Skills in handling various unforeseen factors, including emergency situations, were also developed.

A special program in a simulator mounted in an aircraft for flights along the Keplerian parabola was carried out by the cosmonauts in preparing for entry into open space.

The final stage in cosmonaut training was a test run using a simulator model of the spacecraft. The cabin of this model was equipped with all the actual systems of life support, communications, medical indices recording, and scientific apparatus. This stage included developing and checking the flight assignment and obtaining fundamental background data characterizing basic physiologic functions during the use of actual spacecraft systems and on a time scale corresponding to that of the flight. Moreover, a final check was made on the fit of individual gear and the food ration was improved. The cosmonaut completely accomplished the projected flight program.

A significant amount of time in the cosmonauts' training was set aside for studying the design of the spacecraft and carrier rocket, and for courses in theory.

Cosmonauts considered the training sessions in the spacecraft model to be extremely useful, and to enable them to form complete concepts of the future space flight, improve interaction of crewmembers during the accomplishment of various missions, and introduce the final corrections into the mission. This was true also with the US astronauts (which will be described).

ASTRONAUT TRAINING

The preflight group training program in the US, prior to the first manned suborbital flight conducted for each pilot (and his backup designated for a flight), was to become a standing procedure. The group took part in development and operational activities while also undertaking limited training to maintain proficiency developed during the group training program [37].

This program, which provided the first opportunity to prepare individuals for space flight, used techniques from aviation flight-training, because the role of the astronaut was conceived as similar to that of the test pilot. First, while project Mercury—the first US orbital flight program—drew heavily upon current flight-training methodology, certain requirements of this new program were unique. Since it was not a mass training program, the first seven already highly trained individuals were able to take shortcuts not feasible in larger aviation training programs.

Second, the participants were experienced test pilots, subjects already conceptualizing space flight. The total amount of necessary training was, therefore, reduced, and individual initiative and responsibility were emphasized in determining the training status of each astronaut.

Third, the simulated training program was necessarily flexible because the spacecraft in which the astronaut would operate was still under development and being constantly modified according to developing mission requirements. The training program also had to be designed to assist actively in the actual developmental process of the spacecraft. Since they were engineers themselves, the astronauts thus aided the hardware development engineers in industry by participating in design and review of many of the spacecraft systems; training activities were frequently combined with systems tests to evaluate both on-board and crew equipment. In the USSR the cosmonauts participated in engineering development and systems tests in a similar way.

Project Mercury

The value of high-fidelity simulation was well-known through aircraft flight experience [21]. Dependence upon simulation for space mission success and crew safety generally was greater than dependence on simulation for aircraft testing, because of the nature of the two flight programs. Spaceflight crews were essentially fully committed at lift-off to an entire mission, with a broad range of operational variables. Aircraft test research usually allowed for a more gradual exercising of the total flight through a series of "buildup" flights. While the aircraft test pilot could obtain much of his training coincident with actual flight testing, crews for space missions must receive all their training and be highly proficient in all flight tasks before the mission. Spaceflight simulators thus require the highest degree of fidelity of spacecraft and mission simulation. Aircraft experience was used extensively in the development and operation of the first spaceflight simulator, the Mercury Procedures Trainer. For the subsequent space programs, Gemini and Apollo, the major developmental impetus for the simulators was derived from space program experience.

In project Mercury, as well as in Gemini and Apollo, the effect of spaceflight environmental factors upon crew performance caused considerable concern [8]. Consequently, training emphasized crew exposure to such conditions as high acceleration forces, zero-G conditions, heat, noise, and spacecraft tumbling motion. The Mercury astronauts received many training exercises in an attempt to duplicate these conditions. Particular concern was expressed about crew capability to control the spacecraft manually during the high acceleration loads imposed during launch and entry. As a result, the Mercury astronauts participated in four centrifuge programs [21, 24, 26, 27, 28, 30, 31].

These formal centrifuge programs for project Mercury were conducted in the Aviation Medical Acceleration Laboratory (AMAL) at the Naval Air Development Center at Johnsville, Pennsylvania, as a part of the group training program. The first two programs combined engineering-feasibility and preliminary astronaut-familiarization programs, while the last two were intensive operational training programs. Configuration of the centrifuge gondola and computer control system varied between programs. The gondola was configured to simulate spacecraft for either orbital or ballistic missions, and the simulated attitude control system was run closed loop while the centrifuge was run open loop.

The astronauts wore full-pressure suits, and some runs were made at a simulated altitude of 8400 m (0.34 kg/cm^2) (28 000 ft (4.8 psi)). In all, the first astronauts experienced an average of 45 h on the centrifuge. The training programs appeared to be extremely valuable in providing an opportunity to check out items of personal equipment, to demonstrate the adequacy of the spacecraft instrumentation for viewing under acceleration, and to allow the astronauts time to develop their adaptive capabilities to accelerative forces.

There was general agreement that the centrifuge was the most useful environmental simulation device, and that a short refamiliarization experience on the centrifuge prior to the flight was highly desirable [23, 37].

Project Mercury flight results confirmed that the conditions of space flight have no adverse effects on crew performance for missions as long as 22 h [21]. Consequently, crew-training programs for the Gemini and Apollo missions deemphasized such considerations and concentrated on the many complex operational aspects. The Mercury simulators did not have adequate out-the-window displays, but the value of high-fidelity simulators was verified throughout project Mercury. This established for the Gemini and Apollo programs the requirement for a full-mission-simulator inventory both at the NASA Manned Spacecraft Center (MSC) (later named the Lyndon B. Johnson Space Center), and at the NASA John F. Kennedy Space Center (KSC) launch site [4, 9, 10, 23].

The astronaut group training program in project Mercury ran approximately 2 yr, until the spring of 1961, when the manned flight operation began [42]. Prior to each flight, a preflight preparation program was conducted for the pilot and his backup, as already noted. The length of the program depended upon time available between flights and the nature of the flight. The backup pilot on one flight was often selected as primary pilot for the next mission, which meant that actual preflight preparation of each pilot encompassed about 6 months—the first half as backup and the second as primary pilot.

The astronaut-pilots' contribution to development activities began soon after they had received sufficient indoctrination in the Mercury spacecraft systems. As astronauts, they participated in planning for the subsequent programs, Gemini and Apollo, as early as 1961. Each astronaut was assigned to a Mercury network station as voice communicator, acting in this capacity a minimum of 3 or more weeks. After the group training program, the astronauts devoted time to maintaining their flight proficiency, in addition to mission operational requirements [24, 32, 37, 43].

The state-of-the-art spaceflight external-view simulation at the outset of project Mercury, together with the compressed time schedule, permitted no external view other than that through the periscope trainer. Considerable effort was spent in an attempt to develop new and versatile displays, one result of which was the virtual-image viewing system, which could simultaneously accept inputs ranging from three-dimensional models to closed-circuit television or film strips.

Prior to the six-orbital-pass mission in October 1962, there was considerable concern about whether or not the pilot would be able to detect his yaw position solely by use of the slow translation of terrain or clouds viewed out the window of his spacecraft. The pilot's ability to determine yaw accurately by using out-the-window references is all-important if his gyro attitude information is lacking during retrofire, (which happened on the subsequent MA–9 flight in May 1963 in which the pilot had to rely on his window scene to determine heading or yaw position accurately for retrofire). A yaw-recognition trainer was conceived, built, and activated.

The attitude instrument display mockup consisted of a half-scale transparent model of the Mercury spacecraft mounted on a four-gimbal all-attitude support. The ground-recognition trainer consisted of a prototype molded couch, and actual Mercury periscope, a back-projection screen, and a motorized slide projector. Its purpose was to familiarize the astronauts with the wide-angle optics of the periscope which compressed images of coastlines, rivers, mountain ranges, and other topographical features. The air-lubricated free-attitude trainer moved on an air bearing and had 360° of freedom in roll and 350° of freedom in pitch and yaw. Two attitude-control systems were simulated in the fly-by-wire simulation, with the low-torque jets (used for attitude control in orbit when attempting to minimize fuel consumption).

The multiaxis spin-test inertia facility trainer was used for a simulation training program of recovery from tumbling flight.

The emphasis in this discussion so far has been on the difficulties and experience gained through operation of the simulator hardware; however, by no means does it imply a lesser importance of the software systems. Indeed, a large percentage of the simulation effort throughout all flight programs was associated with the software.

The final impression resulting from the Mercury experience was that, on a day-to-day basis, careful preparation prior to actual flight was the most valuable period of the training program. Consideration must be given in the future to avoiding over-fatigue just prior to launch [4, 8, 21].

The pilots were unanimous in asserting the importance of their participation in the checkout of the spacecraft during the immediate preflight period.

One of the last areas of training activity was the medical and physical preparation of the astronaut. The final physical examinations establishing the fitness of the pilot for the flight were given, and the majority of the baseline data with which in-flight results would be correlated were collected. The astronaut was placed on a special low-residue diet to prevent possible solid waste problems during the flight. Each of the astronauts intensified his physical fitness program. Experience has shown that maintaining physical fitness and avoiding excessive fatigue during this period are vitally important.

For each Mercury flight, full dress rehearsals (referred to as simulated network simulations) of the most significant flight phases integrating the crew, the flight plan, and the ground-support elements were accomplished as part of the preflight preparations. These simulations proved to be extremely valuable for the flight and ground crews and, consequently, were further developed and expanded for the Gemini and Apollo programs.

Project Gemini

The Gemini flights extended manned space flight by yet another step [22]. Although the one-man project Mercury, together with the Soviet experience, proved that man could survive and function operationally in Earth-orbit, the two-man team in Gemini, among other considerations, would test human physiological capabilities to survive and function in space for the time required to make the projected lunar landing and return and to carry out extravehicular activities (EVA). Engineering activities, among others, would include testing rendezvous and docking of the space vehicle preparatory to the lunar mission. Thus, the physiologic demands on the astronauts were not only increasingly stringent, but also the training requirements for them in their role of test pilots became increasingly complex. The two-man Gemini spacecraft was designed to use the pilot as the key "system" in its operation. The flightcrews were to find that even though the spacecraft cabin was small, it could be operated effectively and efficiently [5, 9].

These factors had a direct bearing on training for the Gemini series [12] as contrasted with training for the one-man Mercury series. As the Gemini program progressed, concurrent planning and training for the Apollo program were also proceeding for both pilots and for the new groups of scientist-astronauts [20]. All these considerations would have significant—and interacting—bearing on the pattern of training during the interim between Mercury and Apollo [3, 16].

The Gemini program required more sophisticated simulators than did project Mercury, principally because of the Gemini rendezvous mission objective. Crew capability to accomplish the rendezvous by using primarily out-the-window information was essential to the mission and dictated that an elaborate visual system be incorporated into the Gemini mission simulators. The development and use of an advanced state-of-the-art infinity optical display system added considerably to the realism and value of simulator training for the Gemini crews.

Results of the Gemini program [25] clearly indicated that a well-defined and effective configuration management system was needed to maintain the simulators in a configuration that corresponded closely to the continuously changing spacecraft. This meant a quick-response system operated by personnel knowledgeable on all spacecraft changes and capable of deciding on and contracting for the necessary modifications and incorporating these into the various simulators. A configuration control panel committee, with ancillary working groups, was formed for the Gemini and Apollo programs with good results [10].

Training progressed concurrently for Gemini and Apollo, and involved training both for the pilots and for the astronaut-scientists. An initial training phase for both Gemini and Apollo involved a 6-month academic program. Basically, the training program for projects Gemini and Apollo was similar to that developed in project Mercury, but, as noted, more complex. Early in 1963, training entered a new phase. All pilots were assigned to specific tasks in the establishment of design and operational concepts for the Gemini and Apollo programs. With the completion of Mercury flights, the entire group of pilots worked together toward Gemini and Apollo.

Flightcrews were trained to carry out a number of tasks. They must navigate, correct flight trajectories, and make controlled landings through the Earth's atmosphere and on the airless surface of the Moon. They must also conduct checkout and launch in Earth orbit, in orbit about the Moon, and on the lunar surface, aided only by the instruments aboard the spacecraft and the information obtained by radio from Earth; and they had to learn details of spacecraft, launch vehicles, and ground facilities far more complex than in project Mercury. Participation by crewmembers in testing their spacecraft provided both operational and training experience. Crew participation in the testing of Gemini rendezvous spacecraft required that each crewman spend between 40 and 50 h in the spacecraft and more time observing, troubleshooting, and reviewing the status of the spacecraft [6, 7, 10].

The Gemini program proved that precise flightcrew response during orbital flight was critically dependent upon the fidelity of the simulation training received prior to flight. Flight experiences showed that the majority of the simulators used were indeed of a high fidelity and, in most cases, accurately reproduced conditions of the actual flight.

Training equipment identical to the actual flight hardware was provided for each Gemini experiment. Operating the specific gear in this environment provided excellent training in the use of the individual pieces of hardware. In certain isolated instances, unfortunately, actual experiment hardware was not received until just before launch, placing a difficult workload on the crew in trying to concentrate on new hardware and procedures in the last few days prior to flight.

The dynamic Crew Procedures Simulator at the Manned Spacecraft Center was configured to provide a realistic simulation of the tethered-vehicle evaluations performed during the missions of Gemini 11 and 12. The basic time lines and control task for the tether maneuver were developed using this facility, and the ability of the crew to cope with the large attitude excursions can be directly attributed to simulation training.

The flightcrew training for normal and emergency engineering procedures was initially practiced on the Gemini Mission Simulator at the Manned Spacecraft Center. After the crew moved to the Kennedy Space Center, practice for the normal procedures was emphasized, with less stress placed on emergency procedures so as to concentrate on the planned mission. Final systems briefings were conducted at the Kennedy Space Center, and training in the operation of all spacecraft systems was accomplished in the Gemini Mission Simulator. Network simulations involving the Mission Control Center provided practice for all types of system failures, and provided vehicle training for both ground and flight crews[25].

The variety of simulations available to the Gemini flightcrews produced conditions closely approximating those encountered in-flight. The success with which the flight crews accomplished each Gemini mission was a direct result of high-fidelity simulation training [16].

Certain Gemini experiments did place heavy burdens on the crew at prelaunch time, and the consensus was that an attempt should be made to avoid adding to the crew's workload during this period. A typical example, according to the astronauts, involved the heavy prelaunch activities associated with preparation for the medical experiment M–7 (the calcium-balance study) by the Gemini 7 flightcrew. This involved a rigid diet, complete collection of all body wastes, and two controlled distilled-water baths each day.

The diet went well; the food was well-prepared and tasty; however, the collection of body wastes was difficult to integrate with other activities because the wastes could only be collected at the places most frequented by the flightcrew, such as the launch complex, the simulator, and the crew quarters. Fortunately, the excellent cooperation of the M–7 astronauts minimized problems. For the medical profession, this experiment was of great importance and would be continued in depth in the Skylab program [16].

The Gemini program provided scientists and engineers with considerable information required for further training and the eventual success of a lunar landing [25]. Gemini crewmen proved that man could exist in a weightless environment for at least 14 days (twice the time required for a lunar landing mission); they developed techniques of rendezvous and docking, so vital to the Apollo program; and they proved it feasible to place any space vehicle in orbit and use it later to furnish propellent power for docked vehicles. Gemini crewmen also proved that extravehicular activity [16] for relatively long periods was feasible and that man was capable of performing certain duties while outside the spacecraft. All this was prelude to the actual Apollo lunar mission [3].

Project Apollo

After May 25, 1961, the US was committed to a lunar landing and return "in this decade," and national resources were mobilized to achieve that scientific and technological goal. Both pilots and scientist-astronauts were included in the selection program that would provide the manpower resources for this program, and training for both proceeded concurrently with Gemini training and operations; it proceeded likewise as spacecraft design and development progressed, with the astronauts participating in terms of both their previous experience and their specialized training.

The relatively large size of the Apollo space vehicle made training procedures to "marry" the man and machine increasingly complex. The weight of the first manned Apollo vehicle – Apollo 7 – was 2034 kg (45 200 lb). This was in stark contrast to the first manned orbital Mercury spacecraft (with Atlas booster) which weighed 130.5 kg (2900 lb), and its successor the Gemini 3 first manned flight in a vehicle (with Titan II booster) weighing 320 kg (7111 lb).

The three-man lunar flight crew consisted of the spacecraft commander/pilot; navigator/copilot; and, systems manager.[2] The spacecraft commander and navigator were exceedingly well cross-trained in the propulsion and attitude control of the spacecraft, navigation, on-board computer calculations, communications, and total systems operation. Detailed duties for the systems manager were defined as the system design progressed; he was cross-trained in the pilot's positions and capable of performing the reentry and Earth-landing maneuver. But his primary

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[2] Abbreviations used for each crewmember were: Crew Commander – CDR; Command Module Pilot – CMP; and Lunar Module Pilot – LMP.

responsibility was to manage the various propulsion systems, especially during the lunar landing and lunar takeoff. Dependent upon use of specific rendezvous techniques for the lunar mission, the third crewman might also be involved in vehicle checkout subsequent to the docking operation.

Forecasts of the simulator training requirements for the Apollo program showed that a large inventory of various types (full mission, part task, moving base) of strategically located simulators would be needed. Several basic decisions were made to satisfy the fidelity requirements of the simulators.

One decision was that all spacecraft subsystems would be simulated by the computers; that is, no actual (hardware) spacecraft subsystems would be used. One area which was handled in a special way was simulation of the Apollo on-board guidance and navigation computer. The simulation successfully used was based on an "interpreter" concept in which a general-purpose digital computer was programed to accept the same program as the flight computer and to respond to spacecraft systems precisely as the flight computer would. The interpreter superseded a functional approach for simulation of the on-board computer which was barely adequate, costly, and always late. Another area that required considerable updating and redesign was the difficult visual simulation of the lunar landing.

The crew received extensive practice in performing all nominal and contingency mission tasks on one or more of the NASA simulators. It engaged in various other tasks during the preflight training program, although not programed as part of their formal Apollo training for the specific mission. The tasks were either (a) informal training activities accomplished on an individual basis (study, physical training); (b) general training activities for nonspecific missions (aircraft flying); or, (c) crew activities in support of the mission or Apollo program (suit fits, physical examinations, pilot meetings, travel, flight-monitoring, engineering and operational development effort).

The active astronaut force was 49 individuals as of 1969. The acquisition of astronauts from the US Air Force Manned Orbiting Laboratory (MOL) program in this period counterbalanced the attrition and changes in the existing force structure.[3]

Seventy-three astronauts had been selected during the previous 10-yr period. As of late 1969, four were concerned with management aspects of the spaceflight program at the Manned Spacecraft Center, Houston, Texas. Nine astronauts had resigned or retired from the program.

Flight training for Apollo 9–14 in the capacity of prime crew, backup crew, or support crew was the major effort for the active astronauts. Nine of the scientist-astronauts completed pilot training in jet aircraft and returned to MSC. They would now participate in the NASA Apollo Applications Program (later redesignated Skylab) development and gain operational experience in support of further lunar landing missions. The seven ex-MOL astronauts would be assigned in a similar manner, with one already named to the support crew of the projected Apollo 14 [3].

The in-flight performance of the pilot provided the best indication of adequacy of the astronaut training program [6, 7, 11]. Further verification was provided by comparing performance of specific maneuvers during flight with that of the trainers, and by having the pilots comment on the value of the various training devices. Evaluative materials were obtained from the astronauts during the debriefings following each mission.

The astronauts reported, for example, that while weightlessness was generally pleasant, there was a short period during the flight when they felt time was needed to adapt both to the weightlessness and to the novel view through the spacecraft window. Neither of these features of the space flight could be adequately simulated during the training periods. While this adaptation period to the orbital flight conditions might have been reduced had it been possible to simulate the external view and more prolonged weightlessness, the problem was not considered serious by any of the astronauts.

In conclusion, during the 10 years covered in this chapter, the training of cosmonauts and

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[3] With a redefinition by former President Richard Nixon of the role of the US Air Force in space, Air Force personnel were assigned to NASA to work with them in developing plans for long-duration flight in space.

astronauts was logically structured on established aviation procedures with extrapolation to include spaceflight factors and ultimately the actual orbital flight experience. Inasmuch as all candidates were already experienced pilots, who could adapt to stressful conditions of high-velocity, high-altitude flights, the main medical problem was the influence of spaceflight factors. When the demands of actual space flight became known, it was possible to include persons other than experienced test pilots as spacecrew candidates, such as scientists and engineers.

Training for prolonged space flights of the future will require new knowledge and techniques, which will require the united efforts of representatives of the physical, biological, and engineering sciences in both manned and unmanned flight programs. Foremost in the planning of training, it is vital to recognize that man is a rational, dynamic being and not an object to be evaluated merely by means of physical and engineering criteria.

The inspiring record of successful manned spaceflight programs demonstrated that outstanding achievements were realized in all the essential component fields. A highly critical element by both countries was the training program described in this chapter, and the success of this contribution may be regarded with lasting pride.

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Part 5

FUTURE SPACE BIOMEDICAL RESEARCH

Chapter 17

AN APPRAISAL OF FUTURE SPACE BIOMEDICAL RESEARCH[1]

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The combined experience (at the time of this writing) of the two countries which have launched man into space has demonstrated that man, supplied with fundamental organic needs, is capable of existing, functioning, and carrying out assigned activities normally in an extraterrestrial environment for at least a few months. The US spaceflight programs from Mercury through Gemini and the manned lunar landings of Apollo verified man's capabilities for flight durations up to 14 days, while the Soviet programs from Vostok through Soyuz and Soyuz-Salyut accomplished manned space flights up to 30 days. With the recent completion of the US Skylab Program, man has now flown successfully in space for almost 3 months.

We are now merging into a new era in which manned space flights can be extended to many months and even years. Man can now expand his investigations of the Moon and explore beyond into the solar system. He can advance significantly by gaining new knowledge of his environment, his origins, and himself, and finally, man has the opportunity to mature in the process as well, by learning to join forces with his fellows across the Earth in positive action to launch and sustain this promising future in space.

From the standpoint of science and technology, new growth will be required not only in the realm of space vehicle systems, but also in the development of long-lived systems for the support of man and, most important, for the understanding of man, himself, in the space environment. These requirements will vary, to a great extent, according to the type and duration of mission to be undertaken. This chapter will, therefore, begin with a description of three general classes of manned spaceflight missions of the future: Earth-orbital, lunar, and planetary; and follow with a broad analysis of biomedical science and technology emphasizing areas of research needed to support future manned space flights and the information to be obtained from them.

FUTURE MANNED SPACEFLIGHT MISSIONS

Three distinct categories of future manned flight missions can be identified: in Earth orbit. to the Moon, and to the planets, including the minor planets [1, 28].

In Earth-orbital missions, the astronauts remain in close proximity to Earth, are in instantaneous communication with Earth, and can be returned to the surface within hours should medical emergency demand it. Resupply and replacement

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[1] Grateful acknowledgement is made to Dr. William L. Haberman, formerly of the Advanced Manned Missions Program Office of the NASA Office of Manned Spaceflight, for his compilation of the original section on FUTURE MANNED SPACEFLIGHT MISSIONS; and to G. P. Parfenov of the USSR for his valuable compilations.

of spacecraft components are within easy reach of the operations center on Earth.

In lunar missions, the target is within a week's travel time from Earth, thus increasing the complexity of resupply and replacement. The systems required for lunar missions are more numerous and complicated since operations now include escape from Earth's gravity field, capture by the lunar gravity field, and landing and takeoff from an extraterrestrial body.

Finally, for the planetary missions with round trip durations of 1 year or more, the character and complexity of the mission change completely. The spacecraft now travels to distances of several hundred million kilometers from the planet Earth and, in most instances, the mission cannot be canceled or aborted once the spacecraft has departed from Earth orbit. Mission operation and control will, of necessity, be almost autonomous from Earth. Medical emergencies must be handled aboard the spacecraft since fast return to Earth generally is not possible (Figs. 3 and 5).

The development of spacecraft systems, capable of maintaining the relatively narrow environmental range to which man is accustomed, will depend upon knowledge of the external environment as well as characteristics of the vehicle and mission. The major features of the natural environment of the Moon and several planets are presented in Table 1. Those of Earth are included for purposes of comparison. The

TABLE 1.—*The Lunar and Planetary Environment*

Planet/satellite	Surface pressure (atm)	Solar thermal irradiance (cal/cm² · min⁻¹)	Surface temperature (°C)		Solar illuminance (thousands lx)	Albedo	Day/night cycle (Earth days)	Gravity	Magnetic field intensity (gammas)	Radiation belt	Distance from Earth (millions km)
			Max.	Min.							
Earth	1	1.98	50	−88.3	140	0.34[3]	1	1.00 g	62 000 (poles) 31 000 (Equator)	Yes	—
Moon	0	1.94	120	−170	140	0.07	27.3	0.17 g	36	No	0.4
Mercury	0.001	10.9	340		935	0.058	175.9	0.35 g	Not available		80 to 220
Venus	90	3.88	475		267	0.76	116.8	0.90 g	70	No	40 to 260
Mars	0.005	0.72 to 1.05	20	−70	60	0.148	1.02	0.38 g	50	No	56 to 400
Jupiter	200 000[1]	0.68	−140[2]		5.2	0.51	0.41	2.40 g	500 000	Yes	588 to 963

[1] The existence of a surface on Jupiter has not been proved.

[2] Refers to the cloud layer.

[3] Varies depending on data sources; influenced by numerous factors such as season, wavelength, and areas measured.

presence of a planetary atmosphere not only has implications with regard to exobiology, life support, and toxicology, but also serves as protection against inherent radiation and micrometeoroid penetration, while an appreciable magnetic field about a planet will tend to trap and retain a radiation belt (Table 1).

Earth-Orbital Missions

Manned orbital space flight began with Yuri Gagarin's historic flight in April 1961. Beginning with John Glenn's Mercury-Atlas flight (MA 6), the first US orbital missions were carried out in 1962 and 1963 when four manned orbital missions were completed during the Mercury program. The maximum flight duration during Mercury was about 34 hours on Gordon Cooper's MA 9. The next orbital manned spaceflight program in the US spanned the years 1965 and 1966, when the 10 manned missions of the Gemini program accomplished stay times up to 2 weeks in Earth orbit. The Gemini scientific experiments included, in addition to medical experiments and monitoring of astronauts, synoptic Earth terrain photography, astronomical photography, micrometeorite collection, and Earth vision tests. These flights demonstrated man's capability to live and function under weightless conditions (for at least limited durations) and to perform activities outside a spacecraft with the protection of a space suit.

The only currently approved future US manned spaceflight project, except the relatively short-duration Apollo-Soyuz docking mission of July 1975, is the Shuttle Program which will make available a large experiment capacity for a series of frequently repeated 7-day to 30-day Earth-orbital flights during the 1980s. Future orbital missions beyond Shuttle may be carried out in semipermanent to permanent space stations in orbit where men can live and work for extended periods. A brief description of these concepts follows, emphasizing factors relating to the support of man and the environments critical to man.

Skylab, like Salyut, was a dedicated orbiting laboratory which can be regarded as a space station prototype. Although its flight missions have now been completed, its data yield will be analyzed continuously for information for some time. It is described briefly also.

The Skylab Program was unquestionably the largest and most ambitious Earth-orbital manned spaceflight program completed so far. Its three missions of 28, 59, and 84 days, respectively, were carried out from May 1973 to February 1974. It carried a large complement of medical, astronomic, and Earth resources and other experiments, all of which were successfully completed by its three three-man crews. One of its major objectives was to evaluate man's ability to live and work in space for durations of 2 to 3 months [24]. A number of significant physiological changes were measured, but except for a tendency toward severe motion sickness (space motion sickness) during the initial 3 days of weightlessness, crew well-being and task performance during flight were essentially unimpaired. The resultant data yield from Skylab was very large, and much new information was gained concerning crew support and effective operations during long-duration space flight.

The Skylab orbital facilities consisted of a workshop, modified Apollo command and service capsule, telescope and two interconnecting modules, the multiple-docking adapter, and the air lock. The Orbital Workshop, a modified S–IVB stage, was made suitable for long-duration manned habitation in orbit. It contained the necessary crew provisions, living quarters, and food-preparation and waste management facilities to support a crew of three men for the three periods of 28, 59, and 84 days. The Skylab experiments and necessary support facilities for their operation were also installed (Fig. 1).

The Skylab series began with the unmanned launch of the workshop by a Saturn V launch vehicle into a circular orbit of 430 km altitude with an orbital inclination of about 50°. The first crew, which was to be launched the following day aboard an Apollo Saturn IB (SL 2) to dock with the workshop, was delayed for 10 days while studies were carried out to determine corrective procedures and equipment which the crew would employ to repair damage to the solar panels and heat shield, which had occurred on launch. The crew demonstrated the importance of the human capability very clearly when they salvaged the entire Skylab Program by making necessary repairs during the first 2 weeks after docking with the workshop. They returned via the Apollo command module after their successful 28-day mission, to be followed successively by the SL 3 and, later, the SL 4 mission crews. These missions, launched at 3-month intervals, had stay times from 28 to 84 days.

The launch atmosphere was that used for the Apollo program, which at launch and prelaunch consisted of a 60:40 oxygen:nitrogen ratio at sea level. During ascent, total pressure was reduced to $3.5 \cdot 10^{-1}$ kg/cm^2 (5 psia) (260 mm Hg), and further losses through leakage or after cabin decompression for extravehicular activity (EVA) were replaced with 100% oxygen. On return to Earth, the command module (CM) atmosphere was 100% oxygen at $3.5 \cdot 10^{-1}$ kg/cm^2 (5 psia) (260 mm Hg). In the workshop, the atmosphere consisted of a nominal 70:30 oxygen:nitrogen mixture at $3.5 \cdot 10^{-1}$ kg/cm^2 (5 psia) (260 mm Hg), although oxygen partial pressures actually ranged slightly higher. CO_2 levels were no higher than 5 mm Hg. Once the initial thermal problem was resolved by deployment of the sunshade, temperatures were maintained generally in the range of 21°–27° C (70°–80° F). Relative humidity was kept at 45% to 55%.

The acceleration levels experienced by the crew during launch and return to Earth were those of the Saturn IB vehicle, which imposes a maximum acceleration (in the crew's x-axis) of 4 G during launch, and a maximum of about 3.5 G during return. The data and samples were re-

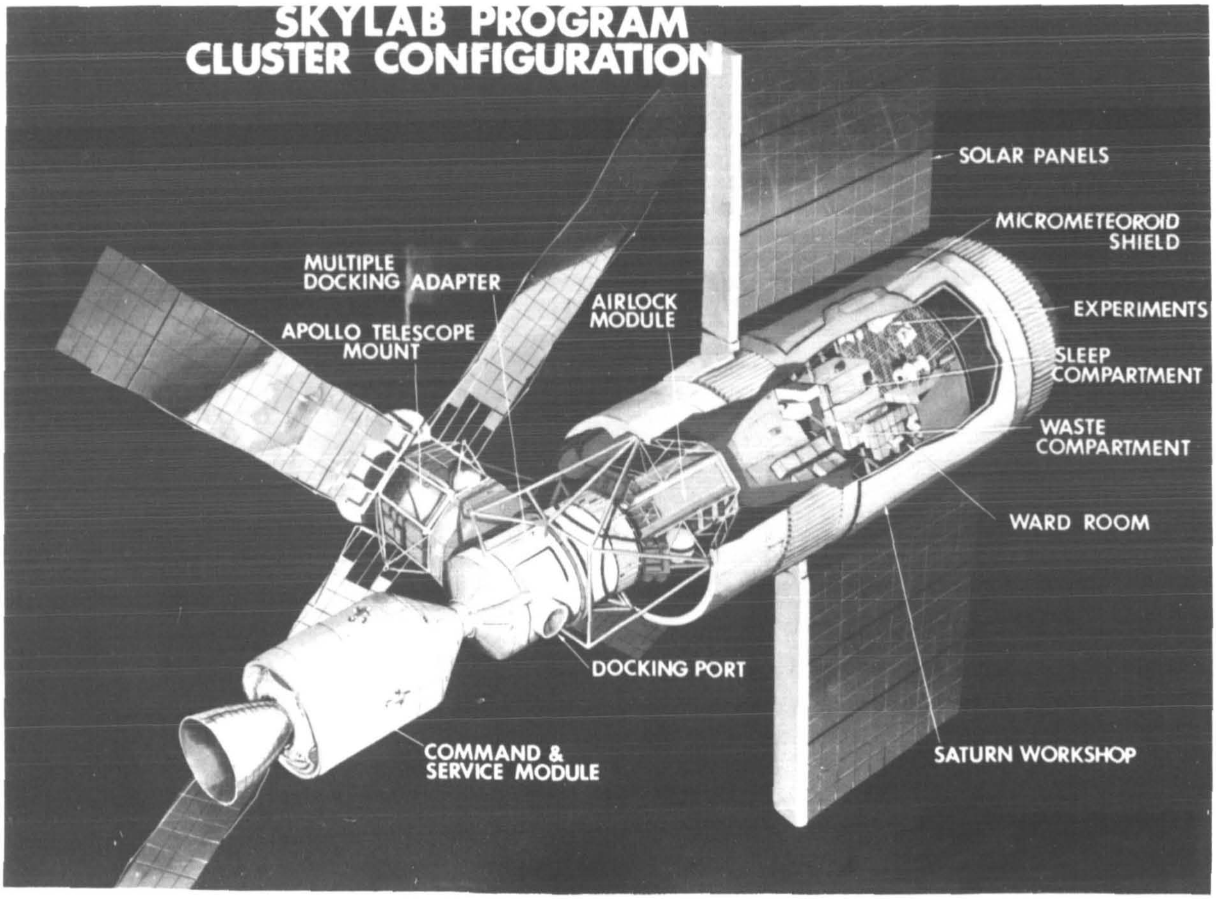

FIGURE 1.—Skylab cluster configuration.

turned with the crew after completion of each of the three missions. Emergency return to Earth was feasible after several hours via the command module, and an emergency rescue capability from the ground was made available.

The Space Shuttle, a new space transportation system, is the only US manned spaceflight program currently approved for the era beyond the 1975 Apollo-Soyuz mission. It was originally conceived as a vehicle to transport personnel, equipment, and supplies to and from a space station [6, 7]. By virtue of its reusability, it is now being pursued as a relatively inexpensive means of facilitating the accomplishment of all varieties of scientific and technologic investigations in space. The Shuttle will consist of a booster and an orbiter. The orbiter will carry a two- or three-man crew, scientists, and supplies and equipment to sustain orbital flights of 7 days. This duration may be expanded later to 30 days. It will also carry a large, independently pressurized habitable enclosure for experiments, called Spacelab, as well as nonpressurized pallets for experiments not requiring an atmosphere. These units, to be carried in the orbiter's aftersection, will be entirely exchangeable on the ground. The booster, which will supply launch power as a first stage, will then be jettisoned. After achieving and maintaining Earth orbit, the orbiter will return, landing on a runway like an airplane. Several flights a year are planned.

Many aspects of the Shuttle are still undefined, but some that are known have important implications to the life sciences. The sea level atmosphere which is to be provided will require further advancements in suit technology and dysbarism research. Although launch and reentry G-levels are not yet known, reentry may, for the first time, impose G-stresses in the long axis (z-axis) of the body. It is likely that these G-levels will be nominally low, of the order of 1.2 to 2 G, but their duration may be up to 20 minutes or more. Furthermore, they will follow a 7-day period of weightlessness with attendant decreases in human resistance to G-stress. Another important first will be the flight of scientist passengers for whom medical selection standards, training procedures, and supportive requirements must be established. Finally, the frequency of 7-day flight opportunities for biomedical experiments will necessitate preflight emphasis on thorough organization and planning of informational requirements and desires, and on the large amount of ground-based research needed to provide relevant experimental control data. These 7-day flights will afford excellent opportunities to obtain important medical data on mechanisms and to look for changes in body functional areas which have not yet been examined.

A permanent space station, as a long-lasting, general-purpose facility in Earth orbit, can provide means of surveying Earth resources and serve as a research base for advanced studies in astronomy, astrophysics, biology, space physics, and the technologies of material processing [17, 25]. The space station can also play a major role in the development of future space systems and operations. Its design, therefore, will be dominated by the need to accommodate a broad spectrum of activities which may change markedly over the years. The design keynotes are versatility and maximum exploitation of man's adaptability and talent for decisionmaking.

The space station is thus envisioned as a flexible, multidisciplinary research center for operations in Earth orbit. Features such as weightlessness, unlimited vacuum, rapid Earth viewing, and unobstructed celestial observation, make a center of this type a unique scientific laboratory capable of many beneficial applications.

The space station concept has been studied extensively, although it does not now exist as an approved flight program. In concept, it would be launched unmanned into an orbit with an average altitude of 430 km at the Equator and an inclination of 55°. This orbital inclination would provide maximum coverage for Earth-related experiments. The first logistics flight would bring the crew (about eight men), and be followed by resupply and crew rotation flights several times a year via a space shuttle.

The space station would be designed to have a high degree of on-orbit autonomy, the crew conducting a variety of experiments and controlling operations with little real-time support from the ground. Operations in orbit would be performed by astronaut-engineers who would control the space station during flight, and by astronaut-scientists who would conduct the many experiments aboard. The tour of duty of each crewmember would range from 3 to 6 months.

The interior of the space station would be pressurized to 1 atm with an Earthlike oxygen-nitrogen mixture. Cabin temperature levels would be maintained at 18° to 24° C (65° to 75° F), with relative humidity range of 40% to 60%. Living quarters volume would be about 10 to 30 m^3 (400 to 1000 ft^3) per crewmember. Accommodations would include private staterooms for on-board personnel, well-appointed wardroom, exercise facilities, large galley, a dispensary for medical and dental care, and well-equipped laboratories. An artificial gravity environment of up to 0.5 G could be provided.

Lunar Missions

The historic first landing of man on an extraterrestrial body was in the summer of 1969 when two American astronauts landed on the Moon, fulfilling the primary objective of the Apollo program [15, 18, 19]. During their 24-hour stay they left their spacecraft, clad in pressure suits, to carry out experiments on the lunar surface and collect samples of lunar soil and rocks to be returned to Earth for analysis. Subsequent Apollo missions have expanded these accomplishments. Further exploration and eventual exploitation of the lunar body will require much longer stay times, varying from several weeks to several months. Such missions will involve the establishment of semipermanent or even permanent stations on the Moon and means of surface transportation over distances of several hundred kilometers. The lunar shelters would contain living quarters and research laboratories, maintain an Earth sea level human environment, and serve as bases for carrying out these objectives of lunar exploration and exploitation:

1. To improve our understanding of the solar system and its origin through determination of the physical and chemical nature of the Moon and its environment.
2. To obtain a better understanding of the dynamic processes that have shaped the Earth and led to our present environment, including development of life.
3. To evaluate the natural resources of the Moon and utilize its unique environment for scientific and technologic processes.
4. To extend man's ability in space and obtain experience needed to explore other planetary bodies.

Acceleration characteristics of manned missions to the Moon will depend on the type of launch and Earth-return vehicles used. A plot of maximum accelerations (x-axis) during an Apollo-type lunar mission (Fig. 2) shows that greatest accelerations occur during Earth launch, Earth orbit escape, and maximally during the aerodynamic deceleration of reentry.

In later missions to the Moon, advanced transportation systems could be utilized. Such systems might employ the Space Shuttle to transport astronauts to a permanent space station in Earth orbit. From Earth orbit, another trans-

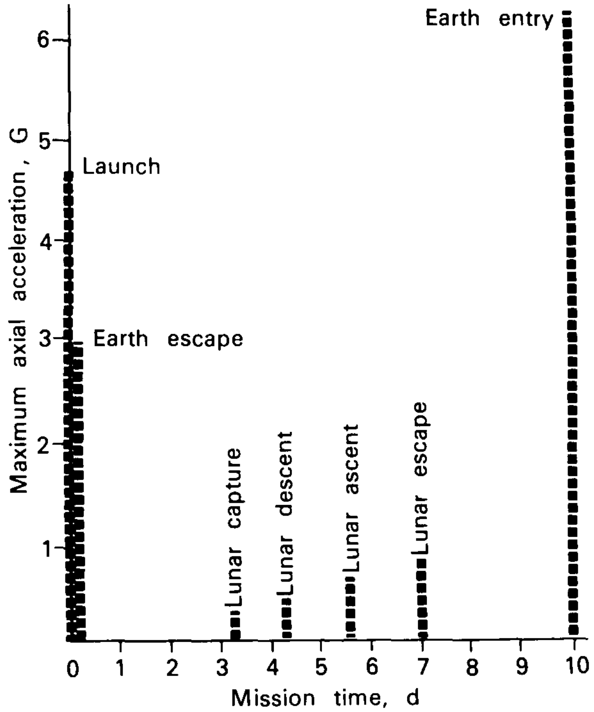

FIGURE 2. — Acceleration levels during Apollo-type lunar missions.

portation system would deliver the crew to a lunar-orbit station and then to the base on the lunar surface. The acceleration characteristics of such a system need not exceed 2.5 to 3.0 G (x-axis). The crew size at the lunar base could be as many as 12 men. Emergency return from the surface of the Moon could be accomplished within 3.5 days. Resupply, data, and sample return missions would be flown as needed, averaging perhaps four per year.

Lunar observations and sorties would be conducted from the lunar-orbit station, which would be a modified space station (already described). Its orbit about the Moon would probably be circular to an altitude of about 110 km with a 90° inclination (polar orbit). The six-man crews would be rotated at intervals of about 3 months. An artificial gravity environment up to 0.5 G could be provided (as in the space station), if needed.

Planetary Missions

As our capability and experience with long-life manned space systems aboard a space station grow, as knowledge of man's ability to survive and function in space is increased, and as investigation of the Moon's surface progresses, manned space exploration missions will likely turn to the planets in our solar system.

By means of flybys and probes, unmanned spacecraft of the Mariner series and similar USSR flights have explored the topography and sparse atmosphere of Mars and examined the hot atmosphere of Venus. Pioneer 10 reached within 130 356 km (81 000 miles) of the planet Jupiter in December 1973, transmitting voluminous data and thousands of pictures of its surface before continuing the journey out of the solar system. Viking, scheduled for launch in 1975, is to land on the martian surface to perform in situ analyses of its soil and surface atmosphere and search for the presence of life. Future unmanned missions may eventually return samples of martian soil for detailed analysis on Earth. It seems certain that unmanned exploration of the outer planets, Saturn through Pluto, will also be carried out.

Unmanned missions are a necessary prerequisite for man's greatest venture into the unknown: his excursion to another planet many millions of kilometers away. Manned as well as further unmanned exploration of the planets would have as goals:

1. The improvement of our understanding of the solar system, its origin and evolution through determination of the physical and chemical nature of other planetary bodies and the interplanetary medium.
2. The search for extraterrestrial life on other planets. It is currently thought that the best planet for this purpose is Mars, where there are some expectations of life existing or having existed.
3. The development of broader understanding of the Earth and life on Earth through comparative studies of other planets.

The planets Mars, Venus, Mercury, and possibly Jupiter are within possible technological reach of manned missions during the next several decades [20]. Mission opportunities also exist to a number of asteroids, such as Eros, Geographos, Toro, and Icarus. The surface characteristics of these planets are shown in Table 1. The asteroids have a surface gravity of 0 and no atmosphere. Since manned missions to the asteroids are technically easier to accomplish, they may precede Mars missions. Table 2 lists typical manned-mission round trip durations and stopover times at the planets. In general, such manned trips are anticipated to be of 1-year duration and longer.

TABLE 2.—*Trip Durations of Manned Planetary Missions*

Planets/ asteroids	Class of mission	Typical total mission duration, d	Typical portion devoted to stopover at planet, d
Mars	Conjunction	1000	460
	Opposition, Venus swingby	600	Up to 100
	Opposition	450	Up to 30
Venus	Long stay	800	450
	Short stay	400–500	40
Mercury	Direct	350	Up to 60
	Venus swingby	400	Up to 60
Jupiter		1500	Up to 60
Asteroids		360–450	30

Mars is the most likely first target of a manned planetary mission; hence, details of the probable mission profiles are given. There are two classes of Mars missions: opposition and conjunction (Table 2). Opposition class missions are, in general, characterized by relatively short durations, short stay time on Mars, and high propulsive performance requirements. Within the opposition class missions are the Venus swingby missions, which permit observations of both Mars and Venus during a single mission. The conjunction class missions are, in general, characterized by lower propulsive performance requirements, longer durations, and longer Mars stay times.

A typical Mars opposition class mission with a Venus inbound swingby (i.e., on the return trip) is shown in Figure 3. Upon departure from Earth orbit, the space vehicle arrives at Mars after a 270-d transit. After an 80-d stay on Mars, the vehicle departs. The return trip to Earth includes a swingby past Venus, 123 d after Mars departure. The remaining Venus-to-Earth transfer requires 167 d. The total mission duration is 640 d.

The vehicle-Sun distance history during the mission is illustrated in Figure 4, which shows that the maximum distance from the Sun is 2.2×10^8 km and occurs upon arrival at Mars. The closest distance from the Sun (perihelion) is 8×10^7 km and occurs during vehicle passage between Venus and Earth. The maximum distance between the space vehicle and Earth is 2.8×10^8 km and occurs during the Mars-Venus leg of the journey.

A typical Mars conjunction class mission is shown in Figure 5. The transit between Earth and

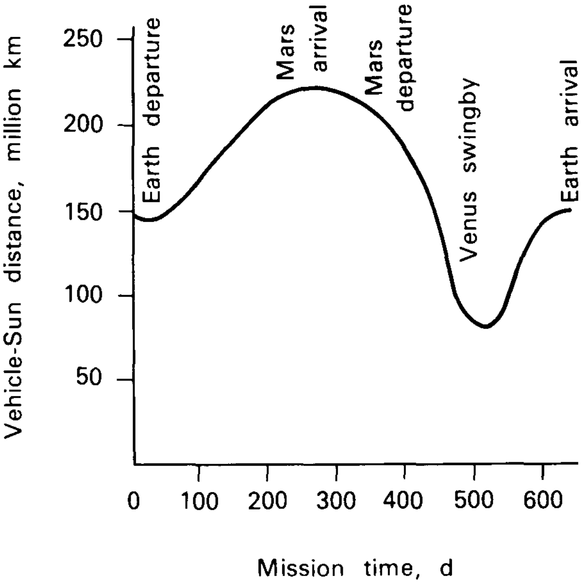

FIGURE 4.—Vehicle-Sun distances during Mars mission.

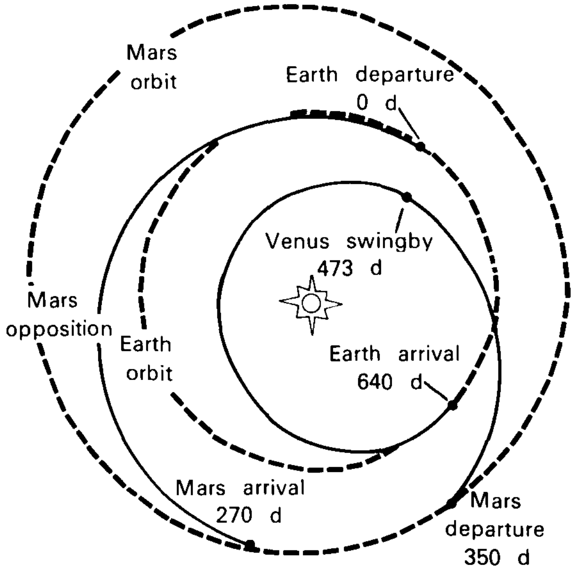

FIGURE 3.—Trajectory of Mars opposition class manned mission.

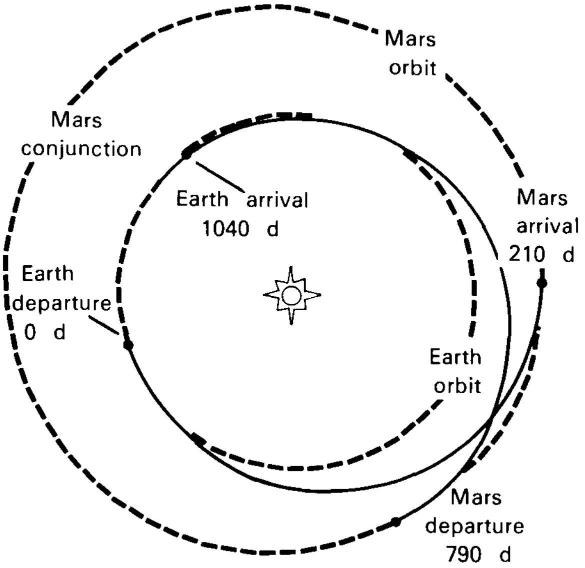

FIGURE 5.—Trajectory of Mars conjunction class manned mission.

Mars requires 210 d. After a 580-d stay on Mars, the vehicle departs for Earth. The return transit requires 250 d, making the total mission duration 1040 d. The maximum vehicle-Sun distance of 2.5×10^8 km occurs midway during the Mars stay, and the maximum Earth-to-vehicle distance of 4×10^8 km occurs at the same time.

A likely example of acceleration profile of a manned mission to the planet Mars is given in Figure 6. Acceleration during launch into Earth orbit will be about that of the space shuttle for which maximum acceleration of 2.5 to 3 G is foreseen. While in Earth orbit, artificial gravity up to 0.5 G could be provided if needed. In the example shown, Earth departure is accomplished by means of 3 propulsive impulses spaced about 18 h apart. Maximum acceleration during the departure phase amounts to about 0.13 G. During the transit phase to Mars, acceleration level is practically zero unless artificial gravity is provided. Acceleration during entry into the martian atmosphere is shown at a maximum of 3.5 G. A different atmospheric entry maneuver could reduce this level to as low as 0.7 G. During ascent from the surface of Mars to orbit, acceleration will reach a level of about 1 G, while about 0.3 G will be reached during Mars orbit departure. The deceleration for capture into an Earth orbit is about 0.2 G. Transfer of the crew from Earth orbit is accomplished via space shuttle; there is maximum deceleration of roughly 2 G on reentry to Earth. The crew size for such a planetary mission would be about 6 to 12, with the volume of crew living quarters about 30 m^3 (1000 ft^3) per man.

The capability for emergency return or rescue is very limited. Specifically, within 2 d after departure from Earth orbit, quick emergency return to Earth orbit is still possible and would take only 1 or 2 d. During the transit period to Mars, a quick return is no longer feasible, although it would be possible to reduce the nominal return time. For example, 50 d after departure from Earth orbit, the return trip would take about

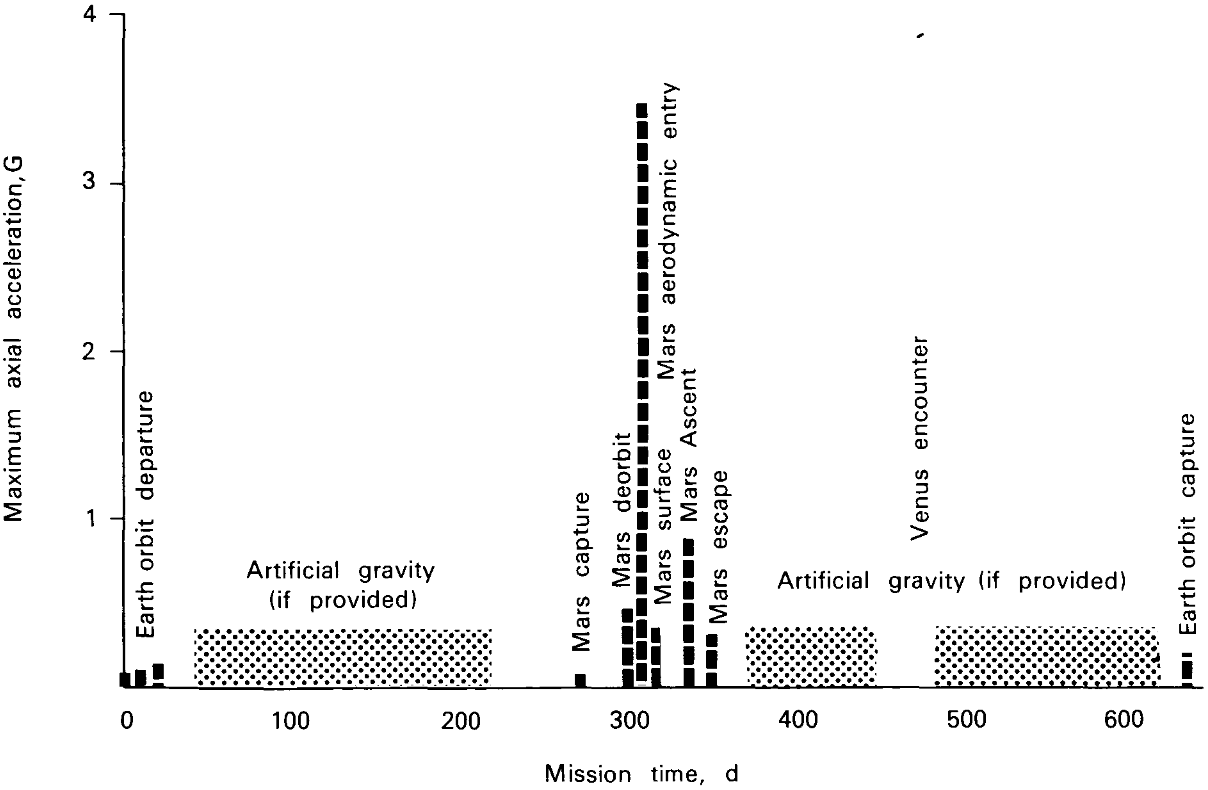

FIGURE 6.—Acceleration levels for Mars manned mission.

200 d. On the other hand, 120 d after departure, the return would require about 350 d. Once the spacecraft has been placed in orbit about Mars, no reduction in return trip time is achievable.

MEDICAL AND BIOLOGICAL FACTORS IN MANNED MISSIONS

The biomedical research which will be needed to support future missions is a subject of such breadth and variety that it may be of practical benefit to begin by establishing a serviceable organization of its content.

The outline (Table 3) divides the area into two major segments: factors which must be supplied to spaceflight personnel, and biomedical information to be gained from space missions. While these two basic elements are as distinctive as "intake and output," they are not entirely independent of each other. Information derived from crew responses to the flight environment supplied for a mission may lead to flight experiments. On the other hand, data obtained from flight experiments are often of importance toward improving flightcrew support techniques and enhancing man's function in space. Indeed, this is a major purpose of the life sciences spaceflight experiments.

Both of these elements have in common the requirement for a strong foundation of ground-based research. In terms of information needed, this total ground-based effort is, of itself, a scientific quest of significant magnitude, whose scope is extremely broad. It requires the inspired activities of many talented individuals of many scientific disciplines, and it is expensive to implement properly. As a fundamental part of the movement of our world to explore other worlds, it seems clear that this large body of research would best be accomplished worldwide.

In the sections that follow, each of the factors outlined is reviewed, especially in light of research still to be accomplished to prepare for the three classes of missions discussed. Since a thorough review of each subject is the purpose of the three volumes of this publication, comprehensive detail cannot be attempted here. Instead, it is intended that the information needs identified will stimulate thoughtful supplementation, planning, approaches to solutions, and constructive research in the direction of an internationally coordinated scientific effort.

Crew/Passenger Support

Atmospheres

The provision of spacecraft atmosphere entails the establishment of desired levels, ranges, and limits of total pressure, gaseous composition, humidity, temperature, and accumulations of toxic gases. Parallel with medically oriented research is hardware design and development to provide new, improved techniques and equipment to meet these specifications.

The first three US manned spaceflight programs, Mercury, Gemini, and Apollo, provided spacecraft atmospheres of 100% oxygen at one-third sea level total pressure; however, future trends favor progressively closer approximation to sea level Earth atmosphere for long-duration flights for two primary reasons. First, it is reasonable to assume that the gaseous environment in which man evolved, develops, grows, and lives, is the one to which he is optimally adapted by nature. Although approximately 80% of this gaseous envelope is chemically inert, it cannot necessarily be assumed to be physiologically inert. The validation of alternative long-term artificial atmospheres for human physiological and functional normalcy would require a very great research effort, since possible gaseous combinations are virtually infinite and the burden of proof would rest with their proponents.

Second, the interpretation of data derived from spaceflight medical experiments will be greatly facilitated by the removal of an unnatural gaseous environment as an experimental variable. Not only will requirements for expensive and complex long-term ground-based chamber studies be greatly reduced, but also flight findings will be more accurately interpretable.

The $3.5 \cdot 10^{-1}$ kg/cm^2 (5 psia) (260 mm Hg) 100% oxygen atmosphere had the advantage of simplicity, low intrinsic weight, and reduced vehicular structural weight. Very importantly, it eliminated the threat of dysbarism during extravehicular activities in the $2.1 \cdot 10^{-1}$ kg/cm^2

(3 psia) (155 mm Hg) suit. Its major disadvantages were its attendant fire hazard and its apparent action to reduce the mass of circulating red blood cells by mechanisms which are still not completely established. These problems, together with the reasons cited above, have resulted in abandonment of the pure oxygen cabin atmosphere for future manned space flights. Currently, increased launch power and vehicular load-carrying capacity have, in fact, devalued all its advantages except one, elimination of the bends problem.

TABLE 3.—*Biomedicine and Behavior in Manned Space Flight*

- I. Crew/passenger support
  - 1. Atmospheres
  - 2. Pressure suits and extravehicular activity (EVA) equipment
  - 3. Nutrition and food-water-waste management
  - 4. Hazard protection
    - a. Toxic substances
    - b. Particulate contamination
    - c. Microbial hazards
    - d. Electromagnetic forces
    - e. Mechanical forces
    - f. Micrometeoroids
    - g. Fire hazard
  - 5. Clinical medicine; preventive and therapeutic
  - 6. Medical selection
  - 7. Training
  - 8. Group integrity
  - 9. Living conditions and standards
    - a. Hygiene
    - b. Work-rest-sleep cycles
    - c. Volume requirements
    - d. Clothing and laundry
    - e. Furnishings and decor
    - f. Exercise
    - g. Diversions
  - 10. Performance factors
  - 11. Artificial gravity
- II. Life sciences experiments
  - 1. Experiment content
    - a. Medical
      - (1) Neurophysiology
      - (2) Pulmonary function
      - (3) Cardiovascular function
      - (4) Metabolism and nutrition
      - (5) Endocrinology
      - (6) Hematology
      - (7) Microbiology and immunology
      - (8) Behavioral response
      - (9) Clinical medicine
    - b. Biology
    - c. Equipment tests
  - 2. Experiment support equipment
    - a. Bioinstrumentation
    - b. Life sciences laboratory

An appreciable amount of research in several countries has focused on an attempt to identify a gaseous mixture which would retain this advantage without disturbing the integrity of human function or creating new hazards. Helium-oxygen and other air substitutes have been studied, but results, while promising in some respects, must be considered incomplete from the standpoint of validating long-term use. In the future, it might be more practical to place greater emphasis on dysbarism research which assumes nitrogen-oxygen cabin atmospheres with normal O_2 partial pressures and total pressures ranging from 1.03341 kg/cm^2 (14.7 psia) downward, depending upon the mission characteristics anticipated. Such research would amplify nominal and emergency denitrogenization standards and techniques, advance suit technology to permit greater freedom of movement at higher pressures, and develop in-flight therapeutic procedures and equipment. This work must not only be centered about highly physically fit flight-crews, but also less stringently selected space-flight passengers. Elucidation of the mechanisms of dysbarism and effects of long-term exposures to non-sea level atmospheres will also continue to merit attention.

Temperature levels of 18° to 24° C (65° to 75° F), and relative humidity of approximately 50% appear to be satisfactory. Technology to provide these levels in the spacecraft is currently available, but as new types of environmental control systems are developed, modifications and new component concepts may be required.

The setting of maximum CO_2 limits at 8 mm Hg, and approximately 3 times that figure for short-term emergencies, appears to be sound for safety purposes. The extent to which prolonged exposure to such ranges as 4 to 8 mm Hg CO_2 might interfere with in-flight physiological investigations has not been precisely determined, but the probability of significant influence appears small.

Carbon monoxide accumulations should not be permitted to exceed 0.01 mm Hg. Visual effects have been observed at levels as low as 0.013 mm Hg [32]. Little carbon monoxide is produced endogenously but significant amounts may accumulate within the spacecraft over periods of a month or more unless ventilation and scrubbing methods are adequate. Other possible sources such as leakage from Bosch or similar CO_2 removal systems must be rigidly prevented.

Spacecraft ventilation requirements are determined largely by comfort factors and adequacy of flow rates through environmental control systems to permit operation within established specifications. Ventilation must be pervasive enough to prevent pocketed accumulations of untreated cabin air.

For extended long-term missions such as future lunar and planetary flights, increasing emphasis must be placed on regenerative systems. There is great need for continuing progress and innovation in perfecting present concepts and creating new ones. From time to time, longer term testing of newly developed components in inhabited integrated systems will continue to be required. By means of careful preplanning, such tests can be utilized as excellent sources of ground-based human data in many other areas of biomedical importance, as has been done in the past [5, 27]. The systems selected for any of the three classes of missions will depend on duration of flight, crew size, power-weight-volume capacity of the vehicle, feasibility of resupply, and the state of the art of regenerative systems. In general, environmental control systems requirements for stations on lunar or planetary surfaces will follow the same principles as those for manned spacecraft.

Pressure Suits and EVA Equipment

The full pressure suit is basically a portable environment essential for performance of tasks away from the spacecraft. It is also a "cocoon" of refuge in the event of failure of the spacecraft environment. Although used for relatively short periods, it must have the same protective characteristics as the spacecraft, with modifications that both provide and utilize its mobility. It must supply a gaseous environment to support life and vigorous activity, adequately remove metabolic heat, prevent accumulations of toxic products, and protect against extreme ambient temperatures, micrometeoroids, high-intensity electromagnetic energies, and mechanical wear and tear. It must permit normal bodily functions such as eating and discharge of wastes, and still afford maximum mobility and manipulative freedom. For EVA activities, it must permit integration of space maneuvering units and sufficient dexterity for handling tools.

The Apollo Portable Life-Support System, thermal garment, micrometeoroid protection, ultraviolet filtration, water cooling, and urine management techniques have proven very satisfactory for the time required on the lunar surface as well as in space. For radiation protection, reliance was placed on probabilities of freedom from solar storms and the ability to move quickly to the relative shelter of the lunar module, and from there to the orbiting command module and return to Earth. The Skylab EVA system, consisting of a slightly modified Apollo suit used with an umbilical, proved to be fully satisfactory for the assigned tasks.

Present soft suits provide reasonable maneuverability and dexterity if operated at $2.1 \cdot 10^{-1}$ kg/cm^2 (3 psia) (155 mm Hg). These attributes are seriously impaired at $3.5 \cdot 10^{-1}$ kg/cm^2 (5 psia) (260 mm Hg). At higher pressures, even the most highly trained athelete is helplessly transfixed in a fully supine, doll-like attitude. Research into capabilities of suits made of harder materials has resulted in retention of some maneuverability at higher pressures, but movements are still somewhat awkward and the suits are excessively bulky and difficult to store.

Foremost among the goals to be achieved in future pressure suit research is increased ease of coarse and fine movement during operation at significantly higher pressures. Ideally, suit pressure approximating cabin pressure would eradicate the specter of dysbarism, and cabin atmosphere approximating sea level would fully satisfy all physiologic and experimental requirements of the spacecraft gaseous environment. An easily stored, quickly donned, relatively long-duration suit with these utopian attributes need not necessarily remain beyond the range of our rapidly growing technology.

Nutrition and Food, Water, and Waste Management

Apollo information indicated that caloric requirements in weightless space will probably be less than on Earth, based on reasoning from the 1/6 g data obtained. By indirect measurement from three forms of data—heart rate, suit coolant-water temperature, and oxygen consumption—metabolic costs of lunar surface activity averaged approximately 300 kcal/h (1200 Btu/h), significantly less than with commensurate Earth-based work [2, 14]. Caloric intake ad libitum showed a wide range of individual variation in the Apollo program, but reasons varied, and cause-and-effect relationships or even trends cannot yet be established. Skylab data are not yet completely analyzed, but preliminary indications are that in-flight caloric consumption was about the same as on Earth. In-flight controlled studies will continue to be required because of the many factors involved and high degree of individual variation. Resulting data will have direct bearing on problems of food logistics and support of man.

Food provisions allowing for average daily intake of approximately 2800 kcal/d · man^{-1} should be adequate for planning according to present indications. Skylab menus were originally planned on the basis of 300 kcal/d less than individual averages on Earth, and supplements were provided. Caloric intakes of some crewmen were phenomenally high normally, and were correspondingly high in space. Food composition similar to Earth diets proved entirely satisfactory; it differed only where specific dietary controls were needed for experimental purposes. Protein intake of high quality was supplied at approximately 1.5 to 2 g/kg body wt · d^{-1} which, on average, matched consumption. Standard vitamin requirements were assured by means of a standard minimum daily requirement tablet taken daily.

There is some evidence to consider supplemental Vitamin E if exposure to high oxygen environments is anticipated [8], and mineral and trace mineral supplements if the diet is high in foods processed by chelation [32]. Vitamin D supplementation would seem indicated to compensate for lack of direct exposure to sunlight. There appears to be a valid case for increasing calcium and phosphorus intake to about double normal daily required levels (i.e., to 2 g and 3 g respectively) on very long missions to decrease the rate of bone demineralization [13]. Salt supplements should be carried in the event of exposures to excessive thermal stress.

Skylab metabolic balance experiments required rigid control of dietary intakes of calcium, phosphorus, sodium, and magnesium. Potable water supplies providing for daily intake for all metabolic purposes (food preparation included) of approximately 3 to 3.5 l/man · d^{-1} should be adequate. It would seem advisable to establish a daily minimum intake of about 1.5 l/l for each crewmember to prevent dehydration and possible nephrolithiasis. Skylab potable water supplies were provided on the basis of 3.5 l (7.5 lb)/man·d^{-1}. Actual use on Skylab 2 averaged 75% of this amount, 90% on Skylab 3, and 90% on Skylab 4.

From the systems point of view, future research in food, water, and waste management should be continued in the same three primary directions to perfect past accomplishments: to provide crew nutritional support with improved ease, palatability, and aesthetic standards; to furnish medical experiment requirements with maximum precision and simplicity; and to develop improved regenerative systems. Although food storage and logistics problems will be a limiting factor, food systems research should be oriented toward providing nutritional and enjoyable Earth-type meals with minimal artificial processing for storage.

Ideally, menus should be punctuated with special meals of unprocessed natural food such as frozen poultry or steaks for morale purposes, as well as to provide needed roughage, dental exercise, and trace components. Requirements for containers can be relaxed to some extent, since it has been demonstrated on Apollo and Skylab that foods with relatively small cohesive properties are easily handled with a spoon during weightless flight. Development of rather simple mechanical contrivances, such as a glove box-type of food preparation unit, might materially enhance appetite and morale by making it possible for the crew to prepare cooked foods, sandwiches, salads, and snacks.

Convenient techniques for precisely recording intakes of food, food components, and fluid should be available for scientific data. Real-time readouts by individual crewmembers would make possible constant intakes of specific components, such as calcium, where necessary for experimental purposes. In support of medical experiments, urine and fecal outputs should also be recorded by automated means to minimize the need for crew intervention. Similarly, automated methods should be developed for the taking, packaging, and labeling of accurately measured urinary and fecal samples.

The disposal of fecal wastes is perhaps best accomplished by vacuum dehydration or freeze-drying. Incineration or possibly some form of reutilization would resolve the problem of storing dried fecal material on long-duration flights. Water reclamation from urine is already within the state of the art, but these techniques must be further perfected. Improved methods of preserving water for long periods and testing it at frequent intervals for chemical and microbial content must continue to be sought.

Hazard Protection

A good deal of forethought and preventive planning will continue to be required to protect crews against potential environmental hazards which are either uniquely important or inherently unique to space flight. These may be classified as toxic substances, particulate contamination, microbial hazards, radiation, mechanical forces, micrometeoroids, and fire.

Toxic contamination. In dealing with toxic contamination, attention must be given to potential sources, means of transmission, purifying techniques, maximum acceptable concentrations, and therapeutic procedures. The variety of materials used within the spacecraft makes the range of potentially toxic substances quite broad. Significant levels can develop by simple accumulation, outgassing at sub-sea level pressures, increased rates of oxidation at high oxygen partial pressures, interactions with other spacecraft materials or energies, microbial action, failure of scrubbing devices or techniques, and leakage of contained substances, such as coolants or fire-extinguishing chemicals.

All materials carried aboard the spacecraft must be considered as potential sources of toxicity, including not only substances of spacecraft systems, supplies, and accommodations, but also human endogenous sources, experimental animals and plants, and reagents, supplies, and various forms of apparatus used for all in-flight experiments. In addition, spacecraft materials must also be carefully selected on the basis of their products of combustion in case of fire.

Transmission of toxic agents to on-board personnel parallels the three classic portals of entry into the body: lungs, gastrointestinal tract, and skin, either by contact or accidental penetration. Vectors of concern, therefore, are gaseous and particulate contamination of the atmosphere; food, water, and accidental ingestibles; wash water, soaps, clothes, laundry materials, and bedding; and all equipment, materials, and substances with which the human occupant will be in living and working contact.

The use of potentially toxic materials cannot be completely avoided; therefore, technical advancement must continue to develop sensors and purifying techniques for all modes of transmission. Filters, catalytic burners, exchange resins, semipermeable membranes, adsorbants, and various combinations of these and other techniques need further investigation.

Maximum acceptable concentrations have been established for an extremely wide range of contaminants on Earth, but almost all are based on 8-hour workday exposures. Relatively few limits have been established for 24 hour a day living environments. While this task applies less to ingested toxins than to respiratory and contact vectors, it remains a formidable future research assignment when one considers the rapidly expanding numbers of types and uses of man-made materials, the additional need for determining toxicities of their pyrolysis products, and the difficulties inherent in this kind of research.

Development of therapeutic procedures will continue to be accomplished primarily by nonspace-oriented clinical research. However, it is anticipated that a few specific therapeutic problems may arise because of substances which may be uniquely produced by interactions within the spacecraft or space suit environment.

Particulate matter. Particulate matter, in more or less even distribution in the weightless atmosphere, is a unique problem of space flight. These particles can be considered to consist of both soluble and insoluble substances, which by virtue of their protean distribution, are potential toxic hazards through all three portals into the body. Insoluble materials, such as fiberglass, asbestos, silicone, and others must be minimized to prevent pneumoconiosis. Beryllium and cadmium, even more emphatically, must be entirely eliminated from the spacecraft because of their extreme toxicity. The problems of particulate contamination should be largely preventable by avoiding the use of certain materials within the spacecraft and by providing on-board control through effective airflow and filtration systems.

Microbial problem. Possible changes in the microbial ecology on long-duration space flight were postulated as a potential problem area about 10 years ago [4]. Ground-based and spaceflight evidence has been accumulated since, which appears to lend some support to that hypothesis [2, 14, 31]. Distribution of bacteria among crewmembers tends to become homogenous, and there is some evidence that the relative dominance of pathogens may change in this closed microcosm. Tenable hypotheses have also been expressed concerning microbial genetic changes as a consequence of the space environment, as well as alterations of host resistance in human occupants who have been removed from the daily microbial assaults of ordinary living [30].

The microbial area warrants further ground-based as well as in-flight amplification, expecially when one considers that experimental findings can be influenced by so many variables, such as initial microbial populations, carrier states, individual resistance, interpersonal proximity, spacecraft or simulator volume, sources of contamination, and personal hygiene. While prevention of infectious disease aboard is a clear requirement, the possibility of microbial shock postflight militates against a sterile spacecraft environment. Consequently, the advancement of such methodologies as microbial filtration, food and water purification and preservation techniques, and perhaps selective destruction of specific kinds of bacteria, viruses, or fungi—in fact, all microbial ecologic control and monitoring techniques—would best be oriented to preservation of an Earth-simulated microbial environment.

Radiation. Areas of particular interest within the radiation spectrum are ionizing radiation, and the ultraviolet, visible, and infrared ranges. Three kinds of ionizing radiation which must be dealt with in space are now well-established:

> Trapped radiation, protons and electrons trapped by Earth's geomagnetic field to form radiation belts enveloping the Earth;
>
> Solar flares, which result in eruptions of protons, alpha-particles, and small fluxes of heavy nuclei into space;
>
> Cosmic or galactic radiation, containing extremely high-energy protons, alpha-particles, and heavy nuclei ranging through z-numbers of 26 and higher.

Our orbital and lunar manned space flights so far have shown that preflight calculations have tended to err slightly on the high side. Actual doses received by astronaut flightcrews have been extremely small [2, 14, 21, 22, 23]. The timing of lunar flights to avoid solar flares has proved to be well-planned and fortunate, since no flares were encountered.

An observation made by Apollo lunar crews, however, may well be related to the relatively infrequent strikes of high-energy cosmic primaries (HZE). Similar occurrences have also been reported by Skylab crews. This is the "flashes of light" phenomenon. The relationship has not yet been established conclusively, however, nor the mechanisms which produce the phenomenon.

As flight durations lengthen, much more information will be needed concerning acute, subacute, and chronic effects of ionizing radiation in terms of both somatic and genetic effects [16]. The relationship between specific dose levels and effects produced (symptoms, signs, pathology, recoverability, and so forth) must be discerned for the types and energies of radiation which will be encountered in space. The modifying influence of dose rates, especially low dose rates, requires amplification. This is very important. Questions concerning the effects of dose fractionation, nonuniform dose distribution, and linear energy transfer (LET) properties on injury and recovery times, and the influence of spaceflight physiological changes on susceptibility to radiation injury must be investigated.

Finally, the technology of radiation dosimetry and development of preventive or modifying medication are in need of more research. Continuing work in radiation shielding must also be emphasized, but as long as shielding effectiveness is a function of its density (disregarding for the moment its proclivity to produce secondaries), duration of flight as a function of acceptable radiation dosages will vary according to weight-load capacity of the spacecraft.

Protection of spacecrews and passengers, particularly eyes and skin, from potential hazards of ultraviolet, visible light, and infrared radiations of high intensities is of considerable importance. Knowledge of these dangers and protective techniques, however, is in general fairly well-established. The laser is a special case within the visible light spectrum, since it is possible that laser technology may be utilized for instrumentation aboard spacecraft of the future. Safety and protective techniques will be required.

Mechanical forces. Potential hazards of mechanical forces are well-known, having been under study for many years in aviation as well as the relatively recent space program. The field includes effects of noise and vibration as well as angular and linear acceleration forces of long-duration, medium, and impact types. Although the general state of the art with respect to tolerance limits and attenuation devices is quite well-advanced, this research should continue because specific applications will be required and improvements desired. The acceleration profile of a given class of missions can be controlled as a function of the power of the launch vehicle and return mode, but contingency modes and violent emergencies must be anticipated as well as changes in G-tolerance after extended periods of weightlessness. Extensive research into the effects of noise has resulted in the establishment of acceptable limits, but considerably less is known about long-term postexposure effects.

Micrometeoroids. The probability of micrometeoroid penetration is relatively small, but introduces the possibility of decompression and, if the cabin oxygen partial pressure is high, the additional danger of flash fire. It is unlikely that decompression from this source would be explosive in character. Yet, in order to avoid dangerous reductions in pressure and to conserve cabin atmosphere, efforts should be directed toward development of an immediate warning system which would not only indicate a puncture, but also its precise location. Repair techniques, automatic puncture-sealing technology, and puncture prevention by means of lining materials, laminated coats, or other devices, must also be investigated, for space suits as well as cabins and shelters.

Fire hazard. The danger of fire is a significant threat to the safety of flightcrews. Although future US plans no longer call for spacecraft atmospheres of 100% oxygen, fire hazard is only reduced, and by no means eliminated. As partial pressures of nitrogen approach those of sea level atmosphere, the danger of fire approaches that at sea level. Although sources of ignition within the space suit are very minimal, operation at 100% oxygen, if only at $2.1 \cdot 10^{-1}$ kg/cm^2 (3 psia) (155 mm Hg), still poses a greater potential threat than a mixed-gas spacecraft atmosphere.

Fire prevention requires use of materials of very low flammability with relatively high ignition temperatures, low propagation rates, and minimal production of toxic materials on burning. The spacecraft must be scrutinized for ignition sources which must be contained. Volatile substances must be eliminated or scrupulously controlled. An immediate alarm system must be developed, and quick-response, automatic, nontoxic extinguishment techniques developed and employed. The capability of isolating at least one compartment of the spacecraft as a fire and smoke refuge should be seriously considered.

Clinical Medicine, Preventive and Therapeutic

Preventive medical procedures are directed toward maintaining optimal health of flightcrews prior to flight, and minimizing possibilities of preflight contact with transmissible diseases which might become manifest during flight.

Broadly, this entails attention to adequate nutrition, sleep, exercise, emotional well-being, and group compatibility; implementation of an adequate schedule of preflight physical examinations; and isolation of the crew to the extent practicable from all other individuals for a selected reasonable incubation period prior to flight. Where feasible, inoculations should be instituted against diseases which may have been carried by suspected contacts. All preflight contacts, of course, must be carefully screened. Research to improve methods for early detection of communicable disease is particularly important.

In-flight therapy on future extended missions will necessitate a considerably expanded capability, depending upon characteristics of the mission. The level of sophistication of treatment facilities and personnel will vary as a function of such factors as duration of flight, "space ambulance" availability, and size and makeup of on-board personnel, i.e., age ranges, physical qualifications, inclusion of both sexes, and training level of on-board medical and dental personnel. For missions of approximately 30 days or more with scientists or other passengers aboard, it would seem wise to carry a physician crewmember. His equipment would be the equivalent of a large physician's bag plus that ordinarily found in an emergency room. He would be able to treat discomforts, acute illnesses, and a wide range of injuries, serving to protect the crew and its morale. He would provide the important diagnostic acumen to prevent an unnecessary abort of the mission.

A larger capability would be needed for a larger crew or longer duration mission; but there is no real need for greater sophistication as long as the flight is orbital, which can be aborted or reached by a shuttle or its equivalent on relatively short notice.

The most extensive in-flight therapeutic requirement would apply to a distant planetary mission with intended duration of 1 to 3 years, and a large crew composed of both sexes with ages ranging to 55. Such a flight would require a medical and surgical team capable in all medical specialties as well as dentistry. Appropriate clinical facilities would be the equivalent of a small but fully equipped hospital.

Future research in this area will involve the development of equipment and techniques suited to a full array of medical and surgical procedures in weightless flight.

Although postlunar quarantine is no longer considered necessary, preparations to reinstitute these procedures following other planetary missions must be maintained, and improved techniques must continue to be pursued.

Medical Selection

The basic objectives of medical selection are to prevent, to the greatest extent possible, adverse effects during space flight or spaceflight training by applying carefully selected principles and techniques to screen out candidates with identifiable predisposing characteristics. This is the first step, and one of the most important in preventive medicine as applied to flightcrews. The trend since the beginning of the US manned spaceflight experience has been to eliminate the extremely rigorous selection tests used originally, such as thermal and isolation tests. In addition, the training period has increasingly come to be regarded as part of the selection process. Extensive jet flight experience in pilot astronauts, however, has proven so valuable a selection criterion that even nonaviator scientist-astronauts now routinely receive jet pilot training.

It seems reasonable that the future course of medical selection criteria will probably parallel the history of aviation medical requirements. As spaceflight experience increases, as crew-protective and supportive equipment is improved, as larger vehicles permit more room for the various niceties of life, and as space flight becomes more routinized in the future, it is envisioned that medical selection requirements will approach the categories and standards of criteria now established for aviation physical examinations. Whereas pilot standards will always remain high, medical standards for other specialized crewmembers will probably become less exacting, and those for passengers might eventually become relatively minimal. At the same time, relaxation to the level of standards for present-day commercial passengers will probably not occur for a very long time.

The area of medical selection criteria warrants continuing reevaluation and considered thought along with development of new, more relevant diagnostic techniques. The success, pertinence, and specificity of criteria used in the past must be continually reassessed against cumulative experience and modified accordingly.

Training

Training is another area calling for continuing study, for appraising and reappraising the relative values of techniques which have been employed by matching them against the events of each mission. The US experience, overall, has tended to endorse our selection and training procedures. The astronauts have responded uniformly well to both nominal and emergency requirements. One of our greatest problems has been shortness of time.

Training schedules are persistently crowded despite our flightcrews having been uniformly avid, retentive, and rapid learners. Considering the complexities of the three classes of future flights under discussion, it may be decidedly advantageous to develop techniques to enhance learning speed without adversely affecting retention or well-being.

The training of scientist-astronauts necessitates indoctrinating these highly qualified young scientists in the characteristics, sensations, techniques, procedures, and equipment of space flight, and at the same time providing time and opportunity to continue to advance in their respective scientific fields. An important part of this training is jet pilot instruction for those not previously qualified (already noted), and continuation of jet flight experience afterward on a regular and frequent basis.

The multifaceted missions and relatively small crews of the near future will require considerable cross-disciplinary training. As crews become larger, even greater mission accomplishments will be obtainable through increased crew specialization. Still larger crews will permit redundancy within each specialty. Improved full and partial flight simulators, cross-training methods, and within-discipline training and reinforcement techniques merit continuing research.

Group Integrity

Group integrity may be defined as the efficient and harmonious functioning of a group or team of individuals. Both Soviet and US manned space missions have progressed beyond the initial single-man flight to two- and now three-man crews. Continuing expansion of spaceflight objectives and capabilities will result in very long missions and larger, more diversely specialized crews. The need for these people to live and work together and depend upon each other for extended periods has unique and important implications with respect to selection, training, and on-board reinforcement of group harmony. Group performance can be either more, or less, than the sum capabilities of its component personnel; even highly qualified, strongly motivated, and emotionally stable individuals may form a disharmonious, noncohesive, and inefficient group [32]. Ideally, a well-selected and trained team, socially isolated, should function harmoniously and with synergistic efficiency under all nominal and emergency conditions, and should resist the deteriorative effects of time.

Several studies have been carried out under various conditions of group isolation; nevertheless our current knowledge of the subject is far from adequate [29]. Furthermore, the complexity of variables influencing such studies and the relative infrequency of opportunities for them lead to the expectation that before significant conclusions are reached, many years of continuing research will be required. Some prominent component problem areas to be evaluated are: group efficiency as a function of individual contribution and individual personality characteristics; adaptation of the individual to group stresses and flexibility of adjustment; group function under various adverse conditions and as related to time; identification of group morale factors, and preventive, corrective, and maintenance techniques; and establishment of criteria and, where necessary, more sensitive, discriminating measurement procedures for selection of individuals as group members and leaders. These and related questions will be difficult and time-consuming to resolve. This highly significant research must therefore be strongly emphasized now, if usable conclusions are to be available for the more arduous space journeys which are in the future.

Living Conditions and Standards

The term, living conditions and standards, is intended to denote an area which gives consideration to the comforts and conveniences of normal human patterns of living. The objectives are to maintain normal physical, emotional, motivational, and intellectual aptitudes, and enhance individual and team efficiency. Living conditions aboard early manned space vehicles were considerably austere, but were, after all, initial flight tests of very short duration. Spacecraft comforts and conveniences were only moderately improved through Apollo and Soyuz, since flight durations increased to a maximum of only 2 weeks for US flights and 18 days for the Soviet experience (Soyuz–9) [26]. Accommodations aboard the Skylab and Salyut were significantly advanced and generally proved to be quite adequate for longer space missions (84 days). Progressive lengthening of future manned space flights will require significantly increased attention to these provisions, especially with nonastronauts aboard. Specific factors include hygiene, work-rest-sleep cycles, volume requirements, clothing and laundry, housekeeping, furnishings and decor, exercise, and diversions.

Many elements are to be considered within the scope of body hygiene. From the standpoint of morale, it would be wise to maintain a high standard of personal appearance, dress, and general cleanliness within the spacecraft. Body cleansing techniques suitable for the weightless environment will require continuing improvement. The control of body odors will be essential. Effort must be sustained to improve methods for maintaining optimal dental hygiene and carrying out such mundane functions as shaving, nail clipping, and haircutting, to minimize particulate contamination of the spacecraft atmosphere. Management of body wastes will require facilities which must be suitable aesthetically as well as hygienically.

Past research in work-rest-sleep cycles has affirmed that the most desirable schedule is the one to which we are accustomed on Earth [32]. Although man can adapt to variations, such adaptation is probably not complete, nor does it occur at the same rate for all individuals. The 24-h schedule which seems most satisfactory for long-sustained missions would consist of 8 h uninterrupted sleep, 8 h work interrupted by meals and suitable breaks, and the remaining 8 h for personal needs, elective activities, and recreation. If the flight team is large enough, two groups operating 12 h of each cycle may be advisable. Studies indicate that the cycle chosen should be adhered to throughout the mission with as little change as possible.

Circadian research has shown that man is best adjusted to a 24-h diurnal cycle, by training, if not by nature. It is somewhat paradoxical that man's natural rhythm is approximately 25 h, according to the preponderance of evidence from free-running studies. This feature can be advantageous when it becomes necessary to shift to a new 24-h day. Indications are that days may be extended to 25 h without ill effect by increasing sleep periods to 9 h until the new start point is reached [33].

Currently there are no universally accepted standards of minimum living space for flightcrews. This depends a great deal not only on size of the flightcrew, but also on age, sex, composition, and duration and kind of mission. A few basic principles are generally accepted, however. The importance of an area of privacy for each individual, if only a bunk and foot locker, is worthy of emphasis. Generally, it is advisable to separate the recreation area from work areas. As vehicular size increases, it should be possible to provide room volumes, arrangements, and accommodations approximating those aboard small naval vessels.

Clothing should be comfortable, nonallergenic, nonirritating, nonflammable, and easily cleaned. The cleated shoes developed for Skylab were comfortably functional on the grid floor. However, other forms of flooring in future vehicles will call for a different type of semiadherent or optionally adherent shoe. Protective gloves and effective, nonbreakable protective goggles or glasses should be provided for tasks requiring them. All clothing materials, like all materials aboard the spacecraft, must be nontoxic. Lint production must be minimized. Laundry facilities, designed to function in weightlessness, must be provided unless trade-off studies favor the alternative of disposable clothing. New principles, such as ultrasonic cleaning, warrant investigation. New trash disposal methods should also be developed since housekeeping will pose a major problem in long-term flight.

Furnishings, illumination, and decor should be designed for pleasant, comfortable, and safe living within the spacecraft. For either weightless or rotating spaceflight modes, they may also be designed to aid visual orientation. Room decoration, furniture, and lighting can and should be fashioned to be conducive to intended functions, whether work, sleep, relaxation, or recreation. The present state of the art is already quite well advanced in these areas.

Exercise is important not only physiologically but also as recreational activity simply because it makes one feel better. New kinds of competitive and noncompetitive recreational exercises suitable for weightless flight need to be developed.

Books, radio, television, games, playing cards, writing materials, educational courses, and other diversionary activities must be provided. Research in this area should be directed not only to the adaptability of these games and materials to weightlessness, but also toward determination of the kinds of competitive activity which will be helpful, and those which may lead to group disharmony.

Performance Factors

Performance factors may be described as equipment, techniques, and design considerations dedicated to the enhancement of task performance efficiency. This field, also called Human Engineering or Man-Machine Integration, deals with the design of any machine or piece of equipment used or manipulated by man to best fit his anatomical, perceptual, intellectual, and motor characteristics for maximum ease, safety, and productivity. Its major origin and impetus were in aviation, where contributing specialties such as anthropometry were developed to a high level of sophistication. Continued expansion of this type of research in the interest of manned space flight has resulted in a quantity of available information on such factors as optimal sizes and shapes of seats, equipment arrangements, switch buttons and toggles, and on operator information devices such as dials, gages, and viewing screens. Yet there is need for continuing research, since much of this knowledge is specific for specific kinds of equipment.

A major element of our work in the future will perhaps center on the determination of those tasks which can best be carried out by man, as opposed to those accomplished better by automated techniques. Remote operation is a special form of automation of extremely promising value. Man's capabilities are vastly beyond those of the most sophisticated machines ever conceived. His inventiveness and his judgment are entirely unique. The scope of his perception and quality of his responses cannot be duplicated. On the deficit side, however, he is a fragile entity who requires a great deal of support and supply, and he is a relatively slow traveler compared to transmitted energies. Through automated remote operation from the ground, or even more intriguing, from a manned spacecraft, the best attributes of man and machine can be effectively combined to extend man's intelligence through forbiddingly distant and dangerous zones. The Soviet remote lunar exploration with return of soil samples was a remarkable demonstration of this technology.

Lastly, the enhancement of human performance and task accomplishment in space must continue to be concerned with the design of adequate body restraints, mobility aids, tools and similar devices adapted for use under the particular circumstances required, whether weightless, during spacecraft rotation, or on lunar or planetary surfaces. The importance of these aids has been amply demonstrated in past US and Soviet experience. From the standpoint of future research, such work aids will probably not be developed primarily by the life scientist. Astronomy instrumentation will be developed by the astronomers, geological equipment by geologists, and vehicular repair tools by spacecraft engineers. The role of the life scientist remains prominent, however, in evaluating and prescribing steps to assure optimal form, fit, and function of the instrument to the structure and function of the man.

Artificial Gravity

Now that Skylab flightcrews have successfully achieved up to 84 days of continuous weightlessness without serious overt duration-related physical difficulties, the need for artificial gravity to maintain crew well-being on missions of extremely long duration has become even less likely than before. It seems increasingly apparent that prevention of physiological changes which do occur will be amenable to much simpler countermeasures than this cumbersome concept. Nevertheless, it is quite possible that at some future time, vehicle rotation may be considered desirable for purposes of housekeeping and creature comforts. Such a case might be a very large, semipermanent space station meant to accommodate ordinary unindoctrinated passengers and, perhaps, long-term resident crews. For this reason, as well as to add more to our knowledge of human vestibular system function as it relates to the space motion sickness phenomenon, research continues to be indicated to further explore effects, optimum procedures, and methods to counteract symptomatology of artificial gravity in space.

At present, the only practical method of producing artificial gravity is by rotation of the spacecraft. Although rotation of the individual by an on-board centrifuge appears to offer a reasonable alternative, the short radius and relatively high rotation rates involved are likely to produce more physiological disturbances than the technique can resolve. In addition, housekeeping and other problems which would be eased by spacecraft rotation are not affected by the on-board centrifuge.

Spacecraft rotation poses a number of human physiological and performance problems as well as those referable to the design, navigation, and operation of the spacecraft. The primary focus of potential physiological difficulty is on equilibrium and the vestibular system, which in turn impact performance and habitability factors. Potential difficulties, such as motion sickness, the tendency to fall in one direction while ascending and the opposite while descending ladders, the imposition of greater gravity levels while walking in one direction then the other, as well as head turning, past pointing, and other manipulative problems are well-known. Ground-based research must seek ways of reducing these effects and explore more thoroughly methods of determining optimal gravity levels and rotation rates, and the effects of rapid transitions from one gravity level to another within the artificial gravity field. At the same time, spacecraft-oriented studies should be undertaken to determine design requirements for the most efficient means of providing artificial gravity in-flight. Because the 1-g vector cannot be eradicated on Earth, the final resolution of these problems will require at least one well-executed in-flight study on a rotating spacecraft, the value of which will depend heavily on careful ground-based research.

A related problem in the field of space biology requires earlier resolution. The opinion has been responsibly expressed that in order to provide truly adequate controls for flight experiments in gravitational biology, the control group of specimens should be flown aboard the same spaceflight as the experimental group and exposed to 1 G throughout the weightless period of flight. Furthermore, it is argued that if artificial G is to be provided for this purpose, additional valuable information can be gained by flying similar specimens at specific gradient levels of G, both below and above 1 G. While this would unquestionably be an ideal protocol, the restriction of our ability to provide these G-forces to an on-board centrifuge imposes angular acceleration problems and associated experimental artifacts which could be considerably less than ideal. Specific trade-off studies are needed with respect to this important and far-reaching experimental problem.

Life Sciences Experiments

Medical Experiments

The objectives of a program of space medical experiments can be summarized as shown in Table 4. The first category of objectives is geared toward manned space flight. The purpose of its four constituent objectives is to determine as precisely as possible man's medical and behavioral responses, functional limitations, and supportive requirements in space flight. This kind of information is essential to planning future manned space flight. The second category is oriented to the advancement of Earth-based biomedical research by utilizing the unique environmental characteristics of space for scientific information, whether or not the resulting data will be applicable to manned space flight. These experiments use space flight as a scientific opportunity.

Because we are dealing with a largely unknown environment, the medical exeriments conducted aboard each mission should be more broadly directed than the exploration of known or anticipated problems. They must include a "monitoring" of all human systems, to the extent possible, in as much depth as is practical. All manned spaceflight missions should provide for medical investigations, since flight opportunities are infrequent and redundant human data are essential for statistical validity. It is especially important that flights of increasing durations be utilized fully, even primarily, for gathering medical information since the length of crew existence in space must be considered the chief variable of medical concern. Of the environmental factors affecting man in space, such as acceleration, radiation, social isolation, confinement, and so forth, the most unique and unknown is clearly long-duration weightlessness. Yet the effects of all factors must be evaluated, both singly and in combination.

In planning an adequate program of in-flight medical experiments, it is necessary first to formulate the problems to be resolved in order of importance. How specifically these problems are defined will continue to depend on the knowledge derived from space flight and ground-based research. As problem specificity narrows, in-flight medical investigations will in turn focus upon greater levels of detail. In the cardiovascular area, for example, the broad question of responsiveness during and after space flight has now yielded more specific problems such as the roles of renin-angiotensin and aldosterone, cardiac stroke volume changes and their role in postflight exercise-tolerance recovery, the relative importance of the Gauer-Henry reflex, and the influence of potassium loss on the development of premature contractions. Similarly, experience in other physiological areas has led to more refined problem definition; areas such as body fluid distribution, red cell mass changes, vestibular effects, musculoskeletal integrity, and the distribution and control of sodium and other electrolytes.

TABLE 4. — *Medical Experiments Objectives*

A. To extend man's capabilities in manned space flight by determining:
   1. The effects of space flight on man and the time course of these effects
   2. The specific etiologies and mechanisms by which these effects are mediated
   3. Means of predicting the onset and severity of undesirable effects
   4. The most effective means of prevention or correction of undesirable effects

B. To obtain scientific information of value to conventional medical research and practice

Biomedical findings from more recent US and USSR manned space flight experience have been summarized [2, 3, 12]. Skylab findings have now added greatly to understanding these problem areas and have further amplified problem specificity. Red cell mass losses were significant despite minimal exposure to 100% oxygen. Paradoxically, these losses were greatest and recovery times longest in the Skylab 2 crew (28-d flight), and least and shortest, respectively, in the Skylab 4 crew (84-d flight), a finding which raises new questions concerning the specific etiology and basic mechanisms involved.

Cardiovascular responses to lower body negative pressure (LBNP) were characterized by increased compensatory heart rates and decreased pulse pressures approximately as anticipated, and may have reached a plateau during Skylab 4. They varied somewhat during flight to the extent that the LBNP procedure had to be aborted on occasion, but the same individual usually tolerated the full LBNP protocol during the next scheduled test. This demonstrates very well, for the first time during space missions, the point that LBNP-tolerance is tangibly influenced by factors other than weightlessness, as one would expect. Generally, the first LBNP responses after return to Earth matched quite well those obtained from the last in-flight tests. However, here again, the time required to return to preflight values was shorter after the two longer flights than after the 28-d flight, probably reflecting the beneficial influence of the far heavier personal exercise schedules of the last two flightcrews.

In-flight exercise-response tests showed no appreciable changes, but tolerances were significantly reduced after return to Earth. Again, postflight recoveries were faster following the two longer flights. Cardiac output and stroke volume were reduced postflight compared with preflight. Despite bicycle and other forms of exercise aboard, calf dimensions and leg volumes were considerably less postflight than preflight. Weight losses were not significantly influenced by flight duration, but were greater earlier than later during flight. Similarly, postflight weight gain was sharper within the first 1 or 2 days after recovery.

Vestibular effects were manifested as space motion sickness which was severe enough to impair task performance during the first 3 days of Skylab 3. Although the Skylab 2 crew was untroubled by such symptoms, all three crewmembers of Skylab 3 were afflicted. Symptoms did respond to antimotion sickness medication and cleared after the initial 3 days of flight. Preventive medication was used for the Skylab 4 crew; nevertheless, two crewmembers did develop this syndrome. Symptoms again cleared after the first 3 days of flight although, like Skylab 3, full recuperation required an additional few days. Contrary to expectations, tolerances to head motions during rotation on the litter chair were much greater in-flight than preflight, uniformly permitting advancement to the maximum protocol of 150 head motions at a rotation rate of 30 rpm. Postflight vestibular responses were: unsteadiness of gait the first day, dizziness on rapid head turning the first 1 or 2 days (which persisted in a few individuals for several days), and decreased rail-walking ability with eyes closed. Yet, in all crewmembers, tolerance to head movements during litter chair rotation remained at maximum for several days postflight before gradually diminishing to preflight levels. The concept that vestibular symptomatology may be related to the redistribution of body fluids inflight has been recently expressed [11].

Sleep responses varied among the individuals evaluated, but quantity and quality appeared to be adequate throughout all Skylab missions. Mineral balance studies revealed losses of calcium and phosphorus approximating those found during bed rest. The same was generally true of bone density changes, in that decreases in the weight-bearing bones were not observed until the longer duration flights. In-flight sodium losses were also noted. A variety of endocrine measurements were accomplished, but the data have not yet been sufficiently reduced for uniform trend indications to be discerned at this time.

A detailed evaluation of the voluminous data obtained from Skylab is well beyond the scope of this chapter. After suitable time for more complete data analysis, a full account of Skylab biomedical findings will be reported elsewhere by the many skilled scientists who participated in this significant and multifaceted scientific achievement. Nine experimental areas for inflight medical investigation are set forth in Table 5, which lists broad problems to be considered within each of these areas. This material is intended to serve only as a systematized framework for more specific new experimental concepts based on flight and ground-based information as it continues to emerge. Each problem area may be examined for further data requirements on specific effects and time courses, mechanisms and specific environmental etiologies, predictive indices, and countermeasures.

The ground-based information necessary to adequately investigate these many unresolved questions and prepare to utilize future flight opportunities for medical experiments to maximum advantage will demand an increasingly strong ground-based research program. As problems are defined in greater detail, the pursuit of solutions to them often tends to delve into more fundamental regions, and their component problems may become increasingly difficult to resolve. Although, fortunately, this ramifying sequence need not be pursued ad infinitum, the study of the mechanisms by which these observed changes are mediated must be continued at least until practical end points are reached, and should be continued beyond as basic research which will ultimately broaden the range of their utility into more and more allied fields.

TABLE 5.—*In-Flight Medical Problem Areas*

1. Neurophysiology, effects of space flight on:
   - The integrative function of the central nervous system
   - Sleep
   - The vestibular system, both otoliths and semicircular canals, under conditions of weightlessness and rotation for artificial gravity
   - Sensory perception and spatial orientation
2. Pulmonary function, effects on:
   - Mechanics of breathing
   - Ventilation/perfusion
   - Alveolar gas transfer
   - Control of breathing
3. Cardiovascular function, effects on:
   - Cardiac output
   - Arterial pressure control
   - Central venous pressure and venous compliance
   - Intrinsic cardiac function
   - Overall circulatory responsiveness to G-loading and 0 G
4. Metabolism and nutrition, effects on:
   - Metabolic requirements at rest and during activity
   - Caloric, water, electrolyte, mineral and vitamin requirements
   - Lean body mass
   - The skeletal system and metabolism of bone mineral
   - Muscular integrity
   - Fluid and electrolyte balance
5. Endocrinology, effects on:
   - Endocrine controlling mechanisms of water and electrolyte balance and distribution
   - Vasoactive hormones
   - Endocrine stress responses
   - Calcitonin output, parathyroid, thyroid, and other hormonal controls of mineral metabolism
   - Endocrine control of glucose metabolism
   - Overall balance of the endocrine system
6. Hematology, effects on:
   - Red cell mass, rates of red cell production and destruction
   - Clotting factors
   - Inflammatory responses
   - Chromosomes
   - Serum proteins
7. Microbiology and immunology, effects on:
   - Spacecraft microbial ecology
   - Distribution and relative dominance of pathogens
   - Microbial genetics
   - Factors of immunity
8. Behavioral responses, effects on:
   - Perception
   - Emotional stability (long-term effects)
   - Stress tolerance
   - Group integrity
9. Clinical medicine:
   - Influence of space flight on medical and surgical therapeutic procedures and materials
   - Effects on pharmacological responses
   - Effects on preventive medical requirements in-flight and effectiveness of instituted preflight procedures

For the purposes of space medicine, these practical end points will be the attainment of a sufficient substructure of information on mechanisms to enable establishment of optimal techniques for prediction, for both medical selection and on-board prognosis, and countermeasures for the prevention and correction of ill effects. Many approaches will be required, among which continuation of both short-duration and longer term simulation studies involving human as well as animal subjects will be needed. The repetition of such long-term bed rest studies, which have already been carried out in the US and USSR, will continue to be required to shed further light on cardiovascular and musculoskeletal response mechanisms, prognostic indicators and countermeasures [10, 13, 34]. Similarly, short-term bed rest, water immersion, animal immobilization, confinement, centrifugation, pressure chamber studies, and other simulation techniques, as well as investigations involving all of the basic medical sciences, must be brought to bear in order to achieve these goals.

Biology

Biological experiments will serve the same two categories of objectives already outlined in the previous section, *Medical Experiments* [9]. In contrast, however, biology tends to place greater emphasis on more fundamental observations applicable to Earth-based sciences and less on the extension of manned space flight. As the medical experiments identify operationally significant potential problems and define their component problems, the use of animals in-flight to resolve these questions will prove to be as necessary as animal experiments on Earth. Some of these requirements have already become apparent, such as the need for animal surgery in space to work out suitable in-flight techniques. Others, perhaps the majority, have yet to be determined, but will be defined as more knowledge is gained.

Flight experiments in more fundamental

biology can be anticipated in such fields as genetics, growth and development factors, intracellular protoplasmic structures and functions, plant physiology, and enzyme chemistry. Planetary investigations dealing with life on other planets, clues to the origins of life, and studies of Earth ecology are highly important fields which require continuing emphasis.

The specific biological experiments to be carried out in space will be determined largely by the needs and desires of active researchers within the scientific community. These, in turn, will be dependent upon the current status of biological research, i.e., the particular array of problems which prevail at any given time and the relative emphasis placed upon them.

Equipment tests. As new and advanced life-support systems and techniques are developed, components and assemblies may be expected to continually evolve which require in-flight testing. Some of these may involve new principles, others merely new arrangements which may pose unknowns regarding their function in space flight. Any component of advanced environmental control systems, bioinstrumentation, food-water-waste management systems, crew equipment, task aids, restraints, and similar apparatus may require such in-flight testing.

Bioinstrumentation. Bioinstrumentation requirements for space flight are predicated, in general, upon four major factors: function in weightlessness, minimal interference with working crewmembers, ease of accomplishment, and safety. The need for accuracy and reproducibility, although extremely important, cannot be considered unique for space flight. Another consideration should be added, however. In common with other endeavors in the field of environmental medicine is a requirement for high levels of measurement sensitivity and precision, because evaluations of healthy individuals under abnormal conditions can be expected to yield data which may prove to be significant, even though falling within accepted clinical ranges of normal.

Research is needed in the development of noninvasive techniques of physiological measurement, such as cardiac output and peripheral and central venous pressure. In biochemistry, techniques and procedures which avoid the use of liquid reagents will obviate the potential dangers of their toxicity, and problems of handling liquids in the weightless environment. Automated techniques would be of great value in saving crew time. Finally, improved techniques must continually be pursued for the storage, compression, display, and transmission of in-flight data.

Life Sciences Laboratory

One of the research efforts of the US Life Sciences Program during the past few years has been the development of a compact and highly flexible laboratory console system to accommodate the measurement requirements of in-flight medical experiments. This Integrated Medical and Behavioral Laboratory Measurement System (IMBLMS), by virtue of its flexibility, is capable of being expanded to include clinical diagnosis, therapy, and equipment for the conduct of biological experiments.

Beyond the current development of Spacelab for the Shuttle Program by the European Space Research Organization (ESRO), it is entirely feasible for future global research to bring about the development and cooperative utilization of a life sciences flight module which can be docked and operated as a part of an orbiting or planetary vehicle. Such a module would make the full potential of space available to the life science community of the world, to provide maximum opportunity for achievements to support the expansion of man's exploration of space, and advance our scientific understanding of life on Earth.

SUMMARY

An effort has been made to define the characteristics of three basic classes of manned spaceflight missions of the future, and to broadly organize and highlight future research requirements in the life sciences for the support and advancements of these space achievements. Whether or not current planning for the next decade includes missions beyond the Earth-orbital class or further extensions of flight duration, it is considered a certainty that in the future, man's intrepid curiosity and irrepressible thirst

for knowledge will lead him inevitably to use his hard-won gains to further expand his horizons in space. As tangible human benefits become apparent and as such missions become cheaper and easier to carry out, their frequency may be expected to increase progressively.

During the intervening periods, the large amount of ground-based research needed to support, improve, and utilize these expanding space explorations can and must be accomplished. In the medical area, our competence to set forth appropriate medical specifications to support man for such missions of the future will be fundamentally dependent upon our knowledge of man's responses, their ranges, and our ability to prognosticate, prevent, and correct undesirable effects.

Even more fundamental to success, and underlying all these essential criteria, will be a thorough knowledge of the mechanisms by which these responses are mediated. The more than 26 000 man-hours of combined US and USSR manned spaceflight experience so far have, to a large extent, served to identify, define, and arrange in approximate priority the more apparent medical problem areas and many of their component issues. When reduced, the great amount of medical data derived from Skylab's 12 300 man-hours of this total will significantly increase information on moderately long-term effects and their time courses.

We are now in a position to make full use of these gains and augment them by placing strong emphasis on ground-based research and shorter duration flight experiments to more fully explore *mechanisms*, i.e., the cellular, tissue, neurologic, endocrine, immunologic, biochemical, and other modalities involved in producing the physiologic alterations, adaptations, and losses of adaptation which have thus far been measured. By this means, we will continue to enhance the ability to support and advance man's future capabilities in space, and at the same time, may expect to derive important new insight into functional human physiology in both health and disease. Similarly, with regard to all other elements of the life sciences, the periods between expanding flight missions should be regarded as periods of preparation, emphasizing strong ground-based research programs to accomplish the multiplicity of diverse tasks required in biotechnology, bioengineering, and experimental biology.

The overall need for research on behalf of man in space is very great, and the welfare, protection, expansion, and intellectual growth of man are of interest in common to all mankind. It therefore seems evident that this need and common interest would best be served by the structuring of an internationally cooperative research endeavor which truly reflects the global scope of man's ventures away from his home planet into the unknowns of outer space.

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том I—Космическое пространство как среда обитания
том II—Экологические и физиологические основы космической биологии и медицины (2 книги)
том III—Космическая медицина и биотехнология

В этих трех томах суммированы накопленные к настоящему времени результаты медико-биологических исследований в космосе и намечены перспективы дальнейших исследований. Издание предназначено не только для специалистов, но и для широкого круга читателей—врачей, биологов, инженеров и лиц, интересующихся проблемами исследования и использования космического пространства. Совместное издание по космической биологии и медицине представляет интерес не только по своему научно-техническому содержанию. Оно служит также доказательством, что ученые двух стран могут эффективно сотрудничать в достижении общей цели.

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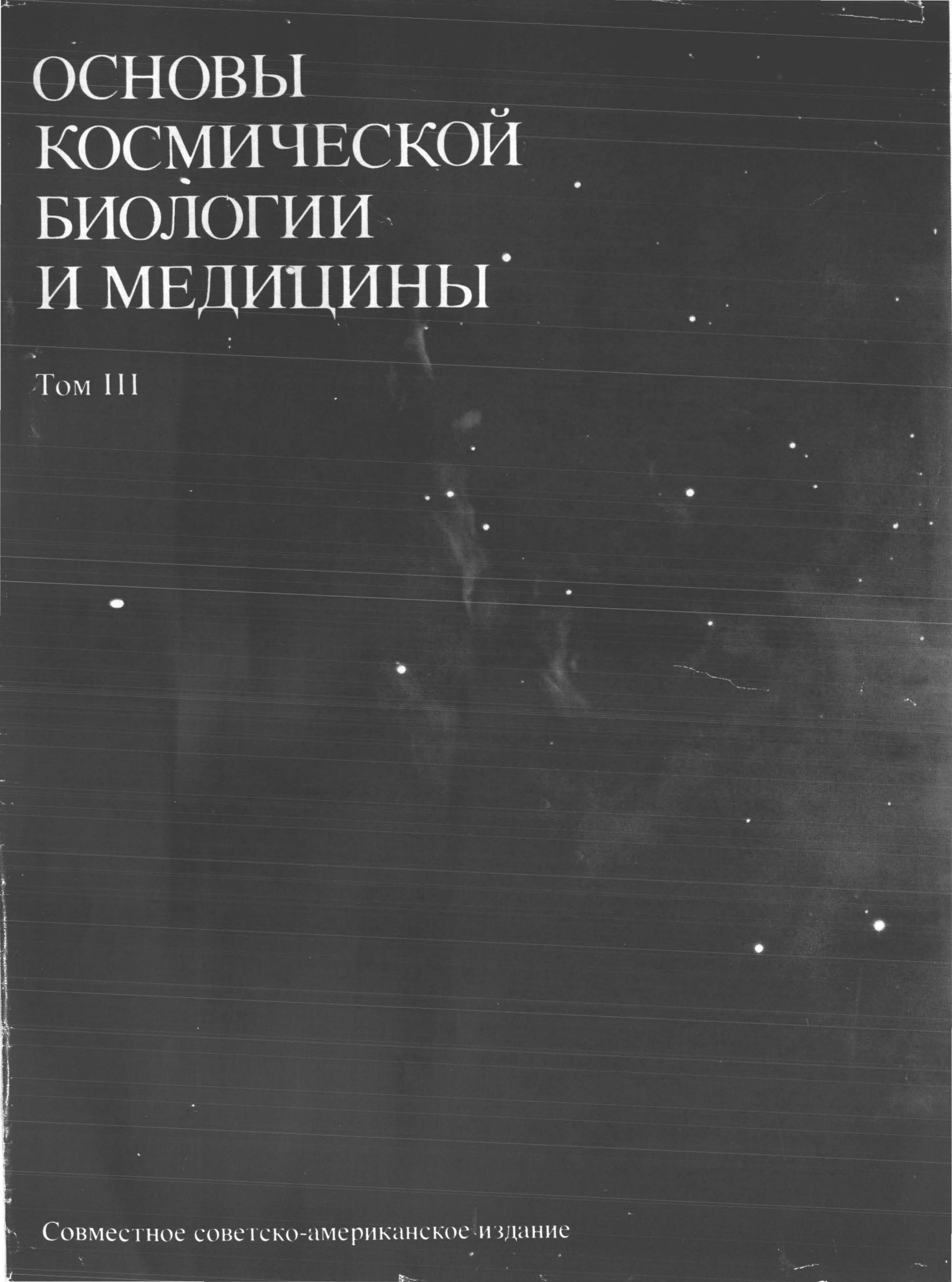

ОСНОВЫ КОСМИЧЕСКОЙ БИОЛОГИИ И МЕДИЦИНЫ

Том III

Совместное советско-американское издание