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CONFERENCE ON

NUTRITION IN SPACE AND RELATED WASTE PROBLEMS

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CONFERENCE ON
NUTRITION IN SPACE AND RELATED WASTE PROBLEMS

University of South Florida
Tampa, Florida
April 27-30, 1964

The conference, sponsored by the National Aeronautics and Space Administration and the National Academy of Sciences with the cooperation of the University of South Florida, was directed by Dr. T. C. Helvey, Associate Professor, University of South Florida.

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Foreword

As part of a continuing process man constantly seeks new habitats. In the late 1950's, he ventured into a vast and challenging new habitat, extraterrestrial space.

Extending the realm of human life has always been a challenge to man, and inherent to all successful extensions of man into new domains is his ability to provide the essentials for life itself, his nutrition and controlled use of metabolic products. The provision of these essential requirements has always been a challenge and a motivating force in maintaining and extending human life on Earth. This challenge has now been extended beyond the Earth. As illustrated in this volume, many men and women of vision who continually devote their energies to feeding man on Earth have accepted the additional challenge of nutrition in space. They have already made inroads into the new problem of nutrition and waste handling in space and have already collected much physiological, psychological, toxicological, and pathological data related to space nutrition, feeding and elimination. They have elucidated man-machine interactions and the effects of these interactions on alimentation and elimination requirements in space. Thus light has been shed on specific research and development programs needed to establish requirements for nutrition and handling of metabolic wastes during manned space missions of 20 days' to 3 years' duration. These initial accomplishments have entailed the considerable efforts of many people and the knowledge and experience in nutrition and feeding gained by the Space Science Board of the National Academy of Sciences.

This volume clearly represents the ability of scientists, engineers, and administrators to attack a problem as it arises; it clearly demonstrates the capability of the scientific and engineering communities to combine efforts, mobilize quickly, and devote their talents to a national need.

MICHAEL G. DEL DUCA
Chief, Biotechnology Branch
Office of Advanced Research and Technology
NASA

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Chairman's Introductory Remarks

C. O. Chichester
Professor, University of California, Davis
Chairman, Panel on Space Nutrition,
Space Science Board

The support of man in any alien environment for a long period depends on the solution of multitudinous problems, both physical and psychological. Certainly, to exist in any environment, man must be fed; and thus the science of nutrition is involved in its very broadest sense. In this field in particular it is recognized that nutritional needs have psychological aspects as well as physical.

Any contemplated travel out of the Earth's atmosphere and gravitational fields presupposes existence, at least during travel, in an extremely confined space. Supplying the individual's nutritional wants is difficult even when confinement is the only stress to which he is subjected. The information available at this time is not even adequate to define the problem. We do not know the stresses to which the individual will be subjected nutritionally when he is required to live in an environment without gravity, breathing an atmosphere somewhat different from that in which he evolved. To compound the difficulties which face us, engineering considerations stringently limit the amount of food which can be carried, and, further, problems of storage and utilization limit the forms in which food may be carried.

Thus, the total problem of supply is extremely difficult. Yet we must add to this the problems involved in the disposal of man's waste, since this is intimately linked with the nutritional supplies. The ultimate solution to these interrelated problems depends on application of the research and observation of many disciplines.

The Working Group on Nutrition of the Space Science Board sponsored this conference in order to review available knowledge which would be pertinent to the nutritional support of the human in space. The Nutrition Committee and the individuals working in this area are acutely conscious of the vacuum of scientific information necessary to develop the most desirable approach to the problem. It is hoped that this conference will help in defining the more urgent problems and thus establish the basis for research in nutrition and waste management which may be applied to space travel.

There is no question that a great deal of research is required, at both basic and applied levels, before solutions will be found for many of the problems that space travel poses. It is apparent that there are needs for additional information in the nutritional area before the problems under discussion can be successfully solved. Since the practical problems and the fundamental facts involved are extremely diverse in nature, this conference was planned to include representation from many disciplines, each of which can contribute to the ultimate solution of supporting a human in space.

The results should point out research needs on nutrition and waste management in space. From this Conference it is hoped that a rational and integrated plan of attack can be formulated that will lead to providing the answers when they are required.

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Conference Introduction

RAYMOND L. BISPLINGHOFF
Associate Administrator
Office of Advanced Research and Technology, NASA

The importance of the subject of this Conference to the Nation's manned space flight program is evident. We may develop boosters and guidance and control systems and reentry systems of exceptional efficiency, but unless we can at the same time sustain life in space we cannot have a manned space flight program.

There are many elements of NASA's research and technology program carried out under the Office of Advanced Research and Technology which are directed toward the exploration of space by man after Apollo: for example, our extensive work on the advanced technology of nuclear rockets and nuclear electric energy conversion, on advanced communications, on reentry at superorbital speeds. All of this work in these fast-moving fields, however elaborate, can be of no greater importance than the work on space nutrition and related waste problems.

It makes very little sense to set the pace of machine development and that of life support at different rates. I urge those in the life sciences to consider this matter carefully, to compare their progress with that of other parts of our program. In studying the titles of papers to be discussed at this Conference, I could not help but reflect on two thoughts.

The first relates to the word "interdisciplinary." I am impressed at the extent to which this subject exemplifies the full meaning of this word. It is truly a meeting ground of the life and physical scientists.

The second thought stems from the first: that on both sides, when we strip away the unessentials, we are really dealing with the conversion and the control of energy. There is muscle, with its tiny fibers, on one hand, and chemical fuel energy converters on the other. There are the electrical activities of the brain and nerve impulses on the one hand, and the computer and feedback loop on the other.

I think the state of man's technology in every age is dependent on his ability to convert and control energy. The Industrial Revolution, for example, brought on an economic structure that could not be operated without knowledge of the equivalence of different forms of energy. It was necessary to put comparative figures of merit on water power, steam power, manpower and animal power; and this was accomplished by the development of the science of thermodynamics, which furnished a common denominator for all forms of energy conversion devices. Thus, the thermodynamics of Carnot formed the cornerstone for the Industrial Revolution. If we look back at the earliest days of our country, we find that human labor furnished about a quarter, and the labor of animals half, of the energy that was required for life. In 1900, each man, woman, and child in the United States had about 2 horsepower working for him day and night. At the present time, I believe, this figure stands at more than ten. Thus, with less than 10 percent of the world's population, we control almost half of the supply of power in the world, and, as a result, our standard of living is seven times the average of the rest of the world. By a very rough calculation, I think if we had lived in the Periclean age of ancient Greece, we should need the exhausting labors of about 10 billion slaves to provide equivalent benefits.

Now the opportunities that are presented for our advancement in energy conversion and control are breathtaking. New methods of energy conversion from solar, chemical, and nuclear energy sources, which will be useful to all mankind, are being pioneered in the space program.

Of late is the direct conversion of energy in the sun's rays to electricity by the solar cell, or by collectors with turbogenerator or direct thermionic energy converters. Incidentally, we find that the employment of a Brayton cycle, with inert gases as the working fluids, shows very great promise in our turbogenerator solar system studies. Then there is the rapid development of electrochemical devices, such as fuel cells, which are strongly related to life support, because of their byproduct, water.

Perhaps the most dramatic energy conversion devices in the space program are the propulsion devices, which convert chemical or nuclear energy to kinetic energy. The figure of merit usually used to measure the efficiency of these devices—a sort of measure of rocket metabolism—is the specific impulse. The rocket engines that we have used to date in the space program with conventional Lox-rp fuels have had specific impulses of less than 400 pounds of thrust per second of fuel. We feel that we can raise this specific impulse for chemical energy systems to about 480 seconds, with hydrogen and fluorine, but that is probably going to be the limit. In order to go beyond this we're going to have to turn to nuclear energy.

The Nerva rocket engine which converts nuclear energy to vehicle kinetic energy by passing liquid hydrogen through a graphite reactor at about 6000° F and ejecting it through a nozzle exemplifies the direction that we are following.

Incidentally, next month we plan to test in Nevada the most advanced form of the reactor for this device. In terms of the figure of merit previously mentioned we can expect about 800 seconds specific impulse with this device, or an improvement of nearly 70 percent over the best chemical engines. When we can master the problems of a gaseous core reactor, we can raise this figure of merit to about 2000 seconds. Electric thrusters—especially the ion thrusters—have yielded specific impulses of greater than 6000 seconds in the laboratory, and we plan a flight test later this year from Cape Kennedy of such a device.

Then there are the Rankine cycle liquid-metal turbogenerator systems for the generation of electrical power. In a NASA–AEC program, we hope to refine the SNAP–8, a 35-kilowatt device, to the place where it will weigh about 10 pounds per kilowatt and will be able to operate reliably for 10 000 hours without maintenance. Whatever we do in space will require efficient electrical power generation, and the use of nuclear energy is the key to this.

Even in reentry technology we are engaged in the business of converting energy. Here we exchange kinetic energy for heat energy, and the trick is to dump as much of the heat energy as possible into the luminescent gases surrounding the vehicle, and as little as possible into the vehicle itself. We are making steady progress in understanding the physics of entry at superorbital speeds, and entry into gases other than air.

Only recently, scientists from the Langley Research Center, working from Cape Kennedy, drove a blunt reentry body into the earth's atmosphere near Ascension Island from a 500-mile apogee at a speed of 26 000 miles per hour. This was man's highest-speed reentry device.

Incidentally, it now appears that for reentry at speeds considerably beyond orbital speeds, we will be wanting to change our reentry bodies from blunt to pointed noses, resembling somewhat the noses of supersonic airplanes.

Our nation has made, I think, very large strides in the 6 years of existence of its space program. One of the popular measures of this progress is weight-lifting capacity. We have moved in this 6-year period from the capability to put very modest satellites, weighing just a few pounds, into earth orbit, to the Saturn I vehicle, which has lifted over 10 tons into the same orbit. And our program is rapidly moving on to the Saturn V space booster and the Apollo two-man space craft, which will provide us in this decade with the technology to permit man to travel, explore, and use the space around the earth outward to the moon. The Saturn V booster will have the capacity to lift 120 tons into earth orbit, and to hurl 45 tons into escape trajectories.

If we can achieve strides like this during the first decade or so, it is quite important and logical to ask, "What next?" Those of us who are scientists and engineers can only answer by outlining the options which technology will permit as the next step.

What is, in fact, done next, must be decided by an assessment of the scientific, social, economic, and political impact of carrying out some of these options.

I think, though, one thing is clear: where there is a reasonable promise of success in the development of new materials, propulsion devices, life-supporting devices, control devices, and so forth we must pursue these directions, even though a specific use is not clearly in view. I believe that world leadership will not be maintained in this fast-moving age, with anything less than imaginative and sustained searching for improved space devices.

The broad options for manned operation beyond Apollo are not difficult to visualize. Exploration and extended visits on the lunar surface should be within our power after Apollo. Large manned space stations, weighing many tons, may be placed over fixed points on the earth's surface, serving as communications switchboards and relays; and as our capacity to develop power in space from nuclear energy materializes, satellite television will allow us to transmit directly to homes over large parts of the globe without intermediate ground stations.

Worldwide weather coverage by satellites is certain to become eventually a permanent tool in the art and science of weather prediction.

The refinement of nuclear rockets will provide man with the capacity of exploring the far reaches of the solar system, with the planet Mars as the probable next target of interest after the moon.

And so, for the first time, I think we are beginning to grasp firmly the key of space technology, by which we may eventually be able to unlock the riddles of the solar system and life on other planets.

Reaching into space in this way will certainly constitute man's greatest adventure, and no man can foresee the dividends which will accrue from this adventure. Whether man participates in person or simply sends his machines is dependent in very large measure on the life scientist and his work.

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SESSION I

National Prospectus on Space Nutrition and Related Waste Problems

Chairman: ***Eugene B. Konecci***
Director, Biotechnology and Human Research
Office of Advanced Research and Technology, NASA

Today we are not only at the beginnings of our space exploration, but also at the beginnings of our understanding of normal man, his body systems, and his overall requirements.

Examining the human challenges of man in space and normal man on the ground requires not only exotic experiments in the actual space environment but also the application of mankind's knowledge collected over 3000 years of civilization. This knowledge has resulted in an explosive technology period, and, as Dr. Bisplinghoff pointed out, energy conversion is the key to man's progress. Dr. Bisplinghoff discussed nuclear rockets and the potential of the gaseous core reactor. There are others that he did not mention in detail—such as some of the electrical propulsion units that may go up to a specific impulse of 20 000 seconds—which we hope will give us a fabulous capability in really learning more about the physical science aspects of energy conversion.

However, in the area we call either human or biological metabolism are some of Earth's greatest secrets pertaining to energy conversion. Each person converts energy in a fantastically efficient manner, at a temperature that is not of the order of many, many thousands of degrees, but rather is something like 98.6° F.

The fundamental processes of biological metabolism and its high efficiency at low temperatures are still mysteries to us. We do have some fundamental information to serve as a basis for the planning of advanced concepts and appropriate laboratory experimentation to promote better understanding of not only human metabolism, but, in fact, the total field of ecology.

Our terrestrial ecological system in its balance state, consisting of almost the entire living world as we know it, depends ultimately on the energy of sunlight. With very few exceptions, organisms can be divided into groups. The green plants and a few bacteria utilize the energy of the sunlight directly through the agency of chlorophyll mechanisms or a very closely related system in the photosynthetic process. Nearly all other organisms derive their energy from the organic compounds synthesized by plants. Man and the animals, with the exception of a few flagellate protozoans, belong in this second group. There is a wealth of knowledge in the general area of ecology or photosynthesis that should be evaluated to aid in planning and executing better research. We in Government responsible for the management of these programs have become acutely aware of the high costs of research and development; hence, we are emphasizing cost effectiveness for research. This conference is a direct outgrowth of not only the desire but the need for bringing together into a forum such as this all elements that can make a significant contribution to a specific subject by a free exchange of ideas and also by a review of our past knowledge.

There is a close relationship among three functions of the body—total metabolism, the total amount of respiration, and the circulation of blood. When the body begins to exert itself, when a muscle contracts, it obtains energy by burning food. Food has become an enigma that is truly a riddle of our time; it has become a subject of great public interest. We are constantly being barraged by what to eat and what not to eat, as, for example, animal fat because of its association with arteriosclerosis. The term arteriosclerosis, as generally employed, embraces all changes in an artery (not caused by inflammation, as from infection) that affect the smoothness, thickness, uniformity, and elasticity of the tissue of the artery.

In relation to the subject of arteriosclerosis, an incident which happened in the early 1930's is of interest. The well-preserved mummies of a young pharaoh and his bride, both under the age of 30, were examined by a pathologist. The pathologist managed to obtain some beautifully preserved samples of the aorta and other arteries of both specimens, and found that, even though these people were herbivorous and had never eaten animal fat, both had had arteriosclerosis. I think this illustrates that we need to apply more of our "across the board" or interdisciplinary knowledge instead of trying to find one cause for a complex condition.

Those of us who are entrusted with justifying Government research to the Congress of the United States have a definite responsibility to know research requirements and prospective results in order to explain to Congress and the general public what those requirements are. From a few million dollars just a short time ago, the annual Federal budget for research and development has grown to about $16 billion today.

Most people from an engineering standpoint will draw a curve that continues to rise steeply, but this cannot continue. The Congress has taken a very dim view of such continuation. So we must utilize the existing dollars and our manpower capabilities to get optimum returns from this research. This is why I think this kind of conference will show the general public and Congress that we are bringing together biologists from the laboratory level to the engineering development man so that they will be aware of each other's interests and problems. There is such a thing as cost effectiveness for research, even though none of us could justify the research to be done today and profited from, say, 10 years from now.

EUGENE B. KONECCI

Nutrition-Waste Complex—A Pressing Problem in Manned Space Exploration

MICHAEL G. DEL DUCA
Chief, Biotechnology Branch
Office of Advanced Research and Technology, NASA

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Space nutrition and waste handling have in the past been treated in the same context—however, as separate problems. In early manned space flight, much attention was given to space feeding and nutrition, but the problem of waste handling was eliminated by eliminating elimination. With the advent of mission requirements up to 3 years and beyond, it becomes evident that nutrition and waste subsystems requirements will contribute appreciable weight and volume requirements to the total manned vehicle complex. At the present state of the art, for example, with mission times of 1 year, the weight requirement for nutrition and waste handling is equal to one-half the total required for meeting all of man's life support needs, including his thermal control. As we look beyond to 3- and 10-year missions, variables as aging and adaptation are introduced which further contribute to the penalties associated with nutrition and waste. It may be argued that boost capability may eliminate the necessity for sophisticated weight-savings approaches to meeting man's requirements. For long-duration multimanned missions, weights for waste and food are extremely large and will remain a pacing item in maintaining man in space for unlimited time. For example, a 10-man year mission utilizing conventional storage methods for providing nutrition, breathing gases, and storing all wastes could require on the order of 70 000 to 90 000 pounds, and volumes of approximately 1800 cubic feet. If we consider a 50-man year mission, which is not great, on the order of 300 000 to 350 000 pounds would be required for nutrition and waste, and volumes on the order of 9000 cubic feet.

Thus, any long-lived manned space system may well have to rely on the use of waste along with a high-energy-density energy source for the synthesis of required nutrients.

In addition, a 10-man year mission requires rejection of approximately 1×10^7 kcal of heat at relatively low temperatures. Reduced convection under reduced gravity conditions and the absence of an easily utilizable heat sink in space also contribute to the expenditure of more energy for the task of rejecting human thermal energy. The point here is that the problem of nutrition and waste in space is not solved. As a matter of fact, it is not even defined.

Of great importance to the definition and solution of this problem is the approach that we take during the planning phases. In the course of planning, space waste and nutrition should be treated as a complex which interfaces with all the other vehicle subsystems. The complexity of waste in low-leakage-rate long-duration sealed cabins for both space and undersea operations further suggests this approach.

A simple illustration is shown in figure 1. We may consider man as a chemical thermodynamic system which converts usable chemical energy in the form of usable nutrients to useful work. In this process, energy is degraded and results in the generation of chemical and thermal waste. In the closed sealed cabin the nu-

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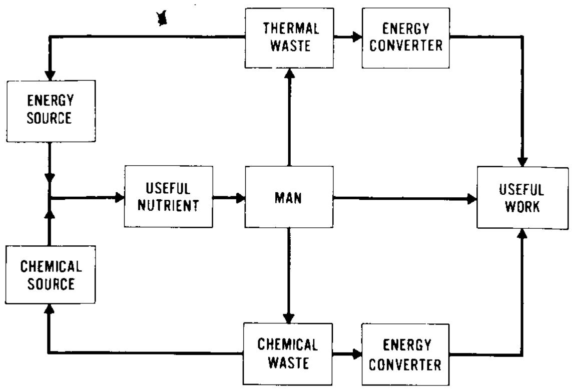

FIGURE 1.—Nutrient-waste complex.

trients must include oxygen for metabolism, foods, and water; the foods consist of fats, carbohydrates, proteins, and essential vitamins and minerals, and so forth.

The chemical wastes include the products of metabolism: gaseous products, such as carbon dioxide, and solids that consist of many forms of molecules from the very complex nonionic type, such as cellulose, to the inorganic ionic atoms, such as calcium and sodium. In addition, chemical wastes include water in different physical states, in the vapor state and the liquid state.

The thermal wastes associated with man are also in various states, and we have to consider these wastes in the latent and sensible form.

When we consider all these factors, we must also consider the fact that there are many ways to provide nutrition and control the waste in the manned space environment. The problem is in the selection of the right method, and this method must result in optimum systems weight, volume, power requirements, human efficiency, and utility at a specific time in a specific mission phase. All of these have to be considered in the selection of the right weight.

We might consider many approaches to the problem of nutrition and waste, but three representative approaches which suggest themselves include:

(1) Storage of all the required foods, water, and breathing gases and collection and storage of wastes.

(2) Storage of conventional nutrients and the use of thermal waste for either generation of power by appropriate thermoelectric converters or as a heat source for the conversion of chemical waste to more easily handled materials.

(3) The use of synthetic or natural nutrients which are generated from waste materials in a closed cycle. Chemical wastes may be used as raw material for generating simple inorganic molecules which can be processed to form complex nutrients. Thermal waste can be used as energy sources for these and numerous other life support processes. An alternate approach is the use of chemical wastes as fuels for the bioelectrochemical generation of electrical energy or for the generation of thermal energy, which, if utilized, may result in systems weight savings and thus permit the provision of conventional foods and other nutrients.

Each of these approaches must be specific to the task. Future studies will show that an entire spectrum of methods will be required for a particular long-duration mission. For example, in the establishment of a lunar or Mars colony, many functions must be considered requiring several methods for provision of nutrients in a controlled manner. Such a colony would conceptionally include a fixed permanent shelter, mobile emergency shelters, one-man operating protective systems for exploration phases and vehicles.

Each of these facilities must be considered in the total system, and also in the waste-nutrition complex. We have to remember, however, that the specific approach to meeting each of the requirements must be consistent with the fact that the total colony is still a vehicle payload, and the critical logistic factors must be considered in any methodology that we develop for the selection of a particular waste-nutrition system to meet the requirements.

For example, a partial loss of nutrients in long-duration manned missions would result in critical logistic problems, and we must give attention to such factors as the direct contamination of the nutrients by waste, or the indirect contamination of the nutrients by the generation of toxins which result from improper choice of nutrition for a specific mission profile.

Thus, critical factors in the selection of a particular waste-nutrition complex include the following:

(1) The toxicity of the materials used in the spacecraft structures, the containers, and the waste processing equipment.

(2) Considerations of the possible generation of toxins as a result of interactions between spacecraft materials at various temperatures and pressures with the normal atmospheric components, such as oxygen and nitrogen.

(3) Interactions must be considered between metabolic products, such as water vapor, carbon dioxide, and hydrogen sulfide, with chemical atmosphere purification equipment used in atmospheric conditioning or regeneration.

(4) Consideration of possible modes of origin of toxic materials from normally nontoxic reactants under stressful environmental conditions.

(5) Origin of toxic contaminants that may be generated in the interaction of the products of food reconstitution, waste conversion, and reclamation systems, including all types—physical, chemical, and biological. These systems include the water reclamation system, waste reactors, and gaseous conversion systems, including those for the generation of breathing oxygen.

In summary, it may be understated that much work remains to be done before extraterrestrial space becomes a new habitat for man.

Several areas require some immediate attention:

(1) Study of nutritional and waste handling methods for controlling the origin of toxic contaminants.

(2) Continued research and development of components and subsystems which can be used for the containment and conversion of wastes to nontoxic materials as usable constitutents in nutrition cycles.

(3) Establishment of standards for allowable concentrations of synthetic nutrients in varied gaseous and thermal atmospheres over extended periods of time.

(4) Study of instrumentation methods for the detection and analysis of toxic precursors or usable chemical precursors in various physical states.

(5) Study of advanced concepts in metabolism which may permit the nutrition and rejection of waste in a manner consistent with man's new environment, space.

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Nutrition and Related Studies in the Office of Advanced Research and Technology, NASA

Frank B. Voris
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and Technology, NASA

N65-18568

One of the missions of the Biotechnology and Human Research Division of NASA's Office of Advanced Research and Technology (OART) is the development of psychophysiological facts relative to man's response to environments, particularly to the stressful environment of space. A number of research tasks are being undertaken by NASA to study the effects on metabolic and physiologic functions resulting from various stresses which will be encountered in manned space flights. These studies are concerned with the atmospheric, nutritional, and metabolic requirements of the astronauts. In order to be aware of metabolic changes in the body, it is important to establish normal terrestrial baselines.

One important area of concern is that of water metabolism. At present, we have a study underway at Stanford Research Institute entitled "Gastrointestinal Tract and Water Metabolism," whose chief investigator is Dr. Calloway. The objective of this task is to develop and understand certain characteristics and functions of the intestinal tract with regard to water metabolism and overall body metabolism. The effect of diet and physical activity on water metabolism is being investigated. Information will be developed concerning intestinal epithelial desquamation, motility, and secretory function relative to diet, isolation and confinement, altered atmospheres, and body irradiation. Earlier studies have shown that exercise or diet can cause body dehydration despite a copious intake of water. Relatively slight dehydration can lead to rapid fatigue, loss of performance, and eventually death. It is therefore most important to understand the mechanisms by which water is absorbed and maintained in the body.

A task complementing this study is being conducted at Ames Research Center. The objective of this task, entitled "Human Water Metabolism in the Space Environment," is to investigate the effects of space environmental stresses such as heat, physical exercise, and atmospheric content on the water metabolism of the human with emphasis on the mechanisms of voluntary dehydration. This task will answer two questions: (1) Is some degree of dehydration beneficial to men performing under stress? (2) How long does it take a man to recover lost water and what physiological changes are involved?

Proceeding logically from our efforts in water metabolism, we must study the metabolism of the basic materials for maintaining life, namely carbohydrates, proteins, and fats. We have underway at Ames a task entitled "Metabolism, Temperature Regulation, Diet, and Performance of Man in Relationship to His Environment." This study will develop information pertinent to the understanding of carbohydrate, protein, and fat metabolism relative to stress tolerance in man and also information concerning dietary factors necessary to maintain optimum performance. One primary objective will be to determine if man can convert body fat into easily utilizable carbohydrate and therefore obtain optimum utilization of the body energy reserves. Procedures such as the feeding of special diets, food deprivation, and the use of certain drugs will be studied for their influence on metabolism and human tolerance under unusual stress conditions.

Many foods are being recommended for space diets on the basis of the principles of nutrition relative to life on earth. However, we do not know whether these recommendations are valid for the conditions of space environments. Factual data probably will not be obtained until actual experiments in space have been conducted. However, on the basis of carefully controlled metabolic experiments under selected simulated space flight conditions, it should be possible to make recommendations concerning space-flight diets with a high degree of confidence. In order to obtain this information, OART originally contracted and then transferred to the Manned Spacecraft Center a task with the Aerospace Medical Research Laboratories (AMRL), Wright-Patterson Air Force Base, for the "study of caloric, protein, and water requirements of young men subjected to simulated space stresses and the evaluation of foods planned for long term space flight." The objective of this task is initially to establish individual baselines and then utilize newly developed full pressure suits to (1) study the nutrient requirements of man subjected to simulated space stresses, (2) to make a nutritional evaluation of foods to be used in space missions, (3) to study the interrelationships of the intestinal microflora and diet.

The experiments to determine the optimum requirement for energy, protein, and water for young healthy males exposed to various stresses are being carried out on 16 subjects per year. Four to eight subjects are utilized at a time in the AMRL Space Vehicle Environment Simulator with and without space suits. Various types of diets are being utilized. Blood, feces, and urine are collected and analyzed. By this study, new and revolutionary space suit systems will be evaluated.

The subjects undergo a stabilization period of 1 week during which baseline data are recorded. This is followed immediately by a 3-week balance study. Careful control of activity is maintained on each subject. Following the balance studies, various stresses are imposed. Each subject is exposed to the various and combined stresses while wearing a pressure suit at various atmospheric states at pressures from sea level to 5 pounds per square inch. Other factors such as 200° F for several minutes are imposed to promote psychophysiological stresses at various intervals.

Individual balance studies are accomplished on each subject to determine optimum energy requirements. Studies are conducted on water, calcium, and sodium balance to determine optimum maintenance levels for the subjects. Ideal protein requirements are calculated on an individual basis. Baseline information is obtained concerning metabolic utilization of diets composed of common foods that have been prepared from predetermined levels of protein and caloric density needs of the individual subject. Urine catecholamine levels are used as an index of stress at suitable intervals. Blood lipid levels are measured twice weekly during each experimental period. The usual physiological measurements are recorded.

Although this project has been underway for some time, evaluation of the data has not yet been made.

As these studies indicate, we are conducting a reasonably intense research program in the various facets of metabolism related to water, protein, fats, and carbohydrates. In addition to these substances, we must know to what extent mineral and vitamin metabolism is affected by various types of stress. Jointly with the U.S. Air Force we support a study into the "effects of environment on absorption and metabolism of minerals" at the Johns Hopkins University under the direction of Dr. Bacon Chow.

The object of this study is to determine the effects of isolation, illumination, confinement, temperature, altered atmospheric pressures and gaseous percentages, noise, and other stresses on the cellular metabolic processes relative to Fe^{59}, Zn^{65}, and Mg^{28} absorption and metabolism. Preliminary studies will utilize rats as the experimental animals with primates being used later.

Iron was chosen because of its role in hematopoiesis, and magnesium and zinc for their roles in certain phosphorylation enzymes. Metabolic zinc deficiency has been reported to be responsible for certain types of dwarfism. This study apparently confirms this fact by showing that zinc deficiency also results in retardation of growth in rats.

Balance of the intestinal flora population influences the nutrition, health, and well being of humans. Many dietary and environmental conditions encountered by the host upset this balance in the microbiological flora of the intestines and have an effect on the health, nutrition, and performance capabilities of man. This fact is of vital concern in space flight.

In order to evaluate the effect of space conditions on the intestinal flora, it is necessary to know the character of the balance of intestinal flora of man in a normal environment. To date this information has been meager, especially in respect to the predominating anaerobic flora. We have underway a "study of the normal fecal bacterial flora in man." This study is being conducted by Republic Aviation Corporation under the direction of Dr. Lorraine Gall. For the first time a rather complete assay of intestinal microbiology will be available. Microbiological studies will be extended to space vehicle environments and to cross-contamination of crew members.

In addition to the studies previously mentioned having direct relation to metabolism and nutrition, we have "studies to determine the optimum space cabin environments" being conducted by the U.S. Air Force at the School of Aerospace Medicine, Brooks Air Force Base, Texas. This task will look into the effect of metabolism of 100 percent oxygen and of varying percentages of oxygen mixed with the so-called inert gases.

Other studies of a similar nature entitled "Atmospheric Conditions" and "The Toxicity Criteria for Gas Environments in Closed Ecological Systems" are being conducted at Ames Research Center. Details of these and the other studies noted in this presentation will be discussed in detail in subsequent papers.

From the foregoing, it can be seen that NASA is concerned about the fundamental metabolism and nutrition of man under the stress conditions of space flight. We have made a start, but we need aid and guidance in this tremendously important field. In order to fashion and execute a well-balanced research program, we look to those engaged in research in nutrition and related fields for additional information and professional advice.

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Nutritional Trends in Future Manned Space Flights

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N65 18569

Nutritional trends in manned space flights might best be discussed in terms of the recommendations relevant to food, water, and waste of the Space Medicine Advisory Group (SPAMAG) in their conceptual study of an orbiting research laboratory (ORL).

The SPAMAG is a working group of 19 consultants in medical and paramedical fields, each of whom is an outstanding contributor in his own speciality area. The Group was organized by the NASA Space Medicine Division, Office of Manned Space Flight, for the purpose of studying requirements for the ORL in order to lend support to other in-house and contractual ORL studies.

By way of providing a proper framework for this report, it would probably be worthwhile to spend a few minutes discussing the general method of approach employed by SPAMAG in this study.

Members of the Group are listed as follows:

John A. Buessler
Loren D. Carlson
Robert E. Forster
Edgar S. Gordon
Douglas Grahn
Ashton Graybiel
Milford D. Harris, Jr.
Andres I. Karstens
Edward C. Knoblock
Joseph F. Kubis
Edward A. Liske
Ross A. McFarland
Samuel Natelson
Herbert Pollack
Ralph Reitan
Scott H. Swisher
John C. Townsend
Sherman P. Vinograd
James V. Warren
G. Donald Whedon
Earl A. Wood

DOD/NASA coordination is effected by the attendance of Lt. Col. Milford D. Harris, Jr., and Dr. Edward A. Liske as DOD observers, and Col. Andres I. Karstens who is serving in the capacity of cochairman. Two-day meetings have been held at monthly intervals since the first meeting of the group in January 1964. Present estimates are that six or eight such meetings will be required to complete the study, after which the Group will meet three or four times a year in order to update its findings in the light of newer knowledge and further contemplation of the total problem.

The first morning of each 2-day session is devoted to briefings, chiefly by NASA personnel. These are designed to familiarize the Group with the unique constraints, problems, and developments of manned space flight. This is considered to be a highly important step toward significantly enhancing the value and applicability of recommendations made by the Group.

Prior to the first meeting, a 12-page format or working procedure was devised. This was adopted by the Group at the time of the first meeting. In general, the study falls into three categories or phases: The first is the establishment of recommendations concerning the constant environment, or life support factors which are to be supplied the flight crew. The second is a definition of the medical experiments and measurements to be done aboard the ORL. Most of these are centered about environmental factors, or stresses, which are experimental unknowns; almost all of them concern weightlessness and combined stresses. The third phase is devoted to recommendations for actual vehicular and operational requirements in terms of the medical support of the crew, and the desired medical experiments and measurements. In effect, this phase is the translation of the first two phases into operational and engineering terms.

It is anticipated that the end products of the entire study will be:

(1) Group of ORL medical experiments in format

(2) Group of additional ORL medical measurements in format

(3) Group of life support recommendations in format

(4) Group of prerequisite ground based experiments

(5) Group of prerequisite spaceflight experiments

(6) Group of recommendations for research and development

(7) General philosphy and recommendations for ORL experimental approach

(8) Recommendations for general ORL decisions

(9) Tentative flight plan

(10) Reviews of work of four study contracts and ORL BEWG

(11) Summary of possible uses of space environment for study and therapy of pathological states

(12) Recommendations for future study effort

It can be seen from the scope of these products that their review and implementation will be the work of all NASA life sciences groups, since they cover the full range from prerequisite basic research to manned space flight support engineering and operations.

With regard to the present status of this activity, the first phase has been completed, and work on phase 2 is now in progress. Phase 1, life supporting environment to be supplied the crew, may be broken down into its major component categories for study as follows:

(1) Atmosphere
(2) Suits
(3) Food
(4) Water
(5) Waste
(6) Living conditions and standards
(7) Group integrity
(8) Hazard protection
(9) Safety monitoring

The Group addressed itself to these areas by dividing into five subpanels, each assigned to specific categories. The metabolism, or food, water, and waste, subpanel, whose work will be discussed, consists of Dr. Edgar S. Gordon, Lt. Col. Edward C. Knoblock, Dr. Herbert Pollack, and Dr. G. Donald Whedon. As is true of all the subpanel reports at this stage, their report is a preliminary one based upon an initial, although painstaking, exploration of the problem. These recommendations will probably be augmented and perhaps even altered throughout the course of the three-phased study, but some of the initial recommendations of the subpanel as approved by the full group are as follows.

Dietary recommendations are that the diet be kept as simple as possible with emphasis on the maximum use of natural foods which will provide balanced nutritional components. The form of the diet preferred by the subpanel is either a liquid formula, or one which can be readily reconstituted to a semiliquid or liquid form.

In attempting to set up particular caloric requirements, one of the first things the Group had to decide was a reasonable schedule of activity. The following schedule was suggested: 8 hours for sleep, 2 hours for eating, 2 hours for exercise, 4 hours for rest and relaxation, and 8 hours for work.

The caloric requirements which the group considered reasonable for a 150-pound man in a shirt-sleeve environment are:

Activity	*cal/hr*	*Btu/hr*
Sleep	70	280
Eating	1.5×Basal	420
Exercise	2.5×Basal	700
Rest and relaxation	1.5×Basal	420
Work Program:		
Flight control	2×Basal	560
Reconnaissance	2–2.5×Basal	560–700
Scientific observation	1.5–2.5×Basal	420–700
Repair	2–4×Basal	560–1120

Suited environment (unpressurized): Add increase factors in percent as follows:

Sleep	+10
Eating	+50
Exercise	+50
Rest and relaxation	+50
Work	+50

For extravehicular work, a maximum of 2000 Btu per hour may be required. This is not tolerated for periods in excess of 1 hour. A steady state of activity is reached at approximately 500 calories or 2000 Btu per hour. Then oxygen debt develops. This maximum requirement should therefore be avoided except under emergency conditions.

Further recommendations are that natural foods of low fiber and low in laxative properties should be utilized and that no adjustment of bacterial flora of the intestinal tract should be attempted. A liquid or reconstituted diet utilizing coded cubes which are preweighed would facilitate the precision of recording food intake for purposes of balance studies. In addition, an oral exercise medium such as a gum or other suitable device is suggested for purposes of oral hygiene.

As to the composition of the diet, the following recommendations are made:

High quality protein, percent	12.5
Carbohydrate, percent	52.5 to 57.5
Fat, percent	30 to 35

This ratio would be used to provide 2700 to 3200 calories per day with a respiratory quotient of 0.8 to maintain a carbon dioxide to oxygen ratio which would spare the carbon dioxide scrubbing requirements of the environmental control system.

Anticipated metabolic degradation relates to muscle atrophy and bone changes which may result in calcium loss. Special attention should be paid to providing a balance of high-quality protein and adequate calcium in the diet. The ratio of polyunsaturated to saturated fat in the diet will be dependent upon the conditions of preservation of diet during the flight program and the method chosen for reconstitution of the diet for feeding in space.

Recommendations concerning mineral and vitamin requirements are as follows:

Calcium—0.8 gram per day.

Phosphate—1.2 to 1.5 grams per day.

Sodium as NaCl for individuals who are acclimatized to the environment—4.5 to 5 grams per day.

Sodium for those not acclimatized, add 1 gram as NaCl for each liter of water consumed per day over 4 liters. This figure is tentative and the suggestion is made that in view of the possibility of adrenal stress, the potential use of 10–15 grams of sodium chloride per day be considered with corresponding reduction of potassium to approximately one gram per day, which might serve as a protective device for the adrenal glands. Accordingly, the water intake may need to be increased to 4 liters or more per day. This would also be useful for maintenance of heat balance.

Vitamin D—1000 units per day.

Other vitamins—the use of a standard minimum daily requirement type of polyvitamin preparation daily is advocated, but in no greater quantity than the minimum daily requirement as recommended by the NAS–NRC. (Nat. Acad. of Science—Nat. Res. Coun.)

Minerals—trace mineral supplements are strongly advocated if the food used is processed by chelation. This is one of the strong reasons for the recommendation for the maximum use of natural foods.

Water—2.5 liters per day (one cc per calorie of food). Water intake should be sufficient to maintain the urine at a specific gravity of 1.015 or less or a volume of at least one to one and a half liters per day to avoid the development of renal stones; urine should be maintained at a normal pH range.

With reference to water supplies, because of power, weight, and volume requirements, recycling of water is not considered practical for flights of less than 30 days duration, but should be considered for flights in excess of that period of time. Water sources for reclaiming include metabolic water and that produced by the fuel cells. The recycling of urine is considered to be costly in both energy and volume-weight requirements. Ion exchange or millipore filters appear to be simple devices for reclaiming metabolic and fuel cell water and converting it to a potable supply. Metabolic water can easily be reclaimed for hygienic use.

With reference to urine and fecal waste, the following recommendations are made. On each voiding, the total volume must be accurately recorded and an aliquot separated for study. Aliquots according to aeromedical requirements can probably be stored in the walls of the cabin to provide additional radiation shielding until they are returned for analysis. Cryogenic preservation is recommended.

To reduce the quantity of fecal material, a low residue diet is recommended. Samples should be collected, adequately identified, and stored in sealed containers for analysis as with the urine. Desiccation and cryogenic storage, utilizing the conditions of space, might well be employed to facilitate this program. It should be borne in mind with reference to the storage of feces that drying without either freezing or sterilization may well introduce the danger of bacterial contamination of the atmosphere.

From the standpoint of metabolic considerations, medical selection for the ORL program should attempt to rule out those who have a tendency toward nephrolithiasis. It is also important to record any food intolerances and idiosyncrasies of flight crew candidates.

The subpanel's recommendations for research and development include the following:

(1) A study of the nutritional acceptability and palatability of such foods as algae, and a reconstituted liquid or semiliquid diet of natural products for extended periods. With this is recommended an investigation of the possibility of extending a natural diet by means of a concentrated, high-density synthetic diet which can be fed periodically and interspersed at intervals during the flight program.

(2) Studies to determine the possible occurrence of ill effects from prolonged maintenance on a very low residue diet. As a part of this study, the exact weight and volume of fecal material produced, for a given diet, should be determined.

(3) Continued work in the field of food packaging to enable the accurate measurement of intake of food constitutents.

(4) Continued development of improved urine and fecal collection devices.

(5) Further research and development on the recycling of water, with purification to acceptable standards of potability.

(6) Further research and development on the conversion of waste materials to carbon dioxide and water by means of free radical oxygen digestion (using a stream of oxygen through a very high frequency radio beam). The conversion of the carbon dioxide to carbon and oxygen also requires further research.

Recommendations for ground based experiments, and flight crew training preflight are as follows:

(1) The study of calcium metabolism at various phases of training under various conditions preflight to establish baseline levels for each potential astronaut.

(2) The provision of extensive training in the handling of special diets during the flight training program.

(3) A study of the effects of centrifuge simulation of the flight launch profile on the antidiuretic hormone (ADH) activity to provide parameters for comparison with both 1 g and zero g determinations.

(4) The preconditioning of the ORL crew members to a low caloric intake is recommended, and their body fat stores should be normalized prior to flight. Metabolic studies to determine the caloric cost of activity should also be done.

Recommendations for space-flight experiments prior to the ORL are as follows:

(1) To fly an animal metabolic cage to determine the effect of weightlessness on metabolism, by means of oxygen consumption and carbon dioxide output determinations, on H_2O balance, and on calcium balance. The effects of weightlessness on peristalsis and on muscle deterioration are also in need of exploration by means of animal flights.

(2) The determination of ADH activity during manned space flights by means of urinary assays. This determination relates not only to fluid requirements, per se, under weightless conditions, but also to blood volume and cardiovascular effects of weightless flight.

In conclusion, it should be mentioned that the industry and the enthusiasm displayed by these busy SPAMAG members in applying their well demonstrated abilities to the problems of our national space effort, are deserving of special note and high praise. Their work has been most laudably representative of the best traditions of the American scientific community.

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Nutrition and Related Studies in the Office of Space Science and Applications, NASA

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N65 18570

The Bioscience Programs Division of the Office of Space Science and Applications, NASA, sponsors basic research in areas having a potential for application or development of systems for use in the space program.

BIOREGENERATIVE LIFE SUPPORT SYSTEMS

Bioregenerative life support systems will be required in future extended manned scientific missions in space. Storage-type systems would impose penalties in weight and space that would not be feasible for voyages lasting months or years.

Looking to the future, the Office of Space Science and Applications has supported limited biological research on gas exchangers involving both photosynthetic and nonphotosynthetic systems and on bioregenerative management of wastes, including water.

A scientific breakthrough has occurred in the development of a biological regenerative system by the Martin Marietta Company. In this system the electrolysis of water (splitting water into hydrogen and oxygen by electricity) is used with *Hydrogenomonas* (soil bacteria) shown in figure 1, which combines the hydrogen with the carbon of carbon dioxide from the astronaut. (See fig. 2.) This method requires, on a batch basis, only 10 percent of the electric power and from 10 to 20 percent of the volume and weight of the best thermophilic algal (*Chlorella*) gas exchanger system. Optimal concentrations of oxygen and nitrogen, tem-

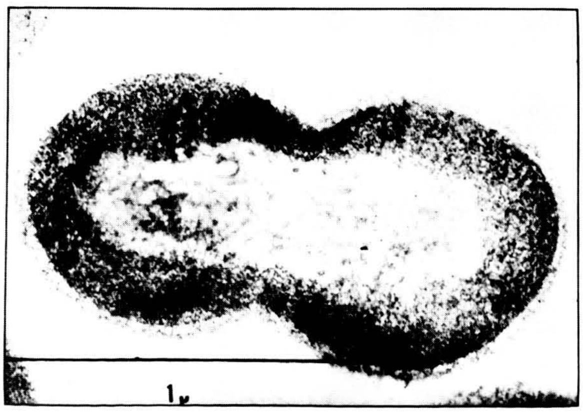

FIGURE 1.—Electron microscope picture of *hydrogenomonas* bacteria.

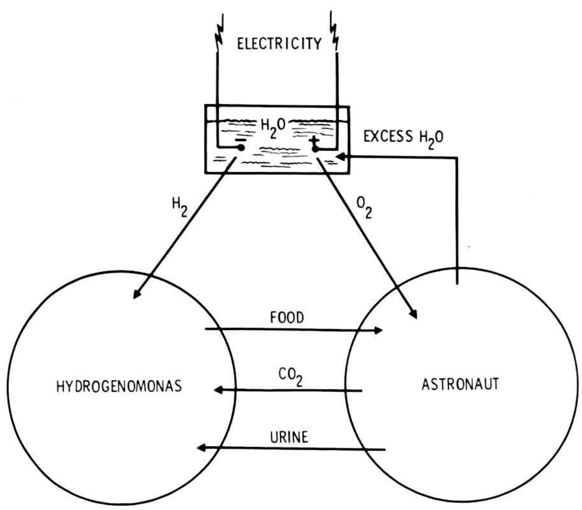

FIGURE 2.—Electrolysis *hydrogenomonas* bacterial bioregenerative system.

perature, and other growth conditions have been established. Special studies were carried out on formation of fat inclusions in the bacteria due to gas limitations.

A continuous culture turbidostat apparatus has been designed and built by the Battelle Memorial Institute. The electrolysis unit feeds hydrogen alternately with oxygen into the bacterial substrate. The system is nearly all automatic but is flexible to allow experimentation.

Mississippi State University is studying the long-term culture methods and possible accumulation of toxic materials. The Magna Corporation is carrying out research on utilization of urine in culture medium.

The rate of progress has been rapid, and the culture methods used for other bacteria in mass culture have been utilized. The electrolysis system developed for other programs has been used effectively. The main problems include change from autotrophic to heterotrophic growth and the presence of a phage which attacks the *Hydrogenomonas* bacteria. These problems are being studied intensively. Quantities of the bacteria are being fed to animals and human volunteers.

At Colorado State University the responses of plants to high-energy radiation (ultraviolet to infrared) are being studied. Plants from high mountain tops normally exposed to higher intensities of ultraviolet light and the effect of temperature on photosynthesis are being studied. Corn, beans, and tomato plants are being grown under germ-free conditions.

Screening of various higher plants for use in bioregenerative systems at Connecticut Agriculture Experiment Station resulted in selection of corn, sugar cane, and sunflower for possible use in bioregenerative systems. Optimal conditions have been established and the amount of leaf surface required to support an astronaut has been shown to be from 100 to 130 square feet of leaf surface.

A recyclostat has been developed, under a NASA grant, by the University of Maryland for continuous culture of *Chlorella* algae. This apparatus is completely automatic and conserves and recycles all water, adds nutrient, and removes excess algal cells. This grant is primarily responsible for basic physiological studies on algae and for determination of optimum algal growth conditions.

The photosynthetic process in plants is being studied intensively by the Research Institute for Advanced Studies of the Martin Company. The respiration process has been studied during photosynthesis and several metabolic pathways have been elucidated. Mechanisms are being studied to explain the inhibitory effects of strong visible light on this process. This program may lead to the use of chloroplasts or chlorophyll without cells in future photosynthetic bioregenerative systems for long-term space travel.

REDUCTION OF METABOLISM

A research program in the Office of Space Science and Applications is being undertaken as a long-range objective for reduction of metabolism in astronauts for long-term manned space flight, such as a Mars mission in the 1980's. The reduction of human metabolic rate may be accomplished by reduction of temperature or artificial hibernation, response to hot dry conditions or artificial aestivation, and depression of metabolism by various pharmaceutical drugs. Reduction of metabolism would result in lowered requirements for food, water, and oxygen, and would produce less carbon dioxide, urine, and waste. It is assumed that the astronaut could be aroused following a long flight and would be active during planetary landing and exploration.

The present state of the art with regard to lowered temperature to produce lowered metabolism is not well advanced. While some human beings have been exposed or subjected to decreased temperature for relatively short periods without serious problems, no long-term sleep or hibernation has been induced. A major problem encountered with humans and primates when subjected to severe cold is ventricular fibrillation, which may result in death. Much research is required to understand this well enough to develop potential use of induced hibernation.

Even less is known of the mechanisms involved in aestivation.

NASA presently supports a modest research program of hypothermia, hibernation, and aestivation with the objective of inducing decreased metabolism in humans.

LOSS OF SKELETAL CALCIUM

When man lives under weightlessness conditions, loss of muscle tone and mass, as well as loss of calcium from the skeleton, is expected. During periods of bed rest, patients lose rather large quantities of bone mineral.

A bone X-ray densitometry method (fig. 3) has been developed by Texas Woman's University for accurately determining the loss of bone mineral (±2 percent accuracy) in humans and animals. The heel bone and spine are X-rayed using a calibrated aluminum wedge for a baseline comparison. It has been recommended that the bone X-ray densitometry method be used on astronauts before and after flights in the Gemini and Apollo programs.

Bed rest and immobilization studies at Texas Woman's University have shown loss of skeletal mineral and increased loss of calcium in the urine and excreta. Four bed-rest studies, each

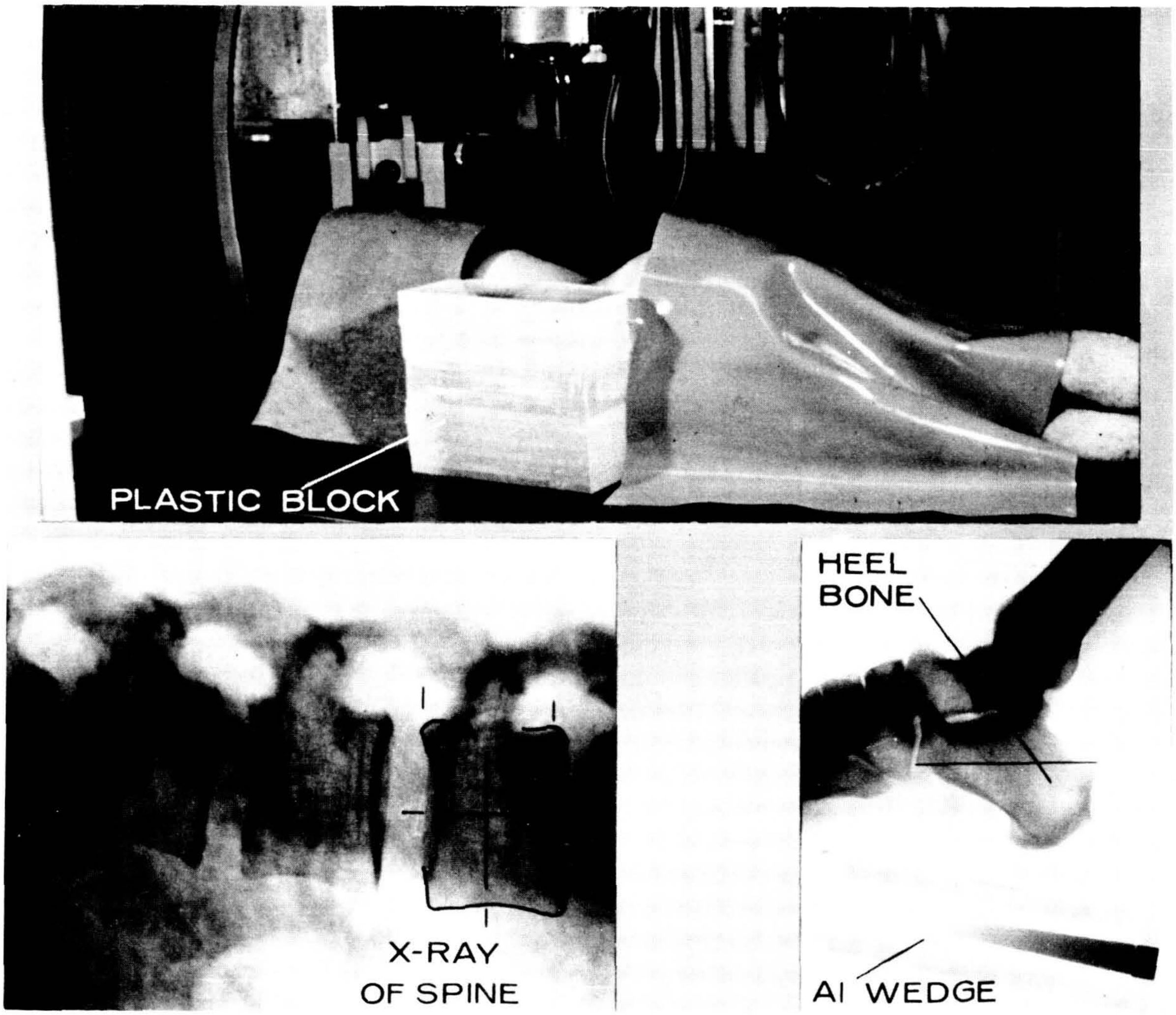

FIGURE 3.—Bone X-ray densitometry studies relating to calcium loss with weightlessness.

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extending for 2 weeks, were carried out comparing different levels of calcium intake. Four men were used in each study and the men served as their own controls during extended ambulatory periods. During 2-week periods, up to 10 percent of calcium mineral was lost from the heel bone (fig. 4). The calcium loss was also determined in the urine and feces. In other studies, isometric exercises have helped prevent some loss during bed rest.

Studies are planned at the Harvard School of Public Health to determine the results of feeding fluorine to animals, preliminary to feeding human volunteers during bed rest simulating weightlessness. It is possible that fluorine may prevent the loss of calcium or decrease the rate of loss.

CHEMICALLY DEFINED SYNTHETIC DIET

A chemically defined synthetic diet for humans has been compounded by Dr. Milton Winitz, formerly with the Medical Sciences Research Foundation. The complete liquid diet is composed of required amino acids, fat, carbohydrate, vitamins, and minerals. A cubic foot of the diet (in 50 percent H_2O) supplies 2500 calories per day for 1 month, and has been flavored with a variety of artificial flavors.

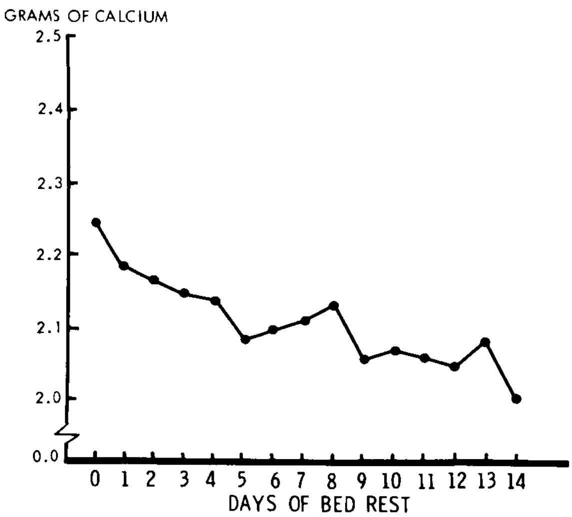

FIGURE 4.—Loss of skeletal calcium from heel bone during bed rest.

The synthetic diet has been fed in a pilot study to human volunteers at the California Medical Facility by the Medical Sciences Research Foundation for a 6-month period, and the results are now being reviewed. The feeding has been completed but analyses of specimens and data interpretation must be completed before determination of what future research is required. It is expected that the Space Science Board, Life Sciences Committee, will be consulted in this connection.

Schwarz Bioresearch, Inc., is carrying out studies on the storage, stability, and packaging of chemically defined synthetic diets for human and animal flights.

STUDIES WITH ARTIFICIAL ATMOSPHERES

Animal growth and development have been studied in atmospheres almost devoid of nitrogen, atmospheres composed of oxygen under a reduced pressure, or of helium and oxygen mixtures at 1 atmosphere. These studies at Ohio State University indicated a deleterious effect of low nitrogen which may mean that nitrogen is necessary for normal adult life.

Continuous exposure of rats at Oklahoma City University to 100 percent oxygen for 25 days at a simulated altitude of 26 000 feet resulted in a 10-percent decrease in total metabolism. Using the radioisotope carbon technique, there was a significant reduction of lipid metabolism in the liver, but no decrease in heart metabolism. Exposure to 80-percent argon and 20-percent nitrogen at sea-level air pressure resulted in slight slowing of metabolism with an increase of two to three times in the amount of fat deposition.

Studies on the ability of test-subject men to exercise at levels beyond which they are able to supply oxygen are being carried out at Indiana University. Men on a treadmill accumulated an oxygen debt in 3 minutes and could continue 8 minutes; however, in this study the debt did not continue for 15 to 40 minutes after stopping exercise as reported in another laboratory. Arterial and venous blood was sampled continuously during exercise by use of catheters.

EFFECTS OF SPACE ENVIRONMENTAL FACTORS

Research in the Bioscience Programs Office includes basic biological studies to determine the effects of space environmental factors on living organisms, and basic research related to manned space flight.

A Biosatellite Program is being carried out to study the effects of unique space environmental factors. The Biosatellite spacecraft will be recoverable, and the first of a series of six flights will be in mid-1966.

Twenty experiments have been selected for flight from 175 submitted by the scientific community to study the effects of weightlessness and decreased gravity at the cellular, organ, and organism levels from 3- to 30-day orbital periods. The experiments include a wide variety of plants and animals from single-celled organisms to higher plant and animals, including primates.

Experiments have been selected to study the effects of weightlessness combined with a known source of radiation to determine if there are any antagonistic or synergistic genetic or somatic effects on various organisms. Experiments are included to study the effects of the unique environment of the Earth-orbiting satellite and removal from the Earth's rotation in relation to biological rhythms of plants and animals. Various animals will be fed different diets and the effects of space flight factors on digestion and metabolism will be assessed.

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Overview of United States Army Medical Service Research in Nutrition

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Within the United States Army structure regarding nutrition, it is the overall responsibility of the Army Materiel Command to provide adequate rations to troops throughout the world. The responsibilities of the Surgeon General are to evaluate the nutritional adequacy of rations, the wholesomeness of foods provided, and to study the relationships of diet to the nutritional status and performance of the soldiers. The Army Medical Service Research and Development Command assists the Surgeon General in this latter function by carrying out nutritional surveys and research programs in diet and overall nutrition. Surveys of the actual diet consumed by troops have been performed, and assistance to Interdepartmental Committee on Nutrition for National Defense has been provided. These provide information on which both the Surgeon General and the Army Materiel Command can judge the actual utilization of food and military rations. Other programs relating to diet and food intake relate to the wholesomeness of irradiated food, the development of an intravenous alimentation, the nutritional adequacy of algae and of cellulose, as well as evaluation of the presence of trace elements and vitamins in the diet as actually consumed. Research programs relating to energy metabolism and performance include studies in body composition; the loss of nutrients in sweat; the relationship of protein requirements to stress, infection, and work; and the effect of varying periodicity of food consumption.

The purpose of this presentation is to indicate general areas of Army Medical Service interest in nutrition and to denote that programs and technical competence exist within the Army Medical Service Research and Development Command which may be of interest or of assistance to researchers in this field.

The Army Medical Service has as its mission the conservation of the fighting strength of the Army. To accomplish this mission, the Medical Service must provide for the prevention and treatment of disease and of injury among its forces. In peacetime, medical care for the soldier differs little from that for the civilian; but in preparation for combat or in actual combat, there may be significant differences in the requirements for prevention, diagnosis, and treatment of casualties. These differences arise from the fact that the soldier must be prepared to be sent into areas of the world where exotic infectious diseases exist and where the climate or the altitude are different from those to which he has been accustomed. Under these foreign conditions, he will be subjected to the multiple stresses of combat. He will live, eat, fight, contract disease, sustain wounds—and sometimes die—outdoors.

The program of the United States Army Medical Research and Development Command is oriented, therefore, toward the identification and solution of problems arising from these differences. It is evident that a large part of this research program must be devoted to development of methods for the prevention and treatment of military casualties due to disease and injuries sustained in combat areas. In addition, however, there is a responsibility for the development of information on methods for protecting the soldier against a serious decrement of performance due to exposure to factors such as cold, heat, high mountain altitudes, sleeplessness, reversal of his circadian rhythm, noise and vibration, or emotional stresses. Many or most of these exposures might arise in a rapid move of the soldier by modern jet airlift to a far-off battlefield. Thus, the Army Medical Service Research and Development program must include many studies on the normal performance of the healthy soldier and on methods to sustain this performance.

Against this broad general background, it is apparent that there will be some differences between the Army's research program in nutrition and that within the civilian community or the program oriented toward the special needs of man in prolonged space flight. The actual differences, however, are not really great since the basic elements of food, man, and stress are common to all nutritional programs, as is technology.

A brief summary of the Army Medical Service research program in nutrition may give an idea of our approach, our methods, and our goals. At the outset, I should like to point out that problems relating to procurement, packaging, storing, distribution, preparation, and acceptability of foods are the responsibility of the Army Materiel Command, and that research in these areas is performed by the Quartermaster Food and Container Institute of the Armed Forces.

The nutritional research program of the Army Medical Service is carried out principally at the United States Army Medical Research and Nutrition Laboratory in Denver, Colorado. Supplementary to this in-service program is a grant and contract program, primarily performed at universities in this country.

The Army Medical Service program may be considered in two general categories—in which there is obviously some overlapping: (1) Foods and intake; and, (2) Nutritional requirements. Included in the first category are nutritional surveys. Careful studies of the actual amounts and types of food consumed by troops in garrison and in the field have provided data necessary for proper evaluation of the Army diet. In addition, members of the Medical Research and Development Command have participated in surveys performed by the Interdepartmental Committee on Nutrition for National Defense in approximately 20 countries, including Burma, Jordan, Uruguay, Chile, Lebanon, Thailand, Taiwan, Malaysia, and Brazil. The results of these surveys are well known and have been of great value in assessing the nutritional status of civilian and military populations in many areas of the world.

For the past several years, an extensive program has been carried out by the Army Medical Service on the wholesomeness of high-dose irradiated foods. Long-term animal feeding studies and short-term human toxicity studies have been included in evaluations of approximately two dozen food items. Canned irradiated bacon has been cleared for general consumption by the Food and Drug Administration, and numerous other foods are in the process of evaluation at this time.

Because of the need for higher caloric intravenous fluids, a program to develop fat emulsions suitable for use by this route has been underway for many years. Several emulsions have been prepared and tested, and work is now in progress to develop an intravenous alimentation which will supply adequate amounts of calories as fat, protein, and carbohydrate.

Although not a major area of emphasis for the Army's research in nutrition, the search for newer foodstuffs has been a part of the program. Feeding of microcrystalline cellulose to man has demonstrated a significant amount of digestibility of this material. The ultization of breakdown products has not been established. Also under investigation is the nutritional potentiality of algae. Methods to improve digestibility and analyses of the nutrient content of various algae are being continued.

The second general area of our research may be considered to cover broadly the fields of nutritional requirements under varying circumstances and nutritional aspects of metabolic needs relating to disease, trauma, and acclimatization.

Teams from the United States Army Medical Research and Nutrition Laboratory have measured the caloric needs relating to work performed in hot environments and have shown that as ambient temperatures increase, there is a corresponding increase in energy requirements. Similar studies have just been completed at mountain altitudes (14 000 feet). Data from these and similar studies provide a rational basis for estimation of caloric needs and for study of the potential value of specific nutrients. In the same category, measurements of optimum water, vitamin, and mineral requirements can provide basic data for further investigations into special needs for special conditions. The intimate relationships between diet and metabolic changes which occur during work, in acclimatization, in disease, emotional stresses, injury, and wound healing have led to a series of studies designed to investigate the metabolic correlates of these and similar conditions in our program in nutrition.

The losses of nitrogen and minerals in sweat have been evaluated in order to include these data in metabolic balance studies. Also, improved methods for measurement of body composition are being developed. The role of periodicity on metabolic function in man is under review to provide information which may be pertinent to special situations of dietary intake.

In the contract program, detailed investigations are being performed on the effects of stresses such as anxiety, sleep loss, minor pathological processes, infection, and work load on essential nutrient requirements in normal man. Other studies are being done on the relationships of nutritional ketosis to "cold ketosis" which are of interest in the programs of acclimatization of man to cold environments. Protein deprivation and the overall effects of protein malnutrition are being evaluated to determine the metabolic processes by which animals adapt to these nutritional changes.

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U.S. Air Force Program on Aerospace Nutrition Research

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The U.S. Air Force conducts a program in research in nutrition intended to meet the requirements peculiar to the Air Force in systems development, acquisition, and operation. These specific requirements occur in the fields of:

(1) Aerospace flight
(2) Unusual operational environments (e.g., arctic)
(3) Survival and emergency conditions

The USAF nutrition research program is concentrated in the Aerospace Medical Division of the Air Force Systems Command. Three of the laboratories in that Division have activity in nutrition research:

(1) School of Aerospace Medicine (SAM)
(2) Arctic Aeromedical Laboratory (AAL)
(3) Aerospace Medical Research Laboratories (AMRL)

In addition to the exploratory development conducted in these laboratories, more basic research, supported by funds from the USAF Office of Aerospace Research, is monitored. The level of effort is quite modest and includes the participation of a total of about 20 people (not man-years) in the in-house activities and slightly less than 400 000 dollars annually in support of contractual studies.

The following information includes all tasks which are presented in four rather arbitrarily divided categories:

(1) Survival situations
(2) Special environments
(3) Metabolism
(4) Aerospace diet

NUTRITION IN SURVIVAL SITUATIONS

High Fat Diets—AAL—In-house

Objective.—To provide the Air Force with concrete, experimentally obtained information regarding the use of high fat diets for subsistence during relatively long periods of time. Use of these diets, if feasible, would save weight and volume required for food in certain flight systems, in overland high altitude and arctic operations, and in emergency situations involving extensive supply drops.

Current status.—Studies concern biochemical alterations resulting from feeding high fat diets for some time. In animals, certain metabolic pathways, especially carbohydrate shunt systems, almost completely shut down when dietary fat is raised to only 25 percent by weight, which is comparable to the average content of the American diet. Reactivation of these systems, however, is often accomplished by feeding only one content of a high carbohydrate meal. Cold exposure has little effect when superimposed on "high fat" diets. In humans, we have observed that formula diets containing as much as 60 percent of calories as fat do *not* cause ketosis or hypercholesteremia when fed for 2 weeks at a 3500-kcal/day level to healthy men.

Future plans.—Fat deserves more study as a calorie source in space nutrition. Corn oil, for example, could be used to beef up formula diets and (as has been found) make them more palatable. Plans for future experiments are somewhat limited as far as human nutrition is concerned, since facilities are not available for well-controlled long-term studies, but it is planned to study human responses to formula diets containing large amounts of corn oil over periods as long as 3 months. In addition, fundamental studies on metabolic alterations arising from high fat intake will be continued.

Human Performance in Survival—AAL—Contract

Objective.—To provide the Air Force with information which will enable aircrew survivors to cope with the initial physiological and psychological shocks of survival in the arctic without food, shelter, or companionship.

Current status.—Dr. Rogers (University of Hawaii) has carried out three winter field studies in which he has investigated electrolyte supplementation as a method for reducing body fluid losses when men are forced to starve under realistic arctic survival circumstances. He has found that either sodium chloride or sodium bicarbonate given daily do reduce these losses. This winter he extended his studies to investigate starvation episodes as long as 7 days as compared with caloric intakes of 500 kcal/day obtained from sucrose or pemmican with essentially the same results as found in the shorter experiments. In addition to these studies, he measured the caloric cost of skiing and snowshoeing across various terrains typical of the subarctic; he was especially concerned with comparing skilled and unskilled subjects.

Future plans.—The basic objective of this project is to determine the physiological parameters of syncope in survivors and from this to devise methods for avoiding syncope, a condition which may well have the most ominous rseults for the survivor. Dr. Rogers believes that dehydration, with its attendant concentration of blood, which may lead to circulation failure, is one of the most important physiological factors involved in syncope. Future investigations should be aimed toward determining whether this hypothesis is true and, if so, whether fluid-saving procedures can make the difference between syncope and no syncope. Dr. Rogers also plans to investigate feeding procedures during survival. This is important because of the often contradictory instructions given to potential survivors. Whether to spread the available ration over a projected period of isolation, whether to starve the first day (which has been advised by some), or whether to eat the bulk of the ration the first day are three alternatives. It might be better for the survivor to eat most of his food the first day, for it is then that he is necessarily most active and shocked, and superimposing starvation on his organism might easily tip the scales toward syncope. After he has built a shelter and made his signals, it may be less dangerous for him to experience starvation dehydration. Dr. Rogers also plans to investigate further the energy requirements of cross country travel in the arctic.

Stress of Refeeding Following Starvation—AAL—Contract

Objective.—To provide the Air Force with information and make recommendations for the proper feeding of victims of starvation or undernutrition.

Current status.—Active. Dr. Johnson (University of Illinois) has carried out several long-term studies of the effects of severe starvation-refeeding episodes in pigs. He has found that if pigs were allowed to gorge themselves on glucose following complete starvation for 30 days, they went into apparent shock. A balanced diet had less effect and corn oil no effect, possibly because the pigs did not eat as much as with glucose. Several starvation-refeeding episodes resulted in labile hypertension and autopsies showed permanent cardiovascular damage. Experiments with rats undergoing the same type of starvation-refeeding showed that supernormal lipogenesis occurred during refeeding glucose. He and his colleagues think that this supernormal lipogenesis may cause extensive lipid accumulation in the vascular system, and thus be a clue to cardiovascular failure during refeeding.

Future plans.—Dr. Johnson plans to continue these studies, both on pigs and on rats. In rats, investigation of the metabolic or hormonal defect responsible for the observed block in carbohydrate utilization following starvation would perhaps provide a clue to the reactions of the pig. The problem of permanent cardiovascular damage arising from starvation-refeeding episodes and methods of preventing it continues to interest Dr. Johnson and his colleagues.

NUTRITION IN SPECIAL ENVIRONMENTS

Amino Acid Metabolism During Stress—AAL—In-house

Objective.—To provide the Air Force with information concerning the effect of various stresses, especially cold and heavy work, on the dietary requirements for protein in general, and various specific amino acids in particular. Investigation of these interactions should make possible more realistic recommendations for the formulation of diets for specialized operations.

Current status.—Several experiments have been made with animals which have some definite bearing on human nutrition, especially during stresses which raise the general metabolic turnover. It is generally known that diets containing imbalanced amino acid mixtures (due to a functional excess or deficiency of one or more essential amino acids) cause growth failure in rats. This growth failure appears to be almost entirely due to appetite failure. To put these two facts together, several experiments have been carried out in which imbalanced diets were fed to cold-exposed rats. In many cases, depending on the type of amino acid imbalance, the cold-exposed animals were able to overcome the appetite depression caused by the imbalance, and when they did, were able to grow in the cold room, in contrast to their behavior at temperate warmth. This was interpreted to mean that if appetite were stimulated by external coolness, these animals were able to "balance" the imbalanced diet, possibly by burning off the imbalancing amino acid. This hypothesis was later verified by using radioactive amino acids.

Future plans.—It is planned to apply these ideas to human nutrition. Humans, unlike rats, regulate their food intake by mechanisms unrelated to nutritional adequacy. Thus, the rather elaborate edifice of amino acid "balance" which has been built by some investigators may have little relevance to human nutrition. It is proposed to study amino acid balances in humans by applying some of the modern techniques of amino acid measurements in serum—in particular, using the varying patterns of sequential changes after specific meals as criteria of amino acid utilization. This technique may be more sensitive than nitrogen balances, which, unfortunately measure only gross long-term changes. If some standard values can be established, it would then be possible to study many interactions, for example, effect of acute cold stress on utilization of various protein or amino acid mixtures, utilization of unusual protein sources, and interactions of other nutrients on protein metabolism, to mention a few.

Nutritional Balance Under Reduced Dynamic Stress—AMRL—Contract

Objective.—To determine the most suitable dietary distribution of carbohydrate, protein, fat, other nutrients, and certain physiological variables, such as exercise, as affected by frequency of feeding and postural changes for the optimal maintenance of the biochemical and physiological efficiency of man in space during prolonged periods of inactivity.

Current status.—Dr. Rodahl (Lankenau Hospital) has provided baseline information concerning the type, time of onset, degree, and duration of several metabolic and physiological alterations in human subjects during 6 weeks of complete bed rest. This research has demonstrated that young healthy men confined to the recumbent position exhibited a marked deterioration of physical work capacity, a decreased tilt table tolerance, and an increased urinary calcium excretion. The deterioration of physical work capacity resulting from prolonged inactivity can be corrected by exercising for 1 hour a day at 600 kilopond-meters while otherwise maintaining the recumbent position. The decreased tilt table tolerance resulting from prolonged inactivity can be prevented by sitting in a wheel chair for 8 hours per day and remaining recumbent the rest of the 24-hour period. Research now in progress is providing additional information concerning the type, time of onset, degree, and duration of metabolic and physiological alterations which can be expected to occur when well-fed physically fit men are subjected to prolonged periods of stress resulting from inactivity and an elucidation of dietary and physiological training modifications and mechanisms which could be utilized to ameliorate the observed response.

Future plans.—Research will be undertaken to provide further insight into the effect of frequency of feeding, exercise, and postural changes on nutritional and physiological balance under reduced dynamic stress. Lankenau Hospital has provided baseline information concerning the type, time of onset, degree, and duration of several metabolic and physiological alterations in human subjects during prolonged bed rest. Further, Lankenau Hospital has independently established procedures to prevent the deterioration in work capacity and orthostatic tolerance; under future contract it will establish procedures to prevent the increased nitrogen and calcium excretion which results from prolonged bed rest. Future studies will simultaneously evaluate the preventive measures to ameliorate the deleterious effects resulting from prolonged bed rest.

Effect of Space Flight (Simulated) on Ca–P Metabolism—AMRL—Contract

Objective.—To determine the mechanism causing increased mobilization and excretion of calcium and phosphorous in response to simulated space flight stress.

Current status.—The stresses expected in long-term aerospace flight produce certain deleterious biochemical and physiological effects. It is important that the metabolic mechanisms involved be elucidated so that these effects may be prevented or overcome. This research will provide information on the degree and duration of calcium mobilization and excretion as related to hormone levels, enzyme levels, isoenzyme patterns, and tissue calcium and phosphorus content.

Future plans.—It is anticipated that this research will gain insight into methods of ameliorating this response and that future research will validate preventive procedures.

NUTRITION AND METABOLISM

Nutrition and Metabolic Individuality—AMRL—Contract

Objective.—To validate the reliability of determining man's individual protein and amino acid requirements by utilizing the plasma amino nitrogen method and to investigate the feasibility of using blood plasma enzyme levels for predicting an individual's amino acid requirements.

Current status.—This research effort is being accomplished by comparing the results of this method with the classical nitrogen balance method. In addition, the contractor is further standardizing the method to permit use of this technique in a clinical laboratory. Determinations are being made on circulating blood enzymes and correlated with amino acid requirements as determined by the plasma amino nitrogen method. It is hoped that a new method for predicting an individual's amino acid requirement may be accomplished by performing an enzyme determination on a micro quantity of blood.

Future plans.—Future research efforts, using information provided by present research on enzyme individuality, will explore the response of various enzyme systems to proposed dietary conditions and altered environments expected in aerospace systems. This research would lead to the establishment of certain enzymes as biological parameters in selecting future astronauts in aerospace systems and in establishing environmental and dietary criteria.

Cerebral and Peripheral Metabolism—AMRL—Contract

Objective.—This research effort is designed to develop and evaluate a method of studying cerebral glucose, free amino acid, and free fatty acid metabolism and to ascertain the relationship between the cerebral and peripheral threshold glucose, free amino acid, and free fatty acid levels.

Current status.—This study is important in understanding what effects prolonged fasting or inadequate nutrition will have on mental acuity and the individual's performance. Information from this research is expected to yield a means of determining individual nutritional requirements for cerebral and peripheral tissue and thus it may be possible to measure psychological and physical performance. This research is being managed and monitored by the Air Force European Office of Aerospace Research.

Future plans.—This is a 2-year effort extending through January 1965.

Protein Absorption and Metabolism—AMRL—In-house

Objective.—To study the mechanisms of intestinal digestion and absorption of proteins in mammals.

Current status.—Of specific concern in this research project is the relationship of the composition and physical state of the foods and nutrients containing the proteins or related nitrogenous materials to the efficiency of digestion and absorption. Also, the stimulatory effects of cofactors, such as vitamin B_6 and its analogues, on the transport of amino acids and/or polypeptides across the intestinal cell wall are being ascertained.

Future plans.—Future research will attempt to establish optimum ratios of essential to nonessential amino acids and of individual essential amino acids in relation to their optimum absorption.

AEROSPACE DIET

Plant Foods in Space Flight—SAM—In-house

The studies of various plant forms which may be considered for use as foods in space flight are reported in the paper by Dr. Wilks.

Nutritional Requirements in Simulated Space Flight—SAM—In-house

The results of numerous experiments in a space flight simulator in which dietary regimes and nutritional requirements were evaluated are presented in the paper by Dr. Welch.

High Energy Synthetic Compounds—AMRL—Contract

Objective.—To provide data on the energy value, toxicity level, mechanism of metabolism, and the in vivo efficiency of utilization of known and newly synthesized energy-dense compounds and biologically efficient polypeptides.

Current status.—This research effort by Dr. S. Miller of the Massachusetts Institute of Technology has provided data on the energy value and the in vivo efficiency of utilization of known and newly synthesized energy-dense compounds. Studies are now being completed to determine the metabolic pathways for these compounds. In addition, long-term feeding studies have been completed to test their toxicity. This work has provided sufficient data to present to the Food and Drug Administration for approval to test these energy-dense compounds on humans.

Future plans.—Two future efforts are planned under this research project. The first research effort will be directed toward the synthesis and metabolism of biologically efficient compounds for human nutrition. This research will be directed toward the synthesis of a polypeptide with an amino acid composition which can be efficiently converted to body proteins. Such a nitrogen source will permit lowering the level of protein in the diet and thereby reduce greatly the water requirements. Such a protein would also provide a further advantage by reducing the weight of supplies needed for man in space. The second research effort will be directed toward the chemosynthesis of energy-dense biologically efficient compounds. Such compounds would efficiently provide energy and nitrogen and thereby reduce the weight of on-board food supplies required to sustain man in prolonged aerospace flight.

Intestinal Microflora and Diet—AMRL—Contract

Objective.—To enumerate qualitatively and quantitatively the gut microflora of animals and man and to elucidate the influence of various diets on this flora.

Current status.—Diets of various types, such as liquid and freeze-dehydrated, and of various compositions of protein, carbohydrate, fat, and fiber will be fed to humans, normal animals, and gnotobiotic animals and the population dynamics of the gut flora observed. The types of organisms observed and the induced changes noted will be correlated with the general gut physiologic status (in animals) and the diet factors, resulting in recommendations of more compatible aerospace diets.

Future plans.—It is hoped that the influence of microorganisms as they contribute to nutrition of the host will be more fully understood and that specific microorganisms can be used as indicators of the nutritional value of a diet. Successful elucidation of the role of gut microflora in nutrition may lead to research efforts to determine the feasibility of changing the human's gut microflora to make him a more efficient machine with respect to a given nutritional regimen.

Protein, Energy, and Water Requirements in Simulated Space Flight—AMRL—In-house

Objective.—To furnish the data necessary to provide optimum nutrition for man during long-term aerospace flights and extraterrestial habitation. This is an effort jointly supported by NASA.

Current status.—Experimentation has been completed utilizing 8 subjects for 42 days. During this test protein, water, and energy balance studies were performed so as to obtain baseline data in a controlled activity facility. A 2-day-cycle metabolic menu with 6 meals per day of ordinary foods was used exclusively and each food item was rated by the subject at each meal. Experimentation now in progress is again utilizing 8 subjects for 42 days. These studies have the same experimental design as the former studies except that each subject is being fed freeze-dehydrated food for 20 days while the remainder of the subjects are being given a comparable fresh prepared diet. A 4-day-cycle metabolic menu with 4 meals per day is being used for each diet. Metabolic biochemical, physiological, psychological, and microbiological parameters are being determined during these studies.

Future plans.—During the next 2 years the following areas will be investigated: (1) study of the nutrient requirements of man subjected to simulated space stresses, (2) nutritional evaluation of foods to be used in space missions such as MOL, Gemini, and Apollo, and (3) study of the interrelationships of the gut microflora and diet. These areas will be investigated during the next 2 years in a total of 8 trials involving 32 experimental subjects with space capsule confinement and under various atmospheres. With this number of subjects, sufficient information will be obtained for the estimation of the magnitude of the interactions between man, environment, and diet.

Evaluation of Nutrients in Space Dietary Regimes—AMRL—In-house

Objective.—To provide data on the usefulness of various food sources in providing for man's requirements during long-term aerospace travel and extraterrestrial habitation.

Current status.—This research is being accomplished jointly with the program on determining nutritional requirements. Food to be evaluated is very carefully sampled for chemical analysis to determine gross nutrients. Carefully prepared and weighted diets are then fed to young healthy men. Digestibility of the foods will be determined by the difference between intake and excretion. Measurement of the levels of nutrients excreted in the urine will permit the calculation of metabolizable nutrients.

Future plans.—Following the present biological evaluation of precooked freeze-dehydrated foods, this effort will be concentrated on developing a liquid diet and then subjecting it to a critical biological evaluation in humans. Based on this experimental evidence, a nutritionally adequate, well accepted diet for MOL will be formulated.

Finally, in support of numerous in-house AMRL efforts, there has been a continued relationship with the Armed Forces Food and Container Institute. The research services of that institute provide a variety of nutritious foods acceptable for USAF use during experiments simulating aerospace missions. Prototype foods and/or packaging may be developed for evaluation. Food items included are: precooked-dehydrated, heat-processed, semisolid, tubed, liquid, precooked freeze-dehydrated, and bite-size solid. The Institute has the technical capability and facilities to meet USAF specific requirements.

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Manned Space Flight in the Context of National Goals

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N65 18573

INTRODUCTION

Identifying National Goals

There are many national goals, some fundamental, and others changing. Some are as basic and enduring as preserving freedom and the other rights we value; supplying our physical wants on an increasingly generous scale; and being able to live the "good life" of wholesome pleasures, pursuit of knowledge, and greater esthetic appreciation. Other goals may be transient, such as the efforts which we must make to marshal our resources when we are faced with a common enemy and war is upon us; or when there is a campaign to conquer a particular disease; or even to build an interstate highway system.

Is space flight, or what it implies, a national goal, and is it basic or transient? This could be as much a practical question as it is a philosophical abstraction. Not every one views space the same way, and this is understandable, for it has become a conscious and active part of public policy only very recently. If space is viewed as something which is an expensive novelty, pursued largely because of Soviet propaganda successes since 1957, then this will color all our national policy thinking, and what we should do about it will tend toward a particular direction. But if space concern represents a revolutionary and permanent change in human thought and society, attitudes and policies may be quite different.

How Space Flight Entered Our Consideration

The intellectual basis of understanding space goes back about 2,000 years, and then after a long hiatus, fairly detailed principles of planetary motion, celestial mechanics, and rocket propulsion were worked out about 200 to 300 years ago. Real engineering began in the present century with Tsiolkovsky, Goddard, and Oberth. But taking space flight seriously remained the domain of a few specialists, and even of crackpots. Only the last 20 years have changed this. The German V–2 represented the beginning of a practical vehicle. After World War II, the Department of Defense sponsored serious studies for design of satellite vehicles; this information was revealed in 1949. Next came satellite plans for the IGY in 1955, and then the full-blown public and political shock of Sputnik in 1957. Space truly seized public imagination. Behind the scenes, rocket engineers knew that the technology of intercontinental missiles brought almost an automatic capability to conduct meaningful space flights, at least to a point. With slight rearrangement, the rocket and guidance system which could deliver a nuclear warhead across an ocean could also accurately place a payload of thousands of pounds in an orbit, or spot it on the Moon.

Contrasting Assessments of Space

But there were other educated and influential people who felt quite different. These men,

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often of the greatest experience, viewed themselves as practical realists. They knew that the cost of orbiting material ran into the hundreds of thousands of dollars a pound; they knew that space was a hostile environment; they knew that by the laws of physics changing orbits and real maneuvering carried an energy cost that limited all easy space flight. To them, all that was left was an occasional experiment purchased at great price, and perhaps at some risk to the financial support of other worthwhile activities.

Fortunately, there were some who had not yet learned the constraints most of us gain with time, as well as others who never lose their sense of adventure and freshness of approach to new problems. They could see something more in space flight. Some of the cost and operating barriers were seen not to be fundamental but self-imposed. As Soviet space successes stayed significantly ahead of our own in weight of payloads and hence in what could be attempted, more ambitious plans were studied which looked beyond adapted ICBM's.

Establishing New Space Goals

Why did the President and Vice President in 1961 identify themselves with a more ambitious space program, including a definite timetable for building the large launch vehicles and manned spacecraft for going to the Moon? President Kennedy was of a newer generation better able to grasp the implications of space than one would expect of most older men. As a Senator, Vice President Johnson had had a long exposure to the details of the missile and space programs, and therefore had an extraordinary basis for such an appreciation. Although many people would deny the connection, it is certainly true that some observers think the proposals of the Administration in 1961 were more palatable to the Congress as a result of the orbiting of Gagarin and the trouble at the Bay of Pigs. An authoritative judgment will probably have to await the definitive histories which have not yet been written. In any event, in the spring of 1961 the President went to Congress with a program for landing men on the Moon in this decade, developing nuclear propulsion, and seeking more applications of satellite technology. Distinguished leaders in the legislative branch, particularly members of the House and Senate Space Committees, had paved the way with their educational efforts over several years, and when the time came for action they were supported by the Appropriations Committees.

REASONS FAVORING SPACE RESEARCH AND EXPLORATION

A Matter of Philosophy

In part, attitudes of people toward space are basically philosophical and hard to test in terms of absolute logic. But also differences of attitude are shaped either by differing assessments of our technological future or through unequal exposure to pertinent facts.

I will state right now that my philosophy is that space exploration is here to stay. I can marshal reasons. But I suppose I found them easier to accept because my father, an engineering professor, started me on Jules Verne and other such books when I was eight, and used to talk to me about the future of science. Since those years, I have continued a lay interest in space. At the time of the Korean War when the Navy caught me a second time, I introduced lectures on space flight into the curriculum and texts of a part of the Navy Postgraduate School. In civilian life as a professor of transportation, I was supposed to be sticking to railroads, ships, and aircraft, but somehow I found excuses to interlard economic analyses of spaceflight. And once Sputnik arrived I ended up in space work full time, with unparalleled opportunities to be exposed to, or to participate in, shaping space policy at the highest levels of Government.

I am convinced that space is here to stay. You may not regard my approach as properly scientific, but even so I wish to support my prior conviction with facts that are pertinent. I assume that some of you share my conviction because of the work and interests you are now pursuing. If others of you are merely interested in special problems of nutrition without regard for the practical possibilities of space flight, I hope you are open to persuasion that there is a significant future coming.

Because Space Flight Is Possible and "Human Destiny"

The United States is committed to space flight of an ambitious nature for several reasons, and everyone will have to apply his own weight to these several factors: First, because flight is possible, it seems to be human nature to believe it should be done. The frontier and new horizons have always been a challenge to some men. Instinctively, too, there are those who just feel that mankind is destined to step beyond his earthly bounds, just as his ancestors once crawled out of the seas. Although the Earth is going to be here a long time, still there is the ultimate dream of colonizing new worlds. Mankind, or his descendants, may be spread to new places and the race will survive even when Earth itself is no longer habitable. Some people worry that though our sun is good for billions of years before the Earth is adversely affected, mankind himself may do something much sooner to risk the habitability of our home on this planet. And there are those who philosophically believe that someday spacefaring mankind will reach other intelligence in the galaxy. After all, our galaxy, one of millions, may have upwards of 10 billion planetary systems among its myriad stars. And who can be sure that life and intelligence are unique to this planet?

But philosophy is usually not enough to sell a program to Congress, when goals are quite remote. Even if such thoughts do occur to many people, they are unlikely to feel comfortable about voicing them in the context of everyday affairs. We feel in public life we have to justify most things in terms of defense, cost effectiveness, increasing employment, and keeping ahead of the Russians.

Advancement of Science

Clearly these more mundane and direct reasons just named are not to be ignored. Study of the space medium can advance science. We can pursue geodesy and mapping by satellite. We can unravel the secrets of the radiation belts, and better understand solar phenomena. But the chances are very good that not all the important mysteries of science were planted on Earth or in its magnetosphere. With 9 planets and 31 moons in our solar system, not to mention countless asteroids and comets, there seems no early limit to investigations. The Moon has a surface area about as great as North and South America combined. Even little Mars has a surface area as great as all the land of Earth. Undoubtedly men will want to go to most of these places in time without having to have reasons. But as we weigh the comparative technical efficiency of relying on black boxes in unmanned probes, or sending men, we shall find a crossover point for ambitious missions when men will more than pay their way. The weight penalty of life support systems will be offset by men's judgment, adaptability to the unexpected, powers of data integration, and facility for equipment maintenance.

Other elements of the scientific community have sometimes begrudged space technology its vast sums of money. A few even act as if we had to choose between their interests and space. Space dollars can actually be compared with many other even more costly uses of arbitrary and superficial natures in the national economy. The practical politics of the matter are that not only has space opened new frontiers, but it has stimulated support for many Earth bound sciences which would not likely have won as much support in isolation from the space age.

National Defense

A concern for national defense clearly has motivated our leaders to put money into space technology. The well-advertised list of responsibilities to promote science and human welfare assigned to NASA is matched by important duties assigned to the Department of Defense. This does not contradict the objectives of the Space Act of 1958, for both agencies' responsibilities were therein identified as different elements of the peaceful use of space. Defense is supposed to help preserve the peace in space so that space can be devoted positively to human betterment. On the other hand, NASA no less than Defense is part of our insurance against technological surprise in military space flight. Defense also develops and uses much of the same technology and for the same purposes as do our purely civilian agencies. Thus, the military have an interest in communications by satellite, weather reporting, observation, navigation, and several other applied uses. These similar needs among many agencies are so inseparable, that the National Aeronautics and Space Council has been required to help promote coordination toward our unified national goals in space. Looking beyond these relatively passive and nonaggressive activities in space, the possibility has been raised that space might be used as a medium for transporting weapons of mass destruction, in addition to the ICBM's which already make up a key part of the strategic deterrent of the great powers. We have declared that under existing circumstances, we shall not initiate the placing of bombs in orbit. The Soviet Union has made a similar declaration. Short of general disarmament and inspection of all launching sites, the major powers are somewhat reluctant to count on these gratuitous assurances as a safe basis for strategic defensive planning. Consequently, a reasonable defense posture implies a certain reserve capacity to detect, track, identify, and react against hostile spacecraft if in time they should appear.

Civilian Applications of Space Flight

Although NASA is pioneering the way into many of the civilian applications of space flight, as operational systems are ready to be used other agencies are finding their place too. Tiros photographs have captured the imagination of the world, and now the Weather Bureau is increasingly involved in future planning of improved meteorological satellites. Historic television pictures have been carried both ways across the oceans, and so a Communications Satellite Corporation has been chartered to carry out practical exploitation of these new intercontinental links. In the planning stage are data-gathering satellites which may pick up information broadcast from thousands of points on the surface of Earth, including, for example, remotely placed oceanographic stations, for central computer processing. These assorted applied uses and others not yet identified are expected to provide a return greater than all now being spent to develop space technology. The Weather Bureau has documented potential billions in savings to the national economy from accurate weather predictions which can be based significantly on satellite-gathered data. It will not be surprising if unexpected returns are the greatest of all. We have the recent experience of radioactive isotopes, once regarded as an unwanted nuisance, whose economic contribution already is greater than the entire cost of the nuclear energy program.

Industrial Spinoff of Space Technology

We have also been concerned with direct product spinoffs of space research, and quite an effort is being made to identify these and to make them available to the economy at large.

Economic and Technical Stimulation

Space flight is having a leavening influence and may be affecting many other activities in ways both subtle and direct. Far more than product and process spinoff is involved. We view space as a general technical and economic stimulus to our society. There may be a few people who do not look beyond the opportunities for the growth of their individual company or university laboratory. But whatever it means in particular cases, we also know that nationally it is bringing industrial expansion to many regions, and aiding higher education, especially in the sciences and engineering. Our ability, too, to work with exotic materials, to maintain higher standards of quality, and to hold to closer tolerances of necessity has been enhanced. Almost inevitably, so much study, building, and exploration invested will bring us unexpected breakthroughs in many areas.

Summary Assessment of Usefulness

It is evident that in my eyes, the space program as already launched can stand on its own feet as a worthwhile endeavor. But I want to strengthen this feeling with two added elements. One is to consider our competitive position in space, a matter of practical concern we cannot afford to overlook. The other is to try to describe in a still-murky future some clues to where we may be going and what they portend. I want to suggest that the allegedly wise men mentioned early in this discussion who knew the limitations of space flight are no more right than their counterparts were in other early negative predictions about steam engines, heavier-than-air craft, nuclear energy, ICBM's, lunar rockets, and antimissiles.

SOVIET SPACE COMPETITION

National Prestige

Even though space research is worth doing on its own merit, there is little doubt but that early Soviet successes were a powerful stimulus to our own efforts, and further Soviet successes remain a useful political goad. We have been concerned about damage to our national prestige; we have feared there might be some military advantage to the other side; and we certainly have felt a competitive urge to match and surpass what others do well. Some people downgrade the importance of prestige, particularly if it costs dollars. But detailed analyses of psychological reactions all over the world have shown that prestige and power are acutely involved and intertwined in the space race. Soviet space successes have been used explicitly to back threats of rocket war in several instances. Their early Sputniks probably enhanced their general reputation for technical excellence so that added export sales of machinery and other merchandise brought in more foreign exchange than the space program had cost them to that time. What is the long-run psychological cost to us of having the backside of the Moon dotted with Soviet names? Will they do the same for Mars? To pretend that national prestige is unimportant is to show a limited awareness of historical forces in society.

The Military Sector

I have already touched lightly on some aspects of the potential military threat. More outspoken individuals have warned that the use of space might be denied us, and that nuclear blackmail could be practiced. But regardless of whether the danger is that extreme in the near future, there are other legitimate defense concerns. They help to explain why over two-thirds of all our space launchings have been for the Department of Defense.

Statistical Comparisons

Let me review more specifically some unclassified highlights of where we actually stand in comparison with the space program of the Soviet Union. I want to stress at the outset that comparisons are tricky, and even the same facts are open to multiple interpretations.

First as to general statistics: As of April 24, the United States had orbited 203 payloads, and the Soviet Union 65 since 1957. But weight comparisons are quite different. They have put up about three times as much net payload as we have. What is more discouraging, every year for the last 5 years, the lead of the Soviet Union in that year has grown larger than it was for the year before.

From this comparison, some people make slighting remarks about the Russians throwing up cast iron, and their absence of sophisticated instruments—particularly inappropriate after our own recent orbital ventures with Florida sand. Others claim the Soviet program is narrow-based and will in the end do much less than our own. An accurate appraisal on all points would take a good deal of time. My best assessment is that the Soviet program has close to the same variety of goals as our own, including undertaking very complex missions. Let us look at just the main outlines.

Scientific Exploration in Earth Orbit

As far back as 1958, the Russians put up Sputnik III weighing 2926 pounds exclusive of the carrier rocket. It did have rugged vacuum tubes in it, but it also had thousands of transistors. Its weight and range of experiments put it into what we would call the OGO (orbiting geophysical observatory) class which 6 years later we are still waiting to launch. Further, Sputnik III operated reliably for 2 years until it burned on reentry.

The Soviet Union is clearly interested in more than spectaculars. In the Earth orbital regime, it has put up 28 Kosmos class scientific and engineering-test satellites with a minimum of fanfare, and these have included a range of experiments. Some of these spacecraft are nonrecoverable and may be modest in size. Others appear to be very heavy satellites in the 10 000-pound class, perhaps unmanned Vostoks. Additionally, the pair of Elektron satellites are providing synoptic measurements of the radiation belts out to 40 000 miles.

Space Applications

When it comes to practical applications of unmanned satellites, the United States has the lead in demonstrated accomplishments. These I have already described briefly. But similar flight operations are not beyond Soviet capabilities. They have made an agreement with NASA to exchange weather pictures taken by satellite as part of a coordinated program. Surely they must feel some confidence that we will not make them look foolish. In addition to their recent interest in exploring point-to-point satellite communications with us, they have shown a stronger interest than we in direct broadcast of television from space to individual receivers all over the world. This is not necessarily remote.

Lunar and Planetary Probes

If they plan to send men to the Moon and planets, they would want to send unmanned probes first. In absolute number of launchings the Soviet Union has made a larger commitment to such flights than we have. As a percentage of total flight effort, their commitment for that purpose is running about fivefold our own. And they use larger vehicles by far. Take a part of the comparative planetary effort for example. Of our two launch attempts to date, the 447-pound Mariner II carried about 40 pounds of instruments near Venus and returned some data. We are rightfully proud of this accomplishment. The Soviet pattern has been to orbit 14 300-pound platforms from which a probe weighing up to 2000 pounds exclusive of the rocket casing can be launched on the interplanetary trajectory. Between 1960 and 1962, ten such launchings were made. Typically, the comparison is a difficult one to make. We met with a great success in Mariner II. Not one of the Soviet craft attained its full objective. In the case of Mars I, there would have been high-definition pictures of Mars. But before Mars I failed, it remained operating for a longer period of time than Mariner II, and returned data from a greater distance. We have no probes scheduled for this decade to match what the U.S.S.R. has been firing with such determination. When they overcome their equipment failures, we could be in for some important shocks. We are still waiting to see whether the recent Zond I contains just such triumphs before its working flight is over.

While neither country should be overly proud of its lunar probe record, the pictures taken by Lunik III back in 1959 are still a high-water mark.

Manned Space Flight

Of particular interest are comparisons of manned space flight. Through the 1963 season each country had made six manned launchings, and neither side had killed an astronaut or cosmonaut. Stories to the contrary are fabrications.

We are proud of our Mercury record which met all its objectives and more. The 3000-pound capsule was limited to that orbital weight by the capacity of the Atlas launch vehicle. Although carrying a number of redundant systems, Mercury took an experienced test pilot to fly it, and partial failures on several flights justified the use of such trained men. They lay in cramped quarters, breathing a rarified atmosphere of pure oxygen, not unlike what is intended in Gemini and Apollo. They communicated by line of sight with one ground station after another strung out around the world.

With the advantage of a larger launch vehicle, the Soviet Vostok craft weighed 10 400 pounds, or three-and-a-half times as much as Mercury, and had an external measure of ten times the volume. The cosmonaut breathed air of normal mixed constituents at sea-level pressure. Where our Mercury was aimed at a nominal three orbits, and then was stretched to a day and a half by stripping it of some redundancy, the Vostok from the outset carried air, water, food, and batteries for 10 days of flight. Live television returned pictures of two different degrees of definition. There was a large flow of continuous real-time biological data from advanced sensors.

Human Safety

Some people make the charge that Soviet early successes in space came from a greater risking of human life. There is nothing invidious in the comparisons I am about to draw, but I do think we should be careful in making such charges. Before Astronaut Glenn's flight, we had gained three orbits of experience, including two with Enos. The Russians sent up, without recovery, Laika, 4 years before Gagarin. The Vostok ship itself completed 100 orbits of fully controlled flight, including successful recovery of four dogs, before the first man was sent. Flight length improved, and we had the spectacular near-rendezvous of Vostok III and IV. By Vostok VI, confidence in the system and its many redundancies had grown to the point where it was entrusted to a woman factory worker, whose orbital flight time exceeded the total Mercury experience, manned and unmanned. By now, the cumulative record of controlled orbits by the Vostok class, including those unmanned under the Kosmos label, has risen to in excess of 1600, as contrasted with the 37 orbits of total Mercury experience. Of course with Gemini and Apollo we expect in the future to do much more than the Russians have demonstrated so far.

Future Manned Missions

We have every expectation of a fairly early rendezvous and docking experiment by the Russians. We do not know positively what their future plans are. Certainly with two or three rendezvous, they have the orbital weight capacity to send a manned probe around the Moon and back. They have talked frequently and positively about manned flight to the planets and to the Moon. Khrushchev was very indignant when the American press headlined that the U.S.S.R. had withdrawn from plans to fly to the Moon. He said he had merely denied there was a race, and that he wished us well.

To the best of our knowledge, the Russians have not yet demonstrated a launch system capable of convenient manned flight to the Moon for a landing and return. But then, if we chose to practice Soviet-style security around our launch sites and factories, there would be no hard evidence available to foreigners that the United States is building a lunar capability either.

Because we are not permitted to inspect their facilities, we have to do our best by inference to judge the truth of their repeated statements that they intend to be first in ambitious manned flights. We know they are producing a flood of lunar and planetary studies, including atlases of the Moon and Mars. We know that they have made a massive commitment of launch craft to escape missions, including multiple shots at Mars and Venus at every launch window since 1960. They have given us signs with the twin Vostoks and with the Polets that they are working on rendezvous in orbit. With the successes they have met from the space program, I find it hard to believe they have been content for a decade to use an existing rocket engine without doing follow-on work with bigger and better engines to come. I suppose the recently announced Soviet work with helium as the inert gas in test space-cabin atmospheres would be consistent with plans for a man to leave a normal-pressure cabin to work outside a ship in assembly of orbiting units into a larger station or ship. He could move more promptly from a normal-pressure cabin to a low-pressure suit of sufficient flexibility to permit some freedom of movement while working in the vacuum of space. With all this circumstantial evidence I feel it is entirely possible and even probable that they are planning officially to make long-duration and distant manned flights. Based on other evidence, I am not impressed with the argument that their national economy cannot afford such an investment. They have gained too much not to afford it.

American Capabilities

I am enthused, therefore, about this meeting to consider the long-leadtime development of the knowledge and the technology required to support American flight to the planets. I feel we have the knowledge, the manpower, the resources, and the facilities, to mount the finest space program in the world. I feel it is worth undertaking on its own merits. I am also aware that we are in a race with a competent and tough-minded competitor. We must recognize the nature of this race and organize to meet it, not by year-to-year reactions, but with sound, consistent planning.

THE HOPEFUL LONG VIEW OF SPACE

In support of this kind of thinking, I want to sketch very briefly some of the ideas our staff has been considering. Our thinking on these matters is far more thorough than this brief outline can imply. Taken together, they are an important clue to our general optimism about the future of space travel, and they represent the final part of the trilogy I have been constructing. The other two parts were, first, that even the existing program is worth doing on its merits, and, second, that our competitive position in the world demands we make a real effort at space achievements.

A Management Philosophy

Our thinking about the future builds upon the base of some general attitudes toward management and policy for space. Here are some of these points:

It is essential that there be identification of long-run goals so that there can both be a directional pattern to our present work and proper attention to the future. We want to see adequate support for long-leadtime work which is not very expensive now, but is essential to keeping open our options as to future directions. We do not believe it is possible to construct today a rigid plan to meet all future needs, because experience has shown how wrong many detailed expectations turn out to be. Our concern with the future clearly is shared by the several operating space agencies, for they have made a considerable investment in a variety of exploratory studies on advanced systems, as well as supporting advanced research on components not required by approved systems already under development.

We are also interested in seeing some continuity in budget levels. This is quite different from supporting spending for spending's sake. It means that we believe some effort should be made to keep those research and development teams which have been successful fairly steadily employed, or they cannot be held together and stay effective. At the national level, we do not want to see, after major programs peak, a deep slump before new starts are authorized, as too much momentum can be lost in national progress.

NASA Goals

A current illustration is that thought must be given today to the work which will follow Apollo, even though our hands are full with informing the public why Apollo's orderly and timely pursuit is as important now as it was in 1961. But setting the priorities on the next projects is not easy, and will require much study and review before the Nation can decide the proper place and order of ambitious Earth-orbital stations, lunar bases and exploration, or manned interplanetary flight.

Department of Defense Goals

Advanced military planning faces some similar difficulties, and an interim solution has been to buy time and experience with building blocks like Titan III and experiments like Gemini B–MOL. Where is the real military future in space? Popular attention focuses on the first 600 miles above the surface of the Earth. Certain current missions are most easily performed there. But spacecraft in such close-in orbits, whether manned or unmanned, may well be most vulnerable to neutralization if cold war should turn hot.

Of course we hope for continued meaningful progress toward mutual disarmament which genuinely supports national interests. If this should fail, even though there is no conscious plan to do so now, one can envision that new military missions will be found, related to space technology. And it may be that military vehicles in deep space with greater freedom from detection and greater room for maneuver will turn out to be most significant to defense. We do not want to hang a military label on Apollo and the Moon, for this would be a gross injustice to our motivation and true purposes. Even so, the work of building a general competence to go to the Moon may in the long run turn out to have more to do with our long-range defense than any other group of space projects. Personally, I find it easier to visualize a long-run military future in space built around manned vehicles rather than unmanned vehicles. Under a treaty of disarmament, I can picture manned craft used for inspection and surveillance, displaying greater versatility and selectivity in data-gathering than a purely automatic system. In a time of cold war, I can see manned craft as less provocative and less subject to interference by a space rival. We would like an end to cold war. But even more so, no one in his right mind wants a hot war, especially of the general war category which could reverse human progress. But in protecting ourselves from what has been called "the unthinkable", I view future manned ships, particularly effective in deep space, as more likely to outsmart and outplay purely automatic systems.

With these background observations, let me turn more specifically to identification of some of our positive ideas about the future.

Space Stations and Integrated Planning

We would like to see a close tie between work on Earth-orbiting manned space stations and our future plans for the Moon and planets. If manned reconnaissance of the Moon becomes desirable, we might save one whole cycle of development costs if every effort were made to build compatibility between Apollo hardware and space-station hardware. In other words, if the Earth-orbital station could be substituted for a LEM vehicle on a particular flight to provide a shirt-sleeve environment of longer stay time around the Moon, this could be very helpful to a number of lunar missions. Also, if we plan manned interplanetary flight in the 1970's, rather than the 1990's, it would be sound if an Earth-orbital station of the period immediately ahead represented a full-scale realistic checkout of an interplanetary ship. Again, this might represent a major dollar saving in development, and, possibly more important, a time saving as well. With such a ship, testing out, among other things, the products of the work undertaken by groups of researchers in the biosciences, how much more ready we would be for the real trek to the planets.

Heliocentric Orientation

Our staff has noted that most thought about space continues to be geocentric in its orientation, which is not strange in an orderly evolution. But already it would be helpful if more thinking were heliocentric. This has implications which are much more far-reaching than it may seem at first glance. In the first place, it is a reminder that our solar system has many exploratory targets of opportunity. In the second place, we should realize that the burden of overcoming gravity in a climb out from Earth distorts our thinking about gravity throughout the solar system. Flights from an orbital base, and particularly from the Moon, are not particularly demanding in energy requirements. And for many classes of maneuvers, gravity can assist as much as it hinders. Thus a flight out of the plane of the ecliptic which seems very costly in energy as viewed from Earth turns out to take a fairly modest increment of energy if one starts at the Moon, and then makes a pass around Jupiter, let us say, approaching it to make a polar orbit pass. There are limitless other tricks of using gravity to conserve total energy requirements.

The Moon as a Base

I have already hinted that quite aside from what else we may learn by going to the Moon, if we locate useful chemical resources there which can turn it into a refueling base, a Moon investment may turn out to be extremely rewarding. It may prove cheaper to replenish from the Moon even ships which operate in Earth orbit than to lift certain supplies from the surface of the Earth. And fairly ordinary chemically powered space transports operating from the Moon to the near planets can show payload fractions and speed performances far superior to anything now under development which must operate from Earth.

Looking Backward

There is a tendency in human affairs to overdo our perfection of techniques whose main usefulness is past. Thus some military men have been accused of working to win the last war rather than the next. And some rocket engineers are looking more to scaling up Saturn V rockets into even more costly conventional systems than to pressing harder on the state of the art.

Cutting Costs of Early Interplanetary Flight

Indeed, some people, who accept the $20 billion price tag for Project Apollo without asking whether that represents the true marginal cost of going to the Moon over and above what we should be doing anyway to build a general space competence, jump to a very hasty conclusion in trying to judge what a first expedition to Mars will cost. They say if Apollo is $20 billion, going to Mars will be $100 billion. Then any realistic individual mentally relates probable budget ceilings for space to such a cost. He knows that even if a Mars expedition were to take most of the NASA money, at $5 billion a year, it would take, at constant prices, about 20 years of funding to make the Mars trip. This would put it after Apollo somewhere around 1989. With this yardstick, we are likely to find disappearing any sense of urgency in pursuing the kind of studies which many groups are undertaking. Why worry now about money to fund fully self-sustaining long-term life-support systems not needed before about the 1990's?

But need we launch into a whole new round of facilities construction and engine and vehicle design of conventional nature before we think about the planets? Suppose that rendezvous goes well in the work already started. Suppose that fairly early in Earth-orbital stations we test out a manned interplanetary ship. Suppose that careful planning shows that four or five Saturn V payloads assembled in Earth orbit would give us sufficient weight capacity to mount a Mars expedition? Under these quite different assumptions, which would use existing hardware, there are estimates that adding Mars to our capability would come to $5 billion, or at most $10 billion. Such a judgment would extensively revise our priorities and sense of urgency about supporting certain elements of our future capability.

Extending Vehicle Performance

If we did have to stretch a little bit the lift capacity of existing launch vehicles, we have several interesting approaches to examine. One approach would be strap-on solid rockets to get the first stage started with a bigger load on it. Another would be an upgrading of the energy potential of the fuel such as changing to flox. A third would be to consider air augmentation of the first stage for the added specific impulse which could be gained.

A High Velocity Probe

Before men do much traveling to the planets, it would be extremely useful to have a launch vehicle which was able to reach most of the solar system and which gave us greater flexibility in opening the launch windows to those planets which now become opportunities only occasionally, such as Venus every 19 months and Mars every 26 months. We are looking with much interest at the capabilities of a cleverly designed chemically fueled rocket using high-energy propellants to give it a total velocity increment of 60 000 feet per second, exclusive of the payload. We can foresee an assemblage roughly the size of Titan II able to put 2000 pounds of payload almost anywhere in the solar system. And if such a system were well designed, it could look forward to an extended period of usefulness. Suppose an average of one a month could be launched to some target within the solar system. In the course of a decade of use, many of the fundamental parameters of the environments of the bodies of the solar system could be defined. We do not preclude use of Saturn V launched unmanned payloads for certain missions to the Moon or planets, but we would regret the fiscal limitation to future exploration if most advanced missions could only be conducted with a launch vehicle in that weight and cost class.

Judging Base Requirements

As we try to judge what cargo weights would be required to support a base on the Moon, we may find a partial clue in the tonnages shipped to Antarctica each season. The United States sends about 50 000 tons a year. Those who think that we would be satisfied with what could be learned from a few handfuls of lunar surface material might find instructive the Antarctica parallel. Obviously most of that continent is ice-covered to a great depth and is beyond easy geological rock study. But where there are rock outcroppings, each three-man team of geologists sent out on independent searches typically collects about 3000 pounds of rocks a month before they are resupplied or returned to the main base. If any tonnages like the Antarctic ones are reasonable, the costs of thorough lunar exploration seem beyond possibility. What are the implications? First, like Antarctica, it may be important to plan a major role for construction and maintenance men in any roster of expedition personnel. Right now we are making the point that test pilots should be accompanied by scientists. Next, we will have to insist that scientists be outnumbered by skilled workmen once bases are planned. Second, it is very important that at the earliest opportunity a lunar base be as independent of Earth supplies as possible. Probably a nuclear power plant will prove essential, even though solar power will be useful, too. We hope that exploration will reveal sources of ice beneath the surface. And if the fragmentary evidence of volcanic activity is borne out, we may even find gas, free heat, and underground water. But even with this kind of planning, how can we seriously consider large-scale lunar exploration? This question is asked in the light of costs of many thousands of dollars a pound for lifting a payload from the surface of the Earth to landing it on the Moon. Perhaps we are back to one of those fundamental facts that prompt some men to see an early limit to space flight.

Paths to Trimming Space Flight Costs

It is true that if one takes the total expenditures for space made to date and relates this figure to the pounds orbited, the cost is frighteningly high. But we also confidently expect the operational marginal cost of orbiting payload with the Saturn V class of vehicle to come down to $300 a pound or less. This is several orders of magnitude less than we typically have paid up until now. It still greatly limits what we could afford to send to the Moon.

Of course, there are hopes of trimming these costs a little bit by reusing vehicles. With recovery and refurbishment of some stages, costs might come down to one-half. They probably would not come down much more because recovery of big stages of light construction may fall well below 100 percent, and refurbishment costs may be high.

There are proposals for vehicles with wings, airbreathing engines, and the like as an approach to a recoverable system. Some of these approaches suggest orbital payload costs all the way down to perhaps $30 a pound. But too often the adding of wings, landing gear, and redundancy eats up the intended payload capacity. It is probably too early to write off schemes for refueling in the upper atmosphere or use of fancy air scoops, compressors, and oxygen extractors. The problems look formidable.

Basic Costs of an Advanced Chemical System

What are we throwing away fundamentally with a well-designed space launch system? Using modern design and hydrogen and oxygen as the propellant, we can envision a ship with roughly 88 percent of the takeoff weight as fuel, and the rest of the weight divided about equally between structure and payload. If the propellants cost 10 cents a pound, and if the payload weighs about a fifteenth of the fuel weight, the actual fuel cost consumed in climbing to orbit would be only a dollar and a half per pound of payload. My arithmetic is approximate, but if we further estimate that structure is about equal to payload, then the structure thrown away is about the equal in pounds of payload orbited. Structure of a modern jet aircraft, a more complicated mechanism than most rockets, costs about $30 a pound. This means even in the absence of a recovery system, the total vehicle and fuel cost of orbiting material could be not much above $30 a pound, about an order of magnitude lower than what we expect of the Saturn V. Obviously our present methods include many other operating costs, such as those of checkout and launch and tracking operations. Whatever we do with our present technology, we seem currently to be stuck with what could be termed an ammunition philosophy. This is normal, considering the route by which we have moved to space flight, that is, its growth out of the missile industry.

A Transport Philosophy

What we would like to do is find a path to a transportation philosophy of design, one where we build and operate ships which are used so many hundreds of times that the overhead cost of capital investment in ships is miniscule per flight. We would still be stuck with the $1.50 part of the cost which is fuel, but we could get rid of most of the $30 which is structure. This is already the situation in air transportation, for example. But it is also obvious that much will have to be done about all the other costs of operation which bulk even larger than the fundamental vehicle and fuel costs. A complex modern jetliner does not have a countdown which involves hundreds of people, and a great tracking system to care for only a few flights per month. Three or four men get in the plane, throw some switches, and after a few minutes have permission to take off. They do not return by falling in an ocean area guarded by a recovery task force of 20 000 men. They use ILS (instrument landing system) or GCA (ground controlled approach) to come back to a prepared runway.

So clearly what the space business needs is a new systems technology of propulsion and vehicle design which operates in a more traditional transportation fashion. Incidentally, as we look at fundamentals, the gravity and resistance load to be overcome in flying to the Moon is less than that for an airplane flying from New York to Los Angeles, fighting gravity and air resistance all the way. The difference is just that we do not yet have an efficient way of applying the required power.

Comparisons of Propellant Economy

Fortunately, the outlook is not as bleak as it may seem. Many of today's solid-fueled rockets have a specific impulse (I_{sp}) of around 250 seconds. Ordinary liquid fuels are a little more energetic, and typical I_{sp} attained is around 300 seconds. Our high-energy upper stages of Centaur and Saturn, and tests using fluorine which is better yet, bring us close to an effective limit of around 450 seconds in a vacuum environment. Only so much heat and expansion through a nozzle can be obtained by chemical processes.

This apparent limit explains the interest in nuclear propulsion. A graphite-core heat-exchanger rocket can extract a small part of the energy output of a nuclear reactor to push the impulse up to about 800 seconds. The only reason we cannot go further is the heat limit to maintaining structural integrity in the core and reactor vessel. Above a very few thousand degrees, the whole core assembly would melt down and spew out the nozzle.

When we look at the history of flight, you will recall that we did not painfully work our way up one Mach number at a time from familiar aircraft to ICBM's and beyond. In fact, we do not yet have an operational commercial supersonic transport, but we have jumped to Mach-25 ICBM's. Likewise, as we search for ever-higher I_{sp} systems, we may not just work up gradually from the kinds of nuclear rockets which are currently under development. That work is worth continuing, but we also want to devote enough of our advanced research to determine whether we can make in effect a quantum jump in the next decade or two rather than only in the indeterminate future.

The Gaseous-Core Nuclear Reactor

As a matter of fact we know pretty well what we are looking for, and we almost know how we are going to get it—perhaps not quite, but not far from it, either. One promising avenue is likely to be the gaseous-core fission reactor as the probable next step. If the core of uranium or plutonium were intended to be in a gaseous state, we would be much less temperature-limited in extracting some larger fraction of the potential energy of the reaction. Parametric studies now begin to picture the total vehicle system toward which we are aiming. It might be about the size of a Boeing 707 or DC–8. In its simplest version, it would produce 2500 seconds of impulse. By running it still hotter, beyond the capacity of the propellant to unload its heat, it would require a radiator system, and the impulse could rise to 10 000 seconds.

These figures are not especially astonishing to those who are familiar with the design possibilities of various electrical rockets, some of which may produce impulses as high as 100 000 seconds. But there is a difference. The gaseous engine assembly is expected to have a thrust-to-weight ratio of 20 to 1, while many electrical rocket systems have such a weight of power-conversion equipment that thrust-to-weight is a very small fraction, and acceleration is so low that it takes a period of many days to attain high speeds and the system is used only after the ship has been boosted to orbit chemically.

The gaseous-core ship with its high specific impulse and good thrust-to-weight ratio implies the possibility of designing a single-stage reusable ship with all the redundancy and flexibility of a transportation craft on Earth.

Chemical Versus Advanced Nuclear Capabilities

I suggested that Saturn V will be able to lift cargo to orbit at a price of about $300 a pound. It will land cargo on the Moon for about $5000 a pound. By contrast, the gaseous-core ship in the parametric studies will deliver cargo to the surface of the Moon at under a dollar a pound. Such a ship on a near run to the Moon would carry as much there in a year as 300 Saturn V's. Ten such ships would carry the 50 000 tons equivalent that Antarctica requires. A budget smaller than NASA now employs would support similar tonnages to several places in the solar system. Flight windows would open wide, and flight times to the near planets would come down to a few days, while those to the outer planets would drop from many years to a few months.

This is not the occasion for detailing the successes already attained in developing such a power plant or the problems still to be faced. The system may never work, but the promise is very great. With the general acceleration of technical progress in this generation, I have great expectations that those systems which are compatible with known physical laws can be developed. Whether the system I have described, or a variant of the nuclear pulse rocket, or a fusion power plant will turn out to be the right one, we do not now know.

Maintaining Present Efforts

Nor should we abandon our work on better chemical rockets for the sake of a superb nuclear system which is not yet here. But neither should we turn our backs on adequate support of promising systems which could have such a tremendous advantage. Meanwhile our present-generation systems under development will teach us much we need to know about space and pave the way for those that are to follow.

CONCLUDING REMARKS

Space travel supported by an adequate transportation system would completely revolutionize and outdate past thinking about the role of space in human affairs. Colonization, resource exploitation, and defense considerations would be entirely different.

Also, clearly some of the most advanced thinking on space nutrition would move from an abstract exercise to a matter of urgent practical concern. I repeat my opening conviction. Space travel is here to stay. I believe America can be the principal space-faring nation.

Recalling my opening statements about those who are negative about space either because they are bearish on our technical capabilities for the future or because they do not have all the facts, I think we have a basis for reappraising some of our thoughts on space. There is serious attention coming to advanced propulsion and vehicle design. Right now, your thinking in the area of nutrition for long-duration manned missions is ahead of the main body of technical concern for space. I almost feel called upon to leave a word of warning to those who fund this work. Let us make sure that limits to our understanding of life support systems do not become the pacing elements to man's advance into our future in space.

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SESSION II

Requirements in Area of Nutrition and Waste Management

Chairman: *Rufus R. Hessberg*
Assistant Chief for Medical Programs
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In this session an attempt will be made to cover the state of the art within the NASA programs. There will be a brief résumé of what has happened in food storage and handling of food, the stresses that go into the determinations of the food requirements of the Gemini and Apollo Programs, the handling of the storage of food for the next generation of systems, and the waste management for the next generation. Generally, these discussions are confined to hardware-developed concepts to date—what is engineered and what can be considered as basically the state of the art within engineering concepts today.

RUFUS R. HESSBERG

Preparation, Handling, and Storage of Foods for Present Space Projects

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In the United States space flights, to date, the food and nutrition aspects have not been of major concern because of the short duration of the missions. Eating during these flights, in most cases, was accomplished in order to obtain gross information as to the effect of stresses such as weightlessness on the chewing and swallowing of food and to ascertain the types of feeding concepts which would be applicable to longer duration space flight. Table I summarizes the types and varieties of foods eaten during the completed NASA manned space missions.

Proceeding from Project Mercury, Crew Systems Division is now in the process of developing a space feeding concept for the Gemini and Apollo projects. Table II makes a comparison between these programs. As can be seen, the maximum mission durations are similar although this does not mean to imply that each space flight associated with these programs will be 14 days long. In fact, the majority of the Gemini flights will be of 2 to 7 days duration. The atmosphere for both programs will be similar as will the water source and the type of food. Main differences in the programs from a space feeding aspect are in free volume available, pressure suit utilization, and in drinking water temperature.

Movement in Gemini will be restricted to the crewman turning in his seat. Both astronauts will have pressure suits on continually during all Gemini flights. There is, however, provision for removing the helmet and gloves, if desired. There is no provision in Gemini for either heating or cooling of the drinking water which will be maintained at cabin temperature (80° to 100° F). In Project Apollo the crewmen will have more area to move around in and for the most part will be in a shirt-sleeve environment. There are plans that one of the three crewmen will be in a pressure suit at all times.

TABLE I.—*Food Eaten—Mercury Spacecraft Flights*

Flight	Date	Astronaut	Duration	Food eaten
MR-3 (Suborbital)	May 5, 1961	Shepard	15 min, 22 sec	No food aboard.
MR-4 (Suborbital)	July 21, 1961	Grissom	15 min, 37 sec	No food aboard.
MA-6 (Orbital)	Feb. 20, 1962	Glenn	5 hr, 5 min, 10 sec	Pureed applesauce, tubed.
MA-7 (Orbital)	May 24, 1962	Carpenter	4 hr, 55 min, 36 sec	Cubes, high calorie blend.
MA-8 (Orbital)	Oct. 3, 1962	Schirra	9 hr, 23 min, 6 sec	Pureed peaches, beef, and vegetables, tubed.
MA-9 (Orbital)	May 15 and 16, 1963.	Cooper	34 hr, 31 min	Rehydratable foods; bite size ready-to-eat foods.

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TABLE II.—*Comparison of Gemini and Apollo Missions*

	GEMINI	APOLLO
Crew	2	3
Mission duration	14 days	14 days
Atmosphere	5 psi, 100% O_2	5 psi, 100% O_2
Environment	Pressure suit	Shirt sleeve
Free volume	40 ft³/man	70 ft³/man
Water	Fuel cell	Fuel cell
Water temperature	80° to 100° F	50° and 155° F
Food	Freeze-dehydrated	Freeze-dehydrated

The prime design requirements for all spacecraft systems are as follow:

Minimum weight and volume
Minimum power usage
Reliability
Ease in maintenance
Environmental compatibility
Integration with other systems
Crew compatability

These requirements have been important considerations in the development of the feeding concept for both the Gemini and Apollo missions. In addition to these prime design requirements, consideration had to be given to the qualification specifications to which the feeding concept would be subjected. Some of the conditions for qualifying the food and food packaging are given in Table III.

For purposes of clarity, this presentation will be divided into two areas: Food and Nutritional Design Concepts, and Food Handling and Storage Design Concepts.

FOOD AND NUTRITIONAL DESIGN CONCEPTS

Menus made up of precooked, freeze-dehydrated foods supplemented by bite-size high-energy food pieces are being designed for use in both Gemini and Apollo missions. Reasons for selecting this food concept are as follows:

TABLE III.—*Food and Food Packaging*

Environmental testing requirements	
Temperature	+20° F; +135° F.
Pressure	19.7 psia (70° F); 1×10^{-8} psia (110° F).
Relative humidity.	98 percent in air at 14.7 psia, 100° F.
Atmosphere	100% oxygen.
Acoustic noise	Overall of 135 db, 37.5 to 4800 cps.
Acceleration (launch).	Longitudinal spacecraft axis: 1 g to 7.25 g linearly with time over 326 seconds.

(a) Water will be produced in-flight as a by-product of the fuel cell operation.

(b) Freeze-dried foods have a high degree of acceptance and will allow for rapid reconstitution prior to use.

(c) Freeze-drying offers an excellent method for food preservation not requiring refrigeration.

In designing these menus, consideration has been given to maintaining a low-residue diet which is highly acceptable and which meets all the nutritional requirements specified by the NAS–NRC Food and Nutrition Board with respect to protein, fat, and carbohydrate distribution as well as mineral and vitamin allowances. Present estimate of caloric requirements for planned missions is 2500 kcal per man per day for Gemini and 2800 kcal per man per day for Apollo.

It is extremely difficult, if not impossible, to know exactly what the caloric demands of the astronauts during extended space flight will be. However, it is felt that, based on numerous simulator tests which have been conducted, the present design is realistic. The exact nutritional requirements for space flight cannot be definitized until nutritional balances are performed during actual space flight conditions.

Table IV (a) to (d) gives a typical 4-day-cycle menu which will be utilized in the Gemini program. As can be seen, plans are for the crewmen to eat four times a day. This lends itself to the planned work-rest cycle in that the period of time to prepare and eat any one meal is shortened. It is anticipated that, basically, the Gemini and Apollo menus will be similar. The main difference between the two is a result of the fact that unlike Gemini where water temperatures will be maintained between 80° to 100° F, Apollo will have provision for both hot (155° F), the boiling temperature of water at 5 psia, and cold (50° F) water. This results in a menu of much greater variety and with more rapid reconstitution times than can be designed for Gemini. In addition, careful screening of drinks which have a high acceptance at the rather warm water temperatures anticipated in Gemini had to be accomplished.

In the development of the freeze-dehydrated sandwiches and the other bite-size pieces particular effort has gone into the development of an edible coating which will afford protection against crumbling. This approach has considered materials such as "methocel" which has

TABLE IV.—*Proposed Project Gemini Menu*

(a) Days 1–5–9–13

Meal A	Meal B
Sugar frosted flakes Sausage patties Toast squares Orange-grapefruit juice	Tuna salad Cheese sandwiches Apricot pudding Grape juice
Meal C	**Meal D**
Beef pot roast Carrots in cream sauce Toasted bread cubes Pineapple cubes Tea	Potato soup Chicken bits Toast squares Applesauce Brownies Grapefruit juice

(b) Days 2–6–10–14

Meal A	Meal B
Strawberry cereal cubes Bacon squares Peanut butter sandwiches Orange juice	Corn chowder Beef sandwiches Potato salad Gingerbread cubes Cocoa
Meal C	**Meal D**
Shrimp cocktail Chicken and vegetables Toast squares Butterscotch pudding Apple juice	Beef with vegetables Spaghetti and meat sauce Toast squares Fruit cake (date) Tea

(c) Days 3–7–11

Meal A	Meal B
All star cereal Bacon and egg bits Toasted bread cubes Orange juice	Beef and gravy Green beans in cream sauce Toasted bread cubes Banana cubes Tea
Meal C	**Meal D**
Pea soup Salmon salad Potato chip cubes Fruit cocktail Grape juice	Pineapple juice Chicken sandwiches Beef sandwiches Chocolate pudding Pound cake cubes

(d) Days 4–8–12

Meal A	Meal B
Apricot cereal cubes Ham and applesauce Cinnamon toast Cocoa	Beef bits Potato salad Fruit cake (pineapple) Grape juice
Meal C	**Meal D**
Orange-pineapple juice Chicken salad Peanut butter sandwiches Peaches	Mushroom soup Chicken and gravy Toast squares Banana pudding Apricot bits Tea

no nutritive value, as well as coatings which would offer some energy. The second approach appears more appealing in that it offers a method of increasing the caloric density of the pieces and, in addition, does not increase the residue of the diet. Research and development efforts in this area to date, however, have not produced a completely satisfactory edible coating.

FOOD HANDLING AND STORAGE DESIGN CONCEPTS

The concepts being developed for food handling and storage design consist of the freeze-dehydrated food items packaged individually in a zero-g feeder, and bite-size items packaged in dispensers. These, in turn, are overwrapped in either man-day packages or man-meal packages depending on the available storage volume and mission duration. All the food packages will be stored in metal containers which become the waste storage containers as the food is utilized. Water will be dispensed in the Gemini spacecraft by means of a pistol-type probe which in addition to providing a method for rehydrating food, will be utilized for drinking water through the helmet during emergency pressurization of the suit. There will be no provision for the metering of water in the Gemini spacecraft; therefore, the crewmen must be thoroughly trained to rehydrate their food by visual inspection. In the Apollo spacecraft there will be water metering devices on both the hot- and cold-water supply taps. In addition, a water probe similar to that provided in Gemini will be utilized for drinking water both normally and during an emergency.

In the design of the food feeder, one of the most important areas of consideration was that of a suitable packaging material. The design properties of a suitable material are as follow:

Water vapor barrier
Oxygen barrier
Minimum bulk and weight
Puncture resistant
Heat sealable
Transparent
Flexible
FDA approval

Since the food utilized will be freeze-dried to a moisture control of about 3 percent, the feeder material must contribute to the protection of this food by providing a barrier to water-vapor transmission. So, too, the feeder material must supply an effective gas transmission barrier in the 100-percent-oxygen environment. Weight saving can be accomplished by the development of a strong lightweight puncture-resistant film. The material must be easily heat sealable since this is often the weakest area in the construction of a pouch. The feeder pouch must be transparent and flexible in order to aid the crewmen in identifying, reconstituting, and eating the dehydrated foods. Finally, in order to maintain the top quality and acceptability of the food, the material must be completely free of foreign odors; in addition, the material contacting the food must have FDA approval.

Needless to say, no one material was found which had all the desirable properties discussed. As a result, the packaging material considered acceptable for space flight is a four-ply lamination of films.

The design of the food feeder was predicated on the requirement for eating in the zero-gravity state. The important design considerations resolved around a flexible container from which foods can be squeezed directly into the mouth without any loss of the contents (fig. 1). Such a feeder must have provision for both the rehydration of the food as well as for eating. Initial attempts to design an acceptable feeder were tested by Astronaut Cooper during MA–9 spaceflight. The design consisted of a feeder having a single tube for both rehydrating and for eating (fig. 2). The water dispenser utilized consisted of a type previously used for drinking water but modified with a cone-like fitting for integration to the feeder. As has been reported, Astronaut Cooper had difficulty rehydrating food with this concept. Most of the difficulty can be attributed to a low water delivery pressure in conjunction with an inadvertent leak evidenced in the body of the valve. Many important observations were made by Cooper which have helped immensely in the redesign of the feeder and water dispenser. Among the most pertinent were:

FIGURE 1.—Use of flexible container.

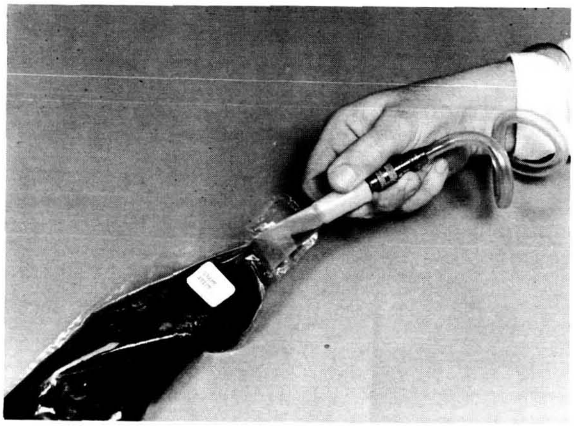

FIGURE 2.—Single tube concept.

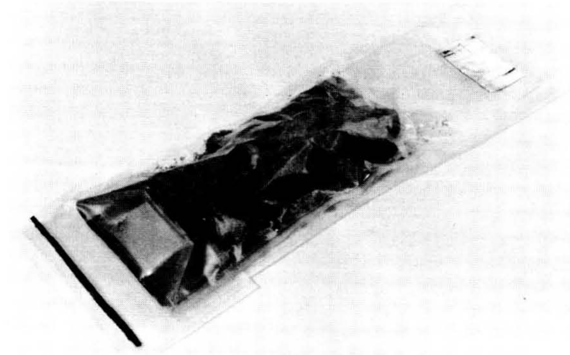

FIGURE 3.—Redesigned food feeder.

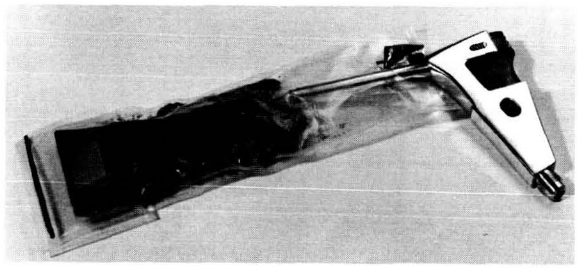

FIGURE 4.—Pistol-type-probe water dispenser.

(a) In the weightless condition the water tended to remain around the neck of the feeder

(b) The water added tended to follow the water dispenser when it was being removed from the feeder

(c) If and when the water made contact with the food it was quickly absorbed

(d) The water dispenser ideally should be capable of being actuated with one hand

(e) The water dispenser should be designed to preclude any water from getting into the spacecraft atmosphere

Taking these observations under consideration, a new food feeder was designed, which has two separate openings, one for reconstituting and one for eating (fig. 3). The rehydration port was designed with a one-way flapper valve and cover tab located on an area of the feeder which will allow the water dispenser to come in contact with the food when inserted (fig. 4). In addition, a pistol-type-probe water dispenser has been developed which seals off by means of a O-ring at the tip of the probe. The results of recent tests with the redesigned feeding concept, conducted in zero-g flights at Wright-Patterson Air Force Base were encouraging but not completely satisfactory. Slight leakage of the feeder one-way flapper valve was observed as was the tendency of the very thin cover tab to become distorted during removal which precluded its correct replacement after addition of the water. Efforts are now being expended to overcome these shortcomings by slight alteration in the design of the feeder rehydration valve and cover tab. Another series of zero-g tests will soon be conducted on this approach.

The bite-size pieces which will be used in the Gemini and Apollo programs will be stored in flexible dispensers (fig. 5). Experiences from

FIGURE 5.—Bite-size food in flexible dispensers.

past Mercury flights indicate that extreme care has to be taken in order to avoid repetition of the highly exaggerated, yet infamous, "crumbling cookie" episode. It appears that with the development of a suitable edible coating and by maintaining careful attention as to how these pieces are handled from the time they are packaged to the time of launch, that we should be able to preclude crumbs from entering the spacecraft environment. Scissors will be utilized by the crewmen to open both the food feeders and bite-size-piece dispensers. This affords the simplest and most reliable method of entry. It is hoped that the prototype dispensers will also soon be evaluated under zero-g conditions.

Before concluding this section on food handling and storage, there are two other extremely important design requirements which should be mentioned. One is the requirement for a method of precluding the individual food items in a meal from floating around the spacecraft during preparation and handling (fig. 6). The solution to this problem which was worked out during previous Project Mercury space flights was found to be the use of small tabs attached to the food feeder which could be anchored to its mating counterpart strategically located in various areas of the spacecraft. Experience has demonstrated that it requires very little surface

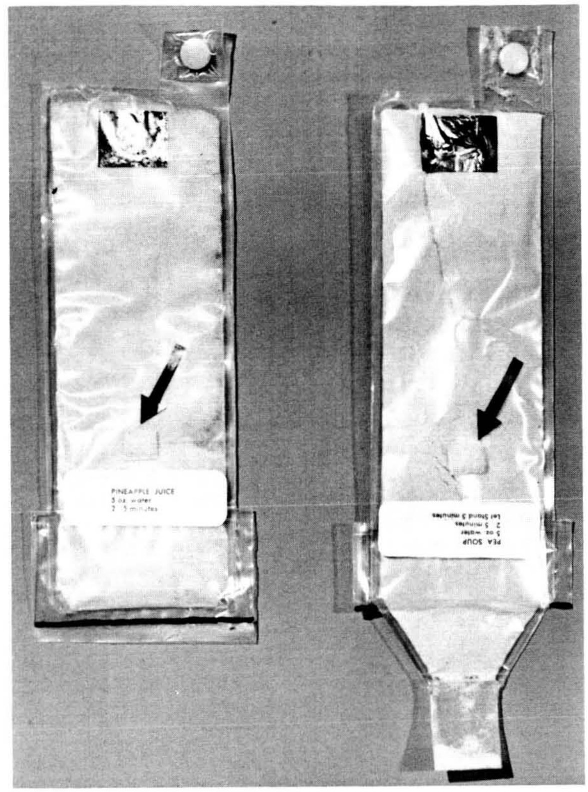

FIGURE 6.—Foods packaged to preclude escape during handling.

contact between the mating parts to provide a secure anchor for the food item.

The other design requirement worthy of mention at this time is the necessity for providing a method for coping with any food wastes which might be generated during a mission. Present plans call for germicide tablets, supplied either in a dispenser or attached to each food package, to be added to any food feeder having waste food or drink prior to its storage. Tests have demonstrated that, in this manner, putrefaction of the waste food and its concomitant gas production can be minimized or eliminated.

DISCUSSION AND CONCLUDING REMARKS

The original design of the space feeding concept for Projects Gemini and Apollo was to provide a nutritionally adequate diet which is highly acceptable, light in weight, easily handled in zero-g, and requires the minimum of storage volume. It is felt that the feeding concept described which requires approximately 1.3 lb/day/man in a volume of approximately 110 cu. in./day/man does approach this goal. This is not to imply that no other problem areas exist. We are well aware of the further work required in the development of a leak-proof food feeder, edible food coatings, and bite-size food dispensers as well as the continual upgrading of the space flight diet as new and improved food varieties are developed. Included in this will be a close look at a high-consistency-food concept which could conceivably allow the crewmen to utilize forks or spoons for eating. Such a concept has been proposed and developed; however, it cannot be incorporated into the existing menu until such time as a thorough test program has established its physiological and psychological acceptability.

The desirability and necessity for obtaining nutritional balances during flight were pointed out previously. We are investigating the use of formula diets for this application, realizing that this is the only way that nutritional requirements for space flight can be established. The effects of space flight stresses must be established prior to flights of longer duration than those presently programed. I do not think that this requires the use of a formula diet in all Gemini and Apollo spaceflights. However, I do feel that a certain flight or flights using such a diet should be programed. The required number of such flights would be predicated by the information or results obtained. The details of a nutritional experiment are presently being worked out in anticipation of inclusion on a Gemini flight.

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Discussion: Preparation, Handling, and Storage of Foods for Present Space Projects

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In the preceding paper it was pointed out that the Gemini and Apollo diets are adequate, in the light of present knowledge, but the flights to date have not shown any real need to concern ourselves about nutrition, and changes can be made as information is obtained from future flights of longer duration. I am sure changes will be made. The basic life-support design requirements have set the requirements for the food and food packaging; such things as cabin temperatures, humidity, and water temperature have had a considerable impact upon the type of food and the food packaging which has been used.

It is worth noting that the semisolids and bite-size pieces that were used for the suborbital and orbital flights through MA–8 were available as a result of foresight by the Air Force in placing a requirement upon the Armed Forces Food and Container Institute to develop products like these several years ago. If it had not been for this, we probably would not have had food capable of being flown on the Mercury missions. Work on freeze-dehydrated foods was also initiated at the Armed Forces Food and Container Institute, but the requirements were much less severe than the present requirements. This was especially true of stability and temperature of water for rehydration.

These dehydrated foods were a spinoff of the Army's extensive ration development program based primarily on freeze-dehydration. The present requirements essentially require stability for 6 months at 100° F. We would like to reduce these stability requirements, because this would allow for some increase in variety, but, essentially, we are pushing for 6 months at 100° F; and, short-time exposure to 135° F is also necessary. These requirements put a high stress on some of the food components. The 80° F water for rehydration is something that has plagued us, as far as making up the menus and having sufficient variety and acceptability.

Certainly we must have adequate packaging for dehydrated foods. We know that we have excellent stability in freeze-dehydrated foods, but this would be impossible if we did not have protection from oxygen and moisture (2 percent or less). The requirement for protection under 100° F and 100 percent relative humidity puts a real burden on the packaging.

Figure 1 shows the food available for the last Project Mercury flight (MA–9).

Further development of food components has led to a good many more items. Figure 2 shows two meat items, beef and gravy and chicken and gravy. The problem with the development of these particular components was reconstitution with 80° F water. Therefore, we gave careful attention to several factors, primarily in special trimming of all fat from the meat to make sure there was no residual fat that would inhibit the rehydration and in the development of special gravies that would rehydrate with 80° F water. By mixing the meat and gravy together, freezing and cutting in blocks, and then freeze-drying, we were able to get more uni-

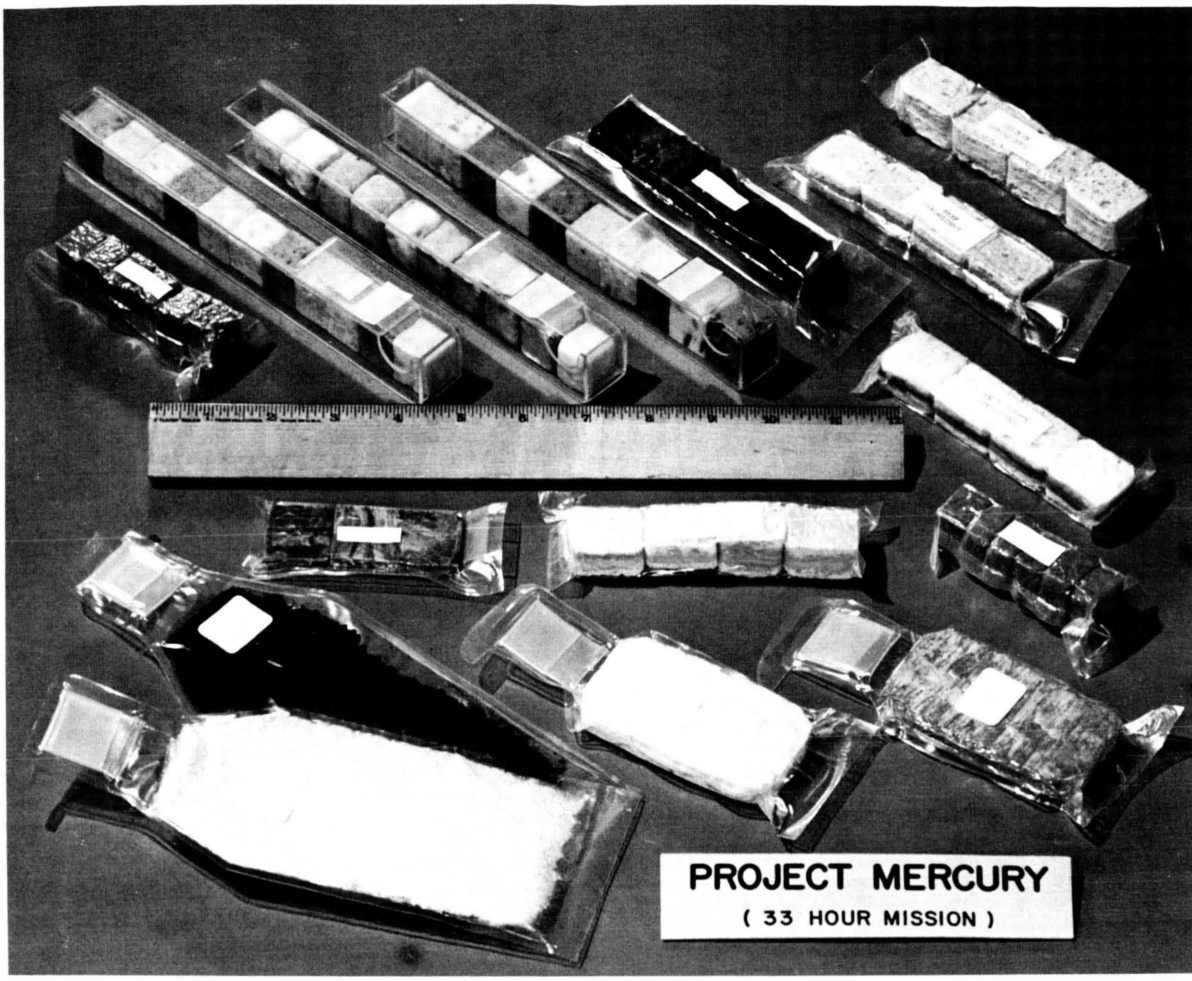

FIGURE 1.—Project Mercury MA-9, 33 hour mission.

form distribution of flavor, although it is difficult to get full flavor at 80° F. We also improved stability; all the components were at the same moisture level because the whole block is freeze-dried as a unit. We also had good portion control, because the weights could be controlled. There was no problem of weighing out an individual quantity; the blocks themselves determined the portion control, and we had a more compact configuration for packaging.

The need for bland foods restricted use of some seasonings and also reduced acceptance at 80° F, because, generally, heat brings out a considerable amount of flavor. Tomato could have

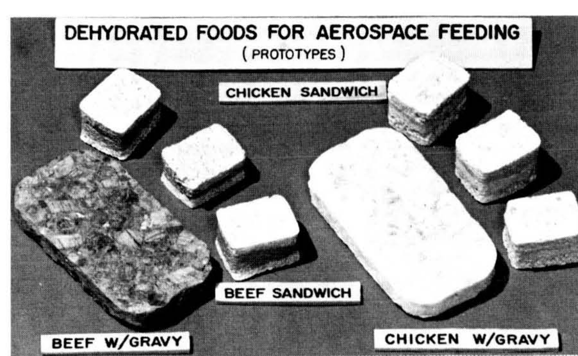

FIGURE 2.—Beef with gravy, chicken with gravy, beef sandwich, chicken sandwich.

been used to improve flavor, but there were problems of stability; for the same reason butter could not be used. The piece size was very carefully controlled, so that it would pass through the three-quarter-inch opening of the tube; we had to do this carefully, so that we would not have too much fine material and lose textural properties. The pieces were carefully cut to about one-fourth of an inch.

Rehydration within 15 minutes at 80° F restricted the variety, as it essentially eliminated use of alimentary pastes. There was only one product with an alimentary paste. This was spaghetti and meat; it was a real problem because the alimentary pastes will not rehydrate well without giving a starchy taste at 80° F. However, we did come up with one product.

We also have a problem with fragility, which we think we have partially solved. We prefer the block shape because food is easier to load in this configuration; therefore, we need to reduce the fragility.

The sandwiches shown in figure 3 are bite-size, freeze-dried, and are soaked in gelatin and coated with acetylated monoglyceride on the edges to prevent crumbling. These coatings also boost calories. The sandwiches are rehydrated in the mouth.

Figure 4 shows salad items. We tried to increase variety with products which were normally eaten cold. We tried several varieties; the biggest problem is fragility—especially with potato salad and chicken salad which are very hard to keep in block configuration for ease of packaging.

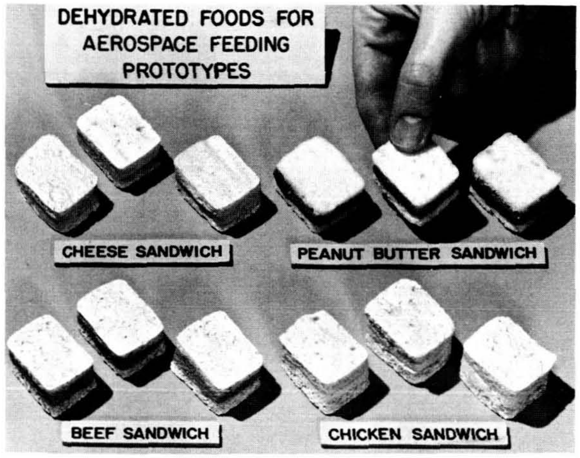

FIGURE 3.—Sandwiches—cheese, peanut butter, beef, chicken.

Figure 5 shows the kinds of fruit and vegetable items available. The problem with the vegetables is that they have few calories. We therefore had to use a cream sauce, and this was not too well liked. Also, the vegetables do not feed well through the tube. We are now attempting to achieve a better sauce for the green beans. The carrots are very susceptible to oxidative rancidity; therefore we are thinking of replacing this item with freeze-dried corn. The fruit cocktail and the peaches are

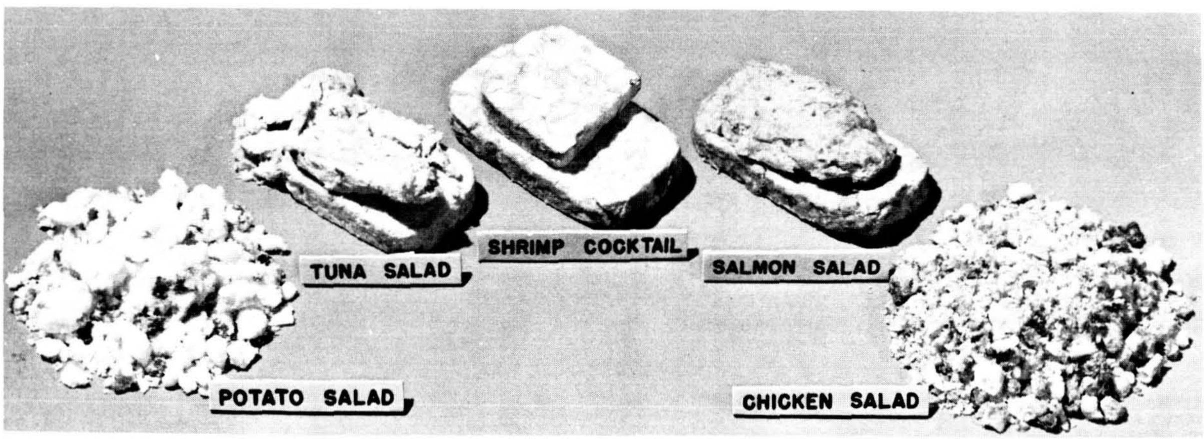

FIGURE 4.—Salads—potato, tuna, shrimp, salmon, chicken.

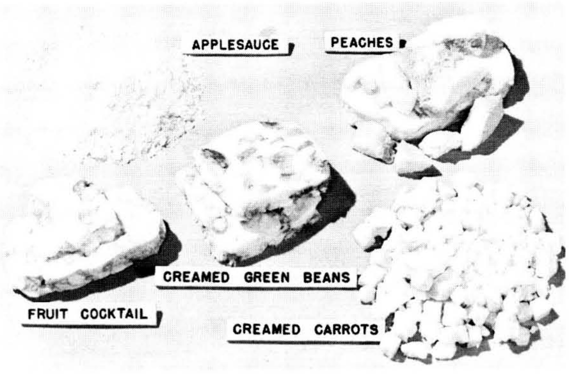

FIGURE 5.—Vegetables and fruits—green beans, creamed carrots, fruit cocktail, applesauce, peaches.

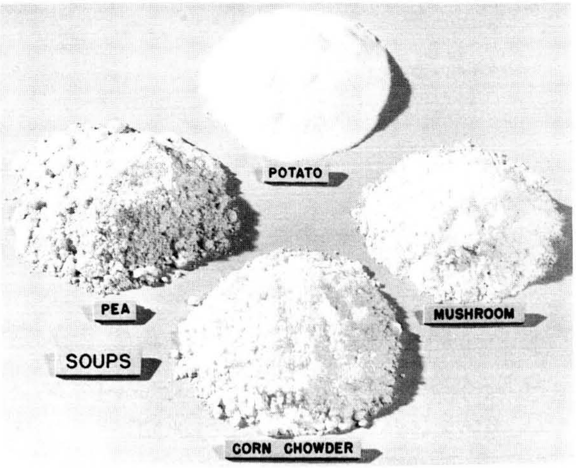

FIGURE 6.—Soups—corn, pea, potato, mushroom.

freeze-dried with a combination of sucrose and calcium cyclomate for sweetness and for control of puffing which occurs with sucrose alone.

Figure 6 shows four soups which are not freeze-dried but are mixtures of ingredients. The greatest problem is acceptability at a serving temperature of approximately 80° F. Personal preferences also increase the problem of providing variety. Calories are boosted with a high-fat nondairy-type coffee creaming agent.

Figure 7 shows four puddings that have been developed using this calorie booster. It imparts desirable body to the product although some people can detect a slight off flavor.

Figure 8 shows the variety of juices available. These are not freeze-dried. They are dried on a cold roll, and the big problem is that the particles have a tendency to stick together when they are kept at 100° F under a vacuum; however, the juices do have good flavor. We have boosted the calories by adding corn syrup solids of low sweetness.

Figure 9 shows an array of bite-size pieces. The bite-size pie is only an experimental item. The calories in the toast are increased by the addition of gelatin containing some fat. The problem with these pieces is much the same as that for the sandwiches—crumbling and too few calories to justify them; however, they do offer some interesting variety as far as texture is concerned. We believe they are useful for this reason.

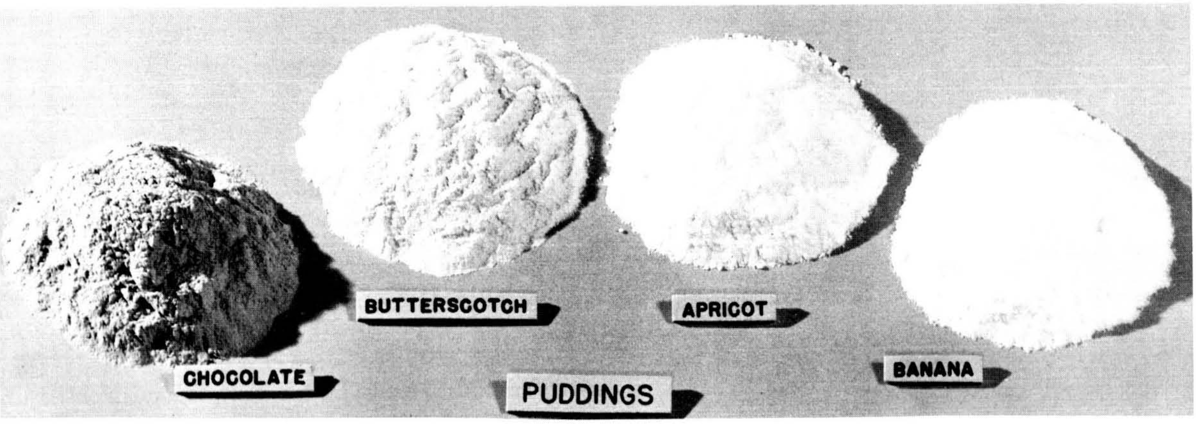

FIGURE 7.—Puddings—chocolate, butterscotch, apricot, banana.

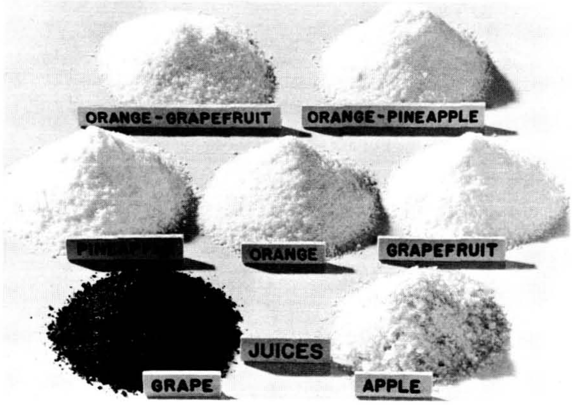

FIGURE 8.—Fruit juices—grape, apple, pineapple, orange.

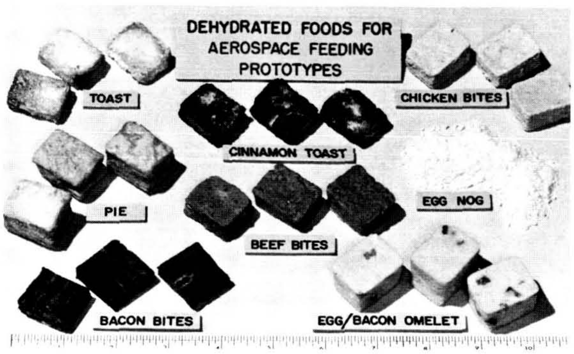

FIGURE 9.—Bite-size foods.

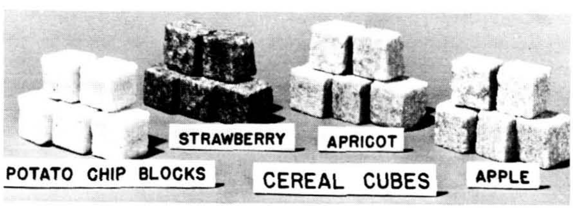

FIGURE 10.—Cubes.

The cereal cubes shown in figure 10 are made with freeze-dehydrated fruits incorporated into something like corn flakes, compressed, and then coated. These give variety and good flavor; they are quite high in calories and provide variety of texture.

There are several other types of bite-size pieces, one with a coating used essentially for desserts where loss of moisture from brownies or pound cake is prevented by coating with a slightly sweet carrier. The problem is to find coating to withstand the 135° F temperature. We also have what we call a fruit cube; this is freeze-dried fruit, strawberries, apricots, and so forth, incorporated in a bland carrier. In order to meet the high temperature requirements, a high-melting-point fat is essential and this decreases palatability. After high-temperature storage some off flavor is developed in the milk solids used as one of the ingredients of the carrier.

Figure 11 shows two types of breakfast cereals. Sugar and instant nonfat milk have been added and the product has been broken slightly in order to facilitate passage through the opening in the food container. Additional variety is possible in order to satisfy personal preference. Also shown are cocoa beverage and tea which have been included to add to the variety of components normally consumed at lower temperature.

In packaging, there was a real problem in getting the right combination of transparent materials. We are very fortunate that there is a new material on the market that has a very low moisture transmission and good protection from oxygen; by combining this with several other materials into a four-ply laminate, we have good protection.

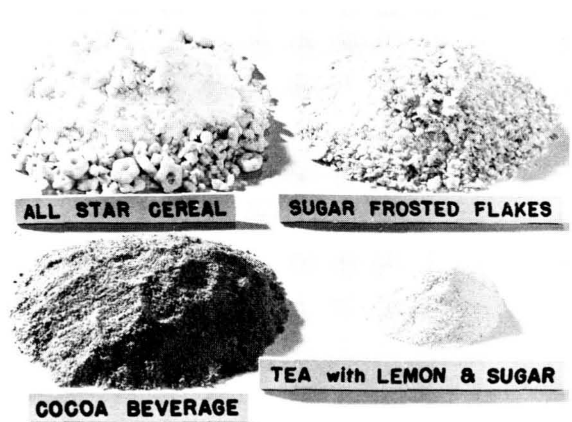

FIGURE 11.—Breakfast cereals, cocoa, and tea.

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Nutrition and Stresses of Short Term Space Flight

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The nutritional requirements for short-term space flights which are most likely to be affected by the expected stressors and operational malfunctions or both, especially that of the Environmental Control System, are water and calories. Evidence accumulated under simulated or analogous situations on Earth would indicate that calcium and protein imbalances may occur. Experiments have been proposed to study selected nutritional parameters during Gemini missions of increasing duration.

The physiological stressors associated with space flight, such as exposure to acceleration-deceleration, vibration-impact, noise, reduced and/or altered atmospheres, radiation, and weightlessness can, in many instances, be considered potentially as hazardous during the early short-duration missions (up to 14 days) as during extended flights. The primary reasons are that the early flights of typical early operational missions were complicated by the elements of inexperience and the definite engineering design constraints imposed by space, weight, and power limitations characteristic of initial exploits.

Historically, during the initial experimental trials of manned systems, such as in submarine or high-performance aircraft, the test pilot or crew had been in a situation where, beyond the need for skill, stamina, and the reliance on the human capability to react and/or adapt to adverse environments, there had been a greater assurance of safety since the experimental system could be tested in stages rather than all at once. For example, the point of no return was some critical speed or depth. In addition, the experimenter was not expectea tc be an experimental subject at the same time. Space flight is a situation where the lack of physiological knowledge pertaining to the total environment of space, coupled with the previously mentioned engineering constraints precludes the pilots or crew from being considered only as experimenters. However, participation as an experimental subject must not in any way compromise the primary functions of the experimental test pilot or crew member.

No matter how great the skill, stamina, and experience of the test pilot or crew, extended space flight is definitely capable of being limited by man's ability to acclimatize to new environmental situations. There is little doubt that the astronaut is capable of adapting to short-duration space flights given the proper life-support equipment; however, if physiological and metabolic adaptation to this new environment actually occurs, it could jeopardize his return to Earth. This would create a need to readapt to a set of environmental factors which are now foreign and capable of provoking serious incapacitating effects.

MAJOR SPACE FLIGHT STRESSES

Short Duration and Emergency Stresses

For the purpose of this presentation, which is to discuss the space flight stresses of major concern from a point of view of nutrition, the stressors can be narrowed to a few of principal concern. The short duration of the acceleration-deceleration, vibration-impact, and the high-intensity noise phases encountered during a routine mission, although capable of being of a severe nature, can by careful spacecraft design and many other factors be attenuated to be within preestablished tolerance limits. Emergency conditions which hopefully will not occur during a routine mission profile, but which must be anticipated are listed as follows:

Emergency Conditions

[Unpublished data from the Douglas Aircraft Co., Inc., 1964]

DECOMPRESSION
- Meteor puncture
- Structural failure
- Hatch failure

EXPLOSIONS AND FIRES
- Experimental hazards
- Electrical fires
- Pressure excesses
- Fuel ignition

ATMOSPHERIC CONTAMINATION
- Particulate matter
- Acids
- Fuel leakage

IRRADIATION
- Systems
- Personnel

LINEAR AND/OR ANGULAR ACCELERATIONS
- Impact-docking, collision, meteoroids
- Uncontrolled gradual onset—
  - orbit keeping, stabilization, puncture leakage reaction, centrifuge imbalance

SUBSYSTEMS MALFUNCTION OR FAILURE
- Environmental control system
- Ecological system
- Electrical power
- Attitude or guidance control
- Onboard propulsion
- Auxiliary power
- Communications and data handling

PERSONNEL HAZARDS
- Accidental injury
- Disease
- Mental disorder

The lift-off and reentry stressors and emergency conditions are of such duration as to preclude the collection of significant nutritional information; however, it is believed that the nutritional status of the astronaut at the time of the stress could significantly affect tolerance at a time when seconds can pose a major threat to the safety of the crew members, if not the individual in the emergency situation.

Infection and Disease

Frequent and stringent medical evaluations prior to short-term flights will hopefully preclude problems related to infections or other diseases.

Radiation

Exposure to radiation remains a potential, rather than a certain, hazard. Experience to date indicates that for orbital missions, the level of exposure is well within allowable limits. With extravehicular operations and the resultant decrease in shielding, these values may rise. Puncture of the pressurized suit by micrometeorites or by equipment being utilized by an astronaut is probably as great if not a greater hazard. Excursions beyond the parking orbit, such as in the vicinity of the Moon, may increase the risk of significant radiation exposure. Solar flares are a definite hazard and difficult to predict. Exposure without shielding for any long period of time to this radiation or the flux of the Van Allen belt could be lethal. The amount of shielding required under these conditions, that is, prolonged exposure to solar flares and the Van Allen belts, or both, is prohibitive. The tolerance limits which have been recommended for the Apollo missions (by W. L. Gill and S. C. White, Manned Spacecraft Center, in an unpublished document) are given in table I. Most of the research on the relationship between nutrition and radiation tolerance has been with animals. The present accelerated interest in human radiation protection is aimed at meeting long-term mission requirements and very little emphasis has been placed on the potential contribution of dietary radioprotective agents.

Atmospheres

The Manned Spacecraft Center has been actively involved in the direction and support of programs leading to the selection and validation of the atmospheres to be utilized in Gemini and Apollo missions (ref. 1). Based on the results of studies to date, there is no reason, from a physiological standpoint, that an atmosphere of 100 percent oxygen at 5 pounds per square inch absolute cannot be utilized for periods up to 14 days.

In several of the atmosphere validation studies, gross measurements of food and water consumption were made. A screening of these data and the biochemical determinations performed for monitoring purposes indicates that caloric and nutrient requirements are not significantly affected by the exposure to these atmospheres and are comparable to the expected expenditures for sedentary individuals. Subtle changes, however, may be occurring which only precise animal and human nutritional experiments of longer duration would reveal. Current design thinking anticipates that a two-gas life-support system will be utilized in longer missions, and, as a result, nutritional studies should probably be oriented toward these proposed spacecraft atmospheres.

Pressure Suit

The need in Gemini missions for the continual wearing of a ventilated but not pressurized garment is a factor which can be considered as more characteristic of the early short-term flights. It is anticipated that the garment will be partially donned, that is, with helmet and gloves removed 12 hours a day, and that it will be pressurized only during extravehicular activities and emergency situations. In Apollo, only one man at a time in the three-man crew will wear a pressure garment approximately 8 hours a day.

Caloric requirements.—In addition to the definite personal hygiene implications, the continual wearing of an impermeable but ventilated garment has implications on water and caloric requirements. Ongoing research by E. L. Michel, H. S. Sharma, and J. Waligora of the NASA Manned Spacecraft Center indicates that when work is performed, with or without the suit pressurized, caloric requirements are in-

TABLE I.—*Radiation Exposure Dose Limits*

Critical organ	Maximum permissible integrated dose, rem	Relative biological effectiveness rem/rad	Average yearly dose, rad	Maximum permissible single acute emergency exposure, rad	Location of dose point
Skin of whole body	1600	1.4 (approx)	250	500	0.70-mm depth from surface of cylinder 2 at highest dose-rate point
Blood-forming	270	1.0	55	200	5 cm depth from surface of cylinder 2
Feet, ankles, and hands	4000	1.4	550	700	0.07-mm depth from surface of cylinder 3 at highest dose point
Eyes	270	2	27	100	3-mm depth from surface on cylinder 1 along eyeline

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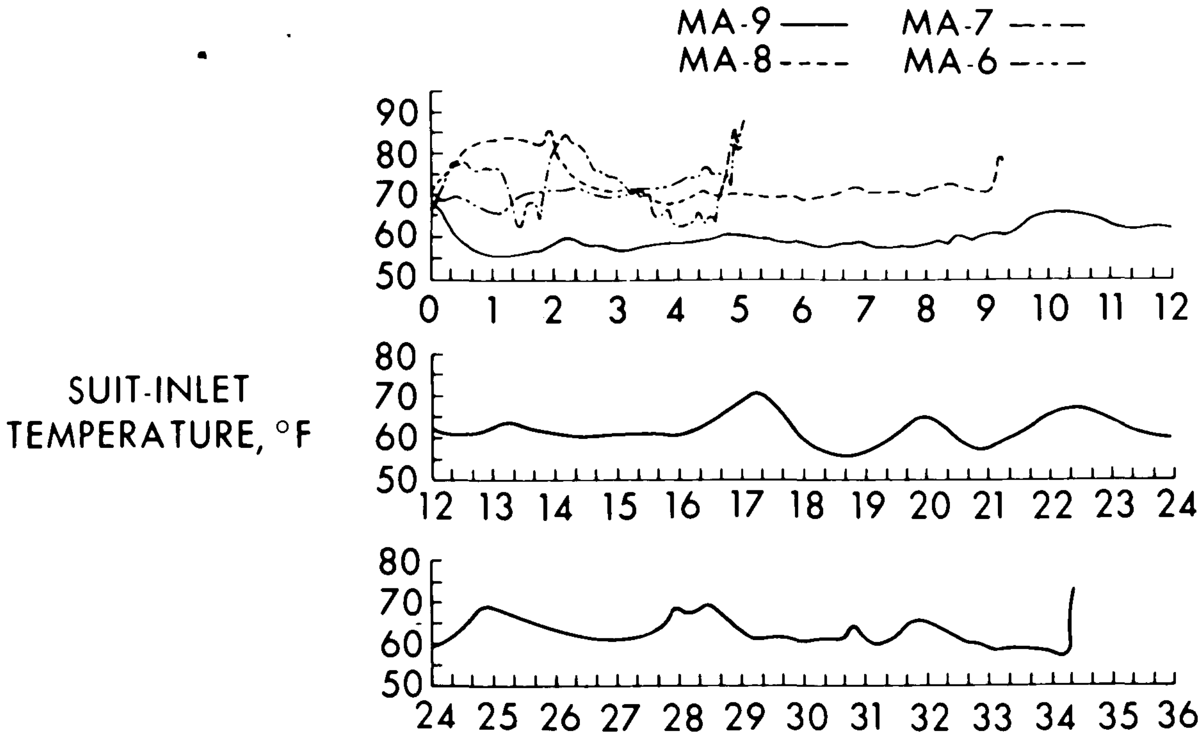

FIGURE 1.—Time history for suit-inlet temperature for manned orbital flights.

creased (table II). This evidence is in agreement with the earlier work of Tiller and Greider (ref. 2) and the recent unpublished work of I. Streimer, D. P. W. Turner, C. A. Tardiff, and T. L. Stephens of The Boeing Co., and E. C. Wortz, T. J. Harrington, O. K. Edwards, and R. Diaz of the Garrett Corp.

Water requirements.—The most critical nutritional parameter affected during flight, especially under suited conditions, is the requirement for water. As figure 1 (ref. 3) indicates, the MA–9 suit-inlet temperatures were considerably better regulated than in the prior orbital flights; however, considerable variation can occur. During the MA–9 mission, active sweating occurred, and, coupled with other factors, the postflight data indicate that water loss was in the vicinity of 0.3 pound (136 milliliter) per hour. Miller (ref. 4) has reported that the daily evaporative water loss at 5 psia is theoretically three times that at 1 atmosphere, or approximately 0.347 lb (157.5 ml) per hour. This substantiates some of his preliminary experimental observations on total evaporative water losses of human volunteers in protective garments pressurized at 5 psig, and ventilated at 15 cubic feet per minute. In a report several years ago an increase was reported in evaporative water losses in nude men exposed to reduced atmospheres (ref. 5). The effect of reduced pressure on water loss is a controversial subject, but there is no doubt that the ventilation rate and the temperature of the inlet air (ref. 6) affects evaporative water losses in suited individuals. Combined with light work (180 kcal/sq m/hr or 1,435 Btu/hr) under pressurized conditions, the cooling capacity of oxygen flow can be marginal, especially if the inlet air temperature is 80° F or more. Conditions favorable for heat dissipation, that is, active sweating with constant body temperature, must be supported by adequate water intake; otherwise, progressive dehydration will ensue. The water requirement for various phases of the Apollo mission as calculated by Billingham, NASA Manned Spacecraft Center, is given in

TABLE II.—*Caloric Requirements*

Activities	Heat production, Btu/hr
Treadmill walking at 0.8 mph: [a]	
Light clothing (normal dress)	520
Space suit, unpressurized	860
Space suit, pressurized 3.5 psi	1520
Space suit, pressurized 5.0 psi	2020
Sitting in mockup activitating switches: [b]	
Space suit, unpressurized	420
Space suit, pressurized 3.5 psi	590

[a]At sea level.
[b]Activating switch once every 5 seconds at sea level.

table III; however, it is assumed that the astronauts will be in water balance. Experience to date indicates that training and prescribed drinking are in order.

Other nutrients.—A report of preliminary nutritional data collected in association with continuous 14-day pressure-suit wear, with the suit uninflated and for the most part of the day partially donned, is given in this volume by J. Vanderveen, et al.

Specific metabolic and nutritional changes under pressurized suit conditions have not been elucidated; however, it is probable that changes will be detected in view of the reported increase in urinary catecholamine excretion associated with the wearing of a pressurized garment (ref. 7). Although long periods of suit pressurization are not anticipated in early flights except under emergency conditions, the duration of routine extravehicular operations will probably increase as flights become more routine and therefore a need exists for data in this particular area.

TABLE III.—*Apollo Water Requirements*

Condition	Water requirement (per man)
Command module, normal operation	6.6 lb/day
Lunar excursion module, normal operation	9.1 lb/day
Command module, decompressed	12.4 lb/day
Lunar excursion module, decompressed	0.81 lb/hr
Lunar surface operations	1.46 lb/hr

Weightlessness

If the lack of stress can be called a stressor analogous to the reactions to sensory deprivation, weightlessness is a very serious stressor. In-flight weightlessness experience to date is given in table IV. Potential adverse effects of long-duration subgravity exposure can be found for every system of the body (table V). However, experience to date indicates that particular concern must be given selected effects, which, during short missions, could impair astronaut function during flight or during reentry. It is also essential to provide valid information to test protective or corrective devices and to obtain information for extrapolation to extended flights. Of immediate concern are the effects of weightlessness upon the following systems: cardiovascular, skeletal, and muscular. Each of these has some degree of nutritional implications. There is increasing evidence that if bed-rest findings are analogous to weightlessness experience, the cardiovascular decrement to tilt table experienced by some astronauts after flight (ref. 3) is the result of decreased venous return secondary to peripheral venous pooling (ref. 8). It is very likely that shifts in body fluid occurred in flight and that, coupled with dehydration previously discussed, further aggravated the response upon return to 1g. It is debatable whether the physiological changes in circulation which apparently occur with weightlessness are simply a readjustment of the "milieu" of a shift which will lead to inferior circulation and consequently incomplete nutrition.

Although the limited in-flight biomedical monitoring data do not reveal evidence of increased urinary calcium, bed-rest findings have consistently revealed significant increases (refs. 9, 10, and 11). Under the latter conditions it is the opinion of Birkhead (ref. 12) that a considerable stimulus, greater than 1 hour a day of moderate bicycle exercise, would appear to be needed to alter observed calcium excretion.

Muscle catabolism as evidenced by negative

TABLE IV.—*Weightlessness Experience*

Astronaut	Launch date	Number of orbits	Flight time, hr:min
United States			
John H. Glenn, Jr	Feb. 20, 1962	3	4:56
M. Scott Carpenter	May 24, 1962	3	4:56
Walter M. Schirra, Jr	Oct. 3, 1963	6	9:14
L. Gordon Cooper, Jr	May 15, 1963	22	34:20
Totals	------------	34	53:26
Russia			
Yuri A. Gagarin	Apr. 12, 1961	1	1:29
Gherman S. Titov	Aug. 6, 1962	17	25:18
Andrian G. Nikolayev	Aug. 11, 1962	64	94:22
Pavel R. Popovich	Aug. 12, 1962	48	70:57
Valery Bykovsky	June 14, 1963	81	119:06
Valentina Tereshkova	June 16, 1963	48	70:50
Totals	------------	259	382:02

nitrogen balance has not occurred in all bed-rest studies—in particular, in those experiments in which a plaster cast of one or more limbs was not utilized. The astronaut will be confined in Gemini flights but not immobilized. In subsequent flights, Apollo, for example, more activity will occur since the vehicle will be larger, and a greater number and duration of extra-vehicular excursions will probably take place. Nonetheless, this potential problem deserves close scrutiny for the reasons previously discussed and because pyschophysiological stresses are believed to be sufficient to provoke negative nitrogen balance (ref. 13).

The question of caloric requirements to perform tasks in a weightlessness environment should be mentioned. The studies reported in reference 14 would seem to indicate that "the tractionless aspect of zero g may cause degradations in the output characteristics of work manually produced by the unbraced operator." Depending on the workload and bracing available within larger spacecraft and during extravehicular operations, as much as a 30-percent increase in oxygen consumption may occur. This is one good reason why caloric estimates cannot be extrapolated only from simulator study data. Actual in-flight measurements are needed.

TABLE V.—*Some Potential Adverse Psychophysiological Effects of Long-Duration Exposure to Zero Gravity*

[Source: Unpublished data from the Douglas Aircraft Co., Inc.]

System	Adverse effect
Cardiovascular	Decrement in response to stress
	Myocardial atrophy
	Cardiac arrhythmia
	Vasomotor instability due to reflex deterioration
	Reduced blood flow
	Capillary fragility
	Hypostatic congestion
Gastrointestinal	Diminished peristalsis and secretion
	Trapped gas
	Constipation
	Liver impairment
Respiratory	Hypostatic congestion (lungs)
	Reduced vital capacity (lungs)
	Inadequate nasal sinus drainage

TABLE V.—*Some Potential Adverse Psychophysiological Effects of Long-Duration Exposure to Zero Gravity*—Continued

System	Adverse effect
Muscular	Atrophy-reduced size and capacity
	Negative nitrogen balance
	Reduced creatine storage
	Fasciomuscular adhesions
Skeletal	Demineralization
	Joint atrophy
	Adhesions
Urinary	Loss of desire to void
	Diuresis
Neurological	Disorientation
	Motion sickness
	Motor skill degradation
	Sensory impairment
	Autonomic reflex deterioration
	Mental aberrations
Endocrine	Maladaptation to stress
	Hypovolemia

IN-FLIGHT EXPERIMENTS

Calcium Metabolism Experiments

Several in-flight experiments have been proposed for one or more Gemini flights. Three of these experiments are concerned with the biomedical problems just discussed.

One experiment would study a facet of the cardiovascular problem, and two experiments are concerned with calcium metabolism. The latter experiments will be outlined here. A demineralization experiment will involve preflight and postflight X-ray measurements of the bone density of the os calcis and the fifth digit of one hand. A calcium balance experiment, which will include nitrogen balance information, will be conducted to study dietary intake and urinary and fecal output during preflight, postflight, and in-flight activities. Blood parameters will be measured during preflight and postflight activities. This latter experiment involves the use of a formulated

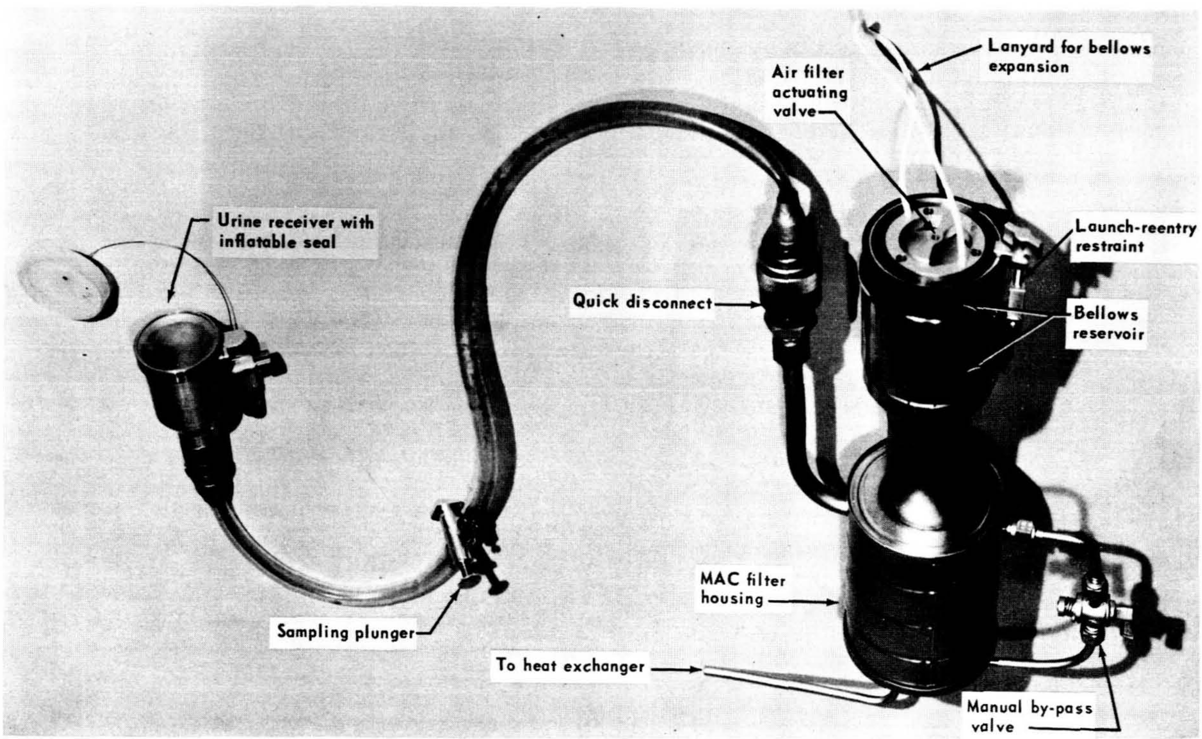

FIGURE 2.—Urine transport system with simulated interface components.

diet of known composition for 2 weeks during preflight, postflight, and flight activities. Several diets are presently being studied for their in-flight suitability.

The results of these experiments are, in addition to the routine biomedical information, collected for monitoring purposes as in the Mercury flights.

In-flight Sample Collection

In flight the urine will be collected in timed aliquots from the Urine Transport System (fig. 2). This device includes a urine receptacle console bellows including filter, volumetric measuring device, and urine sampling device. The remaining urine is filtered and dumped into the heat exchanger.

The defecation glove (fig. 3) also serves as the storage receptacle and the total sample is stored in the storage boxes or emptied food storage boxes.

A considerable number of interface problems are yet to be resolved; however, they are considered surmountable.

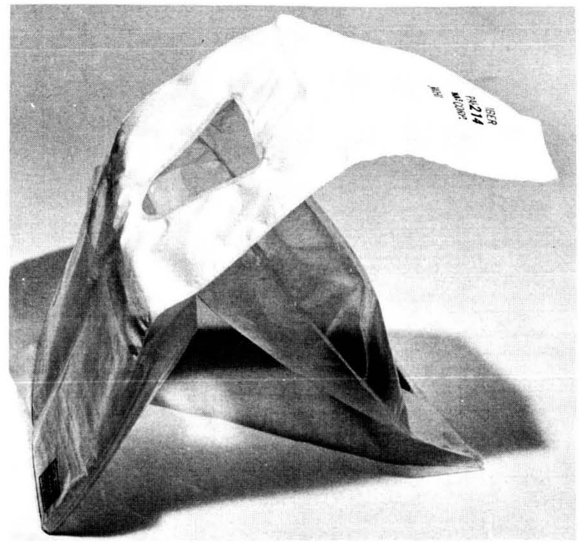

FIGURE 3.—Defecation glove.

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Discussion: Nutrition and Stresses of Short Term Space Flight

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It is generally accepted that, regardless of the stress effects, clinical malnutrition in the conventional sense is not a problem of short-term space flight. However, as the working group on nutrition and feeding, of which Dr. Chichester is Chairman, has pointed out, and as Dr. Voris and Dr. Lachance have emphasized, deficiencies of water or electrolytes could impair the effectiveness of the astronaut and even threaten his life. It is impossible to overemphasize the necessity of not only providing adequate water and salt but also of insuring that it is actually consumed by the astronaut despite all the distractions to which he is subjected. Dr. Lachance has provided a summary of the factors contributing to abnormal water loss under the conditions of space flight.

The increased loss of calcium under conditions of relative immobilization has been mentioned several times. This can be used as an example of the way in which modification of a so-called normal diet may help the body resist an undesirable effect of space flight conditions. Three years ago R. S. Harris and his coworkers at MIT showed in an unpublished report that monkeys with paralytic poliomyelitis fed a diet with a normal 1:1 ratio of calcium and phosphorus, had a markedly increased calcium content of serum and urine. However, changing this ratio to 2:1 or to 4:1 by adding either inorganic or organic phosphate to the diet, reduced the loss by 50 percent. The diet contained calcium 45 and the radioactivity of the bones supported the conclusion that the high phosphorus calcium ratio in the diet decreased bone loss in the partially immobilized monkeys.

If adequate water and salt but no food were supplied, the astronaut could survive on his body stores for many days as has been demonstrated often by voluntary and by forced fasting. He would not, however, be in an optimum physiological or mental state for full efficiency.

If the mistake were made of allowing the consumption of calories without adequate protein, this imbalance could actually interfere with the mechanism for mobilizing body reserve of protein and other essential nutrients.

Furthermore, in balance studies of subjects on low-protein or protein-free diets *and* adequate calories, personality changes have been repeatedly observed. These changes include irritability and difficulty in concentrating on a task; either could be serious for astronauts.

It is in this context that the increased N loss due to stress caused by the various physical and psychological factors to which Dr. Lachance has referred is potentially significant. Most workers who have had experience with metabolic studies in man can recount instances of unexpectedly decreased or negative nitrogen balance in persons receiving presumably adequate protein intake which were thought due to psychological disturbances of some kind; for example, the death of a parent, the disgrace of an illegitimate pregnancy, scholastic failure, or a broken love affair. One published example is well known (ref. 1): the case of a woman in positive nitrogen balance who went into strong negative nitrogen balance for 5 days when she heard that her son had been wounded in Korea. When she received word that he was all right she went into positive balance until she had made up the deficiency; then approximately 6 months later she went through this same cycle again when the boy was again wounded. By and large, such cases are not reported. They occur as isolated instances and laboratory error is almost impossible to rule out in an isolated instance.

With the financial assistance of the Army and the National Institutes of Health, we have been trying at MIT to get objective data on the metabolic defects of certain reproducible situations believed to be stressful. These are presumably similar to, although less severe than, those encountered by members of the armed forces in combat situations or by the astronauts. The results are not spectacular in terms of normal nutrient intakes, but they do indicate that more

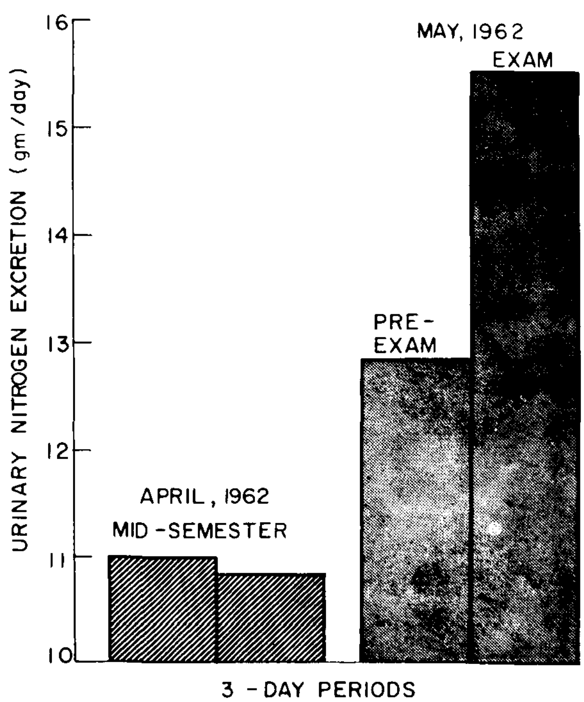

FIGURE 1.—Urinary nitrogen excretion of 11 M.I.T. students during 3-day periods before and during final freshman examination. May 1962.

protein and certain other nutrients are lost from the body under these conditions.

Figure 1 shows the urinary nitrogen excretion of eleven MIT students in 1962 during the 3 days of study period immediately before the final examination of their freshman year, and during 3 days of the final examinations compared with two 3-day periods in midsemester (ref. 2). Eight of the eleven were in negative nitrogen balance in one or both periods of the experimental periods, despite a constant intake of a formula diet supplying approximately 1 gram of protein of high quality per kg per day, which should have been well above estimated requirements.

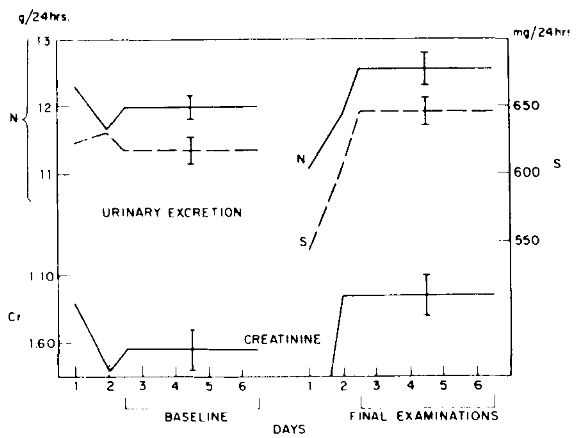

FIGURE 2.—Increase in urinary nitrogen, sulphur, and creatinine excretion for 15 students during examinations.

Figure 2 shows another group of freshmen. Comparison of the baseline with the experimental period indicates that there is an increase in nitrogen and sulphur excretion in the urine and in creatinine excretion although the average differences are not so great as in the previous experiment. (See ref. 3.)

Essentially the same thing was observed with a group of upper classmen during final examinations. The average response was less than in the last two experiments due to the fact that fewer subjects showed a strong reaction to examinations. The behavior of two individual reactors is shown in figure 3.

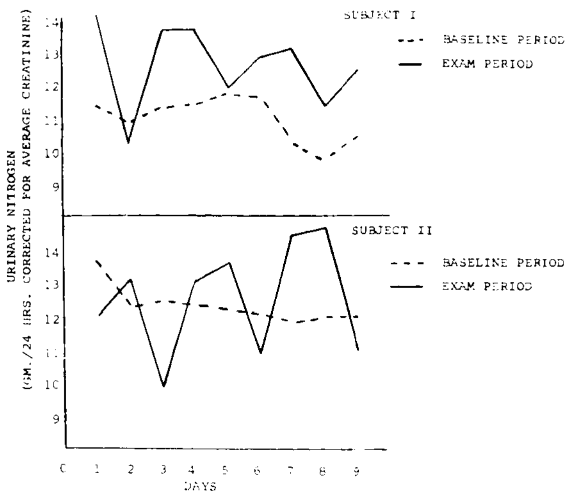

FIGURE 3.—Effect of examinations on the nitrogen excretion of M.I.T. undergraduates receiving a constant protein intake.

The second subject illustrates why the average differences were not significant; the upper classmen and some of the freshmen have recovered periods of higher retention between examinations.

Figure 4 shows a different sort of anxiety phenomena. This is an adolescent high school boy who had a physician father and a psychologist mother who strongly approved and almost required his participation in our metabolic balance studies and thought this would be very good discipline for him. The protein intake of approximately 0.6 gram per kg in a mitmeal III formula diet was supposed to be adequate but for 17 days he continued to lose nitrogen, even without taking sweat losses into account (from unpublished data obtained by Piché, Cholakos, and Vachon). We learned that an adult in whom this boy had some confidence kept repeatedly saying that the experiment was dangerous, that it could produce permanent mental damage and personality change. For this reason, despite the insistence of his parents that he comply strictly with the experiment, he was greatly apprehensive.

When, without previous notice, the same caloric and nitrogen intake, and almost the same food and nutrients as in mitmeal III were given as ordinary foods, there was a distinct change in the pattern of his nitrogen balance as shown in figure 4. When he was given the formula diet once again, he returned to negative N balance and despite the urgings of his parents, soon abandoned the experiment. This subject was one of two close friends participating in the study. The nitrogen balance of the other boy did the same thing up to his return to the formula diet for a second time. It was actually the uncle of this second boy who was responsible for the apprehension. The second boy, when he was put back on the formula diet the second time, stayed in positive balance. The point is, there is much more than nitrogen and caloric intake influencing nitrogen retention; psychological factors can be very important.

Figure 5 shows an increased nitrogen excretion following the complete reversal of night and day (ref. 3). We now have the preliminary results of a longer reversal experiment with essentially the same finding. These differences are not large in magnitude, but they are consistent.

We now also have a study of the metabolic consequences of 2 days of sleeplessness. The sleeplessness nitrogen excretion data follow the same pattern—retention the first day and then greatly increased excretion. The project psychiatrist tells us the main anxiety factor is that the boy wants to sleep but also feels a very strong obligation to comply with the terms of the experiment and stay awake. So, on the second night in particular, he is battling these two opposing influences.

The pulse rate increased during the examination period, as illustrated in figure 6, suggesting some degree of anxiety.

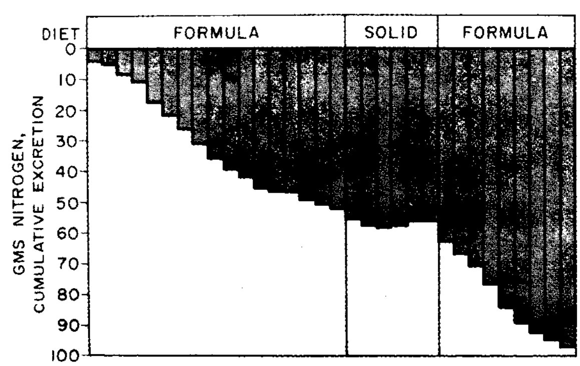

FIGURE 4.—Cumulative nitrogen excretion deficit by days—one subject. Isonitrogenous, isocaloric diets.

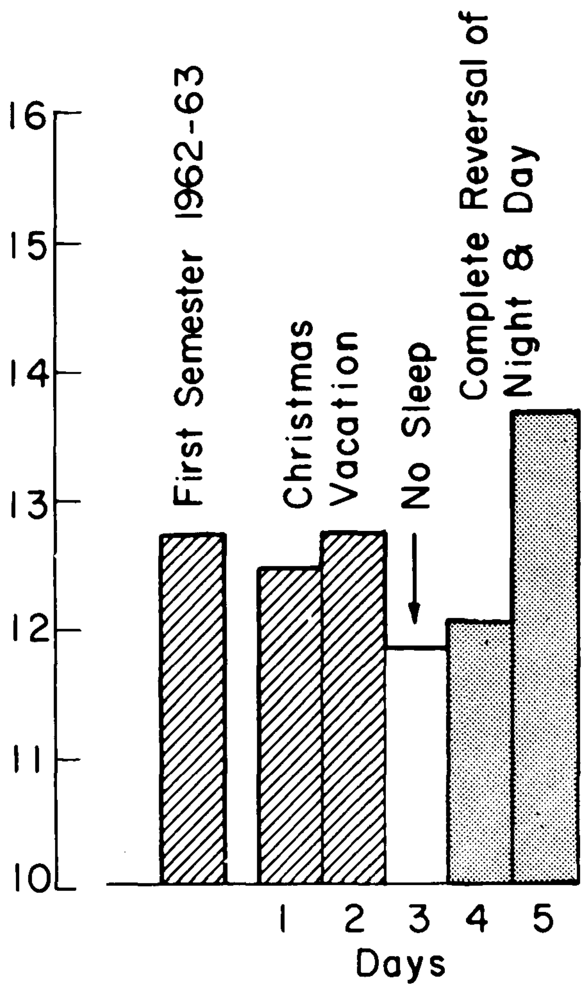

FIGURE 5.—N excretion in 24 hours in six M.I.T. students on sleep deprivation study.

When one is able to measure urinary excretion of 17-hydroxy cortico-steriods by 12-hour instead of 24-hour periods, the differences of figures 7 and 8 are found. There is an increase in the 17-hydroxy steroid excretion in the daytime and what appears to be a compensating decrease in the nighttime.

What is the mechanism of measured nitrogen excretion in stress? This is suggested in figure 8. It is well established that, with infection and trauma, 17-hydroxy steroid excretion by the adrenal cortex is increased. This hormone is catabolic at the level of the muscle and other tissues whose protein is relatively dispensable and anabolic at the level of the liver and perhaps certain other vital organs. The amino

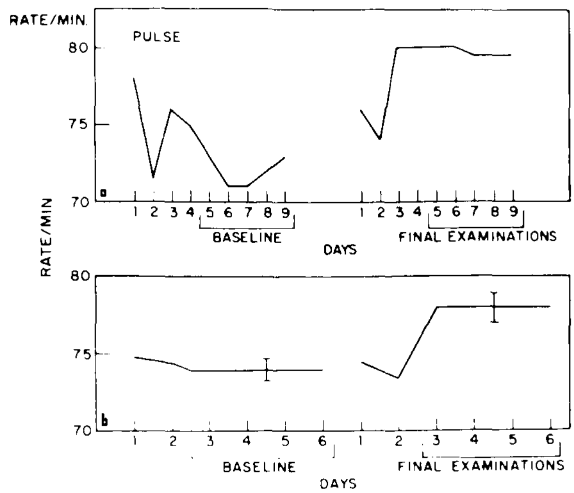

FIGURE 6.—Pulse rate increase during examination period at M.I.T. (a) 11 upperclassmen—winter 1963. (b) 15 freshmen—spring 1963.

acids thus released furnish the liver with raw materials for both protein synthesis and gluconeogenesis. This is the mechanism that enables the child with marasmus, or a starving adult, to consume his own tissues without developing clinical or biochemical signs of protein or other specific nutrient deficiency. This mechanism must also have served a useful adaptive purpose in anxiety situations during the long evolution of man.

In the studies I have cited and in the recent work of Mašek of Czechoslovakia (ref. 4), who describes the similar effects of pain, the stimulus presumably passes from the higher brain centers to the hypothalamus and then to the pituitary-adrenal axis, producing the same end result as the stimulus of trauma or infection. At least this is the most acceptable hypothesis of which I am aware. It is impossible to keep the patient who is in the acute phase of an infection or who is suffering from either surgical or accidental trauma, in positive nitrogen balance without higher than normal protein intake, and this is also true of some psychologically and stressful stimuli. With all of the potential stressors, physical and psychological, postulated by Dr. Lachance, the same may be true of the astronaut, at least during some phases of his mission.

The metabolic response to anxiety is prob-

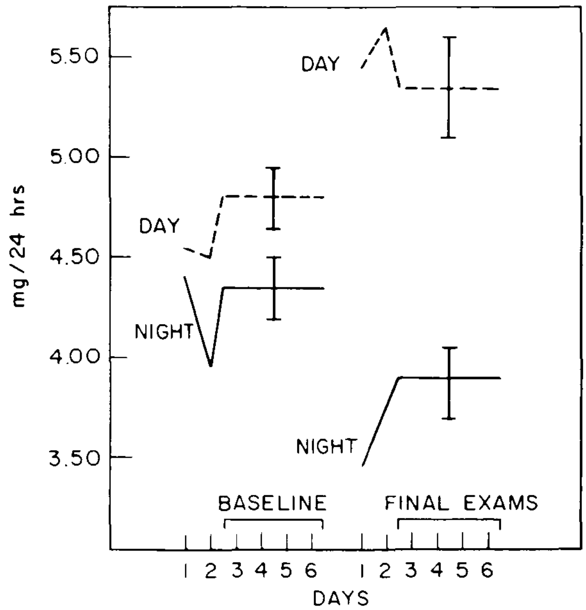

FIGURE 7.—Twelve-hour period measurement of 17-hydroxy cortico-steroid excretion. 15 freshmen—spring 1963.

ably not of much significance for flights of short duration unless it should be combined with a diet excessive in carbohydrates relative to calories. In such an event, I believe it probable that some loss of concentration and increased instability could develop in a few days. How long the effects of anxiety and other stress factors would persist under the conditions of longer space flight remains to be determined. It would probably depend on personality factors and the effects of the coexisting physical stressors which Dr. Lachance has enumerated. The fact that the mobilization of nitrogen from body tissues continues for weeks and even months in children with marasmus, or adults with partial starvation, indicates that the effect of continued exposure to stressors is not necessarily transient. Only metabolic measurements in man during actual space flight can answer the questions raised, and these should be carried out as soon as possible.

I have used the effect of stress on N balance as an example. Individual essential amino acids and various other nutrients are also affected by stress. The simulated space environment studies on earth do not really simulate the complex of stress provoking factors that will occur in space flight. This was very well brought out by Dr. Lachance's paper. Although I agree with Dr. Hessberg that many of these potential stressors are not likely to prove of great significance, some of them may be of critical importance.

My plea is not to let tentative figures, such as were given on the first day of the conference as nutrient requirements of an astronaut, delude us into thinking we know enough at the present time to predict nutrient requirements for space flight with sufficient accuracy. Only metabolic measurements obtained in man during actual space flight can answer the questions raised. It is unfortunate that these measures have not already been obtained to a greater extent. They should be given a high priority for the future.

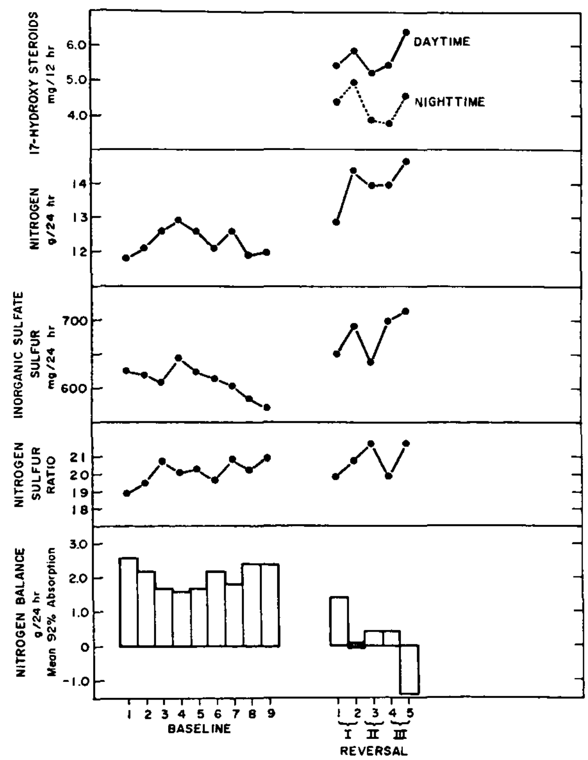

FIGURE 8.—Metabolic changes with reversal of diurnal sleep and work patterns. March 1963. Five subjects.

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Handling and Storage of Food for Long Flights

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INTRODUCTION

Food Management in the Home and in Space

The development of a food management system intended for use in extended manned space flights is superficially analogous to the design of the kitchen found in a normal household. The function of both is to provide facilities for storage, preparation, and serving of food. The magnitude of the operation may also be rather similar, as the size of a space vehicle crew may approximate that of a family. In both situations an attempt is generally made to provide a nutritious and appetizing diet. At this point, however, the similarity ends. In the aerospace field we cannot casually shop the appliance stores for the refrigerator, freezer, stove, kitchen cabinets, and other items needed for a trip to the Moon or Mars.

Very likely, a number of years will pass before all components required for a space-type food management system can be selected "off-the-shelf". The design of hardware components is dictated by the nature of the mission; crew size; duration of the flight or length of resupply period; type of food selected; availability of power; source of water; available space; gravity conditions; and many other factors. It is impossible to meet precisely the requirements imposed by all possible combinations of these variables, with a reasonable number of standardized "appliances". It is necessary, therefore, to custom-design many of the food system components for each specific application.

Further differences between a household kitchen and a space food system should be obvious after consideration of the conditions under which each is operated, the proximity of food sources, food storage time requirements, and other factors.

General Requirements for Space Systems

Despite the wide variation in detailed design requirements, a number of general requirements are common to the great majority of space food management systems. High reliability is always the primary consideration. Operation of the system should require minimum skill and effort, and the safety of the crew must not be jeopardized by malfunction of system components. The more important design criteria are: weight; volume; power consumption; performance level; heat rejection characteristics of the equipment; operating temperature; and compatibility of all materials with flight environments.

The system may be required to operate under conditions of weightlessness, partial gravity, and/or Earth gravity. The handling of food wastes generated by the operation of the system is often an auxiliary function. A modular concept is highly desirable to permit flexibility in arrangement of system components within the space vehicle.

Problems in Logistics

A number of other factors must receive careful consideration in the design of the complete system. Before the problems of storage, preparation, and serving of food are encountered on the space vehicle, means must be devised to insure that the food will reach its destination in acceptable condition. Ground transportation and storage, loading the resupply vehicle, launch operations, docking procedures, and transfer of food to the mission vehicle may involve conditions that will degrade food quality if supplies are not adequately protected.

An Approach to System Design

Solution of design problems encountered in the development of a food management system can best be illustrated by discussion of work currently in progress in the Life Support Department of the Whirlpool Corporation. Although we have engaged in research and development of food products suitable for use in extended space missions, that subject is not within the scope of this paper. We will direct our attention to the storage, retrieval, preparation, and serving of food; the handling of food wastes; and the design of auxiliary equipment directly associated with the space food management system.

The food management system to be discussed is a composite of two systems currently under development in our laboratories. Hardware fabrication is nearing completion on NASA Contract NAS 9-1990, "Design and Fabrication of a Feeding System for Use in Extended Space Station Type Missions." Work on the other, "Food Management System," being developed for General Dynamics/Astronautics, under NASA Contract NAS 1-2934, was initiated just recently. Both contracts involve the fabrication of operating prototypes, with zero-gravity capability, intended for use by four-man crews. Both are predicated on menus consisting predominately of freeze-dehydrated foods. They are based on different mission lengths, and differ somewhat in requirements for auxiliary equipment. The hypothetical system presented in this paper includes components appearing in one or both of these developments, so that the complete range of requirements may be illustrated, and is a composite of the two systems rather than an exact description of either. We assume a 1-year Earth orbital mission with resupply at intervals of 30 days.

Food Management Concept

The system is based on the concept of utilizing dehydrated (primarily freeze-dried), and other room-temperature stable foods, to eliminate requirements for freezers, refrigerators, and ovens or other cooking equipment. As the food items are completely compounded, cooked, and processed before packaging, the necessity for cooking utensils and other food preparation equipment is obviated, as well as dishwashing and cleanup operations. In addition to packaged food, only food storage facilities, a food console, water heater and chiller with metered dispensing means, and seats are required to provide a complete system.

The containers, in which a crew-day supply of food is packed, are later used for the storage of food and packaging waste, which may be removed from the vehicle at each resupply operation.

To use the system, the crewman removes a coded man-meal pack from the food storage rack, seats himself at the food console, rehydrates dry items, opens bite-size items, eats, and discards overwraps, used food packs with uneaten food, and other disposable items in the waste receptacle. The details of these operations will be covered in the following discussion.

HARDWARE DESIGN

Food Packaging

Each dehydrated food and beverage item is vacuum packed as an individual serving in a disposable zero-gravity food package, which is fabricated from flexible, lightweight, transparent plastic laminate with good water vapor barrier characteristics, resistance to puncturing, and adequate physical strength. The food pack, a modification of that developed for Project Gemini, is designed to admit hot or cold rehydration water without spillage, and may be utilized at both normal and zero gravity. Calorie-dense bite-size food items, stable at room temperature, are encapsulated in edible coatings to prevent escape of crumbs. Several such items are sealed into a dispenser package. An assortment of food packages and bite-size dispensers are assembled into a man-meal labeled to permit use at the proper time.

Food Canisters and Storage Racks

An important phase of the food handling problem is delivery of food from the processing facility to the hands of the user. Repeated handling of individual food packages must be avoided to prevent crushing and other damage to the rather friable freeze-dried product. The food must be packed so that any particular item is available at the proper time to insure that the predetermined diet can be followed without difficulty. The logistics of resupply enter into the analysis because space and weight penalties are also important in the resupply vehicle. Unnecessary handling operations should be avoided under weightless conditions present during transfer of supplies from the resupply vehicle. The removal of food and packaging waste must also be considered as part of the overall supply problem.

The logical solution to this delivery problem involves use of the same container, or canister, to carry food from producer to consumer. Arrangement of food packages is not disturbed, adequate protection is afforded, and manual handling is simplified. Size of the canister must be chosen carefully. For a given quantity of food, minimum weight and volume result from use of the largest possible canister, completely filled with food packages. There are other overriding considerations, however. Hatch dimensions limit canister size; a man's arm can reach only a certain distance to the back of a container; he can conveniently carry and manipulate a canister of a certain maximum size; and several smaller canisters can be fitted into irregular storage areas much more efficiently than one large one. Careful study of these factors led to the selection of a canister approximately 9⅜ inches by 9⅜ inches by 9 inches deep. Internal packing efficiency was a further consideration in this selection, because the dimensions of the zero-gravity food packs and bite-size food dispensers had previously been established. On the assumption that four meals are provided for each man during a 24-hour period, a one crew-day food supply (16 man-meal packs) can be packed in a single canister of these dimensions.

The canister, illustrated in figure 1, is fabricated from a drawn aluminum container to provide physical protection to the contents; it has a hinged lid provided with a gasket to seal the canister, a combination carrying handle and lid latch, and a mechanism to allow the canister to be detachably secured to the rack. This design allows the canister to be carried, inserted in the rack, and opened with one hand only. Relief valves and a waste retaining partition are discussed in the section "Food Waste Storage."

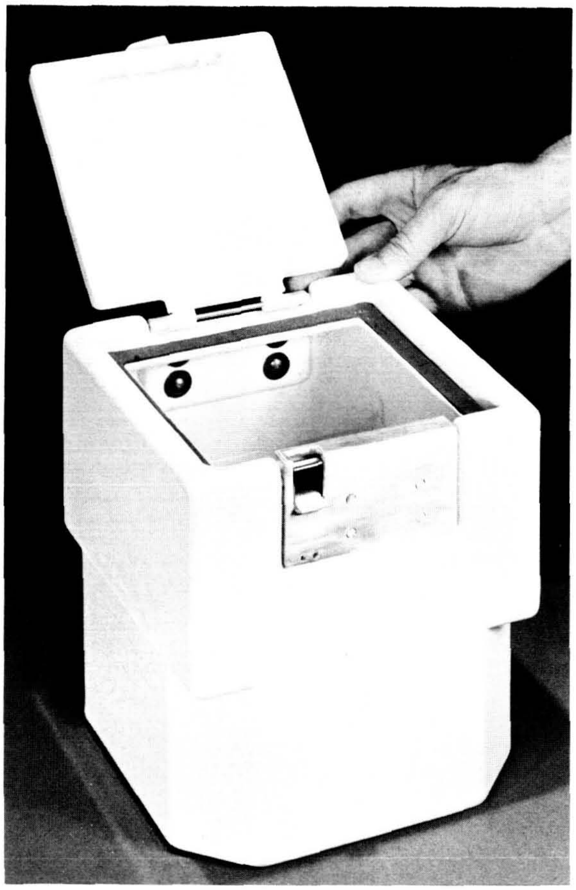

FIGURE 1.—Food canister, open.

The rack and canister are designed to function together as a structural unit. Shells, or "nests", as shown in figure 2, are provided with mounting holes at the rear to permit their attachment to a wall of the vehicle, a bulkhead, a series of channels, or even a special panel. When the required number of nests are installed with the canisters in place, a strong but lightweight structure is formed. Any single canister may be removed without disturbing its neighbors. The rack structure remains assembled throughout the entire mission, the canisters being replaced at the end of each resupply period. A similar set of rack elements are mounted in the resupply vehicle to retain canisters during transportation from earth. This will permit maximum efficiency in use of space on that vehicle. When waste-filled canisters are loaded for return to Earth, the same rack is employed, thereby maintaining the same weight distribution for both legs of the trip.

Water Dispensers

The water dispensers must deliver a measured quantity of hot or cold water for rehydration of food or for drinking purposes. Manual operation of a valve admits water to a metering chamber equipped with a spring-loaded piston. When the chamber has filled with the desired quantity of water the valve is closed, and a second valve in opened to allow discharge of water through the nozzle, or probe, into the zero-gravity food pack. The dispenser is integrated into the water heater or chiller so that the first few ounces of water are discharged at the proper temperature. A sketch of this concept is shown in figure 3.

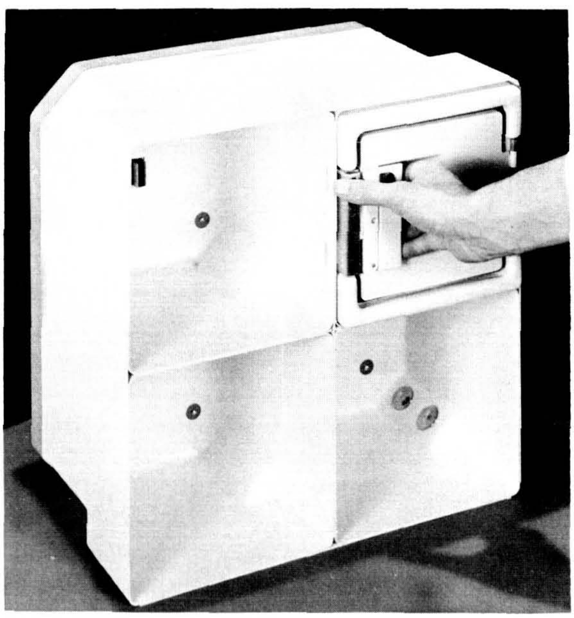

FIGURE 2.—Food canister in rack.

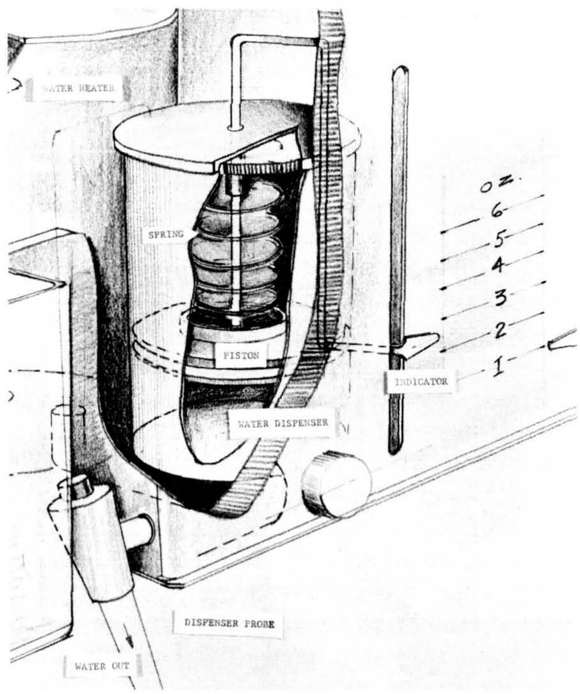

FIGURE 3.—Water dispenser concept.

Water Heater

The problem of heating water under zero-gravity conditions is complicated by the fact that free convection caused by temperature differences does not occur, thereby reducing heat transfer coefficients and inhibiting mixing of water during the heating process. Further, the entire supply of 175° F water is withdrawn within a few minutes during the preparation of meals. Duty cycles and meal schedules permit a maximum recovery period of 3 hours for the heater, assuming that two men eat at one time and four meals are provided for each man during a 24-hour period. A maximum quantity of 3 pounds of hot water is required for each two-man meal period. Heat transfer fluid is provided from another system to heat the water. The heater is designed with a 5-pound capacity tank, baffled to minimize mixing of hot and cold water during drawoff and with heat transfer fluid coils designed to provide the minimum practical distance from a heated surface to any portion of the tank contents. Thermostatically controlled valves are provided to bypass heat transfer fluid around the heater when water has reached the proper temperature. A zero-gravity heater of this general type is illustrated in figure 4.

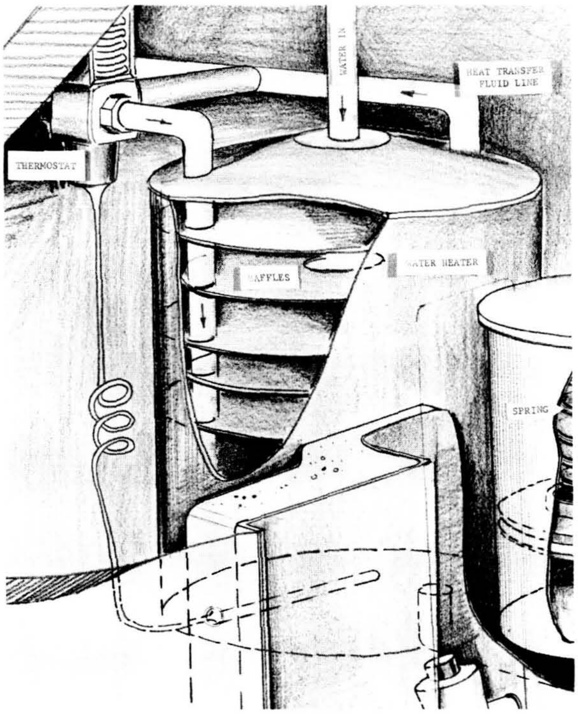

FIGURE 4.—Water heater concept.

Water Chiller

Because cold-water (40° F) requirements are similar to those for hot water, the same basic design concept is used in the heater and chiller. The controls for the chiller are changed as required, and minor modification of heat transfer area is necessary.

Feeding Console

Food console dimensions are specified as even multiples of canister dimensions. This modular approach permits location of the console in any convenient area of the canister bank. The console combines the food preparation and eating areas. The water dispensers, with heater and chiller mounted to the rear, are accessible for drinking purposes when the console is closed, as shown in figure 5. A hinged portion of the console may be folded downward at mealtime (fig. 6) to provide facilities for food preparation by

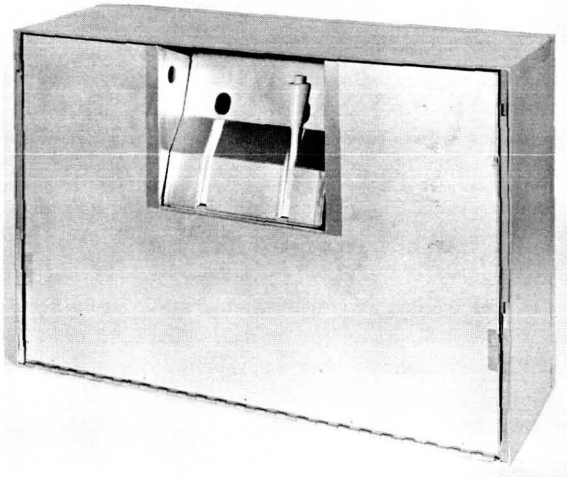

FIGURE 5.—Feeding console mockup, closed position.

FIGURE 6.—Feeding console mockup, open position.

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two men at the same time. Seats with belts and telescoping legs, initially stored in the console, provide restraint for the crewmen during the eating operation.

Under zero-gravity conditions, the man-meal pack is removed from the food canister, the overwrap is discarded, and the zero-gravity food packs are placed in insulated compartments in the upper portion of the console shelf. Bite-size items are placed in elastic retaining bands at the side of the shelf. Each food package is then removed from the insulated compartment, filled with the specified amount of hot or cold rehydration water from the dispenser, and returned to the insulated compartment where serving temperatures are maintained throughout the meal. After the few minutes required for rehydration, a food pack is removed and squeezed to force contents into the mouth as desired. Bite-size items are dispensed directly into the mouth.

If Earth-gravity conditions prevail, the same rehydration procedure is followed. The upper portion of the console shelf is then pivoted upward, away from the user, exposing a number of depressions and mating male "dies," as shown in figure 7. Aluminum foil, dispensed from a roll at the rear of the console, is placed over the depressions, and the dies lowered and raised, as shown in figure 8. This operation forms "dishes" into which the rehydrated food is placed by squeezing the food packages after

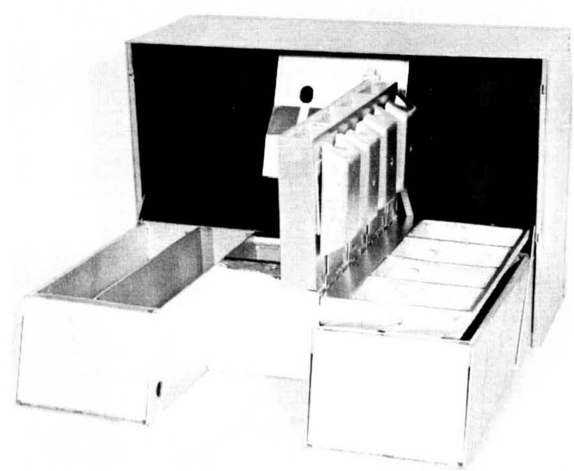

FIGURE 7.—Feeding console mockup, dies elevated.

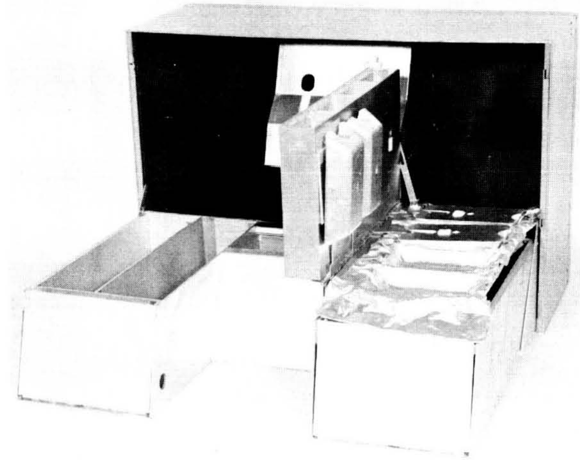

FIGURE 8.—Feeding console mockup, aluminum foil formed.

cutting open the end with scissors. A spoon, which is included in the man-meal pack is then used to eat in the conventional manner. At the end of the meal, the aluminum foil is carefully folded to enclose any remaining food waste, and is discarded into the waste container. Beverages are reconstituted and consumed directly from the zero-gravity packs under all gravity conditions.

Food Waste Storage

Moist food wastes, if stored for any length of time without treatment, will putrefy and generate odorous gases. Experimentation in our laboratories has provided data on the quantity and composition of gases generated during storage of rehydrated food wastes in sealed containers. Calculations have indicated that in most situations, if only small quantities of food are left in food packs, less than 1 pound per square inch of pressure will be developed in canisters of the size described when used for food waste storage. In unusual situations in which the entire contents of a food package are discarded uneaten, sufficient pressure to rupture the canister can develop. For this reason, a relief valve, designed to vent gases at pressures over 1½ psi, is provided in the rear wall of each canister. The space behind the canister rack can be vented directly to the environmental control system to avoid contamination of cabin atmosphere. The same relief valve prevents rupture of canisters in the event of cabin decompression, and a similar valve is provided to admit air to the canister upon recompression of the cabin, thereby preventing crushing of the canisters under such conditions. This approach to the problem imposes much less weight and volume penalty than increasing the thickness of canister walls to withstand the maximum possible pressure differentials.

An extra empty canister is provided in the rack at the beginning of each resupply period. This is used to contain the wastes generated during the first day. On the second day, the canister emptied during the first day is substituted for the filled waste canister, and the process is repeated.

A partition, equipped with a slit rubber diaphragm, is provided in each canister. This partition is hinged down against an interior wall of the canister when it is packed with food. After the canister has been emptied, the partition is folded upward to latch across the opening under the lid. Waste may then be inserted through the slit diaphragm, which prevents escape of canister contents under conditions of zero gravity.

CONCLUDING REMARKS

This paper has described the operation of one food management system that was designed for a specific orbital space mission with a certain resupply requirement. This system will not be suitable for missions with considerably greater or shorter resupply period, of different crew sizes, or with different power and water sources. It does illustrate, however, the assortment of problems that may be encountered in the design of food management systems. A complete system of this general type is illustrated in figure 9.

FIGURE 9.—Complete food management system.

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Discussion: Handling and Storage of Food for Long Flights

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One of the most important of the determinants in the design of a life support system is the concept of an integrated system. There has been a little looseness in the clarification of the conditions under which these systems are to be used. There has not been a clean definition of the different types of missions, the duration, and the different types of orbital capsules. The design of the food and the life support systems will vary considerably with the mission and spacecraft. It is not fair to compare the Gemini type, which is very primitive, with that which Dr. Roth discussed which is based on the large-scale 4-man, or even as the Douglas design, 24-man type orbiting laboratory. These are very sophisticated, and the space and design allow a man a more full-fledged approach to the problem.

The requirements for food become entirely different as the duration of the mission increases and as the experience of man in space is extended. It has been mentioned several times in previous papers that the first missions will require complete metabolic balance studies on the astronauts in order to establish as good a basis as possible for determining possible metabolic deterioration and degradation. This means that the formula type of diet would be preferable because of the simplicity of approach in the analytical procedures before and after flight. However, this does not mean that the formula type of diet is to be preferred when we get into the 30-, 60-, 90-, and 120-day missions, after the basic studies have been completed and after the knowledge of the metabolic deteriorations, if any, has been thoroughly assessed.

Then, again, in design of food and housekeeping problems, I think we must know the mission of the astronaut. Based on whether an astronaut is in a polar orbit where the time will be approximately 90 minutes, with about 18 orbits in 1 day, or whether he is on a 30° orbit where the time of orbit allows about 20 orbits a day, we begin to see the problem of light-and-dark, night-and-day, and diurnal variations and the problems of mission requirements.

Obviously, if part of his mission is Earth reconnaissance or Earth observation, he can do this only during the daylight hours and with the change from day to dark he is not going to have the continuity of daily rhythm that we have here on Earth where we are exposed to a normal variation of day and night so that the meal times, the sleep times, and all the personal hygiene problems will have to be regulated with each orbit on a preset, predetermined basis.

This will be one of the factors in determining the amount of food, the type of food, and the time in which the food is consumed. If it is going to take a period of time for rehydration, then obviously his chores during daylight or light visible time on Earth will not allow him to eat during this period and the food will become cold. Thus, a very carefully manipulated time schedule must be set up to allow him to eat the food at its optimum temperature and palatability.

Probably one of the most important factors for the man in space is his water requirement. The problem of determining whether an astronaut is dehydrating has yet to be solved. We have suggested to our engineers that they try to build a scale so that the astronaut can be weighed every day in space. It is going to be a little difficult to weigh a man at zero-g. One idea of how to do this is based on the use of the spring. The individual is suspended in the spring and his rate of oscillation and the extent of the oscillation determined. This would be a measure of the mass and, by knowing the mass, we probably can determine body weight. Obviously, if he has weight changes greater than ½ pound per day we are dealing with water balance changes, be they positive or negative.

It is possible he may go into positive water imbalance because of edema and circulatory problems; the edema which may develop under certain conditions of zero-g must be guarded against equally carefully as dehydration and, as a matter of fact, would probably be contributory to tissue dehydration. Water requirements, then, become one of the important determinants. The ability to measure the man's state of dehydration in real time becomes an essential part of the monitoring of his life support system. If, as has been mentioned, the fuel cell is used, the amount of water available is no problem because the system will generate more than an adequate amount. The problem will be to have the astronaut consume it.

On the other hand, some of the other designs use the solar-type cell for power generation. Then there is an entirely different problem which is securing adequate amounts of water at the proper time. In this case, freeze-dehydrated food may not be feasible because if water must be carried there is no point to using dehydrated food and then hydrating it in space. This only complicates the lives of everybody concerned.

The system Dr. Roth described is excellent for what it is designed to do, but we must not take this as the prototype for all systems because of the variations which obviously are going to be the designs of orbiting spacecraft.

Another problem is the question of environment. If, as has been suggested, helium is to be the second gas in any oxygen-helium mixture, then the heat loss from the body becomes rather extensive and caloric requirements are altered considerably. We must know what the composition of the environmental gases are before we put any fixed figure on calorie requirements.

This environment presents an engineering problem, too, because the thermo-conductivity of the helium will interfere with some of the electronic gadgets which are often a part of the life support systems. The accumulation of toxic gases and the gassing out problems which may come from some of the insulation material or from some of the packaging material of the food become important considerations. Another problem is the generation of some of these toxic agents by the human himself.

This brings up the question of the leak rate of these spacecraft. One is surprised at the actual amount of oxygen which is required by the astronaut in the spacecraft. Actually, more than twice as much oxygen as is used in the metabolic process is needed. This difference is due to the leak rate, or loss of oxygen, into the surrounding environment. If the pressure of the chamber is increased from 5 pounds per square inch to 14 psi, as the Russians have done, then the leak rate increases tremendously and the whole logistic support must be recalcuated. On the other hand, as long as it is kept at 5 to 7 psi, the leak rate is kept low, and oxygen availability will then cover this extensive loss.

The leak rate, however, has an important advantage. It allows the dissipation of some of the toxic substances into the outer space, so that burners, chemical solvents, and so forth, may be adequate to take care of the situation. Also in connection with this, certain foods that increase flatus obviously must be avoided, a problem which requires much research.

With regard to water, a question is the amount required by the man for the dissipation of heat generated by activity. In the pressurized suit, this may be sixfold times that in shirt sleeves. It would seem that a coolant-type system, associated with the back pack when the pressure suit is utilized should certainly save the astronaut from being the middle man in the water-heat cycle. This would indeed be a much more efficient system for controlling perspiration and for allowing heat dissipation. Less dependence would be on the sweat mechanism which carries with it extensive salt losses. One of the major problems would be the burden on the control system to eliminate the excessive amount of moisture produced by the sweating of the man under conditions of intensive physical activity.

Some of the other problems that come up are the questions of: What drugs does one give this man to take with him in case he does run into gastrointestinal upsets? Do drugs have the same pharmacological activity at zero-g as they do on Earth? There is no absolute knowledge of the pharmacological dynamics of any of our usual therapeutic agents under conditions of zero-g. It can be anticipated that some of them will have a quite different type of activity under these conditions than those with which we are familiar.

These are just some of the problems which must be considered and solved.

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Waste Management for Closed Environments

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Over the past several years, considerable effort has been directed toward efficient handling of wastes and water recovery for space vehicles. During this period, technical documents have been presented on much of the work that has been performed. It is the purpose of this paper to provide a report on the status of engineering design and development as it presently exists.

Any waste management system, be it terrestrial or extraterrestrial, must be concerned with wastes from their point of origin to their ultimate fate, whether re-use or disposal. Obviously the problems encountered in terrestrial waste management systems are different from those of the extraterrestrial, but the underlying objectives are similar. In each case the system must be capable of:

(1) Collection
(2) Transport
(3) Treatment
(4) Instrumented process control.

In addition, the selected system must be compatible with other integrated life support mechanisms.

A closed environment waste management system must include facilities for handling: (1) urine, (2) normal feces, (3) atmospheric moisture, (4) vomitus, (5) diarrhetic feces, and (6) personal hygiene waters.

It is recognized that mission duration and the effects of zero-g environment will be important considerations in the selection of a waste management system, but, as stated earlier, this paper is concerned with current engineering status even though little of the work to date has been on operational-type hardware.

WASTE COLLECTION

Collection device design is a critically important area, for it is here that the wastes are in their most concentrated form (with the possible exception of some treatment process residues) and have their greatest possible access to the total environment. It is, therefore, required that the collector positively entrap not only the solids and liquids but any resultant aerosols and, in the case of defecation, the attendant flatus. In addition, the collector must provide a minimum of discomfort to the user, be in a state of constant readiness for use, minimize the time of contact between user and waste material, and enable the user to readily and efficiently clean both the collector and himself. There are two basic types of collection devices, the in-suit design and the shirt-sleeve design. In general, their design has been approached from the standpoint of separate collection of urine and feces.

Urine

Most designs thus far have included the use of a collapsible bag as the initial urine receptor. The bag is inflated by the urine and sealed at the completion of micturition, it is then emptied by squeezing or a mechanical stripping device. The bags may be either disposable after single use or disinfected for re-use. Bags would be supplied to each individual. One proposed unit utilizes open cell plastic sponges enclosed in plastic bags, the sponge retaining the voided urine.

Where relatively free movement of the crew is possible, the collector may be a fixed unit separated from the user. One study investigated the use of a direct connection to a storage tank with individual penis receptacles. The principal objection to this system was the pressure required to overcome the storage tank pressure. Another fixed collector is the centrifugal urinal which incorporates the use of an electric or hand wound spring motor to turn the centrifugal bowl. Here the buildup of putrescible solids may become a problem.

At present it does not appear that we have a urine collector which will fully satisfy the requirements previously mentioned.

Normal Feces

Feces collection device design, as with the urine collectors, has centered around the use of plastic bags. In-suit designs range from insertable units to hand-held and strap-on devices. Fixed units feature seat-type collectors with various sealing methods and some type of vacuum-inducing means for feces and flatus entrainment. Again the final receptacle is a plastic bag.

The design of feces receptacles has thus far been directed toward storage of waste material. The designs for feces collection put forth to date fall short of meeting the requirements for use in space missions. Minimizing the contamination of the surrounding environment during removal of collector from the body and self-cleansing are problems yet to be solved.

Vomitus and Diarrhetic Feces

Vomitus and diarrhetic feces have been recognized as an ancillary problem to waste collector design, but for the main, have been left as just that—a recognized problem.

Atmospheric Condensates and Personal Hygiene Waters

The problems of atmospheric condensates and personal hygiene waters are less confining since for all practical purposes the adjustment of the system to the human user is largely eliminated. The problems of positive entrapment and minimizing aerosol formation are still present, but should be amenable to sound engineering practices.

TRANSPORT

Transport systems, as such, generally do not exist. This will continue to be the case until the intensive effort, in design of collection devices and treatment processes, arrives at workable combinations. An integrated system may well require interim storage and/or phase separation depending on the fluids involved. The development of a particular transportation system capable of performing the tasks required should not present any insurmountable engineering design problems.

TREATMENT

Treatment, as used in this paper means any process which alters a waste product whether this alteration prepares the waste for storage, re-use, or ejection from the capsule.

Most systems propose application of water reclamation devices to urine, atmospheric condensates and personal hygiene waters with accompanying storage of fecal material. In addition, some, if not the majority, advocate separate treatment schemes for atmospheric condensates. The principal method proposed for the treatment of these condensates is passage through beds of activated charcoal.

Methods for water recovery may be classified as follows:

(1) Change of phase

(a) Liquid-vapor such as distillation steps either at atmospheric pressures or reduced pressures.

(b) Solid-vapor such as freeze-drying.

(c) Liquid-solid such as freeze-crystallization or zone refining.

(2) Membrane processes which include ultrafiltration, ion exchange membranes, and electrodialysis.

(3) Diffusion processes such as capillary and thermal.

(4) Combinations of the above.

(a) Physico-chemical such as solvent extraction.

(b) Vacuum distillation combinations such as vapor compression, spray condensers, vapor pyrolysis.

(c) Electrolytic such as the electrolysis cell-fuel cell.

Tables I and II show the present status of design and prototype fabrication. It should be noted that many of these schemes require either pre- or post-treatment of the waters involved, which necessarily increases the volume and weight of the total system. At this time, the most promising (and advanced) systems appear to be those that couple some type of distillation method to an oxidation step, and the membrane processes. For missions of less than 1 year, investigations concerned with treatment of feces have centered around disinfection and storage methods, without water recovery. The following prototype hardware has been developed:

(1) Freeze-drying with venting of the sterilized vapors overboard

(2) Storage in refrigerated compartments at temperatures below 0° C—addition of chemical disinfectants is contemplated

(3) Storage in heated compartments at temperatures above 120° C—again addition of chemical disinfectants is contemplated

(4) Incineration and ash storage.

Missions of longer duration in which all water must be recovered and food and oxygen regenerated within the capsule will undoubtedly take advantage of biological treatment methods. Studies have been conducted with both aerobic mesophillic- and thermophillic-activated sludge and anaerobic digestion methods. At present, the mesophillic-activated sludge process appears to hold the greatest promise. One of the biggest obstacles to overcome will be that of solid-liquid separation. The separated effluent is highly oxidized and may contain the nutrients necessary to support an algal or broad leaf plant population. Encouraging results have been obtained in limited investigations on these effluents as nutrient sources.

TABLE I.—*Representative Figures of Current Water Recovery Techniques* [a]

Process	Energy, watt-hr [b]	Weight, lb	Volume, ft³	Yield, percent	Treatment		1-g unit built	Comments
					Pre-	Post-		
Freeze distillation	0	35	24	94	No	Yes	No	Water recovered from mixture of feces and urine; 30 sq ft radiation area required.
Membrane electrodialysis.	1182	22	0.5	92	Yes	No	Yes	Potable water has been obtained from this process; unit in development stage.
Vacuum distillation	0	26	10	91	No	Yes	Yes	Water is potable; radiation panels required.
Vacuum pyrolysis	592	56	3.5	90	No	No	Yes	Water consumed by man; radiation panels required.
Vapor compression	2700	60	2.0	92	No	Yes	Yes	Water appears to be potable.

[a] Data are average values obtained from industrial publications (ref. 1). Many of the values were obtained from operating water recovery units. No effort was made to select only the best processes nor to place the data in any order of importance, other than alphabetically.

[b] Energy expenditure to obtain 30 lb/day of water.

TABLE II.—*Comparison of Relatively New Water Recovery Techniques* [a]

Process	Estimated physical characteristics				Comments
	Energy, watt-hr [b]	Weight, lb	Volume, ft^3	Yield, percent	
Electrolysis cell—fuel cell 10 lb/day).	650	86.1	2.6	98	Water requires no post-treatment; much work needed to improve efficiency; in early investigative stage.
Membrane permeation	1450	14	0.8	92	Treatment of water not expected; unit should be simple, but is dependent upon development of suitable membranes.
Spray condenser	300	50	2.0	85	Water may require some post-treatment; unit should be capable of gravity-independent operation; power may be further reduced.
Thermoelectricity	130	Low	1.0	90	Water may require post-treatment; low power requirement; in early investigative stage.
Ultrafiltration	0	Low	Low	90	Treatment of water not expected; no power required; small size unit, but is dependent upon state of membrane development; in early investigative stages.
Zone refining	2600	([c])	High	80	Water may require some post-treatment; power requirement increases rapidly as yield is increased; may be difficult to adapt to space systems.

[a] Data are averaged values obtained from industrial publications (ref. 1). The processes are listed in alphabetical order.
[b] Energy expenditure to obtain 30 lb/day water.
[c] No data available at present.

INSTRUMENTATION

Attendant to any integrated waste management system is the need for instrumentation capable of monitoring the system performance and final product quality. In addition, cabin environment must be monitored for effects of off-gases and system leaks. Components, such as gas chromatographs, oxygen sensors, conductivity meters, pH meters, and so forth, are available or are being developed for instrumentation of integrated systems.

MESA—An Integrated System

The Boeing life support system (MESA) was designed and built for the Office of Advanced Research and Technology of the National Aeronautics and Space Administration. This system includes all elements of life support for a 150 man-day space mission. A recently completed test of MESA (results not yet published) incorporated the following units in its waste management scheme:

(1) Separate fixed feces and urine collectors

(2) Waste treatment by aerobic activated sludge

(a) All feces, urine and personal hygiene waters processed by the biological culture

(b) Exhaust gases (approximately 2 l./min) from this unit passed through silica gel, a Hopcalite high temperature oxidizer, a charcoal bed, and then into the chamber environment

(c) Culture centrifuged outside of the capsule on a batch basis and supernatant sent to water recovery system

(3) Two separate water recovery units

(a) Supernatant evaporated under atmospheric pressure at about 220° F, vapors were then oxidized by passing across a 720° to 800° F platinum alumina catalyst

(b) Vapor condensation effected with an ethylene glycol refrigeration unit and condensates further treated by mixed bed ion-exchange, activated charcoal and disinfection by ultraviolet light

(c) Atmospheric water reclaimed after passing cabin air through a C.B.R. filter by an ethylene-glycol refrigeration unit and condensate processed by pumping through a Dynion bacteriological filter, a mixed bed ion-exchange resin, and activated charcoal

Operational Data

The activated sludge process was monitored by testing for dissolved oxygen concentration, nitrites, nitrates, pH and COD (chemical oxygen demand) in both the mixed liquor and supernatant phases. All waste inputs were tested for COD and total Kjeldahl nitrogen. In addition, the culture exhaust gases were monitored for oxygen, carbon dioxide, and nitrogen dioxide concentrations. Recovered water was monitored by conductivity, COD, nitrites, nitrates, ammonia, and bacteria. During the 30-day period approximately 660 liters of waste waters passed through the activated sludge unit and the evaporator-oxidizer system. In addition, about 240 liters were recovered from the cabin atmosphere. This gave an average usage of 6 liters per man per day. The evaporator required daily draining and this water was lost from the system as were the contained salts. The volume of this drainage averaged 1 liter per day which resulted in a recovery efficiency of 94 percent.

The recovery of acceptable water from the evaporator-oxidizer system required:

(1) Three activated charcoal beds at 1.77 pounds total or 0.013 pounds per man-day. However, the third cartridge was still performing satisfactorily at test termination.

(2) Six Barnstead-Model 0808 mixed bed ion-exchange columns at 21.2 pounds total which is 0.142 pound per man-day. Again, the last cartridge was still in use at the end of the test.

(3) An initial charge of 0.1 pound of activated alumina catalyst was still operating after 30 days.

For this system the results indicate a maximum resupply weight (without charcoal and ion-exchange regeneration) of 0.155 pound per man-day. Turning to the recovery of atmospheric condensates, this system required:

(1) One 3.3 lb Dynion bacteriological filter which is equivalent to 0.022 pound per man-day.

(2) Two ion-exchange cartridges similar to those above for an average of 0.047 pound per man-day. The second cartridge was still in use at the test conclusion.

(3) Barnstead-Model 0812 organic removal cartridges weighing 3.6 pounds each required replacement after 18 hours use, resulting in a weight of 0.96 pound per man-day.

Thus, for this system which recovered about one-third of the total water, a maximum resupply weight of 1.007 pounds per man-day would be expected. During this test the condensate water prior to filtration displayed a range in COD of 200 to 600 milligrams per liter. It appears, with the water quality criteria imposed during this test (COD maximum of 25 mg/liter) that some other method of treatment of atmospheric condensates would be advisable.

The activated sludge culture was fed a total COD of 7800 grams of which 4300 grams were oxidized within the culture for a 55 percent efficiency. This efficiency would have been higher had the culture operated longer at steady state conditions. The culture did not approach steady state cell concentration until the test was one-half over. Steady-state cell concentration was approximately 33 grams per liter (as measured by COD). When adequately aerated, foam in the culture was very heavy and necessitated installation of control methods. Foaming was also a problem in the evaporator system as it is in any system where wastes are heated. These problems were overcome by the use of centrifugal defoamers.

Earlier it was mentioned that compatibility with the other life support systems is a "must". As an example, nitrites were formed within the culture at dissolved oxygen concentrations in excess of approximately 0.5 mg/liter and consequently evolved as nitrogen dioxide. Therefore, silica gel and activated charcoal were installed for their removal. Curiously, nitrogen oxidation stopped at nitrites and did not proceed to nitrates.

Another example of the necessity for auxiliary equipment required to maintain integrated system compatibility is seen in the use of the Hopcalite unit for reducing the bacterial content of the reactor exhaust gases. These gases averaged less than 0.1 bacteria per cubic foot.

Although this system is not at the flight hardware stage, it did provide a solid foundation upon which further engineering design and research and development may be based.

REFERENCE

1. SLONIM, A. R.; ET AL.: Water Recovery from Physiological Sources for Space Applications. Life Support Systems Lab., 6570th Aerospace Med. Res. Lab., MRL–TDR–62–75, Apr. 10, 1964.

Discussion: Waste Management for Closed Environments

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The preceding excellent summation of the state of the art in waste management and the press accounts of successful rocket launchings cannot help but lead to the conclusion that although we may have made great strides in the development of the hardware for sending man into space, we still have a long way to go before we shall have contrived a system for keeping him alive in that perfected hardware. One of the major problems hampering man's attempts to leave his terrestrial abode stems from the fact that man, wherever he may dwell, inevitably is beset with a gradual and relentless accumulation of his own wastes. As is true of any living organism, man's wastes constitute a limiting factor, indeed a determining factor, with respect to his continued survival in a given environment—unless he can get rid of those wastes or in some manner render them innocuous.

What would seem to be the least difficult of the problems of waste management to solve, namely collection and transport of wastes, seems to be as yet in the early developmental stage. The simplicity of the collection and storage problem is only apparent, however, because the rigid requirements imposed by the extremes to be encountered in space make even esthetic considerations assume great importance. An individual can tolerate a great deal of unesthetic emanations, emissions, and so on, provided they originate from him; but he becomes extremely sensitive when they come from others, and this sensitivity is magnified by close and prolonged contact. Although such discomforts may seem minor, under the stressful conditions of a space environment, they have an extremely important bearing on the continued efficient functioning of the crew. Although the difficulty can be minimized somewhat by training the crew to bear with such unpleasantries, the problem is complicated by the cramped conditions to be found in a space vehicle.

As Dr. Ott has pointed out in his paper, a wide variety of approaches to waste treatment are being tried, and rightly so, since it is only by exploring a wide variety of methods that the one most suitable will be found. Inasmuch as the liquid wastes contain the greater part of the water intake of the crew, reclamation of this water must be an essential feature of treatment of these wastes, at least for sojourns other than those of the briefest duration. Reclamation of the water contained in the solid wastes will assume importance when journeys of a year or longer are undertaken.

Of the liquid waste processes required in a space environment, that involving the recovery of water from urine seems to be the most difficult. This is due to the high content of volatile materials in urine, which are readily carried with the vapor phase in distillation, and which are distasteful when contained in drinking water, and to the fact that obnoxious urinary residues are produced as a part of all but the biological methods of treatment. The problem becomes very complex when feces are included in the recovery system, and apparently a completely satisfactory method has yet to be found.

The integrated system developed by The Boeing Company, a system which consists of aerobic activated sludge units for treating all liquid and solid wastes, and a combined distillation-pyrolization unit for water recovery, seems to be a promising approach to the solution of the problem. The use of an activated sludge system for treatment of wastes prior to water recovery eliminates the serious problem of distillation of objectionable volatile substances along with water vapor that occurs in strictly physical-chemical methods of combined treatment and water recovery. This is the case because the volatile matter has either been decomposed or has been converted to cellular matter by biological activity. Moreover, residues that remain are innocuous and thoroughly stabilized. Compared to those for physical-chemical methods, a reasonably wide latitude is possible in operational procedures for the activated sludge process. Activated sludge systems are regenerative and can be closely controlled to prevent a sludge buildup. With suitable modifications—probably some form of compartmentalization—practically all the constituents of wastes can be decomposed. For example, cellulosic and ligneous materials could be decomposed by passing sludge through a chamber in which conditions are such as to promote growth and activity of a population that is predominantly actinomycetes. As with most biological processes, the activated sludge system is relatively simple, and because it is simple, it is reliable.

As with all good things, the use of activated sludge is accompanied by certain disadvantages. The major disadvantages are that the use of activated sludge adds to the oxygen demand in a closed system, since the process is aerobic, and it adds to the carbon dioxide load because of the metabolic activity of the aerobic bacteria involved. In addition to the burden placed on the gas-exchange system, other problems, more or less physical in nature, are encountered. One of these is the necessity of providing a uniform supply, that is, distribution, of oxygen throughout the aerobic bacterial culture. The efficiency of the activated sludge culture is a function of the effectiveness of aeration. As Dr. Ott stated, the aerating problem is accompanied by the nuisance of foaming, a problem also characteristic of terrestrial plants.

In the Boeing setup, the source of oxygen is sodium superoxide, while carbon dioxide is removed by a lithium hydroxide bed as a back carbon dioxide scrubber. Since these methods constitute open systems, they will suffice only for voyages of relatively short duration.

As an alternative method of treating liquid wastes, one way would be to introduce them directly into an algal-bacterial culture. Through rapid bacterial action, they would be converted into nutrients suitable for algal growth, and thereby would be converted into algal cellular material. Since the system would have a photosynthetic phase, it would supply its own oxygen. As with activated sludge—and, indeed, the same types of organisms which predominate in activated sludge are also the active forms in an algal-bacterial culture—no objectionable odors or residues are produced. Water can be recovered directly from the culture by evaporation induced by the conversion of wasted light energy to heat, and then condensing the water vapor. The need for pyrolysis probably would be obviated. Used in combination with a separate activated sludge culture, the system could be expanded to treat solid wastes as well. Solid wastes would be handled in the activated sludge culture. Photosynthesis carried on by the algae in the algal-bacterial culture used for liquid waste treatment would serve as the oxygen source for the activated sludge culture and for disposing of the carbon dioxide evolved by the latter.

Heretofore, a major problem in the incorporation of photosynthetic systems into waste treatment systems, and for that matter, into gas exchange systems, has been one of providing the growth conditions need for maximum efficiency in all the functions of the photosynthetic phase of the system without having to pay an excessive penalty in the form of weight, volume, and power requirements. If algal-bacterial cultures are used to provide the environmental control, shallow, vigorously mixed, omnilaterally illuminated cultures are needed so that high rates of oxygen production, carbon dioxide utilization, and transfer of the two gases may be obtained. Confinement of the cultures between glass or plastic walls to accomplish depth control, illumination, and mixing gives rise to difficult problems in cleaning the confining walls to permit the unimpeded entry of light, in aerating the cultures to bring about gas exchange, and in cooling the cultures so as to maintain a proper thermal environment. The use of double-walled vessels also results in a high ratio of growth unit to active culture weight.

In an attempt to reduce the weight, volume, and power penalties normally accompanying the use of a photosynthetic system in waste treatment, W. J. Oswald of the University of California designed a unit, which he named the "algatron," that embodies a drastic departure from the present concept of what a suitable growth design feature should be. The unit is a rotating transparent drum in which the algal culture is held as a thin vertical film against the wall by the centrifugal force set up by the rotation. The film thickness is regulated by the rotational velocity of the drum, by the ratio of volume of culture to the capacity of the drum, and by the use of specially designed scoops. The resulting unit constitutes a novel, lightweight system in which photosynthetic and nonphotosynthetic microorganisms can be cultured at a controlled depth either in a weightless environment or in a gravitational field. It is designed to utilize light and electrical energy efficiently, and thereby permit incorporation of algal-bacterial cultures into closed ecological systems for oxygen generation, carbon dioxide absorption, waste treatment and recovery, and low-temperature water distillation with a minimum of weight, volume, and power penalty. Despite the use of a rather makeshift preliminary model and an even more makeshift light chamber, he was able to exceed the efficiencies and yields obtained in other experiments with a 3.5-mm culture in a more conventional unit. At present, we are constructing a more sophisticated version of the algatron, with which we hope to explore in more precise detail the potential of the unit as a part of a waste treatment complex.

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Comments: Session II

DR. HOLLY: Why is there a requirement of 100° F for 6 months storage on the food prior to placing it aboard the vehicle?

DR. GOLUEKE: This statement concerned simulation now for realistic analysis from the time of production to the time of use. In other words, 6 months is the maximum storage life that we would like to have for these foods considering the most adverse conditions.

DR. McKEE: Dr. Ott, what problem is there in activating the sludge system in the absence of gravity?

DR. OTT: The first problem we had was with the foam. We couldn't tell where our level was and we had to incorporate it on the spring. It is not ready to go into operation. We think that where it is used on planetary basis or lunar basis it would have some advantage. Placing it in a closed vessel and compacting the air through a pump in a closed system is our plan.

DR. SHEAR: Dr. Lachance, in the disinfectants in the bag, is there a pH indicator?

DR. LACHANCE: No. There is a dye which serves two or three purposes: first, the esthetic to make the feces look like something besides feces during the kneading processes and second, and probably more important, for the germicide to be effective it must be well mixed. There cannot be pockets of unmixed feces. The dye is added primarily for efficiency.

DR. SHEAR: Are you dealing with a germicide and not a disinfectant?

DR. LACHANCE: It is a germicide supposed to inhibit all growth. The germicide itself is not colored but the dye is there as an indicator of adequate mixing.

DR. SHEAR: What is the germicide?

DR. LACHANCE: It is a Quartermaster developed germicide used for latrine disinfection, in a more concentrated form.

DR. HESSBERG: When we first started using the germicide, we found out there was no way of knowing when it was thoroughly mixed through the feces, and the dye was added merely as an indicator to tell.

MISS GALL: Dr. Golueke, you spoke of the possibility of jettisoning the fecal matter overboard. Is that being seriously considered?

DR. GOLUEKE: It has been. The fecal matter has to be ground to micron size so that it does not make debris in space. It would be disinfected.

QUESTION: Dr. Ott, what is the dilution factor of feces and urine compared with the sanitary sewage water?

DR. OTT: We used 4½ liters per man per day. It is 4:1.

DR. MYERS: Dr. Hessberg, there has been talk about the regenerative systems and concern with what the design numbers were. In the preceding papers data were presented on the preparation of dehydrated foods. What is the design figure in pounds per day?

DR. HESSBERG: The value is 1.3 pounds per man per day.

DR. MYERS: How much water does that still contain?

DR. HESSBERG: About 2 to 3 percent water.

DR. MYERS: What is the design figure for water per day?

DR. HESSBERG: For a normal temperature cabin environment, 5 psi, 100 percent oxygen, 6.6 pounds per man per day. Calculating certain mission modes, suited and so forth, it has gone up to as high as 14 pounds per man per day in the lunar excursion module for the 24-hour mission requirement and the 24-hour additional contingency. This is water for nutrition, not hygiene.

Dr. Vanderveen: Does that figure include the container for the food?

Dr. Hessberg: That is the food package, the console container—not the metal container but the overwrap and the food content; 1.3 pounds per man per day which is about 2500 calories daily.

Dr. Luckey: Has a modified BMR been run on the astronaut wearing a space suit?

Dr. Hessberg: It has not been done at zero-g, nor has it been done in the laboratory. It will be done when we get into some of these well modulated, well studied programs in the flight program.

Dr. Del Duca: In the studies in which 6g conditions were simulated by orienting the subject 9° to the horizontal, are the values for the suited astronaut?

Dr. Hessberg: There are metabolic data but they could hardly be called BMR data. They are working basal metabolic rates.

Dr. Jones: I think we might begin to examine the kind of physiological adaptation that the suited operator will exhibit on exposure.

Dr. Hessberg: A good deal depends on training. An individual who has worn pressure suits before will certainly exhibit, just from that amount of training and familiarization, a lower average calorie expenditure than someone who is in a suit for the first time. There are even differences between suits and the fit of the suit.

SESSION III

Nutrition Aspects of Long Flights

Chairman: ***Nevin Scrimshaw***
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A little over a year ago the Working Group on Nutrition and Feeding Problems of Space Science Board, National Research Council, organized a Symposium on Food and Nutritional Problems in Prolonged Space Travel at the meeting of the Federation of American Societies for Experimental Biology. The discussions made it quite clear that precise knowledge of the nutritional requirements is grossly inadequate to predict with confidence the long-term needs of individuals on Earth, much less of astronauts on space voyages, before we know the effects of the added stress. It was shocking to many that our information on the variation of nutrient requirements in individuals because of genetic and environmental factors was so limited. It is true, however, that recommended allowances are developed to provide reasonable safety for most persons in population groups. By the same token, an unnecessary excess is provided for most individuals, but the recommendations are still inadequate for a few.

In October 1963 the WHO/FAO Expert Group on Protein Requirements debated protein and amino acid requirements for nearly 2 weeks with no concern for the added problems of considering them under the conditions of space flights. Again, lack of much of the fundamental knowledge required was surprising and their report details experimental data which must still be obtained. Although in Session II a list was given of proposed standards for the nutrients to be supplied by the daily diet of the astronaut based on recommended dietary allowance, I am sure that discussion in this session will indicate that these are unnecessarily liberal for some individuals and could prove inadequate for an astronaut whose nutritional needs are unusually great. We tend to forget that variations in requirement as great as 300 percent have been described for certain of the essential amino acids in young men and women, even when environmental differences are minimal and subjects are protected from stress.

This session will place major emphasis on the limitations of our knowledge and on the urgent need for more research rather than on present knowledge and state of the art. Rations planned for future astronauts should not only meet their special nutritional requirements but should also provide an added margin of safety for the duration of the mission.

NEVIN SCRIMSHAW

Caloric Requirements of Long Flights

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Some of the most qualified observers in the field have stressed constantly that one of the essential factors for top physical efficiency of active men is the maintenance of good nutrition and health. There is no question that failure of an individual to comply with certain basic physical and mental requirements will eventually lead to inadequate performance. Three basic conditions must be complied with to maintain top physical performance (ref. 1). These conditions are concerned with (a) the general physical and mental health of an individual, (b) adaptation to and control of the environment, and (c) adequate nutrition. Factors important in optimal nutrition include (a) quantity and quality of food, (b) energy requirements for the resting and basal metabolic states, (c) the specific dynamic activity of foods (usually equal to 10 percent of the basal calories when consuming a mixed diet), (d) anticipated excretory losses (including urine, feces, and sweat), and (e) requirements for specified physical activities.

These factors can be complied with only by defining the minimal energy requirements or allowances that will prevent the eventual breakdown of men living and working under extreme environmental conditions. The daily calorie allowances prepared by the Committee on Dietary Allowances of the National Research Council (NRC) (ref. 2) and the Food and Agriculture Organization (FAO) of the United Nations (ref. 3) have been devised to provide energy in sufficient quantities to maintain body weight or rates of growth at proper levels. Allowances are adjusted so that individuals are maintained in energy equilibrium.

REQUIREMENTS (NRC, FAO)

The caloric requirements are usually determined by at least five variables including age, sex, physical activity, environmental temperature, and body size and composition. Other variables may include relative humidity, radiation, and altitude. In preparing requirements or allowances for individuals the FAO and NRC have utilized the "reference man or woman." The NRC's daily allowance for the reference man living in a temperate environment of 20° C is now set at 2900 kilocalories per day. This reference man is defined as being 25 years of age, weighing 70 kg, and performing moderate physical activities. Table I shows the increased caloric allowances in relation to increases in body weight.

The FAO also uses a reference man 25 years of age, but with a lower body weight of 65 kg, living in a temperate environment of 10° C. It has been shown that the energy requirements are decreased with an increase in age because of the decreased basal metabolic rate and the lessened physical activity. The new (1964) NRC allowance has reduced the energy requirement by 5 percent for each decade between the ages of 35 and 55 years, by 8 percent for each decade from 55 to 75 years, and by 10 percent in the decade after 75 years. As an example, at 45 years of age the allowances are decreased by 5 percent and at 65 years they are 18 percent less than at age 25 years.

TABLE I.—*Caloric Requirements of Adult Males*

Body wt., kg	Kilocalories required at age:			
	25 (FAO 1957) [a]	25 (NRC 1964) [b]	45 (NRC 1964) [b]	65 (NRC 1964) [b]
45	2453	-------	-------	------
50	2644	2300	2050	1750
55	2831	2450	2200	1850
60	3016	2600	2350	1950
65	3198	2750	2500	2100
70	3379	2900	2600	2200
75	3557	3050	2750	2300
80	3734	3200	2900	2450
85	-------	3350	3050	2550

[a] Mean environmental temperature of 10° C and average physical activity (ref. 3).
[b] Mean environmental temperature of 20° C and average physical activity (ref. 2).

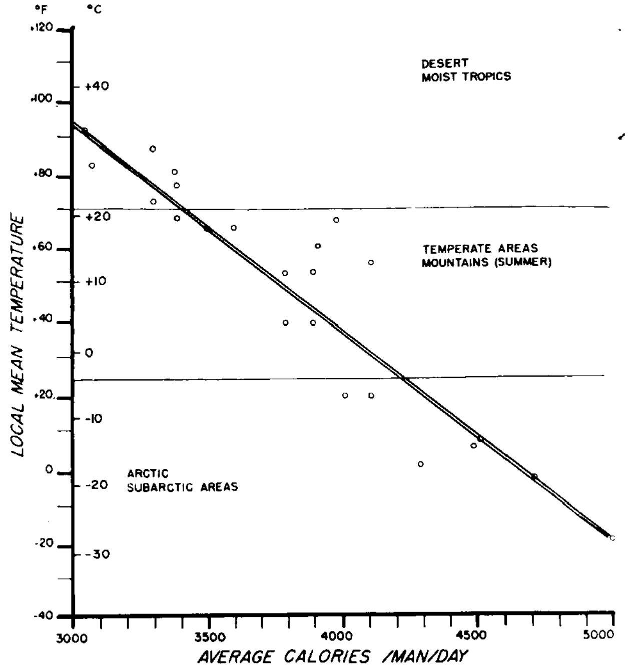

FIGURE 1.—Relation between voluntary caloric intake of North American troops and environmental temperature. Averages for groups of 50 or more men, with abundant food supplies in different parts of the world.

In 1947 Johnson and Kark published their work (ref. 1) showing that the energy requirements of men were inversely proportional to the environmental temperature. (See fig. 1.) These data were collected on normal healthy American and Canadian military personnel consuming rations that were provided for temperate, extremely hot, and extremely cold environments in North America, Europe, and Asia. The figure shows that at 35.5° C the energy requirements of men performing moderate physical activity were 3000 kilocalories per day, while at −29° C the daily requirements were approximately 5000 kilocalories per day. Johnson and Kark observed that the increase in requirements in the cold could not be explained in terms of size or different physical activities, but believed that the increased energy requirements in the Arctic were due, in part, to the increased needs for maintaining thermal equilibrium and to the binding or "hobbling" effect of the clothing worn. This was later confirmed by Gray et al. (ref. 4) who measured the energy expenditure of men engaged in hard physical activity in three different environments while wearing standard arctic, temperate, and desert clothing. The results showed that the energy expenditure for a given amount of external work performed at a constant temperature increased approximately 5 percent when the clothing was changed from desert to temperate attire and approximately 5 percent more when the clothing was again changed from temperate to arctic wear. These authors regarded the heavy clothing as playing a major role in the increased requirements at the lower environmental temperatures but felt that the requirements under these conditions could not be increased by more than 100 kilocalories per day. Belding et al. (ref. 5) also observed that as the bulk of the clothing was increased, there was a greater increase in energy expenditure than could be accounted for by the increased weight of the uniform. As a result they also attributed the extra energy expenditure to the "hobbling" effect of the clothing worn.

On the basis of the work of Johnson and Kark (ref. 6) the recommended dietary allowances of the Food and Agriculture Organization of the United Nations (ref. 3) and NRC's Food and Nutrition Board (ref. 7) were adjusted for climatic differences. The FAO formula employs a 5 percent decrease in food consumption for every 10° C above the base temperature of 10° C, and a 3 percent increase in food intake for every 10° C below the base temperature of 10° C. This would mean a decrease in requirements of 15 percent at 40° C and an increase in food requirements of 9 percent for men living at −29° C. The NRC formula employs a base temperature of 20° C and increases the allowances at lower environmental temperatures by 5 percent for the first 10° C decrease in temperature and by 3 percent for every additional 10° C decrease in temperature. Allowances for higher environmental temperatures are reduced 5 percent for each 10° C increase above the base temperature of 20° C. This would mean an increase of 14 percent in the allowances of men living at −20° C and a decrease of 10 percent for men living at 40° C.

The new NRC caloric allowances (ref. 2) for cold environments, assuming an adequately clothed individual, are not increased except to compensate for the 2 to 5 percent increase in energy expenditure due to carrying or wearing of the cold-weather clothing (hobbling effect). Under conditions where the individual is not adequately clothed the allowances are increased to provide for the increased metabolic rate of shivering. The new NRC allowances for hot environments suggest that the energy requirements are increased in men performing prescribed work and living at high temperatures. They recommend little or no adjustment of requirements when living at environmental temperatures between 20° and 30° C, but with increased activity the requirements should be increased by at least 0.5 percent for each degree rise in environmental temperature between 30° and 40° C (5 percent increase for 10°).

The work of Johnson and Kark (ref. 6) has been the subject of controversy for some time, and a considerable amount of work has been done in this area during the past 10 years to clarify these conclusions. Some of the main criticisms of this work have been (a) that the men living in the cold may not have been adequately clothed, (b) that the men in each area were not performing the same grade of physical activity, (c) that there may have been differences in the methods of measuring food intake, and (d) most important, that the body weights of these men were not comparable.

A review of the literature on the relationship between energy requirements and environmental temperature is now presented.

TEMPERATE ENVIRONMENT

During the past 10 years a program of surveys to determine caloric requirements has been in progress at the United States Army Medical Research and Nutrition Laboratory (USAMRNL), Denver, Colo., and to date has included studies at U.S. Army camps (refs. 8 to 15) and on our metabolic ward. These surveys were all performed under temperate environmental conditions and were designed to measure the food intake of individuals performing light, moderate, and heavy physical activities (table II). On the basis of these data one can presume that the kilocalories consumed per kg of body weight may range from 32 to 44 for men performing light physical activities, 45 to 52 for moderate, and 53 to 63 kcal/kg for men performing heavy physical activities. This maximum activity rate of 4200 kcal/day for the trainees is equivalent to a man working at a rate of 5 kcal/min for an 8-hour day (2400 kcal) plus 1800 kcal (112 kcal/hr) for the remainder of the day.

COLD ENVIRONMENT

Some of the greatest advances in studies of the effects of cold were made by Rubner (ref. 16) who found that the metabolic rate of the clean-shaven dog was markedly increased in the cold. Magee (ref. 17), working with goats, observed a slight increase in the metabolic rate below environmental temperatures of 55° F.

TABLE II.—*Summary of Studies on Relation of Physical Activity to Caloric Intake in a Temperate Environment* [a]

Physical activity	Body wt., kg	kcal	kcal/kg body wt.
Low			
30 min/day light activity (ref. 9)	80.5	2716	33.7
Light to moderate			
180 min exercise (ref. 10)	84.6	3097	36.6
90 min exercise (ref. 11)	73.2	3149	43.0
100 min exercise (ref. 12)	73.2	3240	44.2
Moderate			
3 hr exercise (ref. 13)	80.6	3547	44.0
3 hr exercise (ref. 14)	59.1	2812	47.6
3 hr exercise (ref. 15)	71.3	3137	43.8
Heavy (training)			
Camps:			
Pickett (ref. 8)	69.6	3698	53.1
Riley (ref. 8)	69.7	3952	56.7
Ord (ref. 8)	70.3	4179	59.4
Benning (ref. 8)	68.4	4227	61.8

[a] In all studies food consumption was measured by chemical analysis of food composites.

Lefevre (ref. 18), Herrington (ref. 19), and Schwabe et al. (ref. 20), working with small animals, reported a significant increase in metabolic rate that was presumably due to extreme cold. In studies on the nude man, Hardy and Soderstrom (ref. 21) observed that the basal metabolic rate increased as the environmental temperature dropped below the critical temperature. This increase in metabolic rate was shown to be linear but it was not considered to be significant in nutrition since the human animal normally protects himself against extreme environmental temperatures by wearing warm clothing. In addition, he lives in a home with a central-heating system and is transported in heated vehicles. Many workers in the field were convinced that the increase in metabolic rate in the cold was due to shivering, but Swift (ref. 22), studying the increase in metabolic rates of men in the cold, was convinced that any increase was due to increased muscular tension. On the other hand, Hardy and DuBois (ref. 23), who found that women showed an earlier increase in metabolic rate with cold than men, without frank shivering, considered muscle tension to be insufficient to account for the increase in metabolic rate. Crile and Quiring (ref. 24) and Rodahl (ref. 25), working with Eskimos and Indians living in a subarctic environment, observed the basal metabolic rate to be from 14 to 29 percent above normal standards, but they attributed this increase to dietary factors and to apprehension. Increases in basal metabolic rates in the cold have also been reported by Krogh and Krogh (ref. 26), Rabinowitch et al. (ref. 27), Heinbecker (ref. 28), and Haygaard (ref. 29). On the other hand, Bollerud et al. (ref. 30) observed only a slight increase in the basal metabolic rate of Eskimos when compared with Air Force personnel, and Levine (ref. 31) found the basal metabolic rates of Eskimos to be similar to those of whites.

A review of the cold-weather studies up to 1957 is presented in table III.

Rodahl (ref. 33) published a study on the energy requirements of men living the year round in Alaska. In this study it was observed that the energy requirements were not increased in any environment, but these men were adequately clothed when outdoors and in work areas, and they lived and slept in barracks that were maintained at a temperature of 24.0° to 29.5° C.

TABLE III.—*Summary of Studies on Relation of Physical Activity to Caloric Intake in a Cold Environment*

Physical activity	Body wt., kg	kcal	kcal/kg body wt.
Light to moderate:			
Ref. 32	71.2	3178	44.6
Ref. 33	70.6	3250	46.0
Moderate:			
Ref. 34	75.6	3750	49.6
Ref. 34	74.1	3335	45.0
Ref. 14	68.1	3356	49.3
Moderate to heavy:			
Ref. 35	69.9	3664	52.4
Ref. 35	71.1	3764	53.0
Ref. 36	73.1	3730	51.0
Heavy:			
Ref. 37	67.3	4259	63.3
Ref. 34	73.8	4260	57.7
Ref. 14	69.7	4196	60.2

Stadler et al. (ref. 36) agreed with the work of Rodahl (ref. 33) and also concluded that troops performing normal duties in a subarctic environment would not require more than 3500 kcal/day in either summer or winter. On the other hand, their results disagreed with the work of Johnson and Kark (ref. 6), Swain et al. (ref. 38), and Kark et al. (ref. 39), who reported much higher caloric intakes for men working under reasonably similar conditions. They recommended further studies of men living in extremely cold environments.

A strictly controlled study by Welch et al. (ref. 40) was designed to obtain information concerning the maximal caloric requirements for men existing on a self-sufficient basis in the Arctic and performing hard physical work for extended periods. Caloric intake, fluid balance, and body composition were studied in a group of 26 men during a 28-day stay at Fort Churchill, Manitoba, Canada. (See table IV.) The first 7 days were spent in a prebivouac situation preparing for the bivouac. The remaining 21 days were spent in the field in a moving self-sustaining bivouac. The mean outdoor temperature averaged −21.8° C for the three bivouac periods.

During the prebivouac period the caloric intake averaged 3355 kcal/man, or 48 kcal/kg body weight, for moderate activity. During the bivouac period the intake was increased to 4196 kcal/man/day. This value may be regarded as a maximal value for sustained (more than 5 days) hard work in the cold. These men exercised vigorously, marching at least 8 miles a day, in addition to pulling sleds with their field equipment. Each morning the men broke camp and in the evening they made camp at a new site.

A small loss in body weight did occur during the bivouac periods but the attempt to correct for this loss was of dubious validity. The basic assumption in a manipulation of this kind is that the man is at the optimal weight, from the standpoint of work performance, when he begins the study. This probably is not true since a "bene-

TABLE IV.—*Food Consumption During Heavy Physical Activity at Fort Churchill, Canada* [a] *(from ref. 40)*

Bivouac week	kcal	Body wt., kg	kcal/kg body wt.[b]	Percent of total calories consumed		
				Protein	Fat	Carbohydrate
Control day 1	------	70.3	------	------	------	------
I	3902	70.2	56.6	14.8	37.3	47.9
II	4199	69.7	61.6	14.6	36.4	49.1
III	4488	69.1	65.5	14.3	36.2	49.5
Mean (21 days)	4196	------	61.2	14.6	36.6	48.8

[a] Mean for 26 men.
[b] Weight loss of 1.2 kg for 21 days or 56.6 g/man/day, which was apparently water, on the basis of water balance and deuterium space calculations.

ficial" redistribution and/or loss is likely to occur with continued heavy physical activity, that is, substitution of muscle for fatty tissue. An assessment of the body composition change in the study of reference 40 yielded a slightly different picture, depending on the method utilized for detecting the changes in composition. It seems clear, however, that the food intakes recorded during the bivouac periods in this study were very similar to the actual energy requirement. During the prebivouac period, when the men were sleeping and eating indoors but working outside, the mean caloric consumption was 3355 kcal/man/day and the mean outdoor ambient temperature was −32.9° C. During the bivouac periods the mean intake was 4196 kcal/man/day and ambient temperature was −21.8° C. Although the temperature increased 11.1° C. between these periods, the food intake increased as the men worked harder. In other words, the food intake was not associated with the mean outdoor temperature, but with the activity level. The time per day spent outdoors was somewhat less in the prebivouac than in the bivouac situations.

In view of these studies, it would seem that in a cold environment a caloric requirement of 4200 to 4500 kcal/man/day should be adequate for men who are working hard and living on a self-sufficient bivouac basis. This value should be regarded as maximal for all but the most strenuous short-term (1 to 5 day) work situations.

It is important to assess the physical activity level for an operation in a given environment prior to establishing the caloric (food) logistics. Although a cold environment has a well-known stimulating effect on the metabolic rate when the body is cooled, body cooling may occur during only a small fraction of the day in the well-clothed man, working and residing in the cold. His "macro" climate (outdoor ambient conditions) is far different from his "micro" climate (inside his clothing). In situations where extensive body cooling results in shivering and involuntary muscular activity, an elevation in metabolic rate occurs, thereby increasing the daily energy requirements.

Welch et al. (ref. 40) concluded that there was no basis for the idea that the energy requirements should be increased in the cold unless (a) enough time is spent in the cold to make a man shiver, (b) a man wears extra-heavy clothing which would impose a resistance to body movement, or (c) an individual wears heavy footgear which would result in an increase in energy expenditure.

Le Blanc (ref. 41), using both direct and indirect evidence, also reported that there was no correlation between the energy requirements and environmental temperature usually encountered in temperate, subarctic, and arctic regions. The conclusion of both these authors and of Rodahl (ref. 33) was contrary to all published data in the literature at that time.

The energy requirements for men performing the various grades of physical activity can be classified in terms of kcal/kg of body weight. These values for sedentary to light physical activities range from 35 to 40 kcal; for light to moderate activities, 43 to 46 kcal; for moderate activities, 47 to 50 kcal; for moderate to heavy physical activities, 51 to 55 kcal; and for very heavy physical activities, 57 to 68 kcal/kg of body weight.

HOT ENVIRONMENTS

Mitchell and Edman (ref. 42) performed a comprehensive survey of the literature up to 1949 and found many studies on the effects of high environmental temperature on the basal metabolic rate, but they observed that the conclusions drawn by the various investigators were very divergent. In two separate reviews De Moura Campos (ref. 43) concluded that the basal metabolic rate was decreased in hot humid environments, but, on the other hand, Albagli (ref. 44) concluded that the basal metabolic rate was independent of any environment. Burton et. al. (ref. 45) observed a slight decrease in the metabolic rate of men living in hot environments. Mitchell and Edman (ref. 42) also observed that the energy requirements were decreased in the heat and concluded that it was due primarily to (a) a lowered basal energy expenditure, or a greater efficiency in performing various types of physical activities, associated with the wearing of lighter clothing, (b) a lessened capacity for work, or (c) a lessened motivation, or a combination of all three. Swift and French (ref. 46) concluded in their study that the food intake was decreased in the heat, and that in some cases the proportion of calories from fat intake was increased when men were exposed to heat for considerable periods of time.

On the other hand, as far back as 1924, Magee (ref. 17) observed a significant gradual increase with temperature in the metabolic rate of goats living at ambient temperatures above 21.2° C. He noted this increase to be from 34.5 kcal/hr at 22.8° C, to 41.0 kcal/hr at 31.1° C and 44.0 kcal/hr at 36.0° C. He related this to the increasing effort of the animals to dissipate heat. Similar significant increases in metabolic rates have also been observed by Welch et al. (ref. 47), Shapiro et al. (ref. 15), and Harrington (ref. 19).

Since very little information was available on the energy requirements of men living and working in the heat, the USAMRNL embarked on studies in this area, to evaluate the daily requirements.

A preliminary desert study was conducted by Consolazio et al. (ref. 48) to attempt to establish the minimal energy requirements and nutritional status of troops performing light physical activities, while living in an extremely hot environment. (See table V.)

The mean daily temperature averaged 33.7° C and 35.0° C for the two periods, respectively, and the maximum averaged 43.8° C and 42.8° C for the same periods. The mean daily humidity averaged 21 and 25 percent for the two respective periods.

Over a 13-day period the food consumption from all sources averaged 4065 kcal for the headquarters company and 4416 kcal/day for the military police group. Since the body-weight changes were negligible, no correction was made for body composition changes. The food intake in this study was comparable to that of men performing hard physical work in either a temperate or a subarctic environment. These values are considerably higher than the 3096 kcal/day that would be calculated for men performing light physical activities at the prevailing temperature according to the formula recommended by the NRC's Committee on Dietary Allowances (ref. 7), and the FAO of the United Nations (ref. 3). On the basis of this study (ref. 48) it was first shown that there was a definite increase in the food consumption of personnel living and working in the heat. This was not in agreement with the published observation of Welch et al. (ref. 14) and Le Blanc et al. (ref. 41). It should be pointed out that these workers may have been working under somewhat different conditions and that their conclusions were too broad. It is felt that the high food consumption observed in this study

TABLE V.—*Food Consumption During Light Physical Activity in Hot Desert Environment of Yuma, Ariz.* [a] *(from ref. 48)*

Group	Kilocalories		Protein		Fat		Carbohydrate	
	Total	kcal/kg body wt.	g	Percent of total calories	g	Percent of total calories	g	Percent of total calories
Headquarters Co.:								
Period I	3999	------	123.5	------	179.1	------	453.9	-----
Period II	4130	55.3	126.4	12.4	183.9	40.2	473.9	47.4
Military Police Co.:								
Period I	4237	------	128.5	------	198.9	------	473.8	-----
Period II	4595	60.7	143.4	12.3	205.9	41.2	527.4	46.5
Mean, both groups	4240	------	------	12.4	------	40.7	------	46.9

[a] Average/man/day.

could be related to the hours of exposure to direct sunlight and the outdoor heat, the rate of sweating, and the increased body temperature of personnel exposed to an extremely hot environment. All these factors aid in increasing the energy requirements. Since the men in this study were not on a constant daily physical-activity regimen, and since the food intake of the individual man was not measured, a subsequent controlled study was designed.

In 1959, Consolazio et al. (refs. 10 and 49) conducted a strictly controlled study in the extremely hot desert at Yuma, Ariz., in an attempt to answer some of the questions pertinent to the energy requirements of men living and working in the heat. The effects of solar radiation and extreme heat on the energy requirements of men performing a constant daily activity and on an ad lib. food and water intake were evaluated from (a) the daily energy expenditure and energy balance, (b) the fluid and nitrogen balances, (c) the sweat rates, (d) the body-temperature changes, (e) the daily body-weight changes, and (f) changes in body composition.

The study was divided into three 10-day experimental periods, using eight normal, healthy, young conscientious objectors as test subjects. During period I the men were kept outdoors in the direct sunlight from 7 a.m. to 5 p.m. daily (40° C). In period II the men were also outdoors (40° C) but were kept in the shade under a large tarpaulin, and during period III the men were moved indoors into an air-conditioned room. In the first two periods, as well as the last period, the men lived in air-conditioned barracks at 26° C from 5 p.m. to 7 a.m. daily. Food was supplied ad lib. during the meals and only measured soft drinks and an occasional measured beer could be consumed after the evening meal. For convenience, a normal army garrison ration was fed during the entire study.

The energy cost of the various daily activities was measured both morning and afternoon by means of indirect calorimetry using Muller-Franz metabolimeters (ref. 50). Activities measured included walking on a treadmill, riding a bicycle, and the various resting activities. The daily activity level was kept constant through the entire experiment and included a walk on the treadmill at 4 miles/hr for 30 minutes and riding a bicycle for 45 minutes, both in the morning and in the afternoon. The men spent the remainder of the time in sedentary-type activities.

Body-weight changes were an integral part of the study and were measured at the beginning and at the end of each 10-day period. Blood volume, hemoglobin, hematocrit, and plasma proteins were also measured at the beginning and at the end of each 10-day test period. Other pertinent data collected included daily fluid, nitrogen, and energy balances.

The average daylight temperatures for each period were 40.5° C for period I in the hot sun, 40.3° C during period II in the hot shade, and 26° C for period III in the cool shade. The relative humidity averaged 30.3, 48.0, and 58.5 percent for the same periods, respectively. The evening indoor temperatures were fairly constant during each period, averaging 24.1°, 24.3°, and 26.1° C, respectively.

The daily morning body weight changes were small for each period, showing a gain of 62, 36, and 17 g/man for periods I, II, and III. (See table VI.) The blood volumes showed an average increase of 225 ml in period I, a decrease of 212 ml in period II, and a decrease of 20 ml in period III. (See table VII.) Hemoglobin and serum proteins were not significantly different for all periods, but the hematocrit values showed a significant decrease of 2.5 percent at the end of period I and a significant increase of 1.8 percent in period II.

The sweat rates, including insensible water loss, averaged 6382, 4900 and 2050 g/day. As expected, all differences in sweat rates between periods were highly significant. The nitrogen balances for the three test phases are presented in table VIII. These values averaged -0.42, -0.66, and $+1.39$ g of nitrogen per day for the three phases.

The daily food consumption is also presented in table IX. The intakes for period III were significantly lower than those for either period I or II ($P < 0.005$).

TABLE VI.—*Energy Requirements Calculation From Body Composition Changes (from ref. 49)*

	Period I, hot sun		Period II, hot shade		Period III, cool shade	
	g	kcal	g	kcal	g	kcal
(a) Bomb calorimetry (M.E.)	----	3560	----	3516	----	3156
(b) Body-weight change	+62	----	+36	----	+17	----
(c) Water balance	+120	----	+121	----	−55	----
(d) Weight change not due to water retention or loss, (b) − (c)	−58	----	−85	----	+38	----
(e) Protein balance, N×6.25	−2.7	----	−4.2	----	+8.6	----
(f) Weight change not due to water or protein (due to fat), (d) − (e)	−55	----	−81	----	+47	----
(g) Caloric equivalent of item (f), 9 kcal/g	----	−498	----	−729	----	+423
(h) Energy requirement, (a) − (g)	----	4058	----	4243	----	2733

The metabolic rates were also significantly different when comparing period I with period III or II with period III. The daily energy expenditure averaged 3517, 3439, and 3196 kcal/man/day for the three periods. Energy balance showed differences of +44, +77, and −40 kcal/man/day for the three test periods, respectively.

The body-weight changes were corrected by using fluid-balance data, and showed a body-weight loss of 58 g for period I and 95 g for period II. In period III there was a weight gain of 38 g (table VI). These body-weight changes were further corrected for the nitrogen balance, so one must assume that the remaining weight change was fat. The energy equivalents of these body-weight changes were +498, +729 and −423 kcal/day for the three periods, making the energy requirements 4058, 4243 and 2733 kcal/man/day for periods I, II and III, respectively.

Body temperatures in period III were consistently lower than in the other two periods. The differences were significant at noon and at the end of the working day. Even though the evening temperatures increased only 0.7° and 0.5° C for periods I and II, they were significantly different from period III ($P < 0.001$). The daily patterns for pulse rate and blood pressure were not significant.

The National Research Council's Committee on Dietary Allowances, in 1958, and the Food and Agriculture Organization's Committee on Calorie Requirements have recommended a de-

TABLE VII.—*Blood Changes (from ref. 49)*

Subject	Day 1, control	End of: Period I, hot sun	Period II, hot shade	Period III, cool shade
Blood volume, ml	6663	6888	6676	6656
Blood volume change, ml	--------	+225	−212	−20
Hemoglobin, g%	14.1	14.3	14.8	14.3
Hematocrit, %	48.7	[a] 46.2	[b] 48.0	48.3
Plasma protein, g%	6.9	6.8	6.8	6.9

[a] Initial versus end of period I, $P < 0.025$.
[b] End of period I versus end of period II, $P < 0.005$.

crease in caloric intake with an increase in environmental temperature. The NRC's Committee suggested a decrease in caloric requirements of 5 percent for every 10° C above the base temperature of 20° C. The FAO Committee uses a 5 percent decrease in requirements for every 10° C above the base temperature of 10° C. Using the old NRC (1958) and FAO formulas (kcal=154 ($W^{0.73}$)), energy requirements of a 74.5-kg man living in Yuma, Ariz., at 40.3° C would be 3037 and 2865 kcal/day, respectively.

TABLE VIII.—*Nitrogen Balance* (*from ref. 49*)

[All values in g/man/day]

	Period I, hot sun	Period II, hot shade	Period III, cool shade
(a) Nitrogen intake	20. 49	19. 69	20. 57
(b) Output in urine	17. 64	17. 24	16. 76
(c) Output in feces	1. 83	2. 02	1. 91
(d) Output in sweat [a]	1. 44	1. 09	0. 51
(e) Total output, (b)+(c)+(d)	20. 91	20. 35	19. 18
(f) Nitrogen balance, (a)−(e)	−0. 42	−0. 66	+1. 39
(g) Protein balance, N×6.25	−2. 62	−4. 19	+8. 69

[a] Mean for 8 men for 10-day periods.

These decreased dietary allowances have made it increasingly apparent that a reevaluation of the energy requirements in extremely hot environments is necessary, especially since very few of the studies in the literature are comparable to each other, because many of the factors have not been strictly controlled.

Mitchell and Edman (ref. 42) feel that the energy requirements are decreased in the heat because of (a) lowered basal energy expenditure, (b) a greater efficiency in certain types of work associated with light clothing or a lessened capacity for work, and (c) less motivation. Welch et al. (ref. 40) and Le Blanc (ref. 41) have stated that there is practically no increase in energy requirements of men in any environments, except for the 4 to 5 percent increase in the cold, possibly due to the "hobbling" effect of heavy clothing. Recently Consolazio et al. (ref. 10) and Shapiro et al. (ref. 15) suggested that there was an increased requirement in the heat due primarily to the increased heat load upon the temperature-regulating mechanism of the body.

In the 1959 Yuma study, where work was maintained at a constant level, the food intake was significantly greater during the hot-sun and the hot-shade periods than during the cool-

TABLE IX.—*Energy Balance* (*from ref. 49*)

[All values in kcal/day]

	Period I, hot sun	Period II, hot shade	Period III, cool shade
(a) Food consumption, bomb calorimetry	3843	3778	3394
(b) Excretion in urine, feces, and sweat	283	262	238
(c) Nonexcreted calories, (a)−(b)	3560	3516	3156
(d) Energy expenditure	3368	3326	3148
(e) Expenditure for cold water	149	113	48
(f) Total energy expenditure, (d)+(e)	3517	3439	3196
(g) Balance, (c)−(f)	+44	+77	−40

shade period. Food intakes were considerably higher than the FAO–NRC (1958) minimum requirements of 3069 kcal/day for men living and working in the heat. Changes in body water and body composition would be expected to contribute to the caloric requirements, so that when one corrects for changes in body water and nitrogen balance these increases in energy requirements are even more significant. The water gain in period I and the water loss in period III (from water-balance data) are supported by a similar magnitude of water changes in the blood volumes and by blood hematocrits.

The daily energy expenditure of each man for each period was computed from actual energy cost of the daytime activities and from time-motion studies during the evening activities.

These energy requirements in the 1959 Yuma study were equivalent to 55.5, 56.4, and 36.6 kcal/kg, respectively. The blood hematocrit values also confirmed the fluid-balance data, being significantly different in both the hot-sun and the hot-shade periods. The corresponding increase in body water retention in period I, and the decrease in period II, were in the same direction.

These significant increases in energy requirements also hold true if one uses (a) correction for the body-weight change by means of the Keys et al. (ref. 51) factor of 6.18 kcal/g, (b) correction of the water balance by means of blood-volume data, (c) correction of the food-intake data by means of the actual energy utilization data (food intake minus the excretion of urine, feces, and sweat calories), and finally, (d) the increased energy expenditure data.

It has been shown that for each degree rise in body temperature there is an increase in metabolic rate of 11 to 13 percent (according to Eichna et al., ref. 52) or 10.8 percent (according to Christensen, ref. 53). Christensen feels that this is partly due to the increased activity of the heart, lungs, and glands, but is primarily due to increased cellular metabolism.

The average difference in body temperature between periods was 0.7° C, and even though it seemed small it was highly significant. If (on an average) there is an 11.6 percent increase in metabolic rate for each degree centigrade rise in body temperature, a 0.7° C temperature rise would be equivalent to an 8 percent increase in metabolic rate. The 8 percent increase in metabolic rate, due primarily to the increased heat gain of the body, is sufficient to explain most of the increased food intakes found during the hot periods.

Some of the main criticisms of this study (Consolazio et al., refs. 10 and 49) were whether the men in this experiment were fully acclimatized to the heat and whether the increase in energy requirements was due to insufficient training prior to the beginning of the experiment. A study was designed to rule out these two factors by measuring the metabolic rate of eight men under three strictly controlled levels of temperature and humidity (Consolazio et al., ref. 12). The environmental temperatures for the three phases were 21.2°, 29.4°, and 37.8° C, each of 4 days' duration for a total of 48 days. The daily activity levels were controlled at a constant rate and comparisons of metabolic rates were performed at three activity levels: riding an ergostat at a fairly heavy level for 50 minutes per day, riding an Exercycle at a moderate activity level for 50 minutes a day, and various resting activity levels.

The individual differences in body temperatures, taken at the end of each work day, were significantly greater during the 37.8° C phase than during either the 29.4° or 21.2° C test periods. The mean energy expenditures for the 37.8°, 29.4°, and 21.2° C periods were 0.304, 0.282, and 0.273 liters of oxygen used per minute for the low activity, 0.590, 0.525, and 0.521 liters for the moderate work, and 1.570, 1.404, and 1.422 liters for the heavy activity. (See table X.) When the 37.8° and 29.4° C phases were compared all the individual differences were significantly higher, $P<0.001$ for the low activity, $P<0.005$ for the moderate activity, and $P<0.025$ for the heavy activity.

This study again showed that there was a significant increase in the metabolic rate of men living in the heat. It is of interest that for each man the average at 37.8° C was higher than his average at 29.4° C. The consistency of re-

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sults may be of biological interest because it showed up even though there was a considerable variation among the averages for the men at a common temperature and activity level.

The significant increases in metabolic rate averaged 11.4 percent for the light, 13.3 percent for the moderate, and 11.7 percent for the heavier activity. It is felt that these results are very important since they show that neither acclimatization nor training were factors in the increased metabolism and increased energy requirements in the heat.

The average 0.5° F increase in body temperature at 37.8° C was significant even though it may seem low. References 52 and 53 have shown that there is an approximate increase of 11.6 percent in the metabolic rate for every degree centigrade rise in body temperature. Thus the increase in body temperature observed in this study could account for only a 4 percent increase in metabolic rate. Other factors such as increased action of the blood in heat transport and increased action of the sweat glands will also contribute to the increase.

TABLE X.—*Summary of Mean Energy Expenditure (from ref. 12)*

[All values in liters of oxygen used/min]

Subject	Light activity			Moderate activity			Heavy activity		
	37.8° C	29.4° C	21.2° C	37.8° C	29.4° C	21.2° C	37.8° C	29.4° C	21.2° C
A	0.344	0.313	0.279	0.754	0.691	0.674	1.835	1.680	1.621
B	.276	.263	.280	.624	.563	.471	1.784	1.511	1.486
C	.260	.230	.236	.445	.389	.405	1.334	1.035	1.119
D	.291	.278	.269	.562	.433	.435	1.461	1.574	1.650
F	.333	.322	.296	.682	.597	.598	1.705	1.579	1.381
G	.300	.276	.296	.559	.531	.579	1.586	1.331	1.376
H	.322	.295	.257	.505	.470	.484	1.284	1.116	1.323
Mean	.304	.282	.273	.590	.525	.521	1.570	1.404	1.422

One can safely say that the metabolic rate of a designated physical activity is increased in the heat and is not affected by acclimatization or training. This increased metabolism leads to an increase in energy requirements of men living and working in the heat.

NITROGEN LOSSES IN SWEAT

It appears that the sweating process plays an important role in determining the energy requirements of men exposed to solar radiation or high temperatures. The relationship of the sweating process to the energy requirements of man may be attributed to several factors. At high temperatures, or when exposed to sunlight, an increased work load is imposed upon the temperature-regulating mechanism of the body. For example, the transport of heat by the blood may require more work and energy. Likewise, the sweat glands may perform more work in order to dissipate the excess heat acquired from the environment and metabolism.

A loss of calories in the evaporative process deprives the body of energy required for normal physical functions, and thereby creates a demand by the body for a greater caloric intake.

The results of two recent experiments at three environmental temperatures and two levels of physical activity again show that a considerable amount of nitrogen is lost in sweat under conditions that produce profuse sweating (ref. 54). These values average 149, 189, and 241 mg/hour during exposures to temperatures of 70°, 85°, and 100° F. (See table XI.) The free amino acids were approximately ⅕ of these nitrogen losses, with lysine excretion accounting for approximately 15 percent of the amino acid losses.

TABLE XI.—*Sweat Rates and Sweat Nitrogen Concentrations (from ref. 54)*

Study I					Study II			
Environmental temp.		Sweat rate, g/hr	Nitrogen in sweat		Days at 100° F (37.8° C)	Sweat rate, g/hr	Nitrogen in sweat	
° F	° C		mg/hr	mg per g sweat [a]			mg/hr	mg per g sweat
70	31.2	143	149	1.04	1–4	310	310	1.00
85	29.4	242	189	.78	5–8	350	219	.63
100	37.8	312	241	.77	9–12	382	207	.54
					13–16	406	217	.53

[a] 10 samples analyzed at 70° F, 52 samples at 85° F, 66 samples at 100° F.

The nitrogen losses in sweat of men performing a minimum of physical activity in extreme heat are reduced to approximately 200 mg/hour after acclimatization to heat. It has been observed that the nitrogen losses in sweat will increase with an increase in physical activity and sweat rate.

The nitrogen-balance data are presented in table XII. It has been speculated (ref. 55) that the question of increased protein requirements depends on the relationship between the dermal loses of nitrogen and the losses through the kidneys and alimentary tract. In study II the urinary and fecal nitrogen losses were remarkably constant regardless of whether the men were living in a cool or extremely hot environment. This signifies that the increased nitrogen excretions in the sweat were not compensated by decreases in the urine and feces and suggests that the daily protein requirements of men living and working in extreme heat may be increased at least to the extent of the dermal nitrogen losses. Although the NRC (1958) and the FAO publications on protein requirements have not taken into account the possibility of increased requirements because of dermal losses, the new NRC allowances (1964) have been adjusted for losses through the skin and integumental growth by approximately 0.8 mg of nitrogen per basal kilocalorie per day. The NRC Committee on Evaluation of Protein Nutrition also recognizes the fact that sweat losses might result in significant misinterpretation of nitrogen-balance data. The NRC's minimal daily protein allowance of 1 g/kg of body weight is fairly generous in comparison to FAO's requirements for adults of 0.35 g/kg of body weight. The possibility of increased protein requirements under conditions that produce profuse sweating should be reevaluated, especially in individuals living and working in extremely hot environments and consuming low amounts of protein. One should also remember that these values represent nitrogen in the cell-free sweat after centrifuging; in actuality the losses from sweat may be even greater due to the epithelial cells and other debris. Darke (ref. 56) has estimated that the debris contains approximately 20 percent of the total sweat nitrogen.

It has been observed that the increased nitrogen losses in sweat, even after acclimatization, are not compensated for by decreased nitrogen losses from the kidneys and alimentary tract. As a result, these increased excretions in sweat may be closely related to increased protein requirements, since the dermal nitrogen losses can account for 13 to 14 percent of the total daily nitrogen intake. These fairly high excretions may be more significant in individuals consuming diets low in proteins and amino acids.

These findings are very important since they show an additional nitrogen loss that has been ignored in many balance studies. Past studies where equilibrium was apparently attained should be reevaluated in the light of these dermal nitrogen losses.

TABLE XII.—*Nitrogen Balance (from ref. 54)*

[g/man/day]

Environmental temp.	Intake	Output in—			Balance	
		Urine	Feces	Sweat [a]	Sweat excluded	Sweat included
Study I						
85° F (29.4° C)	14. 90	10. 98	1. 18	1. 67	+2. 74	+1. 07
100° F (37.8° C)	14. 90	10. 95	1. 37	2. 06	+2. 58	+. 52
Study II						
Control: 75° F (23.9° C)	13. 63	10. 67	1. 75	0. 36	+1. 21	+0. 85
100° F (37.8° C): 1st to 4th day	13. 63	11. 23	1. 78	2. 63	+. 62	−2. 01
100° F (37.8° C): 5th to 8th day	13. 63	11. 09	1. 91	1. 89	+. 63	−1. 26
100° F (37.8° C): 9th to 12th day	13. 63	11. 16	1. 95	1. 80	+. 52	−1. 28
100° F (37.8° C): 13th to 16th day	13. 63	11. 33	1. 89	1. 88	+. 41	−1. 47
Recovery: 75°F (23.9° C)	13. 63	11. 40	1. 89	. 36	+. 34	−. 02

[a] An assumed value of 15 mg/hr was included during the comfortable hours.

ALTITUDE

During the past year MRNL completed a study at Climax, Colo. (elevation 11 400 feet), in which the food intake patterns and physical performance of young men were evaluated during a 21-day exposure to altitude. The food intake, corrected for body weight changes, did not change appreciably for the three weekly periods (table XIII). Since the daily physical activity was fairly limited, the caloric consumption was equivalent to that of men performing light physical activities in a temperate environment. These data suggest that there is no increase or decrease in the energy requirements of men living at an altitude of 11 400 feet. The food intake and the distribution of calorie data are presented in table XIII.

METABOLIC RATE IN RELATION TO IMMERSION IN WATER

There seems to be no question as to a direct relationship between metabolic rate and gravity. As far back as 1935 Crowden (ref. 57) reported a marked decrease in oxygen consumption (almost 50 percent) for a designated exercise in water when compared with the same exercise in air. This decrease was later confirmed by Hill (ref. 58). In another study Goff et al. (ref. 59) measured oxygen consumption and observed that the isometric workloads for exercise and for rest were not significantly different in air and submerged. Data presented by Donald and Davidson (ref. 60) suggests that reduced postural effort may account for the near-basal oxygen uptake they observed in sitting submerged subjects in water at 70° F. McCally and Lawton (ref. 61) in their summary feel that "the relationship between metabolic rates and postural muscular activity suggests that the basal metabolic rate of weightlessness may be closely related to that of recumbency, inactivity or immersion."

DISTRIBUTION OF KILOCALORIES CONSUMED

With the exception of the work of Sargent et al. (ref. 62) very little factual information is available as to the best combination of pro-

TABLE XIII.—*Food Consumption at High Altitude*

[kcal/man/day]

Altitude	Days of study	Kilocalories [a]		Percent of total calories		
		Total	kcal/kg body wt.	Protein	Fat	Carbohydrate
Group I						
Control (Fort Carson, 5200 ft)	1–10	2732	38.1	13.6	37.0	49.4
Altitude, 11 400 ft	11–17	2801	40.0	12.5	32.9	55.9
	18–24	2866	40.9	12.4	36.5	51.1
	25–30	2802	40.0	13.5	40.9	45.6
Group II						
Control (Natick, sea level)	1–10	2690	37.0	15.0	38.7	46.3
Altitude, 11 400 ft	11–17	2889	40.5	12.5	31.1	56.4
	18–24	3085	43.4	13.3	37.8	48.9
	25–30	2754	38.8	13.0	36.2	50.8
	31–34	2562	35.8	14.4	39.6	46.0
Sea level	35–42	2812	39.4	11.6	32.2	56.2

[a] Corrected for body weight changes.

tein, fat, and carbohydrate consumption for maintaining maximum efficiency and well-being in extreme environments. For a good survival-type ration they recommended 2000 kcal containing 15 percent protein, 35 percent fat, and 50 percent carbohydrate.

The NRC's Committee on Dietary Allowances (1964) has recommended daily allowances of 1 gram of protein per kg of body weight. No recommended allowances for fat and carbohydrate intakes are available, since only limited data are available on a reasonable fat allowance and the characteristics of a mixture of fatty acids that would be most favorable to promote good health. It is recommended that low protein diets be utilized in the space program to minimize the consumption of water. Food items in the dietary must be made up of good quality protein, fat, and carbohydrates, and must be highly acceptable, digestible, and above all, nontoxic.

In our studies we have found that the same proportions of protein, fat, and carbohydrates are consumed in extreme heat, extreme cold, a temperature environment, and at high altitude (table XIV). It is the general feeling that this distribution of food calories is a matter of food habit and preparation. Americans are accustomed to a high fat intake because of the

TABLE XIV.—*Distribution of Calories Consumed in Various Environments*

Environment	Percent of total calories from—		
	Protein	Fat	Carbohydrate
Temperate	12.2	42.4	45.4
Extremely hot	13.0	38.6	48.4
Extremely cold	14.6	36.6	48.8
Altitude (11 500 ft)	13.1	36.5	50.4

high economic level of individuals. In countries of lower economic level the trend is toward a diet high in carbohydrate and low in fat. Rice and wheat products are relatively inexpensive and are the main food items in these countries. Regardless of the environmental temperature and humidity the distributions of protein, fat, and carbohydrate calories in the diet appear to be relatively constant.

SUMMARY—EXTREMELY COLD ENVIRONMENTS

Newer evidence collected during the past few years indicates that there is no basis for the conception that the energy requirements of humans (at a given activity level) are increased in a cold environment, except under the following conditions when the metabolic rate is also increased: (a) in the unprotected or clean-shaven animal, (b) the nude or inadequately clothed human, (c) when enough time is spent in the cold to make an individual shiver or to cause nonperceptible shivering (muscle tone or muscle activity), (d) in the wearing of extra-heavy clothing or footgear that imposes a resistance to body movement, or (e) in any other unusual condition that increases the metabolic rate.

The data suggest that the energy requirements of men living and working in a cold environment are not increased, provided the men are adequately clothed, except for the 2 to 5 percent increase in metabolic rate due to the "hobbling" effect of the heavy clothing. It is believed that the energy requirements, as in a temperate environment, are primarily a function of body weight, physical activity, and age.

SUMMARY—EXTREMELY HOT ENVIRONMENTS

In view of the new evidence presented during the past few years, there is a strong suggestion that the energy requirements are increased in men living and working in extreme heat. This, of course, excludes the individual living in an air-conditioned atmosphere. These studies show that the metabolic rate of all daily physical activities is significantly higher in an extremely hot environment than in a temperate environment. Significant increases were also observed in the food intake, in the sweat rates, and in body temperature, when comparing the same environments.

These increased requirements are probably due to the increased heat load imposed on the body by solar radiation and the extreme heat. The increased requirements, in all likelihood, are a combination of increased action by blood in heat transport, increased action of the sweat glands, increased caloric loss due to sweat vaporization, and the increase in metabolic rate due to the elevation in body temperature.

As shown in table XV, the energy requirements in kcal/kg of body weight may be classified for the various levels of physical activities and environmental temperatures as follows:

(a) In extremely cold environments a man performing light physical activities may consume from 35 to 46 kcal, for moderate work from 47 to 55 kcal, and for heavy physical activities from 56 to 68 kcal per kilogram of body weight.

(b) In a temperate environment the requirements for a man performing light physical activities range from 32 to 44 kcal, for moderate work from 45 to 52 kcal, and for heavy physical work from 53 to 63 kcal per kilogram of body weight.

(c) In extremely hot environments the energy requirements may range from 55 to 61 kcal per kilogram of body weight for men performing moderate types of daily physical activity.

CONCLUDING REMARKS

The caloric requirement of the future space traveler can be determined only by actual studies on the individuals themselves, living and working in their own environment. These studies should include (a) energy expenditure measurements during weightlessness, while wearing pressurized suits, (b) food intake and balance studies, and (c) measurement of sweat rates, and so forth.

There is no question that the astronauts during the Apollo-type flights will be performing only sedentary to moderate physical activities.

TABLE XV.—*Energy Requirements in Relation to Environment*

[kcal/kg body weight]

Physical activity	Environment			
	Temperate	Extremely cold	Extremely hot	Altitude (11 500 ft)
Light	32–44	35–46	[a] 40–54	32–44
Moderate	45–52	47–55	55–61	45–52
Heavy	53–63	56–68	[a] 62–74	------

[a] Assuming an increase of 12% in energy requirements for men working in extremely hot environments.

The men will probably spend approximately 33.5 percent of the day sleeping, 34 percent sitting, 28 percent lying down, and possibly 4.5 percent standing. Table XVI shows the daily energy expenditure of a sedentary individual with a somewhat similar schedule. Under these conditions the daily energy expenditure will be approximately 2200 kcal/day for a 70 kg man living in a 20° C environment.

The following factors will increase these requirements:

(a) An increase in body weight

(b) A decrease in body temperature which will cause shivering

(c) An increase in body temperature

TABLE XVI.—*Daily Energy Expenditure of a Sedentary Individual* [a]

Activity	Percent time spent in each activity per day	Kilocalories per hour expenditure	Kilocalories per period
Sleeping	33.5	75	600
Sitting, etc	34.0	110	902
Lying down	16.0	80	307
Standing	13.0	110	351
Personal activities	3.2	120	95
Total daily expenditure			2,255

[a] Ideal condition of 22° C and 30% relative humidity with a very minimum of physical activity.

(d) An increase in physical activity

(e) Added clothing or footwear, including a pressure suit

(f) An increase in environmental temperature, resulting in an increased sweat rate

(g) Physiological and psychological stresses

The following will decrease these requirements:

(a) A decrease in age

(b) A decrease in physical activity

(c) A decrease in body weight

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COMMENTS

DR. FARRIS: Mr. Consolazio, are the ambient temperatures dry bulb or effective temperatures? I would think you would have to take the effective temperature into consideration. Wouldn't it perhaps be better to relate the temperature to the body temperature, rather than the ambient temperature? This probably controls the metabolic activity.

MR. CONSOLAZIO: The temperature is dry bulb. We could relate this to body temperatures, although we have not done so, because in two of our studies we have an increase in body temperature: in one study it was 0.8° C, and in the other 0.6° C.

DR. MAYER: Mr. Consolazio, I think that it takes about 3 weeks for adaptation to cold in terms of reduced shivering. Do you observe anything of that sort as regards heat, a long-term effect, after 3 or 4 weeks?

MR. CONSOLAZIO: There has been a good deal of work done in terms of acclimatization and heat. It has been found that at 100° and about 50 percent relative humidity, it was possible to acclimate within 4 days. This meant that body temperature dropped 1.5° during this period of time. Pulse rate dropped about 40 beats per minute.

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Discussion: Caloric Requirements of Long Flights

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In this discussion I shall diverge from further consideration of the many important factors that can affect the total energy requirement of the astronaut. Instead, I will discuss the following question: Would it be possible to reduce the astronaut's dependence on exogenous calories by helping him to utilize his own fat stores more efficiently?

This general problem always has been of importance in medicine because so many patients, for one reason or another, are unable to consume sufficient calories to remain in nitrogen equilibrium, even though it is possible to provide them with enough carbohydrate and amino acids to meet specific needs for these nutrients (ref. 1). There is evidence that when the calorie intake is reduced significantly below requirements, normal subjects will exhibit a nitrogen deficit even while they may be receiving theoretically adequate amounts of protein and carbohydrate.

Figure 1 illustrates this phenomenon. In this experiment (ref. 2) a normal healthy subject was placed on a diet providing approximately one-half his estimated calorie requirements. The experimental regimen provided about 9 grams of nitrogen per day, representing protein of good quality. In period II an attempt was made to meet total calorie needs by supplementing the basic oral diet with appreciable quantities of intravenous fat emulsion. As calorie intake increased, potassium and nitrogen balances improved. Period III constituted a second control period. In period IV, oral fat

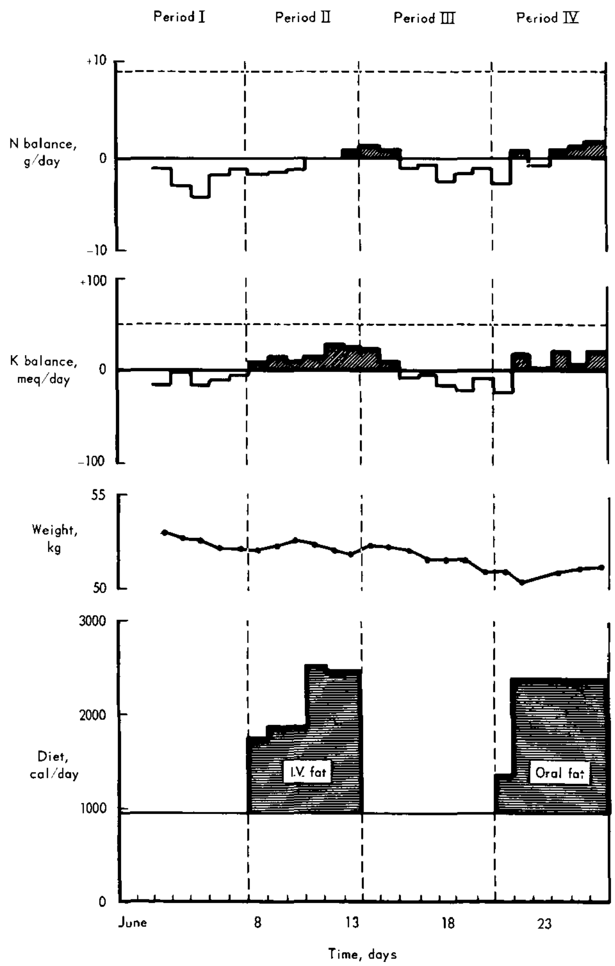

FIGURE 1.—Comparison of intravenously administered fat and supplementary oral fat in terms of their respective effects on nitrogen and potassium balances in a subject on a calorically deficient diet. Dashed lines indicate, respectively, amounts of nitrogen and potassium provided in diet.

emulsion was added to the diet to increase the calorie intake. Again, potassium and nitrogen losses were reduced. During both experimental periods, the oral intake of carbohydrate was decreased to compensate for the small amount of saccharide in the supplemental fat preparations. This study and other similar ones suggest that the body does not use its own stores of fat to reduce nitrogen losses as effectively as it uses dietary fat.

To explore the possibility that an augmented rate of free fatty acid release might increase the efficiency of protein utilization during calorie restriction, we initiated some studies with human growth hormone (ref. 3). As shown in figure 2, one of the actions of human growth hormone is to increase the rate at which adipose cells mobilize free fatty acids (from unpublished results obtained by Pothier, Hashim, and Van Itallie). Preliminary nitrogen balance studies with growth hormone made on two subjects are shown in figure 3. In the first of these studies (fig. 3(a)) the subject went into negative nitrogen balance during the first two periods. Period I was considered the period of adjustment to the new regimen, which was restricted in calories and somewhat reduced in protein. Period II served as the first control

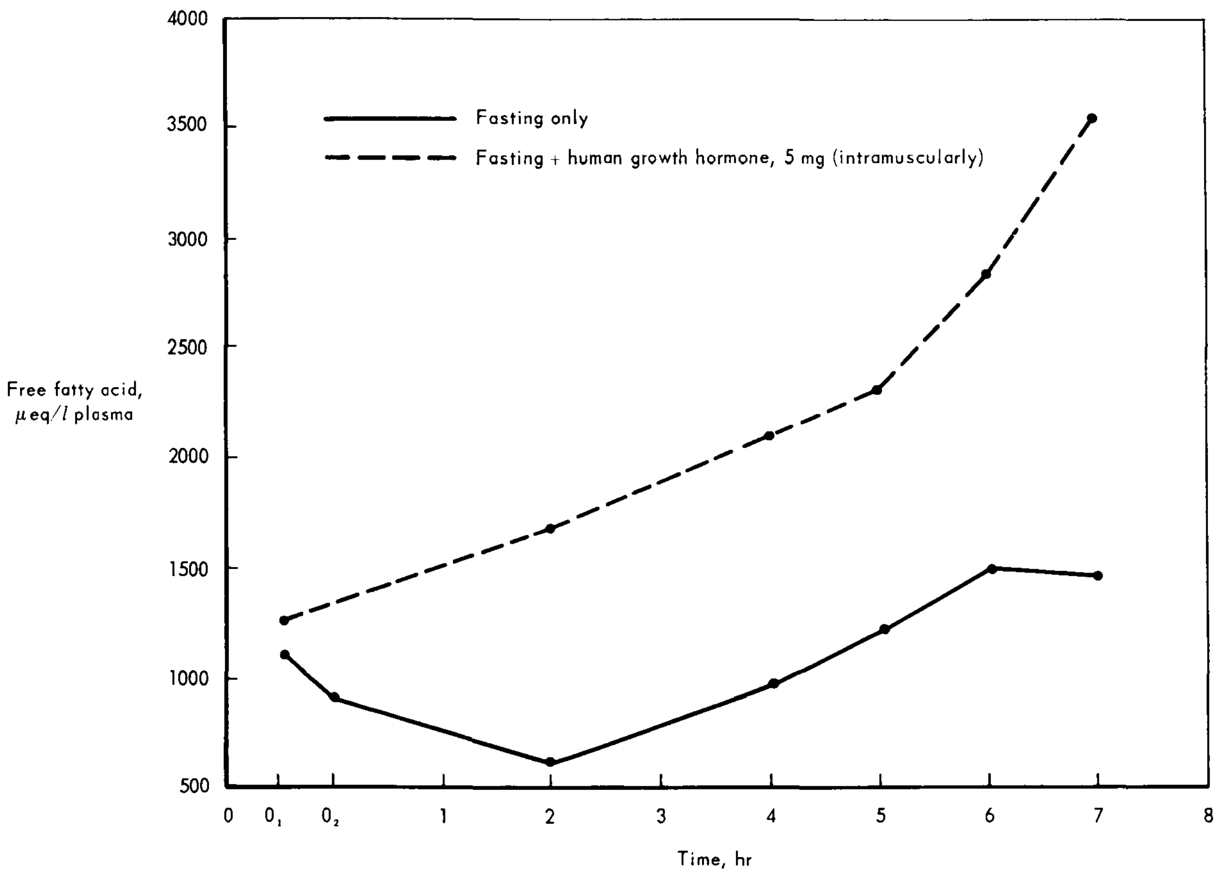

FIGURE 2.—Effect of human growth hormone on plasma free fatty acid concentration in a normal fasting subject.

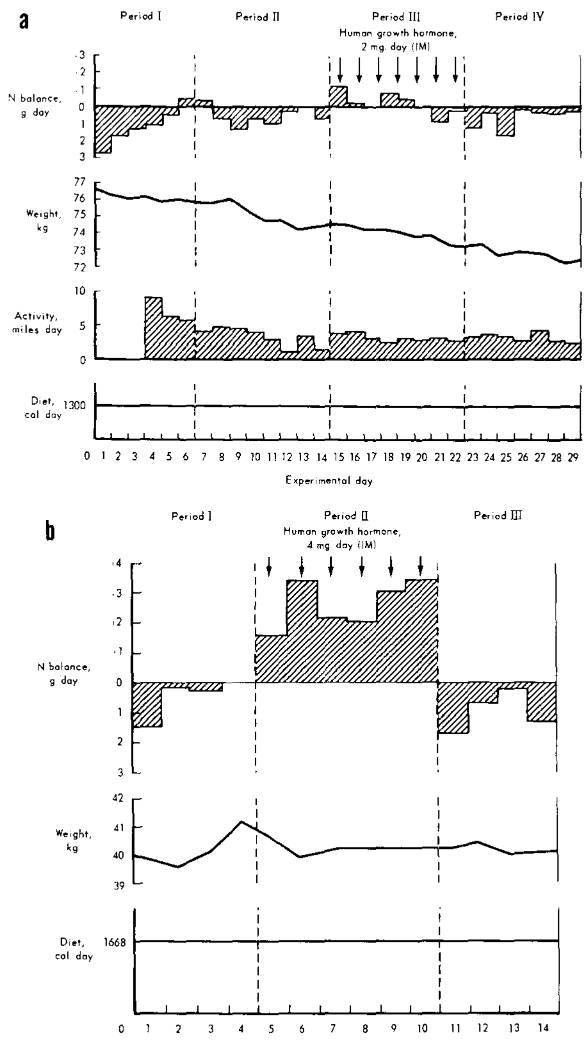

FIGURE 3.—Effect of human growth hormone on nitrogen balance in normal subjects on calorically restricted diets. (a) Subject 1. (b) Subject 2.

period. When human growth hormone was given intramuscularly during period III there appeared to be some improvement of nitrogen balance for the first 5 days. Period IV represents a second control period.

The second subject, who was fatter than the first, showed a more striking response (fig. 3 (b)). During period II, growth hormone seemed to induce a definite decrease in the nitrogen excretion rate.

This is as far as we have gone to date with the human studies. We have initiated studies in rats on calorically restricted diets that suggest that under these circumstances growth hormone administration favors greater utilization of body fat while sparing protein (from unpublished results obtained by Chopra, Pothier, Van Itallie, and Hashim).

On the basis of these admittedly preliminary studies I offer the following thoughts:

(1) During consumption of a diet appreciably restricted in total calories, the body does not mobilize its own fat stores efficiently enough to prevent the occurrence of a nitrogen deficit.

(2) Under such circumstances, there may be ways of helping the body to use its own depot fat more effectively, thereby sparing protein and, by extension, reducing losses of water and certain electrolytes.

(3) If the provision of adequate calories to the astronaut becomes a serious logistical problem it may be worth pursuing the possibility of storing extra fat in his depots and also exploring ways in which the energy represented by this fat can be made available, when needed, to spare body protein.

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Proteins in Space Nutrition

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The order of priority of nutrients, based upon the time it will take to affect performance when they are inadequately supplied, is, probably, water, then calories, and then protein and certain electrolytes. The available evidence, limited though it is, suggests that lack of protein will probably be of little or no importance during the first week or two provided adequate calories are supplied. For short flights, there appears little justification for elaborate means of providing protein or amino acids. Critical data should be collected upon the changes in physical and mental performance with time when the protein intake is severely limited. Variations in the kind and amount of carbohydrate and fat should be included in these studies. The food must be adequate to meet calorie and water requirements.

In longer flights, I assume that the diets should be low in protein to conserve water and minimize wastes. The protein should be of high quality; approximately 0.5 gram/kg/day or perhaps 7 to 8 percent of calories should be sufficient.' Lesser amounts would probably not be significantly more useful. Data are needed on long-term effects of protein at such levels. Considerable effort will be needed to produce acceptable and satisfying diets of this kind.

In very long flights one may suppose that the recovery systems for water will be well developed. Some of the protein will have to come from the support systems, but reutilization of nitrogen will not be very efficient for a long time to come. Higher protein intakes will be acceptable but the problems in food technology of utilizing the proteins produced will be great. Supplementation of such diets with proteins or amino acids will probably be required.

As has been emphasized elsewhere, the data available on amino acid requirements are very poor and totally inadequate to estimate difference in individual requirements. Large variations in requirements due to individual differences or induced by the diet may be critical.

The whole problem of the interrelationships between energy requirement and protein intake and the possible effects of the sources of energy upon protein requirements should be given further study. Much of the older data on specific dynamic action may be relevant but are not adequate for our purposes. A reexamination of this field should be useful. The higher energy expenditures reported on diets containing free amino acids should be confirmed or refuted, and if true, an explanation should be sought. The studies which suggest that carbohydrate and fat may have independent effects on protein metabolism should be further examined. Basic studies on the origin of and the mechanism which produces the endogenous nitrogen losses might be very pertinent.

Finally, neither the cause nor the origin of the nitrogen losses induced during the catabolic phase following stress or injury is known. While we do not necessarily assume that these will lead to high protein requirements, it is apparent that this field is relatively static. An understanding of the fundamental causes may lead to their control.

INTRODUCTION

The ideal diet for space flight will presumably be one which provides optimum amounts of nutrients, requires minimal space and weight, and places the minimum load upon waste disposal and recovery systems. The relative importance of these three criteria cannot be definitely established at this time, and will undoubtedly vary with the length of the flight and supporting equipment.

The provision of the correct amount and kind of protein will be essential and will present a number of difficult problems. It will be important from a logistic point of view since the amount of protein will be relatively large, second only to the materials supplied as calories, and the water requirement will be a function of the protein intake. It is clear that the load placed upon the recovery systems will be, to a considerable extent, dependent upon the protein which is supplied. Much of this discussion is based upon the supposition that the dietary protein intake should be relatively low. This supposition is based not only upon considerations of the recovery systems, but also on the fact that the complexity of the protein may make it difficult to supply.

On the other hand, the opposite situation may apply since the recovery of water will probably be quite efficient. The regeneration of nitrogen wastes as protein, by either plant or animal systems, will probably be relatively inefficient for a long time to come. Hence, it is possible that minimal nitrogen and water excretion may not be desirable. We may need considerably more nitrogen to get these systems to work than minimal nitrogen excretion can supply. I do not have information which permits me to make any judgment on this.

In developing this discussion I have allowed myself considerable latitude. We are dealing with an area in which relatively little is known; we are not sure exactly where we are going or where we will be in the future. I believe that one can justify a considerable amount of the most basic kind of research under these circumstances with the reasonable expectation that much directly relevant information will be obtained and with the certainty that the scientific fallout will be most useful.

TOTAL PROTEIN NEEDS

The subject of protein needs as it applies to the general public has been reviewed in recent years (refs. 1 to 3). As already mentioned, it is difficult to know how to approach this problem in terms of space travel since so many factors will influence the final decision. Nevertheless, it seems that there are some known facts that are relevant and there are some obvious gaps in our knowledge that should be closed in the near future.

In short flights, 1 to 2 weeks, the most pertinent question is probably whether any protein at all need be supplied. There is not a great deal of information on physical performance with protein deficient diets that seems to be directly applicable. The extensive studies with survival rations reported in reference 4 are important. These were done with young men over 9-day periods doing either hard or moderate work. The proportions of protein, carbohydrate, and fat were varied widely and in the test periods the total calorie supply was limited to either 1000 or 2000 calories per day. It is clear from these studies that insufficient calories have great and rapid effects upon performance and tolerance. Since these were tests of survival rations it is clear why such limitations were imposed; however, these restrictions limit the applicability of the data for situations where total calories will not be limited. Furthermore, it is probable that even moderate work as defined in reference 4 may well be above the energy expenditure of astronauts. Another limitation of these studies is that the diets were often greatly simplified. For example, one diet was simply carbohydrate supplied as candies and a starch-jelly bar. Another was a meat bar that contained no carbohydrate but 30 percent protein and 70 percent fat. We may suppose that some of the reactions of the test subjects simply reflect the nature of the food independent of their nutrient content. Much more appealing diets could undoubtedly have been prepared and certainly will for flight into space. Even with all these limitations for the purposes of our present discussion, the data are of much interest. If I interpret the studies correctly, they indicate that very low protein diets are probably compatible with reasonable performance, perhaps adequate performance, over 9-day periods. The variations in proportions of carbohydrate and fat in the various diets as well as the limited supply of calories do not permit a clear identification of the role of protein.

On the basis of these studies as well as general knowledge of protein metabolism, I conclude that it is likely that the protein supply will be of minor importance in short flights, and it is quite possible that it might be omitted entirely without detrimental effects. Studies to test the time required for protein deficiency to affect physiologic and psychologic performance should be made. Particular attention should be given to the production of a variety of palatable low protein diets in order to avoid the influence of nonnutritional factors as much as possible. Such studies should not be particularly diffcult. I can find no justification at this time for elaborate schemes to provide high quality protein or amino acids during short flights.

MEDIUM FLIGHTS

Although I believe that the protein intake will be of little consequence during the first week or so, it is certain that effects of protein deficiency will become manifest unless protein is adequately supplied in longer flights. It would appear to me that in the next stage the recovery systems will be relatively small and not very complex and that the protein will have to be carried. Hence, I would suppose that the diets should be devised to supply a minimal but adequate amount of protein and that in order to do this efficiently, the protein should be of very high biologic quality. From what is now known of protein requirements, I think we might estimate that about 0.5 gram/kg/day, or perhaps 7 to 8 percent of the calories would be the most logical estimate. This may not be minimal but further restriction will not yield enough saving in water supply, for example, to make it worthwhile. Again, the evidence available is not sufficient to support a statement that this level will maintain maximum efficiency over long periods of time. This is, however, a testable proposition and we should know whether diets acceptable over longer periods can be prepared and what they do to physical performance.

The likelihood that such diets are entirely compatible with health is indicated by the studies of Chittenden (ref. 5) many years ago. Recruits and students consumed relatively low protein diets over many months and apparently performed very well, even won athletic contests. Chittenden thought they were probably better off than when consuming high protein diets, but the evidence is not clear. Much better data could now be obtained. Also, it turns out that low protein diets in 1905 were not as low as low protein diets would be now.

I should like to emphasize that as time increases it is probable that the dietetic and psychological aspects of food will be more important. Much attention should be paid to this aspect in the preparation of diets.

LONG TERM FLIGHTS

I think it is generally agreed that at some stage major reliance must be placed upon the life support systems to supply food. Just when this is, I do not know. My supposition is that when one begins to get to this stage, the whole problem will change. The recovery of urinary and fecal nitrogen as food proteins will probably not be very efficient until the system is exceedingly large and it is doubtful that we need to worry about completely supplying food by this means. The systems for recovering water and oxygen will undoubtedly be well developed, the water requirement of the human inhabitants will not be a major consideration, and limitation of the nitrogen intake because of its effect upon water will be of no importance.

Rather, the problem will then be one of finding appropriate utilization of those proteins which can be produced in the recovery systems. The preparation of high quality proteins will be difficult and I would suppose that we may find that we will have to be concerned with appropriate supplementation of the diet with either amino acids or proteins from the outside. So far, the proteins from algae, molds, and so forth, do not look very promising. The problems in food technology seem to me to exceed those of nutrition when we get to this stage.

It is known that in most human societies and particularly in the U.S., relatively high protein intakes are consumed whenever they are available. The relative importance of the psychological and physiological components behind this clear preference is not known. In any event, the level and kind of protein has important implications in terms of satiety, acceptability, and general ability to keep people happy. As others have pointed out, there is no point in supplying food that people do not eat, and much effort is needed to determine and evaluate the

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role of protein in this area and the dietetic problems imposed by diets low in protein.

REQUIREMENTS OF AMINO ACIDS

In reference 6, I discuss the serious limitations in our knowledge of amino acid requirements. In table I, I have reproduced the estimated mean requirement of each of the essential amino acids as determined by studies in which amino acids have been fed to human subjects. If one accepts two standard errors of the mean as a reasonable test of the accuracy of the mean value, it is seen that the mean value is very poorly defined; the data are useless as estimates of differences in individual requirements. Individual requirements could not possibly vary as much as these data might suggest. The lack of knowledge in this area is almost intolerable and additional efforts must be stimulated in this direction. If there are differences of 200 to 300 percent in the amino acid requirements of men, diets which meet only the average requirement will be disastrous. It does not necessarily follow that the amino acid requirements are constant under varying conditions. Nor does it necessarily follow that the pattern of amino acids, that is, the relationship of the amino acids to each other, is necessarily a constant. Although considerable evidence tends to support the idea of a widely applicable ideal pattern of amino acids (refs. 1 and 2) the evidence is not entirely consistent. Studies on chickens (ref. 7), for example, would seem to have established that the Protein: Calorie ratio in the diet modifies the amino acid requirement. What we are concerned with is the best pattern and amounts of amino acids under the conditions and limitations of space flight. It seems certain that one of these limitations will be a restriction in the total nitrogen intake. Very little is known of the effects of total nitrogen restriction upon the requirements of the individual amino acids.

PROTEIN AND ENERGY REQUIREMENTS

Two areas of observation with regard to protein and energy requirements, which may or may not be related, are: (1) specific dynamic action and (2) the record of high energy intakes upon diets in which the protein component has been supplied as amino acids.

Specific dynamic action (S.D.A.) was once a topic of intense interest and neither the cause nor the implications have been satisfactorily determined. In any event, following a meal there is a considerable increase in energy expenditure. The amount of energy thus wastefully expended depends upon the amount and composition of the diet. A meal of high protein or amino acid content has a high specific dynamic action and is thus inefficiently utilized. The data available indicate different degrees of S.D.A. for different amino acids but the adequacy of the quantitative data can be questioned. Similarly, the effects of various combinations of carbohydrate, fat, and protein are not quantitatively known, although it seems that the effects of combinations are not the sum of the S.D.A. of individual components tested separately. This conclusion, however, apparently rests upon the assumption that the S.D.A. of a specific item is a certain percentage of the calories, independent of dose. I doubt that this has been demonstrated.

The point can be made, nevertheless, that the efficiency of calorie utilization may depend upon the amount of protein fed and upon the proportion of carbohydrate and fat in the diet. Additional evidence is required to determine whether this is important and whether there are possibilities for substantial savings in the total energy supply.

In studies in which human subjects have been fed purified diets containing amino acid as the nitrogen source, there appears to be a very inefficient utilization of calories. In reference 8 it was reported that in order to maintain weight and nitrogen balance some 45 calories/kg/day were required, whereas with the diet containing intact proteins only 35 calories/kg/day were needed. One might suppose that rapid absorption of free amino acid leading to a high S.D.A. of the diet could be responsible, whatever may be the cause of S.D.A. These studies indicate that such diets are very inefficient, leading to

TABLE I.—*Estimates of Amino Acid Requirements of Adults*

[Data compiled in reference 6 from various sources]

Amino acid	Amino acid requirement of women			Published estimates	
	Correlation coefficient,[a] r	Requirements, mg/day: Mean	Requirements, mg/day: 95 percent confidence limits [b]	Women, mg/day	Men, mg/day [c]
Tryptophan	0.70	168	146–193	157	250 (150–250)
Phenylalanine in presence of Tyrosine	.74	258	215–310	220	300
Threonine	.70	375	270–515	305	500 (300–500)
Isoleucine	.71	550	280–1065	450	700 (650–700)
Lysine	.61	545	355–835	500	800 (400–800)
Methionine (500 mg cystine)	.77	194	164–230	180	200
Methionine (10 mg cystine)	.53	700	250–1950	550	1100 (800–1100)
Valine	.68	622	550–705	650	800 (400–800)
Leucine	.71	727	560–940	620	1100 (500–1100)

[a] The correlation between amino acid intake and nitrogen retention.
[b] These values refer to the mean value, not to individual requirements.
[c] Numbers in parentheses indicate estimated range of requirements for individuals studied.

total requirements of food some 25 percent above those with a more conventional diet.

Holt in reference 9 concludes that the high energy requirement of the subjects studied in reference 8 might have been due to the inclusion of considerable amounts of the unnatural D-forms of amino acids in the diets and states that the high energy requirement is lowered but not eliminated by the use of only naturally occurring amino acids. The adequacy of the evidence to support this statement is not clear to me. Studies on rats fed amino acid diets did not show a higher energy requirement than with conventional diets (ref. 10). Thus, the whole subject remains in a very unsatisfactory state.

EFFECTS OF FAT AND METHIONINE

It has been generally assumed that the protein requirement is, one might say, an independent physiologic variable. It is recognized that the energy requirement must be met but, if this is provided, the protein and amino acid need is then primarily a function of body size and physiological state. I wish to point out two observations which may be important for our consideration. At least, I feel they deserve further exploration.

The first relates to the nature of the principal energy components: fat and carbohydrate. Does it make any difference how the energy is supplied? In reference 11, Swanson reports that with calorie restriction, the amounts of nitrogen excretion were markedly affected by the proportions of fat and carbohydrate. These data indicate that when the calories in rats were restricted to 50 percent or more of their usual intake the nitrogen excretion was about twice as high on low fat diets as when considerable fat was supplied. Apparently the critical level was about 10 percent fat in the diet, or about

20 percent of calories. It seems likely to me that these effects might be explained by a differential rate of metabolism of fat and carbohydrate. It is unlikely, of course, that we shall be concerned with severe caloric restriction, but the point is that we cannot assume that the type of energy source is of no consequence.

It is also of interest that on nitrogen-free diets the administration of methionine alone greatly reduces nitrogen excretion. This finding was made by many individuals during World War II and never adequately explained. Swanson (ref. 11) observed this effect particularly in calorically restricted animals.

The role of sulfur containing amino acids seems particularly confused at the moment. In reference 12 it was reported that methionine supplements had adverse effects when added to cereal proteins unless other essential amino acids were adequately supplied. There is the possibility that the role of methionine, a lipotropic agent, will be in part determined by the fat content of the diet. The whole area of amino acid imbalance, the time of feeding, the kind and amount of carbohydrates and fat perhaps deserves more extensive exploration. It would seem particularly important if it should become necessary to utilize less than ideal proteins, such as algal protein, as an important dietary constituent.

PROTEIN AND BASAL METABOLISM

During the past 30 years a great deal of information has been collected which has been interpreted to mean that minimal protein needs are proportional to basal metabolic rate (ref. 13). Whether there is a causative relationship between these two parameters or whether they happen to be related in the same way to some other body component or function is unknown. It may be a good guess that both are related to "metabolic mass" but this statement does not improve our understanding very much. Creatinine excretion appears to be more directly related to total body weight or lean body weight.

The point here is that the origin of the unavoidable endogenous losses, the causes of the losses, and the metabolic machinery involved is not understood. The relative contributions of the various components of the body, such as the viscera and the muscles, are unknown. It is possible, at least, that weightlessness may cause considerable modification in the normal metabolic machinery. Some suggestive evidence might be obtained by complete fractionation of the urinary nitrogen from astronauts even on short flights. I assume this has been done, but I am not aware of the findings. Appropriate studies with isotopically labeled intermediates might help explain the origin of these losses and the controlling mechanisms.

PROTEIN STRESS AND INACTIVITY

An increase in urinary nitrogen excretion and a negative nitrogen balance are the hallmarks of the catabolic phase following stress and injury (ref. 14). We can suppose that space flight will constitute a rather severe stress of some kind, but I am unable to assess the probable importance of such a stress. It is, I think, clear that either mental or physical stress may induce a negative metabolic balance, but I would not yet conclude that this will necessarily be related to higher nitrogent requirements.

In this regard, it is of much interest that while the adrenal hormone is necessary for the catabolic response, it occurs in adrenalectomized animals given constant amounts of hormone. Thus many of the early explanations of the cause of catabolic response seem inadequate.

This is an area in which reawakening of interest and development of new techniques are needed. More adequate explanations might be most useful in control or prevention of the adverse effects of continued stress.

Finally, atrophy of muscle and loss of muscle constituents are known to occur rather rapidly with disuse. While I assume that this is not a nutritional problem, and other means will be found to prevent it, it may be a complicating factor in attempting to evaluate metabolic data obtained during flight and must be considered.

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COMMENTS

DR. SARETT: One important stress is the stress of changing a diet. This is a stress that everybody knows about in animal feeding, as well as in human feeding. You can't take an astronaut who has been eating steak and put him in a spacecraft with a new diet without imposing a stress on him. The astronaut should be put on the diet that he is going to have in space for some time beforehand so that he will become acclimated to this diet; also, this will provide an opportunity to do some physiological testing to see whether this diet is adequate for him.

DR. PEARSON: The proposal has been made and is currently under consideration that the astronauts be given a minimum of 14 days preflight dietary balance—that is, on the diet that they are going to eat in flight—and that this period be used to get an established baseline, so that excretory data can be used subsequently.

DR. HESSBERG: With reference to the adaptation of the individuals to diets, in all of our simulators and test runs we feed the in-flight diets 8 to 10 days preceding the test.

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Discussion: Proteins in Space Nutrition

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The point which seems most impressive is the interdependence of the topics being discussed, and the impossibility of being accurate and realistic without some knowledge of the developments that can be expected from the engineering side. What is being accomplished in propulsion? How large a spacecraft is feasible? How soon can what size spacecraft be sent how far? What is being accomplished in regenerating systems? How heavy is a good practical recovery system for water? What are the prospects of recovering *edible* nutrients in considerable quantity from human wastes such as carbon dioxide, urea, and minerals, recovery with *absolute reliability* in a limited amount of space with lightweight equipment? What are the economic limits within which all this must be accomplished? These are only a sampling from the vast number of questions which bear to a greater or lesser extent on each of the topics under discussion and questions to which I, at least, have only the vaguest sort of answers.

To gain some perspective on the problem of protein nutrition I set up what I considered to be nutritional priorities, assuming, as Dr. Hegsted indicated, that whatever the final solution to the problem of nutrition in space may be, each individual must be provided with oxygen, water, and food which each day provide approximately 2000 to 2500 calories and 35 grams of high quality protein.

The first priority is for oxygen. This can be considered a nutrient because essentially it is required for the oxidation of foodstuffs to yield energy. We are seldom concerned with it as a nutrient on Earth, but in a closed system it is the primary nutritional requirement. Man can, under highly favorable conditions, survive for a few days with oxygen alone. He must have for the basic nutrient allowance just mentioned about 600 grams of oxygen a day or 220 kg/man/year. He would need somewhat more than this to allow for periods of exertion and elevated metabolic rate. Recovery of oxygen from the carbon dioxide of which it becomes part is no mean problem. Recovery from water through electrolysis seems feasible, as indicated previously; but unless recovery from carbon dioxide can be accomplished, there will be substantial losses that must be replenished. The solution to the problem of oxygen supply may provide the key for solving many of the other nutritional problems, for if oxygen can be regenerated the weight saving will be substantial.

The second priority is for water. With water and oxygen man can survive many days, in fact, many weeks. The requirement I have selected is 2 liters/man/day, although much more than this will be required under conditions of heavy work or high temperature. Water, fortunately, is not chemically altered by the body, and also it is an end product of metabolism and of certain types of fuel cells. For these reasons the problem of water supply is simplified. It is a matter of recovery, not regeneration, and this should be feasible with high efficiency, as has already been indicated, with apparatus weighing considerably less than the 730 kg/man/year that would be required to provide 2 liters/man/day.

The third priority is for calories. About 400 to 500 grams of dry food per day will be required to provide 2000 to 2500 calories/day, a requirement of 145 to 180 kg/man/year. This food will be largely converted to carbon dioxide and water and the regeneration problem here is much more complex than that for oxygen or water, for not only must a regenerating system be capable of reducing these products to organic substance, it must be capable of yielding wholesome, nutritious, highly digestible, and palatable organic substance. This is a problem that must be solved for continuous occupancy of a hostile environment unless replenishment from Earth can be accomplished for some economically reasonable sum by the time continuous occupancy is contemplated. Low cost replenishment may be accomplished earlier than we have thought, perhaps well before a workable regenerating system can be devised.

This brings us to protein which I would consider to be the fourth priority. Dr. Hegsted suggested an allowance of 0.5 gram of high quality protein per kilogram body weight per day. With this I agree, even though there may be stresses that will increase the requirement from time to time during a space mission. With this allowance 12.8 kg/man/year would be the load for protein. I am therefore skeptical that there will be any need to worry about protein regenerating systems for space flights in the foreseeable future.

Now, what about the form of protein? We hear much about chemically defined diets in soluble form. Chemically defined diets have certain advantages for experimental work, but what advantages do they have in practical dietetics? They are expensive, unpalatable, and difficult to reconstitute. Free amino acids contain less nitrogen per unit of weight then do proteins. There is some evidence, although it needs confirmation, that they increase caloric needs for the maintenance of nitrogen equilibrium. So while they may be the diet of choice for certain experiments, they have no value that I can see as a practical diet.

What about the use of liquid diets and reconstituted diets? I can see little to be gained from either. Primitive tribes survived well on pemmican, biltong, and blubber. The early European explorers of America supported themselves successfully for months on dry, monotonous, unpalatable foods. We can produce many palatable dry foods—in fact, I suspect that many dried foods, for example, dried fruits and dry biscuits, are as palatable as many of the freeze-dehydrated foods. Dried foods have their own unique characteristics and are substitutes for, not imitations of, something better. They can be coated just as freeze-dehydrated foods can, and can also be made into mouth-sized units to avoid the problem of crumbling. They can be devised to provide not only protein but all needed nutrients and can be eaten directly. They also occupy a good deal less space than freeze-dehydrated products. We do not normally rehydrate all dried foods before we eat them. We rehydrate primarily in an effort to simulate something better. How do you hydrate cheese and crackers—usually by sipping beer between each mouthful. I can envision many esthetic advantages and some very practical advantages to rehydration in the mouth and stomach instead of in an unesthetic plastic squeeze-bag. The squeeze-bags are well suited, however, for rehydration of beverages.

So where are we left with protein? Dr. Hegsted touched on many unanswered problems. Appetite can be depressed by amino acid imbalances; we should know why and under what circumstances, but we can certainly avoid such problems with our present knowledge. How significant is specific dynamic action? What is the basis of it? How much does stresss affect nutrient requirements? How much do requirements of individuals vary? What is the source of endogenous nitrogen losses? To what extent can these losses be modified? All of these are important questions and to all of them we need answers so that we can improve the efficiency and reliability of feeding programs. We should support research on them, but I believe we have enough information so they do not pose insurmountable stumbling blocks for us even now. They merely increase the size of the safety factor that must be included. The relationship between dietary monotony and physical and mental performance is, to my mind, a more immediate problem. Again, I suspect it is exaggerated and that satiety is more important than variety—particularly when the objective of eating is survival rather than the allaying of boredom and monotony.

Therefore, I would conclude that just as we do not know all there is to know about efficiency and economy with respect to rocket fuels, so also we do not know all there is to know about protein utilization and requirements. Nevertheless, we know enough to accomplish our immediate aims. We should not limit ourselves by devising complex answers to problems that can be solved simply with sufficient accuracy for current needs. It is a delusion to calculate ten-place answers to problems based on measurements that are accurate to only two significant figures. Nevertheless, if research on the present areas of ignorance is properly supported and the talent of outstanding research workers is used effectively, I am confident that we shall be able to keep pace with the increasing nutritional demands posed by developments in rocketry and capsule fabrication.

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Mineral and Vitamin Requirements of Long Flights

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This brief review does not permit an extensive evaluation of such stresses as radiation, reduced atmospheres, zero or reduced gravity, wearing of pressure suits, possible effects of extremes in environmental temperature, and atmospheric toxicants. Neither has much attention been given to such psychological stresses as isolation, monotony, loneliness, frustration, and speed-time or day-night sensations. These areas will require much attention and definitive answers are in most instances lacking. What has been emphasized is that present methodology for evaluating nutrient requirements of individuals under normal day-to-day stresses on Earth imply that there is considerable variation among individuals. This would suggest strongly that in the selection of astronauts considerable attention should be directed toward establishing physiological behavior of individuals under controlled nutrient intake conditions. This might at least assure that individuals with unusually high requirements for individual nutrients could be eliminated for consideration for extended explorations into outer space. Since it is already known that adaptive phenomena exert an effect, the suggested physiological studies should extend over a sufficient period to allow for evaluation of individual adaptability to specific stresses.

Even considering the relative importance of minerals and vitamins, with minor exceptions, possibly thiamine, several months to several years are required to deplete mineral and vitamin stores in healthy adults placed on deficient diets. In meeting requirements for extended space flights, first consideration should be given to the allowances for salt since both excessive and deficient intakes have marked influences on maintenance of water balance. The total requirement for other minerals and vitamins can be furnished, as they are now known, without unduly adding weight to the total nourishment needs of man. Their total weight would at most represent only a few percent of the total weight of food and water. Brief note is taken of the special needs for considering ration or nutrient stability under conditions of prolonged storage under flight conditions.

All climatic regions of the Earth are inhabited by man. With the development of submarines man was exposed to a very limited microclimate. The development of aircraft and expeditions to high altitudes subjected man to still other environmental deviations. Now, ventures into outer space add still another environment. The limited exploration of the latter, and the wide experience with the Earth-bound environments leave us with the conclusion that man is adaptive and can nourish himself under a variety of environmental stresses. Our object here is to examine what we know about man's nourishment under conditions of outer space.

Although first concerns should be for water and energy, then protein, some consideration must be given to minerals and vitamins even though the total quantities needed for a 3-year exposure may not equal more than a few percent of the body weight of the astronaut.

In considering minerals, first concern should be for the electrolytes prominent in the circulation, namely sodium and chloride. Traditionally we consume the equivalent, in table salt, of 7.5 to 18 grams per person per day (ref. 1). Urine ordinarily contains 60 grams of solids (24-hour sample) of which approximately one-fourth consists of sodium, potassium, and chloride. Excessive intakes of these electrolytes would increase the obligatory urine volume. An intake of 2 grams of sodium chloride per 1000 calories per day has been suggested as protective of the body water when water is limited. This is an amount which would support physical function with moderate sweating. An intake much in excess of this would require extra water for its elimination via the urine (ref. 2) unless balanced by losses through sweat. It must be assumed that if excess sweating is to be encountered not only sodium but other mineral losses, such as potassium, calcium, and iron, would have to be given consideration. Water consumption in excess of 4 liters per day would require approximately 1 gram of additional salt per liter of water (ref. 1).

In considering food sources, it should be recalled that plant foods, in general, are higher in potassium content than in sodium content. Since excess potassium intake elevates sodium excretion, it is common for herbivorous animals to crave salt. Certainly, attention must be paid to the relative balance of sodium and potassium in foods for astronauts. It is proposed that potassium should be limited to approximately 1 gram per 1000 calories per day.

In considering other minerals and vitamins I think it is appropriate to affirm that considerable variation exists among individuals, especially when we consider the population from which astronauts are selected. Our population is generally well nourished. In many individuals overnourishment is a prominent feature. Thus, we must assume that even though we have no precise knowledge as to the true variations in requirement for nutrients, the astronaut will not be characterized as an individual who has been exposed to nutritional stresses as a measure of his capacity to adjust to unusual situations. This being the case, it may be appropriate to examine variations in nutrient requirements or allowances, recognizing that at present we do not know whether physiological requirements actually vary greatly or whether much of the variation found may ultimately be attributable to faulty experimental techniques. Table I summarizes selected mineral and vitamin allowances, physiological minimum need, and acceptable ranges of intake. In developing the recommended dietary allowances it should be emphasized that they are intended to maintain good nutritional health in essentially all individuals in the population (ref. 3). With variation present, it must be assumed that these allowances are actually excessive for a significant number of individuals in the population. In the development of acceptable ranges, cognizance of variation is implied and the acceptable range for some nutrients is considerable. Estimates of requirements, or minimum physiological needs, are taken from the literature and from summaries by the Food and Nutrition Board.

Table II summarizes an attempt by Pett (ref. 4) to illustrate variations in intake in adults for achieving calcium balance (food calcium = fecal + urine calcium). The range implies more than a threefold variation, with concentrations of individuals in the intake range of 400 to 500 mg of calcium per person per day. This can be compared with the results of the careful and extended studies of Malm (ref. 5) on 26 men (fig. 1). The distribution of the indi-

TABLE I.—*Standards for Vitamins and Minerals—Reference: Male; Age: 25 Years*

Vitamins and Minerals	Amount daily		
	NCR allowance	Estimated requirement	ICNND acceptable range
Calcium, mg	800	457	400–800
Iron, mg	10	-----	9–12
Thiamine, mg/1000 kcal	0. 4	0. 2	0. 3–0. 5
Riboflavin, mg/1000 kcal	0. 6	0. 3	[a] 0. 4–0. 5
Niacin, mg/1000 kcal	6. 6	4. 4	[a] 3. 3–5. 0

[a] Assuming 3000 kcal intake.

TABLE II.—*Calcium Requirements for Balance*

[Source: Ref. 4]

Interval, mg Ca/day	Number of cases
0.25–0.29	11
.30– .34	11
.35– .39	11
.40– .44	21
.45– .49	10
.50– .54	12
.55– .59	8
.60– .64	7
.65– .69	3
.70– .74	1
.75– .79	1
.80– .84	1

vidual requirements is again extensive, the range being about as extensive as that found by Pett in examining the earlier data. Malm's average estimated requirement is equal to 457 mg per man per day, almost the same as the average summarized by Pett from earlier data. Figure 1 also contains data on calcium retention in 45 preadolescent girls. It is intended to show that individual variations here are also extensive and that some girls (open circles) retain calcium as well or better on 900 to 1000 mg daily intakes as others (filled circles) consuming 10 to 15 percent more calcium. These data suggest that with appropriate advance physiological studies, it should be possible to select astronauts and maintain them in good nutritional health with regard to calcium on daily intakes of about 300 mg. The probability cannot be stated in exact terms, but it is probably safe to assume that at least one in 20 healthy young men would fall into this category.

Table III summarizes the attempt by Pett (ref. 4) to illustrate individual variations in the adult requirement for iron balance. Although the data source is not made clear, it can be assumed that both males and females are included. It is generally recognized that the monthly loss of iron through menstrual flow in women is equal to the loss via other channels. Hence, it is reasonable to assume that the female would require twice as much iron for balance as the male. On this basis the data suggest that there is at least a fourfold variation in dietary iron need for maintaining balance in adult men. Again, the data are limited, but one of 20 young men could again be assumed to remain in good health with respect to iron on a daily intake of 3 to 4 grams. It is known that bed rest leads to disuse atrophy and this may be of importance in connection with prolonged space flights and the maintenance of a healthy skeletal structure. In searching the literature on healthy young men subjected to an immobilized state I failed to uncover data that would permit an estimate of the daily calcium losses that can be expected. Johnston's studies (ref. 6) on convalescent children refer to the classical studies of Cuthbertson (ref. 7) who, in healthy men, found daily losses of 1 to 1.5 grams of calcium as not uncommon in young men subjected to complete bed

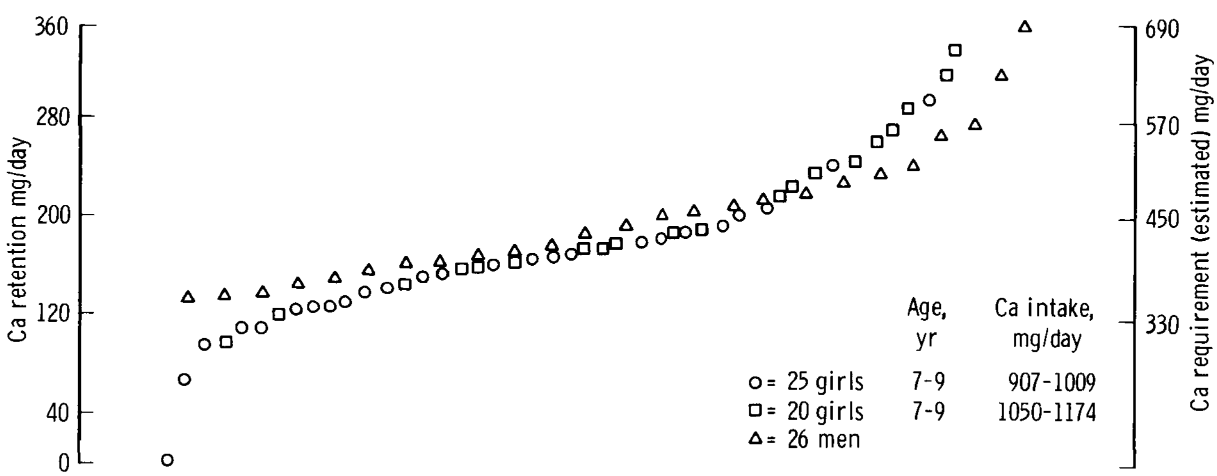

FIGURE 1.—Calcium retention in children and estimated requirement in men. (Source: Children, Sou. Reg. Stdy., S–28, 1954–58; men, ref. 5.)

rest. Unfortunately, in these studies the calcium intake was not measured although it was stated that intakes were liberal. The data in table IV are for two children with active tuberculosis studied by Johnston. The data suggest that transfer from complete bed rest to limited muscular exercise can improve calcium retention to the extent of 200 to 300 mg per day. More extensive studies are needed to define more accurately the extent to which very limited muscular activity may be able to overcome the losses associated with complete muscular inactivity. It can be assumed that limited muscular activity will be possible in space travel.

The relation of emotional state and calcium balance has likewise received only minor attention. The data in table V are those of subject 12 in the long-term study by Malm (ref. 5). There is rather convincing evidence here that increasing tension, a phenomenon that astronauts will no doubt encounter, has a profound effect on the calcium balance. During the 98 days when his calcium intake was 1024 mg daily the subject retained only 205 mg. It was a period following an attempted escape from the prison during which he was teased incessantly by his tougher comrades for having failed to escape. He adjusted to this and was able to retain calcium for 210 days with an intake of only 574 mg daily.

Then he began worrying about passing examinations. He had turned into a good prisoner-student and was attending classes. This was followed by mounting tension because of threats that he might be subjected to isolation. Since his fecal calcium was consistently exceeding that in the food the isolation threat was imposed to be sure he was not cheating on his food intake.

TABLE III.—*Variations in Iron Requirement for Balance in Adults*

[Source: Ref. 4]

Interval, mg Fe/day	Number of cases
3–3.9	1
4–4.9	0
5–5.9	3
6–6.9	4
7–7.9	4
8–8.9	2
9–9.9	2
10–10.9	1
11–11.9	2
12–12.9	1

TABLE IV.—*Calcium Balance During Rest and Activity*

[Source: Ref. 6]

Days	Calcium, mg/day				Remarks
	Intake	Urine	Feces	Balance	
Case 1: 2-year-old boy, active TB					
18	1779	68	1186	525	Active [a]
18	1789	140	1410	239	Rest
18	1797	131	1379	287	Rest
18	1725	101	1463	161	Rest
24	1739	82	1360	297	Active
Case 3: 5-year-old girl, active TB					
36	2105	230	1623	252	Rest
36	2105	139	1968	−2	Rest
36	2157	118	1831	208	Active [b]

[a] Attending school in a wheelchair.
[b] Bicycle, 9 minutes twice daily.

TABLE V.—*Calcium Balance and Emotional State—Subject 12*

[Source: Ref. 5]

Days	Calcium, balance mg/day				Remarks
	Intake	Urine	Feces	Balance [a]	
126	954	125	482	347	Adjusted
98	1024	193	626	205	Tense, depressed
210	574	157	357	60	Adjusted, relaxed
322	543	187	596	−240	Increasing tension
14	563	224	1020	−681	Tension high
14	560	232	1249	−921	Tension climax
56	599	247	358	−7	Relaxed
28	566	185	565	−183	Tension rising

[a] Negative balance=8.8 percent of estimated total body calcium.

He objected violently to isolation and won his point. The resulting relaxed period coincided with a marked decrease in calcium loss, with balance essentially being obtained. The final rising tension was brought on by his increasing insistence that he be released from further participation in the study, having at that time been a subject in the study for 2.5 years. It is of some importance that during the period, in excess of 1 year, when the daily calcium losses sometimes reached as high as 921 mg per day, the total calculated calcium loss did not exceed 8.8 percent of the estimated total body calcium (ref. 8). It would be difficult to measure this degree of skeletal depletion with bone density measures currently in use (ref 9). Nevertheless, in view of the observation that emotional state can influence calcium utilization it would appear advisable to subject astronauts to emotional stresses during metabolic balance studies in order to have some advance measure as to the extent to which such stresses may influence individual calcium losses.

Sweat losses of nutrients have generally been ignored in evaluating nutrient requirements. That they can be considerable, at least for calcium and iron, is illustrated in the data shown in tables VI and VII from the studies reported in references 10 and 11, respectively. It should be noted that in the case of calcium there appeared to be adaptation with continued exposure to the temperature of 100° F, the average per hour sweat loss of calcium declining from an initial 4-day hourly rate of 36 to a rate of 17 mg per hour during the 13th to 16th days. Under normal temperature climatic conditions the estimated daily calcium loss is assumed to be about 20 mg (ref. 1). In the data for iron (table VII) there was no clear adaptation evident.

A consideration of variations in nutrient requirement indicates that vitamin requirements may vary fully as much as mineral requirements, if we can rely upon present methodology for assessing nutritional status. With respect to ascorbic acid it is widely accepted that there is wide variation among individuals if one uses degree of tissue saturation as a measure of nutritional status. The studies of reference 12, in which regression equations for mean response

TABLE VI.—*Calcium Loss in Sweat in Young Men*

[Source: Ref. 10]

[Calcium intake: 581 mg/man/day; Data average: three men; Calcium loss in sweat during cool period: 3 mg/hr; Activity: moderate exercise 30 min daily]

Days at 100° F	Average calcium loss, mg	
	per 7.5 hr	per hr
1–4	270	36
5–8	153	20
9–12	125	17
13–16	127	17

TABLE VII.—*Iron Loss in Sweat in Young Men*

[Source: Ref. 11]

[Iron intake: 23.4 mg/man/day; Data average: three men; Activity: moderate exercise 30 minutes daily]

Days at 100° F	Average iron loss mg/man/day
1–4	1. 01
5–8	. 96
9–12	1. 07
13–16	. 86

in blood ascorbic acid in postoperative patients were compared with those found in young healthy adults (ref. 3), led to the conclusion that individual variability was extensive. From regression analyses of data collected during controlled intakes, ranging from 0 to 300 mg per person per day, it was concluded that 200 mg of ascorbic acid daily was required to maintain "near-saturation of tissues" in 95 of 100 individuals in the population. Half-saturation of blood could be achieved with 95 percent confidence on daily intakes of 75 mg. From animal studies (refs. 14 and 15) this level of saturation is probably sufficient to prevent defects in wound healing.

Ascorbic acid has been demonstrated to play an important role in development of tolerance to cold in experimental animals. Whether this applies to man is much less clear (ref. 15), although it would appear appropriate to examine this further if cold exposure is to be anticipated in space flights. At least one proposal has been advanced that astronauts be provided with 100 to 250 mg of ascorbic acid per day and that this level would not be considered superfluous overnutrition based on present knowledge (ref. 16).

An evaluation of variations in requirements for the B-vitamins is difficult because of limited studies on man for extended periods. Pett's (ref. 4) summary of variations in the estimated thiamine requirement is given in table VIII. A threefold to fourfold variation is implied, with daily requirements ranging from 0.4 mg to over 1.5 mg. Figure 2 illustrates the variations in thiamine excretion encountered in studies on 17 preadolescent girls who were on a constant intake of 0.5 mg of thiamine per 1000 calories for periods of 4 to 8 weeks. There was no evidence of trend toward increasing or decreasing thiamine excretions during the course of the study so it can be assumed that the intake was probably similar during the preexperimental period. One standard deviation around the mean daily excretion of 250 mg encompasses about two-thirds of the sample. The coefficient of variation is about 20 percent. Extending to 2 standard deviations, or about 95 percent of the observations, reveals an excretion variation ranging from 135 mg to 365 mg, or a threefold variation. If excretion is related to requirement, as is assumed, the variation is about as was concluded from Pett's analysis of the earlier data. It is rather striking that some of these children were rejecting as much as 40 percent of intake, whereas others were excreting only about 10 percent of the intake. Even though total needs for B-vitamins for the astronaut could be supplied by a few capsules, it might be worthwhile to develop uniformity data in order to eliminate those individuals who exhibit unusual metabolic patterns.

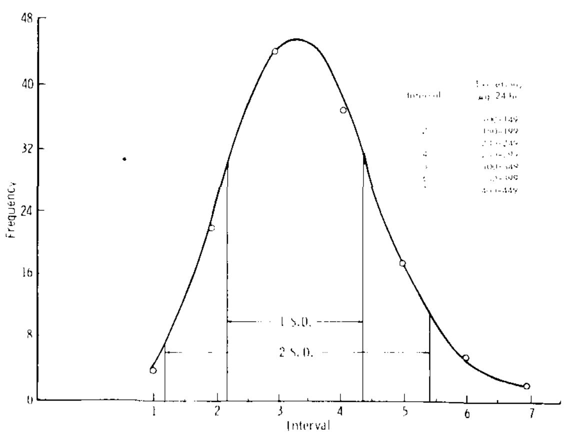

FIGURE 2.—Distribution of urinary thiamine excretion in children. Intake: 0.5 mg/1000 cal; Mean: 250.31±57.5. (Source: 17 girls, age 7–9 yr, Sou. Reg. Stdy., S–28, 1954–58.)

TABLE VIII.—*Adult Thiamine Requirement*

[Source: Ref. 4]

Interval, mg thiamine/day:	*Number of cases*
0.4–0.59	3
.6– .79	4
.8– .99	4
1.0–1.19	2
1.2–1.39	1
1.4–1.59	1

Figure 3 shows individual distributions of urinary riboflavin excretions in men who were maintained on daily intakes of 0.3 or 0.5 mg per 1000 calories for a period of 9 months (ref. 17). The indications are that prolonged studies are advisable and may considerably reduce variations encountered in short-term studies. The daily excretion range extended from 60 to 100 μg when the intake was 300 μg per 1000 calories. About the same range (100 to 150 μg) was observed for those whose intake was 500 μg per 1000 calories. Using this distribution for predicting variations in requirement one could conclude that the range of requirement for individuals varied but little. Nevertheless, the last individual in the 0.3 mg per

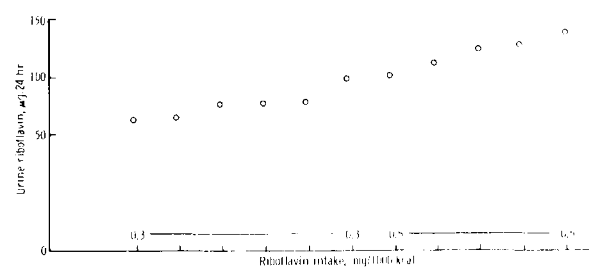

FIGURE 3.—Urinary riboflavin after 9 months of constant intake. (Source: Ref. 17)

1000 calorie group appeared to be similar to the first individual in the 0.5 mg per 1000 calorie group, suggesting that for some individuals the 0.3 mg per 1000 calorie intake provides tissue saturation levels equal to those achieved by others with an intake nearly twice as high.

Concerning other vitamins, there is some reason to believe that vitamin E and other antioxidants (refs. 18 and 19) should receive some attention in rations for space flight, particularly if protection is not afforded for the food supply against ionizing radiation. Vitamin A destruction can also be anticipated under conditions of radiation exposure.

Consideration must also be given to the possible influences of environmental contaminants as they may influence nutrient requirements. Reference has been made to the value of pyridoxine as a protective agent against the toxic effects of one rocket propellant (ref. 16).

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Discussion: Mineral and Vitamin Requirements of Long Flights

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As Dr. Engel and others have suggested, an adult astronaut will require about 1100 kilograms of exogenous nutrients per year of space flight if we feed him the National Research Council allowances and allow him 2 liters of uncycled water and 500 grams of oxygen per day. Of this amount, only 1 kilogram will consist of vitamins and minerals and we are thus not particularly restricted in terms of weight since this is less than 0.1 percent of the maintenance load.

Dr. Engel has alluded to the possibility that the mineral and vitamin requirements of the astronaut may be altered. In general, it would seem that two opposing factors may operate in the long term flight situation, one of which may tend to decrease nutrient needs and the other to increase them. Weightlessness and the relatively low index of physical activity in the space capsule will seemingly result in a reduced need for most nutrients. On the other hand, it is conceivable that "stress" may increase nutrient need. If these are the major factors to be dealt with, the nutrient needs of the astronaut aloft will probably not differ radically from those on Earth. Unfortunately, we have no assurance that such will actually be the case and a variety of other considerations suggest themselves. What, for example, will be the results of long term exposure to an atmosphere that contains no inert gas? Will the bacterial flora be altered sufficiently to produce more or less micronutrients? Indeed, have we sufficient evidence to exclude the possibility that gaseous nitrogen is an essential micronutrient? Also, how can we be certain in long term flights that the stainless steel microcosm of the astronaut will furnish him the metal contaminants we get in our earthbound environment? The recycling of water will presumably remove contaminants. Will the increased exposure to irradiation alter nutrient requirements? What will be the magnitude of the nutrient losses in sweat? The forced ventilation design of pressure garments enhances evaporation from the skin surface. In reference 1 it is reported that the water intake of an astronaut wearing a ventilated pressure suit with an air inlet temperature of 60° is increased by almost 1200 milliliters per day. Will the unbathed astronaut be encrusted in an exoskeleton composed of sweat deposits after several months in space? If so, how will it be removed? Will its presence reduce further mineral losses? The psychological effects of a low-residue, high-monotony diet must also be considered but I am inclined to minimize this as a problem area.

Having raised many questions and answered none, I would like to turn briefly to "stress" and the specific question as to whether it increases vitamin requirements. In at least one publication on the nutritional needs of the space traveler a multivitamin tablet was included to "alleviate" stress (ref. 2).

Even if it is agreed that the astronaut is subjected to considerable stress during flight, there is no convincing evidence to suggest that extra vitamins will, in fact, be of benefit. The literature relating to this subject is characterized by poorly controlled studies and conflicting conclusions (ref. 3). There is some evidence that vitamin *deficient* animals have difficulty responding to stresses but, in general, it has not been convincingly demonstrated that the vitamin supplementation of persons having normal vitamin reserves will improve performance or mental well being (refs. 4 to 7). I am unimpressed, therefore, by the supposition that astronauts should have additional vitamins. I am, however, reconciled to the fact that the first spaceship to be launched on an extended probe will contain bottles of vitamin tablets since the weight burden of doubling the NRC allowance for all vitamins would amount to less than 100 grams of material per year per astronaut. The supplemental level of each vitamin should be carefully considered. In this regard I am a bit confused about a figure given in a preceding paper concerning the SPAMAG recommended diet. A vitamin "Supplement" was listed as a standard NRC minimum-daily-requirement polyvitamin tablet. Aside from the fact that NRC does not have an MDR list, it is not clear to me if this supplement is to be given in addition to the vitamins found in the diet. I would also like to caution against the use of a blanket increase of x times the NRC recommended allowances. It is one thing to increase the intake of vitamin B_{12} several fold. It is another thing to effect a similar increase in the intake of vitamin D. Although the rapid urinary excretion of excess water-soluble vitamins takes care of these vitamins, this route of excretion is not available to handle large excesses of fat-soluble vitamins. The latter are stored in large quantities in the liver and excessive intake can result in toxicity. The tolerance limits for excess vitamin D is particularly low. I would also like to point out that the act of swallowing a vitamin capsule does not necessarily insure that its contents will reach the tissues. It has been found, for example, that the vitamins contained in some vitamin tablets are not fully available to the body (ref. 8). If astronauts must have vitamin tablets, they should be in a form that disintegrate readily so that the vitamins can actually be absorbed.

The profound effect of various factors on calcium balance has been emphasized by Dr. Engel and others. This mineral deserves particular attention since Cockett, et al. (ref. 9) have suggested that weightlessness and relative immobilization during space flight may produce significant decalcification of the skeleton and a concomitant increase in the tendency to form urinary calculi. Weightlessness tends to produce stasis in the bladder which is further complicated by a decrease in urinary urgency. These workers suggest that astronauts be well shielded from ultraviolet light while in space, since this would promote the synthesis of vitamin D and thus enhance the uptake of calcium from the diet. This possibility seems remote to me. If a marked alteration in the calcium intake of the astronaut is anticipated it should be introduced a considerable period of time in advance of the flight since it has been reported that animals who are accustomed to high dietary calcium intakes are unable to decelerate the turnover of calcium when faced with a restricted intake later in their lives (refs. 10 to 12).

To me this calcium problem is a particular dilemma. If the astronaut goes into negative Ca balance as a result of weightlessness and immobilization, should an attempt be made to increase his intake to maintain his stores, or should he be permitted to reach a new equilibrium at a lower level of body stores? This would seem to me to be an important consideration.

In conclusion, I certainly agree with Dr. Engel and others who have pointed out the need for the biochemical examination of astronauts to determine if they have any aberrant nutritional needs. In addition, a dietary history to determine their usual levels of nutrient intake would be very informative, with particular attention being paid to calcium. Although the use of vitamin supplements is of questionable value, it is probably inevitable, and I would therefore urge careful consideration be given to the magnitude of the increased intake and to its physical form.

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Human Nutritional Requirements for Water in Long Space Flights[1]

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DEFINITION OF THE WORD "REQUIREMENT"

Some authors have defined the requirement for water in terms of balance without reference to function (ref. 1, p. 208). Others prefer to discuss it in terms of efficiency or health as related to changes in the total body water or its various subdivisions (ref. 2). In our studies of the survival ration problem we have preferred the latter approach as being both more logical and more meaningful practically (ref. 3). The first definition demands that over a given stretch of time the water balance be neither positive nor negative. The second definition requires that the total body water and its related osmotic concentration be adequate to support efficiency in the performance of assigned tasks and to prevent clinical evidence of syndromes such as orthostatic hypotension, impairment of renal function, or hyperthermia, to name three conditions which can result from a severe water deficit.

Various words which have been used commonly in discussions of the water requirement are in some instances ambiguous, etymologically unsound, or both. We propose the following terms and their definitions:

(a) normohydration—adequate hydration by whatever criteria an author specifies

(b) hypohydration—a water deficit

(c) hyperhydration—a water plethora

(d) normohydremia, hypohydremia, and hyperhydremia—normal, low, or high concentrations of water in the blood

(e) dehydration—to be reserved for dried foods and tissues from which all or virtually all the water has been removed

(f) hydropenia—a deficiency of water for drinking

(g) exchangeable water pool—chemically identifiable water which is available for detectable and definable physical or chemical transactions in the body's metabolism

THE WATER BALANCE

Components

The water balance is definable as the difference between the input from all sources into the exchangeable water pool and the output from all sources:

$$H_2O_{balance}=H_2O_{input}-H_2O_{output} \qquad (1)$$

The various components of the water balance are listed in table I. The direct measurement of some of these components, or at least their computation, is possible. Examples are: Water in beverages or food; water injected; water in the feces, urine, or blood; and water lost through

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the skin, mammary glands, and lungs. Of the five reactions shown that comprise metabolic water, only the water of oxidation and associated water are commonly mentioned. It is doubtful that any of them can in fact be measured with available techniques, and there is good reason to question our present equations even for H_2O_{ox} and H_2O_{assoc}. (See ref. 4, p. 112.)

To make his work a little easier, any human metabolist is tempted to simplify his system. He will keep his subject comfortable and quiet, without sweating. He will choose a healthy young man, and so avoid complications such as H_2O_{milk} or H_2O_{misc}. He will keep his young man without change of body weight or composition, and so duck awkward questions about H_2O_{poly}, $H_2O_{nonexch}$, H_2O_{hydr}, and H_2O_{assoc}. Then his equation for water balance becomes:

$$H_2O_{balance} = (H_2O_{fluid} + H_2O_{food} + H_2O_{ox}) - (H_2O_{fecal} + H_2O_{pulm} + H_2O_{derm} + H_2O_{urine}) \tag{2}$$

However, in real life, more often than not we must face non-steady-state situations. We may be dealing with the ill or injured, who are in a catabolic state; or with athletes, whose metabolism and water turnover is high because of frequent exercise, hyperventilation, and sweating; or with growing adolescents, laying down protein, fat, and carbohydrate in their strongly anabolic fashion; or with a sedentary scientist, becoming obese; or even with a pregnant cosmonaut. The measurement or calculation of the water balance under such circumstances is unlikely to be accurate, although these may be precisely the circumstances in which inadequacy of the water balance may be injurious to efficiency, health, or even life.

Simplification of Peters-Passmore Equation

In another communication we have suggested that an ingenious method for calculating the water balance without measuring either the water input or water output be named after Peters of Yale, who proposed a complicated form of it, and Passmore of Edinburgh, who rescued and simplified it for metabolic purposes (ref. 5, p. 318). I now propose a further simplification of this equation, and an extension of it. The full derivation follows:

Assume a comfortable environment and no change in the gravitational constant. Let the

TABLE I.—*Sources and Avenues of Input and Output for the Exchangeable Water Pool*

Source or avenue	Input	Output
Gastrointestinal	Beverage (H_2O_{fluid}) Moisture in food (H_2O_{food})	Feces (H_2O_{fecal}) Vomitus or saliva
Pulmonary	Absorption of gaseous or fluid water (H_2O_{pulm})	Vaporization (H_2O_{pulm})
Dermal	Absorption of gaseous or fluid water (H_2O_{derm})	Transpiration (H_2O_{derm}) Sweat (H_2O_{sweat}) Milk (H_2O_{milk})
Renal		Urine (H_2O_{urine})
Circulatory	Infusion or injection (H_2O_{misc})	Hemorrhage (H_2O_{blood}) Exudation or transudation (H_2O_{misc})
Metabolic (H_2O_{met})	Oxidation (H_2O_{ox}) Condensation or polymerization (H_2O_{poly}) Release of nonexchangeable water of hydration ($H_2O_{nonexch}$)	Hydrolytic reactions (H_2O_{hydr}) Water associated with protein, fat, or glycogen (H_2O_{assoc})

change in body weight W be measured from time 1 to time 2. Then, if all measurements are in the same weight unit,

$$W_2 - W_1 = (\text{Gas absorbed} - \text{Gas expired}) + (\text{Fluid ingested} - \text{Fluid excreted}) + (\text{Solids ingested} - \text{Solids excreted}) \quad (3)$$

For the simplified situation described in equation (2), the only metabolic gases involved are oxygen and carbon dioxide; the only liquid is water; and the solids are the total solids measured after drying. Then equation (3) transforms to:

$$W_2 - W_1 = (O_{2,\,abs} - CO_{2,\,exp}) + (H_2O_{fluid} + H_2O_{food}) - (H_2O_{urine} + H_2O_{fecal} + H_2O_{pulm} + H_2O_{derm}) + (\text{Solids ingested}) - (\text{Solids in urine and feces}) \quad (4)$$

Add H_2O_{ox} to both sides. Then:

$$H_2O_{ox} + (W_2 - W_1) = (O_{2,\,abs} - CO_{2,\,exp}) + (H_2O_{fluid} + H_2O_{food} + H_2O_{ox}) - (H_2O_{urine} + H_2O_{fecal} + H_2O_{pulm} + H_2O_{derm}) + (Sol_{ing}) - (Sol_{urine}) + (Sol_{fecal}) \quad (5)$$

But the terms involving H_2O in equation (5) define the water balance exactly as in equation (2). Rearranging the terms of equation (5) gives

$$H_2O_{balance} = (W_2 - W_1) + (CO_{2,\,exp} - O_{2,\,abs}) + (Sol_{urine} + Sol_{fecal} - Sol_{ing}) + (H_2O_{ox}) \quad (6)$$

This is the form in which Passmore cast Peters' awkward equation. The items involving body weight and solids are easily measured directly. The metabolic CO_2 and O_2 are measurable by ordinary respiratory methods. Water of oxidation must be computed. Peters did this by assuming a steady state, in which tissue protein metabolism may be calculated from urinary nitrogen, the carbohydrate is that of the diet, and fat is calculated from the change in body weight. Passmore calculated it from the nonprotein and protein respiratory metabolism (after ref. 6).

We have discussed in another publication the mathematical redundancy that exists in the Zuntz-Schumburg formulation (ref. 5, p. 317). The only actual measurements made are the oxygen consumed, the carbon dioxide produced, and the organic nitrogen excreted in the urine. As we have shown, the assumption that carbohydrate and fat are oxidized fully to CO_2 and H_2O and that protein is oxidized to urea, CO_2, and H_2O leads directly to a set of simultaneous equations for calculating protein, fat, carbohydrate, calories of heat, and water of oxidation. The data for some pure compounds are given in table II, and for common foodstuffs in table III. These tables enable one to demonstrate algebraically that all the named calculations are functions of the three variables O_2, CO_2, and urinary nitrogen N_u.

In the present context, we are interested in H_2O_{ox}. Its equation for a metabolic mixture is:

$$\text{Grams } H_2O_{ox} = 0.0434 \text{ gram } O_{2,\,abs} + 0.3349 \text{ gram } CO_{2,\,exp} - 1.04 \text{ grams } N_u \quad (7)$$

Substituting equation (7) in equation (6) gives

$$H_2O_{balance} = W_2 - W_1) + (CO_{2,\,exp} - O_{2,\,abs}) + (Sol_{urine} + Sol_{fecal} - Sol_{ing}) + (0.0434\ O_{2,\,abs} + 0.3349\ CO_{2,\,exp} - 1.04\ N_u)$$

and combining terms yields

$$H_2O_{balance} = W_2 - W_1) + (1.3349\ CO_{2,\,exp} - 0.9566\ O_{2,\,abs} - 1.04\ N_u) + (Sol_{urine} + Sol_{fecal} - Sol_{ing}) \quad (8)$$

This would seem to be the ultimate in operational simplicity for the Peters-Passmore equation.

The practical uses of equation (2) and equation (8) are illustrated by the following examples. A healthy young man fasted for 36 hours, with water ad libitum. The various components of the input and output were either measured directly or computed from the following list of factors:

Total solids of blood = 0.2 gram/gram whole blood

Total solids of feces = 0.2 gram/gram original feces

Total solids of urine and sweat are measured after exposing urine and sweat for 12 hours in

TABLE II.—*Metabolic Reactions of a Carbohydrate, a Glyceride, and a Peptide*

Substance and measurement	Chemical equation and values					
Glucose (Respiratory quotient, 1.00).	$C_6H_{12}O_6$	$+6\ O_2$	$=6\ CO_2$	$+\ 6\ H_2O$	$+673$ kcal	
Gram-mol weights	180	192	264	108		
Vol. equivalent	----------	134 liter	134 liter	134 liter (gas)		
Heat equiv., kcal	----------	5.01/liter	5.01/liter	5.01/liter (gas)		
Palmitin (Respiratory quotient, 0.70).	$2(C_{51}H_{98}O_6)$	$+145\ O_2$	$=102\ CO_2$	$+98\ H_2O$	$+15\ 233$ kcal	
Gram-mol weights	1612	4640	4488	1764		
Vol. equivalent	----------	3247 liter	2284 liter	2175 liter (gas)		
Heat equiv., kcal	----------	4.66/liter	6.67/liter	7.00/liter (gas)		
Glycyl-glycine (Respiratory quotient, 1.00).	$NH_2{\cdot}CH_2{\cdot}CO{\cdot}NH{\cdot}CH_2{\cdot}COOH$	$+3\ O_2$	$=(NH_2)_2CO$	$+3\ CO_2$	$+2\ H_2O$	$+471$ kcal
Gram-mol weights	132	96	60	132	36	
Vol. equivalent	----------	67 liter	----------	67 liter	45 liter (gas)	
Heat equiv., kcal	----------	7.03/liter	----------	7.03/liter	14.66/liter (gas)	

TABLE III.—*Products of Oxidation of 1 Gram of Foodstuff in the Body* [a]

Substance	O_2 consumed, g	CO_2 produced, g	H_2O produced, g	Heat produced, kcal
Monosaccharides, e.g., glucose	1. 067	1. 467	0. 600	3. 8
Disaccharides, e.g., sucrose	1. 122	1. 543	. 579	4. 1
Starch	1. 185	1. 629	. 556	4. 3
Fat (lard)	2. 876	2. 805	1. 071	9. 3
Protein	1. 382	1. 522	. 396	4. 1
Urinary N [b]	8. 638	9. 513	2. 475	25. 6

[a] Adapted from reference 4, p. 149.
[b] The factor 6.25 is assumed to correct urinary N to protein catabolized.

vacuum oven at 80° C and pressure of about 720 mm Hg (28 in. Hg).

Specific gravity of whole blood=1.05

1 liter CO_2=1.9769 gram

1 gram CO_2=0.5058 liter

1 liter O_2=1.4290 gram

1 gram O_2=0.6998 liter

Blood water=0.8 gram/gram whole blood

Sweat water=0.95 gram/gram sweat

Fecal water=0.8 gram/gram feces

The numbers used in the orthodox calculation of water intake minus water output (eq. (2)) are conveniently put in the form of an "income tax computation" as shown in table IV.

When the Peters-Passmore equation is used, the various factors related to water disappear;

TABLE IV.—*Example of Computation of Water Balance From Fluid Gains and Losses During 36 Hours of Starvation According to Equation (2)*

WATER GAIN				
1. Fluid water			400	
2. Food water			0	
3. Metabolic water				
(a) O_2	$287.7\times0.0434=$	12.5		
(b) CO_2	$283.3\times0.3349=$	94.9		
(c) Add lines (a) and (b)		107.4		
(d) N_u	$1.3\times1.04=$	1.4		
(e) Subtract line (d) from (c)			106	
4. TOTAL WATER GAIN (add lines 1, 2, 3(e))				506 grams
WATER LOSS				
1. Dermal plus pulmonary (insensible water loss)				
(a) Body weight 1		77 427.0		
(b) $O_{2,abs}$		287.7		
(c) Food		0.0		
(d) Fluid		400.0		
(e) Add lines (a)–(d)			78 115	
(f) Body weight 2		76 467.0		
(g) $CO_{2,exp}$		283.3		
(h) Urine		217.3		
(i) Feces		0.0		
(j) Blood		29.4		
(k) Add lines (f)–(j)			76 997	
(l) Subtract line (k) from (e)			1 118	
2. Fluid (sensible water loss)				
(a) Urine water		208.6		
(b) Fecal water		0.0		
(c) Blood water		23.8		
(d) Misc. water		0.0		
(e) Add lines (a)–(d)			232	
3. TOTAL WATER LOSS (add lines 1(l) and 2(e))				1 350 grams
WATER BALANCE				
Subtract Total Loss from Total Gain				−844 grams

but the final answer must be the same for the same data. An example for the 36-hour fast described above is given in table V.

Measuring Metabolic Water

If equation (8) is to be valid, the only input of metabolic water must be from water of oxidation, as listed in table III for common foodstuffs. However, there are several potentially invalidating sources of gain and loss of metabolic water in the system, as listed in table I. Examples of these for each of the major nutrients are:

(1) Polymerization of glucose

$$C_6H_{12}O_6+C_6H_{12}O_6=H_2O+C_{12}H_{22}O_{11}$$

(2) Condensation of amino acids

$$NH_2{\cdot}CH_2{\cdot}COOH+NH_2{\cdot}CH_2{\cdot}COOH$$
$$=H_2O+NH_2{\cdot}CH_2{\cdot}CO{\cdot}NH{\cdot}CH_2{\cdot}COOH$$

(3) Esterification of glycerol

$$CH_3OH{\cdot}CH_2OH{\cdot}CH_3OH + CH_3{\cdot}COOH = H_2O + CH_3OH{\cdot}CH_2OH{\cdot}CH_2{\cdot}CO{\cdot}CH_3$$

(4) Hydration of protein

$$\text{Protein} + nH_2O = \text{Protein } (nH_2O)$$

(5) Water of association

It is stated (ref. 1) that 1 g protein is associated with 3 g H_2O; 1 g neutral fat with 0.1 g H_2O; and 1 g glycogen with 1 g H_2O.

The older terminology lumped all these together with water of oxidation under the term *performed water*. When the water supply is unlimited, and under steady-state conditions of input-output, these reactions would cancel out; the sum of water of oxidation and water of polymerization would remain constant. However, if water were limited, especially when a catabolic situation existed, as in a starving castaway, then water of hydrolysis might represent a significant drain on the body's water supply. At the same time, some water of association would be released with each mol of protein, neutral fat, or glycogen catabolized; but this would not be enough to cover the hydrolytic demand of one mol of water for each mol of disaccharide, dipeptide, or monoglyceride, as the data of the above list and table III can be used to demonstrate.

As a matter of some interest, both theoretical and practical, in using deuterium oxide as an isotopic tracer we have encountered conditions when an initial test dose gave satisfactory data for total body water, and yet 2 weeks later, after a catabolic regimen with restricted water, a repeat test dose did not give good data, even when all appropriate corrections were made for loss of D_2O from the skin, lungs, kidneys, and gastrointestinal tract as well as translocation of D for H within the body (refs. 7, 8, and 9). The analytical procedures were impeccable; both the falling drop and the infrared spectrophotometer agreed. The values for the second determination came out as much as 10 percent higher than the first even after water deprivation. We speculate that some D_2O was used for hydrolysis, and thus in effect was sequestrated, resulting in a falsely high ratio of H_2O to D_2O.

We conclude that the shakiest part of all calculations of the water balance is in the various fractions of the metabolic water.

TABLE V.—*Example of Computation of Water Balance by the Peters-Passmore Equation During 36 Hours of Starvation According to Equation (8)*

1. Add the following:		
(a) Weight 2	76 467	
(b) CO_2	$283.3 \times 1.3349 = 378$	
(c) Solids in urine	9	
(d) Solids in feces	0	
(e) Solids in sweat	0	
(f) Solids in blood	6	
(g) TOTAL (add lines (a)–(f))		76 860 grams
2. Add the following:		
(a) Weight 1	77 427	
(b) O_2	$287.7 \times 0.9566 = 275$	
(c) N_u	$1.3 \times 1.04 = 1$	
(d) Solids in food	0	
(e) Solids in beverage	0	
(f) TOTAL (add lines (a)–(e))		77 704 grams
3. WATER BALANCE (subtract 2(f) from 1(g))		−844 grams

DISTURBANCES OF WATER BALANCE

In this discussion we are presumably not concerned with diseased persons, but only with healthy astronauts. However, we must consider stresses and disturbances of organ and tissue function which could lead to inefficiency or jeopardize health. Indeed, the definition of requirement that we have chosen implies a consideration of the abnormal to define the normal. The types and causes of disturbed water balance are as follows:

I. Hyperhydration
   A. Primary
      1. Overdrinking
      2. Inappropriate intravenous therapy
   B. Secondary
      1. Edema
         a. Cardiac
         b. Renal
      2. Nutritional (increased osmotic balance)

II. Hypohydration
- A. Primary
  - 1. Deprivation
    - a. Withholding
    - b. "Voluntary dehydration," i.e., inappropriate thirst responses
  - 2. Increased loss
    - a. Sweating
    - b. Evaporation from skin and lungs
- B. Secondary
  - 1. Fever
  - 2. Renal dysfunction
    - a. Diabetes insipidus
    - b. Nephritis
  - 3. Gastrointestinal dysfunction
    - a. Diarrhea
    - b. Vomiting
  - 4. Nutritional
    - a. Osmotic deficit
    - b. Osmotic plethora
  - 5. Dysfunctions of the skin
    - a. Hypohidrosis and anhidrosis
    - b. Dermatitis and burns
    - c. Inappropriate clothing

Hyperhydration (plethora of water) and hypohydration (deficit of water) may both be primary or secondary. Diseases of the kidneys, heart, or gastrointestinal tract can lead to retention, but hyperhydration is rare in healthy persons. It is exceedingly rare in the primary form, overdrinking. Secondary hyperhydration, even leading to water intoxication, can occur when the osmotic balance is strongly positive and the supply of water is unlimited.

Primary hypohydration is a present danger for all living systems. It results from simple deprivation or from an increased loss from the skin in sweating, or from the skin and lungs in a hot dry environment. Inappropriate thirst responses may lead to voluntary hypohydration (ref. 8). Excluding diseases of the kidney, heart, gastrointestinal tract, or skin, secondary hypohydration may occur in hyperthermia, osmotic plethora, or osmotic deficit. These later two as major factors in the water economy have been stressed in other publications (ref. 10).

In attempting to set up quantitative criteria for the water requirement, we must recognize its formal similarity to calories and no other nutrient. The amount of both that is needed varies within very wide limits depending on conditions. Both are strongly affected by physical activity, the thermal environment, and clothing (in the broadest sense). Additionally, the water balance is strongly affected by at least three other independent variables: (a) the intake of nutrients including water, minerals, protein, carbohydrate, and fat; (b) the ambient water-vapor pressure; and (c) the air motion.

Some of the relationships between the water balance and other independent variables can be described quantitatively (ref. 11). The conceptual framework we shall adopt has been used by others; for example, Gamble (ref. 12) and Adolph (ref. 13). It is the recognition of a basal maintenance requirement plus identifiable increments for activity or other factors (ref. 1).

Minimal Basal Requirement

In order to arrive at the basal maintenance requirement the items of equation (2), already stripped down to a steady-state, nonworking level, must be further reduced to an absolute minimum, still retaining the balance at zero. The necessary data are presented in table VI. It is unlikely that water of oxidation, preformed water, and insensible water can be reduced at all. The reduction of intake has to be secondary to the reduction of output. Gamble (ref. 12, p. 49) calculated 300 ml of urine as a minimum; Sargent and Johnson (ref. 7) estimated 280 ml as the demonstrable minimum with normal kidney function. Let us take 300 ml for urine, and cut fecal H_2O to 0 (bowel movements often cease on low-calorie diets). Water output then becomes about $300+1100=1400$ ml, and adjusted input becomes $270+845+250+35=1400$ ml. Beverage plus food will be 1115, regardless of the distribution between the two. This theoretical minimum is in close agreement with the experimentally established minimum of 1 liter per day of Sargent and Johnson (ref. 7). This is the absolute minimum, and hazardous.

Although no success has ever attended the use of generalized antisudorific drugs or of local styptics or astringents for abolishing the dermal

TABLE VI.—*Water Components and Daily Water Turnover of a 60 kg Man* [a]

(a) Water components

Component	Percent of body wt.	Vol., liter
Extracellular:		
Plasma	5	3
Interstitial	15	99
Intracellular	50	30
Total	70	42

(b) Typical daily water turnover

Source	Wt., g
Input:	
Beverage	268
Food moisture	2018
Water of oxidation	254
Preformed	333
Total input	2573
Output:	
Urine water	1482
Fecal water	105
Insensible water	1102
Sweat	0
Total output	2689
Water balance (Input-Output)	−116

From data of references 1 and 14.

loss of water vapor or sweat, still it might be possible, if the heat balance can be maintained, to cut down on the minimal insensible water loss by raising the aqueous vapor tension of the ambient air. For both the lungs and the skin, evaporated water is a mathematical function of the difference between the water vapor tension at lung or skin temperature, saturated, and the tension of the ambient air at its own temperature and humidity. The fundamental relations are:

$$\text{Aqueous vapor tension of any solution} = f\ (\text{Temp. and osmotic press}) \quad (9).$$

$$\text{Pulmonary } H_2O \text{ loss} = (\dot{V}_{exp} \times \text{Absolute humidity}_{exp}) - (\dot{V}_{insp} \times \text{Absolute humidity}_{insp}) \quad (10).$$

where V is volume of air for given time.

$$\text{Dermal } H_2O \text{ loss} = f_1(P_{H_2O} \text{ at skin temp. and osmotic press of plasma} - P_{H_2O} \text{ in ambient air}) \times f_2\ (\text{Surface area}) \quad (11)$$

From equations (9), (10), and (11), the ideal astronaut would be a cool, slow breathing, hyperosmotic dwarf. Paradoxically, to reach the absolute minimum requires a hot, humid atmosphere. This in itself reduces the capacity of the body for heat regulation, which requires, under these conditions, the evaporation of water equivalent to 25 percent of the caloric expenditure (refs. 4, 14, and 15). In the end, a compromise has to be struck among the needs of the kidney for water to excrete solutes; the needs of the skin and lungs to evaporate water to maintain heat balance; and the needs of the planner to keep all water loss to a minimum. I guess that the item "Insensible water" of table VI(b) cannot be lowered safely beyond 500 ml/day.

In summary, the absolute minimum requirement for water under any circumstances will be 300+0+500=800 ml. Of this, 250 will be metabolic and 550 will be fluid in beverage or food. This is a precarious, dangerous level. It cannot suffice if any stress at all is placed on the water economy.

Increments for Activity and Other Factors

By contrast with the pitifully small savings in the water economy that can be made by juggling with the osmotic balance and the aqueous vapor pressure of the ambient air, the losses that may be produced by changing the rate of dermal loss, pulmonary loss, and renal loss are spectacular. Sweating may go on at the rate of a liter an hour all day long (ref. 16). Increasing the pulmonary ventilation from resting at about 10 liters per minute to moderate work at 30 liters per minute can increase the pulmonary loss by a factor of 3. An extra osmotic load equivalent to 10 g NaCl per day can increase the urinary water loss by 300 ml per day. All of these increments are susceptible of at least a semiquantitative analysis.

Activity Increment.—Under moderate conditions about 25 percent of the heat load is dissipated by the insensible water loss. Sweat has virtually the same heat of evaporation as water, 0.58 kcal per gram. A daily increase from resting at 2000 kcal to moderate activity at 3000 kcal will require an increment of about 400 ml of water (i.e., $1000 \times \frac{1}{4} \times 1/0.58$) for heat dissipation.

Osmotic Increment.—The obligatory water requirement for excreting the osmotic load brought to the kidney is about 200 ml per day for each increment of 100 milliosmols per day (ref. 12). There is an optimum; for intakes below about 700 milliosmols per day, there is a loss of body water attributable to hyposmotemia (ref. 3). For such a situation, increasing the water intake does no good; there is a loss of water by way of the kidney, which must have a normal osmotic load from which to elaborate urine.

Thermal Environment.—Although in formal algebraic respects the thermal heat load of the environment is equivalent to the caloric effect of activity, yet there is a physiological difference, and the combined impact of temperature and humidity must be accounted for. The internal production of heat, especially in work, is mainly a mathematical function of body mass. The dissipation of heat from the body and the effects of heat and humidity are mainly a mathematical function of the body's surface area. For our purposes the most useful formulation of the water requirement as related to the thermal environment is the predicted 4-hour sweat rate index of McArdle et al. (ref. 17). As our standard man, we shall take a man with body weight of 70 kg and a surface area of 1.7 square meters. Table VII is the formulation to establish the predicted daily water requirement for any condition the astronaut is likely to meet. All of the parameters required for the computations of table VII are readily measured or calculated. To the best of our knowledge it represents the most comprehensive attempt to quantitate the water requirement in terms of its several components.

Practical Considerations

The last Mercury flight emphasized once again the quickness of the deleterious effects of a water deficit (ref. 18). In a matter of an Earth day, Astronaut Cooper lost some 3 kg of weight, appeared clinically to be hypohydrated, complained of thirst, and suffered from orthostatic hypotension. Astronaut Schirra also had these symptoms. No other syndrome from nutritional causes except actual food poisoning can appear so quickly as that of hypohydration.

To find practical ways of satisfying the water requirement, attention must be given to both the input and the output, with major emphasis on the input. All other losses are minor when

TABLE VII.—*Basal Minimum Water Requirement and Increments for Activity, Osmotic Balance, and Thermal Environment*

Basal minimum [a]	= Renal + Dermal + Pulmonary = 800 ml
Renal increment for osmotic adjustment [b]	$= \pm$ (Predicted excretion, mOsm/day − 400) × 2
Insensible water increment for caloric output [c]	$= \dfrac{\text{(Estimated kcal above basal)}}{0.58 \times 4}$
Sweat increment for temperature, humidity, air motion, work, and clothing [d]	= 6 × (Predicted 4-hr sweat rate)
Pulmonary increment for hyperventilation [e]	= (Estimated pulmonary minute volume − 10) × (Absolute humidity of expired air − Absolute humidity of inspired air)

[a] See references 4, 12, and 13.
[b] See reference 3.
[c] See references 15 and 19.
[d] See references 17 and 20.
[e] See reference 5.

compared with renal, dermal, and pulmonary output. The turnover of total body water may range from 2 percent per day to more than 20 percent per day. Renal loss can possibly safely be reduced to 500 ml per day. Losses through the lung and skin may be minimized by reducing physical work, maintaining a cool environment with the highest practical humidity, and keeping sweating low.

Main reliance will have to be placed on a satisfactory intake. Most Americans take most of their fluid as a beverage, not as pure water; and they like their beverages hot or cold, not tepid. As a minimum, 2 liters of fluid should be provided daily for drinking purposes, but with provision for increments if demanded by osmotic, activity, or thermal stresses. However, inappropriate thirst responses or individual idiosyncrasy may precipitate a water deficit, and must be guarded against (refs. 8 and 9).

The astronauts should be instructed about nutrition in general, and about water in particular as the most critical nutritional need after oxygen. They should, as they certainly will, be thoroughly trained physically and mentally for the stresses that might disturb their water balance. Evidence is against the idea that the hazards of a water deficit of given magnitude can be diminished by training or adaptation. However, repeated exposure to an identical stress may diminish its effects in general, including those on the water balance. This should be one goal of the astronaut's training.

So far as applied physiology and preventive medicine are concerned, Projects Gemini and Apollo offer two opportunities and responsibilities. The first is to conduct research on the actual water requirements of the astronauts. Equation (8) offers the chance to make a reliable estimate of the water balance, as all of the required parameters can be measured or estimated relatively easily. Second, the concepts and equations that went into table VII are susceptible of experimental verification, amplification, or revision. Without adding either to the weight of the vehicle or to the duties of the astronaut, these measurements could be made. Of all nutritional considerations they are the most important, for in a matter of hours, the life of the astronaut could hinge on a correct assessment of the water requirements and a successful meeting of those needs.

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Discussion: Human Nutritional Requirements for Water in Long Space Flights

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It was certainly appropriate in the preceding paper for Dr. Johnson to emphasize the terminology to be used in the discussion of water requirements. His comments show that it is difficult, if not impossible, to state exact requirements without precise information concerning the various conditions which have a pronounced influence on water losses by the body.

A number of groups, including the military, have been interested in the influence of environmental temperature on water requirements. Figure 1 shows the relation of fluid intake in g/man/day to mean daily outdoor ambient temperature. This graph is taken from a paper by Welch, Buskirk, and Iampietro (ref. 1) of the Army Medical Nutrition Laboratory and the Quartermaster R & D Command. The curve suggests that there is only a slight increase in fluid intake with increased ambient temperatures until about 60° F is reached. The exact point of the marked increase in water requirement may be expected to vary slightly, according to the observation of Benzinger of the Naval Medical Research Institute, who has worked extensively in the area of temperature regulation (ref. 2).

The amount of water required to meet the demands of sweating in hot climates is quite amazing. Observations in southern Iraq showed that healthy men might regularly be sweating 10 liters per day. Ladell (ref. 3) has indicated that a man in such a tropical area might deteriorate more in 12 hours without water than another in 4 days of deprivation in a more temperate environment. It has been suggested by some that a 5-percent loss of body weight due to water loss is tolerable, but with a 10-percent loss gross physical and mental deterioration begins to set in. These figures, of course, are not to be taken as exact limits of safety and may be seriously questioned by many.

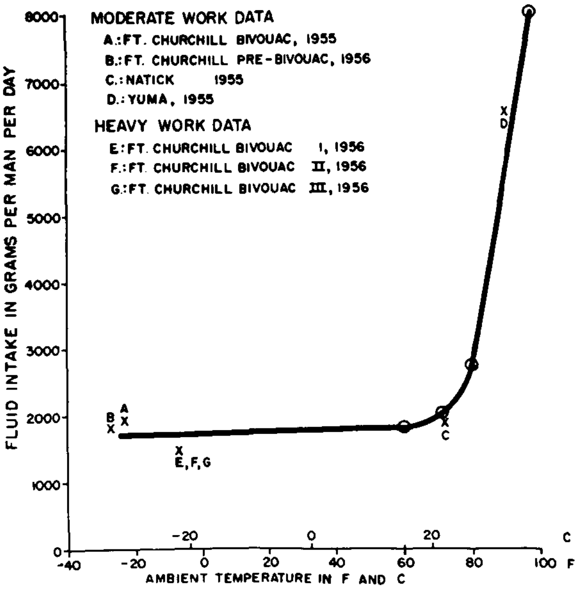

FIGURE 1.—Relation of fluid intake to mean daily outdoor ambient temperature. The circles represent data taken from Adolph et al.

It might be worth mentioning that the pattern of drinking available water may influence the urine loss. Kenny (ref. 4) has described experiments made to determine the most economical way of administering a water ration to a group of men exercising in an environment representative of the climatic conditions found in a deep mine in Nigeria. The results indicated that when water is taken in volumes greater than about 100 ml at one dose a significant diuresis results, leading to a greater loss of body water during the experimental exposure. It appears, therefore, that if a man is to use a water ration to the greatest advantage he must drink small volumes frequently rather than larger volumes at longer intervals. In the studies reported, drinking small volumes during 90 minutes at 100° F led to savings of 300 to 400 ml.

The results of the Navy's shelter habitability trials are of interest in regard to the fluid balance. Two trials with 100 men each were undertaken, with the men confined to the shelter area of 25×48 feet for a period of 2 weeks and fed a low-protein, low-spice diet. The reasons for the selection of a low-protein ration are discussed in Dr. Hegsted's paper. In the winter trial the dry-bulb temperature was generally between 70° F and 80° F except for the warm-up period on entering the shelter. Effective temperatures were generally in the comfort zone of 70°. In the summer trial mean dry-bulb temperatures of 87° to 90° F were observed, with effective temperatures generally above 80° Table I shows the water balances of the two trials (from refs. 5 and 6). It can be seen that the average man required almost 1 liter more water per day during the summer trial than during the winter. This group of men was relatively inactive, and the increased water requirement was due to sweating. If there had been any higher level of work activity, the water intake would no doubt have increased considerably more. These results are not unexpected, however; they are presented merely to demonstrate the relative level of water intake which may be required under specific conditions of temperature and humidity with a low level of work.

TABLE I.—*Comparative Water Balance in 24 Subjects of the Shelter Habitability Study, NMMC, Bethesda, Md.*

[Mean daily weight loss of 189 g/day in winter and 180 g/day in summer]

	Winter (Feb. 17 to Mar. 3)	Summer (Aug. 1 to Aug. 15)
Gains		
Mean daily water intake [a]	1263	2209
Water content of food [a]	170	170
Oxidative water, food [a]	235	235
Oxidative water, tissue [b]	157	149
Tissue water [c]	33	32
Total gains	1858	2795
Losses		
Mean daily urine volume [a]	790	697
Evaporative water, waking [a]	960	1433
Evaporative water, sleeping	240	478
Fecal water	100	100
Total losses	2090	2708
(Gains/Losses) × 100	89%	103%

[a] By direct measurement or from known composition and quantity of food.
[b] Winter, 142 g fat and 12 g protein; summer, 135 g fat and 11 g protein.
[c] Winter, 47 g lean tissue; summer, 45 g lean tissue.

It might be worthwhile to give some consideration to the possible influence of zero gravity on those factors which in turn influence the water requirement of an individual.

In the first U.S. manned orbital space flight, the astronaut excreted some 800 ml of urine in the period from 3:30 a.m. to 2:10 p.m. (approximately 11 hours). In the second orbital space flight (ref. 7), 2360 ml of urine was excreted in the period from 1:15 a.m. to 3:40 p.m. (approximately 14½ hours). In this flight the water balance was complicated by high suit-inlet temperatures that caused excessive sweating, and the increased fluid taken in to compensate for this. The astronaut lost 6 pounds of weight. This fact plus the slight hemoconcentration and the low specific gravity of the in-flight urine specimen lead to the opinion that a moderate diuresis occurred. The NASA report indicates that 1213 ml of fluid was ingested by the astronaut during flight and before recovery. No indication was given of the pattern of drinking, but if it was confined to a few large quantities this may be the reason for part of the diuresis.

The diuresis observed in the second manned orbital space flight may be partially due to the condition of weightlessness, since high urine volumes have routinely been observed in the hypodynamic states produced by recumbency and water immersion (ref. 8). These states have been considered analogs of weightlessness

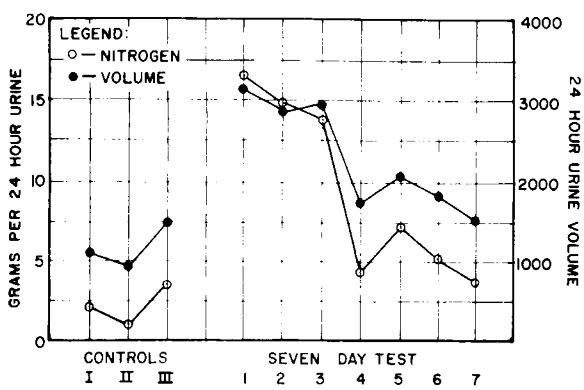

FIGURE 2.—Twenty-four-hour urine volume and urinary nitrogen excretion during 7 days of immersion, demonstrating the polyuria which was most marked during the first 3 days.

in regard to certain physiological systems. The effects of the hydrostatic pressure of body fluids due to gravity are minimal in recumbency and are counteracted by the supporting fluid in immersion. Figure 2 shows data taken from a paper by Graveline and McCally (ref. 9) from the Aerospace Medical Research Laboratory, Wright-Patterson AFB, Ohio. The diuresis began soon after immersion, and after 6 to 12 hours it was accompanied by a demanding polydipsia. Diuresis has also been reported by many investigators in prolonged recumbency; however, the condition is transient, whereas the diuresis of immersion is rather persistent. It is interesting to note in figure 2 that the excretion of nitrogen is also elevated, and indeed this may be partially responsible for the water loss. A decrease in osmotically active muscle tissue due to decreased muscular activity may occur during immersion, resulting in the loss of nitrogenous components in the urine. Other mechanisms such as the reflex inhibition of the antidiuretic hormone have been suggested to explain the diuresis of recumbency and immersion.

Dr. Johnson pointed out the influence of muscular activity on water requirements. Confinement and inactivity will undoubtedly be characteristics of space flight. A report by Welch, Morgan, and Ulvedal (ref. 10) on the caloric intake of two subjects confined for long periods (up to 30 days) in a space-cabin simulator indicated near-basal intakes. Crowden (ref. 11) has reported a marked reduction in oxygen requirement for exercise in water compared to air. Others support this position. Recently, however, Goff et al. (ref. 12) measured the oxygen uptake of four subjects at rest and during mild isometric exercise in air and in water in the temperature range of 29.5° to 36.5° C over 20-minute periods. The average oxygen consumptions at rest and during work indicated that for comparable isometric work loads there was no significant difference in metabolic rate between dry and submerged subjects. The limited data available on this particular subject suggest that additional information should be sought.

I would like to support Dr. Pollack's position that some way should be found to monitor the astronaut's water balance. Thirst alone cannot be counted on to indicate balance and many studies have indicated a dehydration during heat stress although drinking water was available.

In the absence of any sophisticated device for regulating water balance, the old idea of drinking enough to produce 700 to 800 ml of urine might be considered. However, this idea, which is fine on Earth, loses its value in view of the diuresis which might occur in space. Perhaps it would be possible for the astronaut to monitor his urine volume and to be instructed to drink at least this quantity of water plus an increment for estimated losses via other routes.

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COMMENTS

DR. SCRIMSHAW: There is one point which may not have been sufficiently emphasized—that it isn't enough just to make the water available, but to be sure that the astronaut has instructions to consume a certain minimum quantity. It can't be assumed that he will do this spontaneously.

DR. HESSBERG: We have written into the Gemini programs specific periods when the astronaut will be instructed to drink. We can't force water into the astronaut, but it is written into his mission plan.

DR. SARETT: Would it be possible to monitor dehydration by some means of watching the capillary flow in the ear, to monitor hemoglobin level, or something of that sort, which will give an indication of whether there is any dehydration, rather than just using weight?

DR. JOHNSON: My general feeling is that this suggestion might be useful. I don't think there can be any intravenous monitoring of the hemoglobin, but there could possibly be some type of telemetering from the ear. This is a tremendously important thing to do in real time.

Water Generation in Space

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In considering the problems of existing in space, we are considering extraordinary things, and extraordinary dimensions are necessary. The most severe conditions will arise while the astronaut is in the capsule, and the physicist and engineer can help by making the period of travel reasonably short. The time in travel to the Moon will be short, and even for trips to neighboring planets, which are the most interesting planets in many ways, the time can still be kept quite short.

But the situation is different upon arrival, for instance, on the Moon. After all, we are not going to the Moon to establish a record or to make a stop. We are going there for knowledge, and to gather knowledge will take time. It will be extremely important to find ways to maintain scientists participating in this magnificent adventure for a considerable period—such as a year or more. They must be maintained in very good health, and even in good spirits. Obviously, this will not be an easy task.

Technically, it is very important that we begin to give thought to the question of how we can use the materials we are likely to find on the Moon—materials which we hope will contain some water, certainly will contain oxygen, iron, carbon (in the carbonate form), and nitrogen—practically all the elements that we need for maintaining life.

In using lunar materials, or planning to use them, we do have the advantage that in nuclear energy we have a very cheap and a very light energy package. The question is always how we can use this energy package to convert the materials on the Moon into a usable form.

We are not sure that there will be water on the Moon. The astronomical bodies probably have been assembled from interplanetary material in similar ways, and there is no strong reason to suppose that the composition of the Moon is very different from the composition of the Earth's crust. In most of our terrestrial rock, we have at least a low percentage of water. In fact, the oceans were born out of this crust, in volcanos. Meteor craters have been identified on the Moon so, probably, water was there, but the gravitational field of the Moon may not have been sufficient to keep it.

We must first determine whether there is any water, and early samplings should answer that. We certainly should find it, but then the question is can we afford, on the Moon, to squeeze water out of rocks—possibly out of rocks that are a few hundred feet below the surface—when the water content is likely to be only a few tenths of a percent? There is one complete experiment which gives hope that this indeed can be done. Two and a half years ago we made a nuclear explosion a thousand feet under the surface of the Earth in New Mexico. It was called the Gnome Event. It was a small explosion, and out of the explosion, through the hole which we put there, came water vapor—hundreds of tons of it. The soil contains something like 1 percent of moisture, and we just squeezed that out and vaporized it.

Something quite similar might happen on the Moon in what might be called *Project Moses*. Can we make our nuclear explosions clean enough so that the water we get will be usable? Even that is not a foregone conclusion, because in our clean devices we always have some radioactivity that is particularly difficult to separate from water. But, if we have water, the problem of cleaning it up will have to be considered separately; at least for many purposes, cleaning up a fraction of the water ought to be entirely possible.

Project Moses will not be a cinch, and I think that at least the technical discussion and consideration of its many problems should proceed now. Obviously, its execution will have to wait until we get to the Moon. Also it should not be done imediately upon landing because we first want to do enough exploration to know how the Moon looks before any radioactive materials have been introduced. Once we know that—and we should know it rather soon after landing—the limited radioactivity caused by Project Moses really should not matter.

In the execution of Project Moses, for safety and to contain water initially, we will have to drill down 500 to 1000 feet. Now, drilling techniques are well developed, and it will not be too difficult to construct light drilling rigs, but all these drilling rigs need one thing: cooling. When we drill the hole, we will not yet have water to use for cooling. The problem is one of how to drill a hole with the minimum development of heat and the minimum use of cooling mechanisms. Probably drilling should be done at maximum temperatures, because, if we drill at high temperatures, a small amount of coolant will radiate effectively and thus get rid of the heat effectively.

However, executing even that relatively small task will be difficult on the Moon. In surroundings where eating, drinking, and walking are problems, any engineering will be indeed a problem.

Next, if we do get this water, what do we do with it? We can make sure that the water comes out at a definite spot. The operation probably should be done at night when the temperature is low. A big plastic bag might be able to contain this water for a moment; it will cool very soon and can then be poured and used—even, we hope, to grow algae.

There are many lunar materials that are extremely valuable for the purpose of sustaining life and activities on the Moon. This emphasizes the need for more and different energy sources on the Moon. For a steady energy source, I recommend a nuclear reactor—probably a very powerful one, much more powerful than those which are usually considered for space vehicles. A powerful nuclear reactor is not much heavier than a weak nuclear reactor. What is heavy in a nuclear reactor is its shielding, and there is no reason to believe that material on the Moon is any poorer shielding material than that we find on Earth. We will have to carry along the reactor core and the equipment that goes in and around the reactor. All of these can be light, effective, and durable; for these purposes no amount of money should be spared. We have the freedom of using any material, but we have the requirement to use as little weight of it as we possibly can. For the shielding, we can depend on lunar material. We probably can put up a reactor that will be equivalent in power to the most powerful reactors on Earth. We probably will be able to make electricity, which will give us a considerable amount of freedom for various operations. At the same time, we can and we should use this reactor for the purpose of making processed heat.

An adequate supply of oxygen will be a critical factor in survival on the Moon. If on the Moon we find any ferric oxide, of which we have plenty on Earth, simple and not very high heating of it will release oxygen. If we do not find any ferric oxide, probably other rock materials will have to be heated to a higher temperature before oxygen is released. Even the water that we hope to find might be electrolyzed to produce oxygen.

The second most important ingredient for lunar survival is carbon dioxide. If we find any limestone on the Moon, we will find carbon dioxide. However, most of our terrestrial limestone is the product of biological activity, so it is not certain that we will find calcium carbonate. But other carbonates may be common, and to drive carbon dioxide from carbonates just by processed heat is not too difficult an undertaking.

Our various Moon probes will bring back information about the composition of the Moon in a relatively short time. The plan is to irradiate the Moon as we approach it and to produce characteristic activities of the lunar surface. Then the decay of these activities will be observed by the lunar probe, and from this we should be able to determine the lunar composition. Hydrogen probably will not be found this way, and, in the end, we shall have to bring back a bit of the Moon for analysis in Earth laboratories. Only then shall we be able to make detailed plans on how to utilize lunar material.

But there are few things that even today we know will have to be prepared and will take long preparation. To construct a nuclear reactor—such a one has never been constructed before—will take 2 years here on Earth. To plan a nuclear reactor of the lightest materials which can easily be put together, to develop the technique of putting shielding around it, using the material on the Moon to develop techniques of working with an appropriate nuclear explosion—are engineering problems on which work could very usefully start right now. What we need at present for our nuclear reactor project is not yet billions of dollars—a small part of the many-billion-dollar amount will suffice to do the thinking and to make the preliminary plans now. When we combine this with the information we shall soon get back from the Moon, it is very likely that we shall find some way to make life, exploration, and scientific work easier and more possible—if not in space, then, at least on our satellites.

COMMENTS

DR. SCRIMSHAW: Dr. Teller, what is your definition of "long-term"? Some people are considering 30 days as long term. You indicate a year or more.

DR. TELLER: Looking into the future, going to the Moon will require a day, and, on a fast jet, it should take only hours. When we try to go to Mars—and that surely is to come—if we try to do it by ion propulsion, it may take years; but I don't think we will do it by ion propulsion, and I think that better means will be available. Furthermore, to stay out too long without protection from solar flares might be risky. I would think that to stay for as long as 30 days in the capsule would be quite a feat. Although longer terms could and should be contemplated, I do not believe that this is the immediate goal; once the destination is reached it will take a long time to take full advantage of the adventure.

DR. SCRIMSHAW: Dr. Teller, please comment a little more on this matter of the availability of power, raw materials, or water for chemical food synthesis, as well as biological synthesis, in a fixed base on the Moon.

DR. TELLER: Nuclear energy provides a very ample supply of energy, and it is entirely permissible—particularly in a fixed base—to use this energy wastefully. In fact, practically the only problem is how to get rid of the energy, or to cool it, once it is created; therefore, when designing the intricate, important, and, hopefully, light units for food synthesis, I think it would be well if it is assumed that as much energy as desired can be obtained. Don't economize on energy. Economize on weight.

DR. ROBINSON: Dr. Teller, what information is available regarding subsurface temperature on the Moon? Do you think that this relationship will be about the same as that on Earth?

DR. TELLER: I believe that once we penetrate beyond a few feet the temperature on the Moon may not be very different from the temperature on the Earth. The average radiation that the Moon receives from the Sun is the same—perhaps a little more, because there is no reflecting atmosphere. On the other hand, the reradiation—the albedo of the Moon—may be a little bit different than the albedo of the Earth. The temperature even a few feet down will depend only on the heat balance of what is received from the Sun and what is radiated; therefore, in trying to look into conditions of drilling down, at least in that one phase, I do not think that we are going to encounter exotic conditions.

DR. LUCKEY: Using a pond for producing food may be fine, but chemical synthesis—carbon, oxygen, carbon dioxide, and so forth—takes time, as well as expensive equipment and man hours. It seems to me it would be much easier to bring food to the Moon with another rocket.

DR. TELLER: Such supplying will be extremely expensive. What I have in mind is a pond with algae in it; I think that it would be a very interesting and a very impressive biological project to look into the question of whether, at least in the polar regions of the Moon, where the temperature is perhaps a little more uniform, something like a pool—if necessary, even a heated pool, because we have plenty of energy—

could produce this food. I am sure that vitamins and some other materials will have to be shipped to the Moon, but every ounce—certainly every pound—that can be saved in shipment will pay for itself.

Dr. Hessberg: Would a laser, which could use a light KIWI or some type of reactor to drive it, not be a cleaner method of producing both heat and power on the Moon rather than trying to take a complete reactor capability?

Dr. Teller: A laser is a wonderful and expensive instrument, for several specific purposes. To make lasers that would produce water, I think, is, in an engineering sense, out of the question; but a modification of this suggestion could be possible. If there is real difficulty with the radioactivity produced—and I don't know that there will be such difficulty—then a reactor could be placed in a hole appropriately deep and it could just heat itself and its surroundings. It might then be possible to transfer this heat, with appropriate heat transfer fluid, to the surrounding rock and escape from the difficulty of any radioactivity. This problem merits very careful thought.

Dr. Harper: Would you be willing to speculate on how long it might take, and how many men would be required, to put this lightweight ractor into operation and to begin to produce something that might be considered edible?

Dr. Teller: I don't know how long it will take. Here we have to consider prefabricated reactors. I am sure that the number of people required won't be less than two, but how many I don't know. One design criterion could be that the reactor should be of the kind that can be put into operation by 12 men in a month. It will take quite a bit of thought to decide if this requirement or anything like it can be met.

Dr. Harper: There will be, then, a considerable period of time before something edible is produced, and, in the meantime, some intermediate process will be needed to support those who are going to put this operation into effect.

Dr. Teller: It is quite clear that at first food, oxygen, everything needed, will have to be taken to the Moon; however, I think that the real exploration of the Moon, finding out what is there, taking maximum advantage of it, will take many years and will take many dozens of people, and whether this type of work can go on will depend on whether longer range plans will work. Furthermore, learning to exist on the Moon—using its materials—will be very helpful to astronauts when they reach Mars, which is, because of its atmosphere and presumably because of its slight water content, much more livable.

Dr. Allen: There is some reason to believe that the water content beneath the surface of Mars and perhaps the Moon is fairly high. Could the water content be higher closer to the surface of the Moon than you indicated?

Dr. Teller: It could. I tried to be a little conservative. There is also reason for conservatism. The best theory of the growth of the Moon is that the Moon used to be relatively close to the Earth and that the Earth had several moons, and that tidal friction, which even now is going on, slowed down the Earth's rotation and allowed the Moon to drift away. In so doing, the Moon swept up all the other moons. The formation of the Moon was probably connected with the coalition of quite a few of these bodies, and the lunar craters show the mark of some of these catastrophes. In every one of these a lot of heat was produced, and a great deal of water was lost. I hope some was retained but I doubt that great amounts were retained.

Dr. Robinson: Do you think that the early probes will have to be manned?

Dr. Teller: The probes that gather material from the Moon need not be.

Dr. Brown: If we are contemplating growing microorganisms on the Moon, and the requirements for confinement in a small space are removed, might it be wise to consider the possibilities of the limits at which growth can occur, rather than optimum conditions?

Dr. Teller: I think it is most important to look at these limits.

Dr. Kasha: Chemically it has already been demonstrated that it is possible to synthesize quite a large number of food components simultaneously under very simple conditions; these methods are still relatively new and their full potential has not been fully realized. However, I think this supports the kind of thing you had in mind.

SESSION IV

Physiology and Psychology of Nutritional Processes

Chairman: ***William Darby***
Professor and Chairman, Department of Biochemistry
Director, Division of Nutrition
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When one hears the word "nutrition" there too often is an automatic response "deficiency" or "requirement". Seldom does the hearer respond with "appetite", "acceptance", "attitude", "comfort", "emotion", or even, in this era of cellular biology, with the concept of "physiology", much less "gut physiology". Yet these are the determinants which often make the difference between nutritional health and disease under ordinary conditions of life, and they unquestionably will determine the practicality, indeed the validity, of most of the new concepts and measures being discussed in an effort to prepare a design for feeding man in space.

The planning Committee recognized the urgent need for directing attention to these areas, the need for greater knowledge of the areas, and a broader appreciation of their general importance. Opportunities for expanding our understanding by becoming acquainted with newer methodology and concepts were also recognized. It is hoped that this discussion will serve widely to stimulate attention, interest, and active research, the results of which can be applied in meeting the pressing needs of the space program, and also in furthering the science of nutrition under ordinary conditions of terrestrial life.

WILLIAM DARBY

Dietary Regimes in Space Cabin Simulator Studies

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A series of 16 experiments has been completed. Data obtained on 40 test subjects show that the caloric requirement for an inactive man in a confined space is 32.7 kcal/kg body weight/day. No effect of the gaseous environment is evident.

The dietary regimes used in these studies were dehydrated, liquid, and frozen foods. Acceptability was highest with the frozen foods. The use of each of these various dietary regimes in space has certain advantages and disadvantages. Close cooperation between mission-oriented personnel and those concerned with nutrition and metabolism should provide an optimum solution to the 14- to 60-day mission.

AUTHOR

The problem of establishing an adequate dietary regime for use in prolonged space missions is unique in the annals of nutritional research. Minimum weight and volume, maximum palatability, total acceptability, and zero gravity compatibility are dietary characteristics that require the highest level of ingenuity in the design of diets to fulfill the demands of prolonged space missions.

The definition of man's energy requirements in space constitutes the focal point for several key aspects of life support systems: oxygen requirements, carbon dioxide removal production, heat production, and water requirements. Thus, an accurate definition of energy requirements not only has a direct influence in terms of weight and volume of material to satisfy those requirements, but also has a secondary influence in gaging such items as oxygen supplies, carbon dioxide removal systems, heat exchangers, and so forth.

One of the unique problems of defining the energy requirements or a dietary regime for man in the zero gravity or space station environment is the lack of adequate knowledge regarding the effects of the environment on man's requirements. It would appear doubtful that the basal metabolic rate (BMR) would be changed in the weightless environment. The possibility does exist, however, that the degree of relaxation and comfort in zero gravity will be such that "true" basal metabolic rates may be determined and might be lower than the standard used on Earth. In considering the active man, Clamann (ref. 1) has suggested that zero gravity would not reduce the energy cost of movement since muscles are still accelerated and decelerated during the course of movement. Lawton (ref. 2), on the other hand, assumed that a working metabolic rate of three times the BMR at 1 g would be only twice the BMR under weightless conditions.

Since longterm weightlessness can be achieved only in actual space flight, it is necessary to consider other means of examining the problem. One approach is that of using ground-based simulators. With this technique, it is possible to obtain similar degrees of confinement, inactivity, and gaseous and thermal environments. From these data, one can better extrapolate to the weightless environment for a prediction of requirements in actual space conditions. During an experimental program designed to investigate man's responses to potential spacecraft atmospheres, data were obtained relative to the dietary regime of man in prolonged space missions. The purpose of this paper is to discuss these data in terms of caloric requirements, caloric intake and requirements in different environments, and acceptability of the dietary regimes used in these studies.

MATERIALS AND METHODS

Data obtained from 16 experiments are included in this paper. Twelve experiments conducted in the two-man space cabin simulator provided data on 24 test subjects. There were four subjects in each of the four remaining experiments which were conducted in an altitude chamber modified to permit positive control of desired environmental conditions. Details of atmosphere control, the facilities used, and experimental protocols are described in references 3 to 8.

Approximately 2.3 square meters (25 square feet) of floor space were available to the test subjects for movement, sitting, working, conducting tests, and so forth in those experiments conducted in the two-man space-cabin simulator. This simulator was an elliptically shaped cylinder with a total volume of 10.75 cubic meters (380 cubic feet). Floor-to-ceiling height was 1.8 meters (6 feet). In those experiments conducted in the modified altitude chamber, approximately 9.3 to 11.6 square meters (100 to 125 square feet) of floor space were available. This device was a rectangular structure with a total bound volume of 53 cubic meters (1875 cubic feet) and a floor-to-ceiling height of 2.4 meters (8 feet). Floor-to-ceiling height in both cases was sufficient to permit the test subjects to stand erect.

A summary of the environmental conditions, test duration, number of tests, and type of diet used is shown in table I. The environment in the experiments listed under group I in table I provided an alveolar oxygen partial pressure equivalent to that found at sea level. The experiments listed under groups II and III were designed to study the atmosphere contemplated for the Gemini and Apollo space vehicles and to provide an alveolar oxygen partial pressure of approximately 170 mm Hg, or 70 mm Hg above that normally found at sea level. Experiments in groups IV and V were conducted in an oxygen/nitrogen atmosphere at reduced pressure with an alveolar oxygen partial pressure of approximately 90 to 95 mm Hg. Group VI was a control experiment for group III in that the alveolar oxygen partial pressures were identical, even though nitrogen partial pressure was approximately 450 mm Hg in group VI and less than 1 mm Hg in group III. The experi-

TABLE I.—*Summary of Experimental Profiles*

Experimental group	Total pressure, mm Hg	Oxygen, percent	Duration, days	No. of subjects	No. of experiments	Diet [a]
I	192	96	17	8	4	D
II	258	97	14	6	3	D
III	258	99	30	4	1	F
IV	380	41	14	2	1	D
V	380	41	30	2	1	D
VI	700	33	30	4	1	F
VII	750	21	17	4	1	D
VIII [b]	700/200	23/88	8/8	8–2	2–1	L–D

[a] D = precooked dehydrated food; F = frozen foods; L = Liquid diet.
[b] Special studies to examine effect of increased carbon dioxide concentration.

ments in group VII were conducted at ambient pressures (San Antonio). The experiments in group VIII were special studies to determine the effect of increased levels of carbon dioxide on man at different barometric pressures. A total of 8 days was spent at total pressures of 700 mm Hg and 200 mm Hg, respectively. Carbon dioxide was elevated to an inspired partial pressure of 21 mm Hg in the last 4 days at each altitude. Temperature was adjusted to the thermal comfort of the test subjects in all experiments. Relative humidity ranged from 30 to 60 percent.

Three different dietary regimes were used: (1) precooked dehydrated foods obtained from the Food and Container Division, U.S. Army Natick Laboratories; (2) a formula diet prepared according to Scrimshaw (obtained in a private communication) and (3) frozen foods obtained from local commercial outlets. Table I indicates the experiments in which each of the dietary regimes was used. The liquid diet was used in two of the experiments in group VIII, with dehydrated foods being used in the others. Table II shows a random sampling of the types of food items used in the dehydrated and frozen food regimes. The dehydrated food diet contained such items as bread, cake, jelly, and so forth that were not dehydrated. The frozen food diet contained additional items such as dry cereal, milk, bread, and so forth that were not frozen. The liquid diet was bland with no additional flavoring and consisted primarily of toasted soy protein, homogenized oats, vitamin A, and powdered skim milk. This was supplemented with orange-grapefruit juice containing dextrin. In addition, a restricted amount of hard candy was provided each subject.

TABLE II.—*Representative Samples of Foods*

Precooked dehydrated

Cubed steak	Peas
Swiss steak	Green beans
Fish patties	Peaches
Chicken and rice	Fruit cocktail
Roast pork	Grapefruit-orange juice
Mashed potatoes	Chocolate pudding
Buttered rice	Cocoa
Carrots	Milk

Frozen

Juices	Miscellaneous
"TV" dinners:	dry cereals
Beef	"Pot pies":
Chicken	Tuna
Shrimp	Chicken
Turkey	Beef
Pork	Turkey

Caloric information was obtained from the Food and Container Division personnel in the case of the precooked dehydrated foods, by bomb calorimetry (ref. 9) in the case of the formula diet, and from the manufacturer or published values in the case of the frozen foods.

Test subjects for all experiments were selected from Air Force personnel who volunteered to participate in this program. A description of the test subjects used in each group of experiments is given in table III.

RESULTS

A summary of the caloric intake data is shown in table IV. Data on the dehydrated foods were obtained over an average of 15.3 days. Data on the formula diet and the frozen foods were obtained over an average of 16 and 30.5 days, respectively. The mean caloric intake of 2292 kcal/day shown in table IV represents a weighted mean, based on the number of subjects in each dietary regime. Average daily ad libitum caloric intakes ranged from a low of 2047 kcal/man/day for the precooked dehydrated foods to a high of 2716 kcal/man/day for the frozen foods. The liquid diet intake averaged 2330 kcal/man/day, but was not consumed on an ad libitum basis. The lowest caloric intake recorded for an individual in this series averaged 1406 kcal/day, which occurred during an experiment at 380 mm Hg total pressure. Precooked dehydrated foods were the source of energy. The highest individual caloric intake was an average of 3494 kcal/day, observed during an experiment at a total pressure of 258 mm Hg. Frozen foods were the source of energy in that study.

Caloric intake was also expressed in terms of kcal/kg initial body weight/day. This permits one to consider variations in caloric intake as a result of variations in total body weight. The

TABLE III.—*Physical Characteristics of Test Subjects*

Experimental group	Age, yr	Height		Weight		Body surface area, m²
		in.	cm	lb	kg	
I	30.9	68.7	174.6	162.8	74.0	1.87
II	27.0	69.3	175.9	152.5	69.3	1.82
III	18.0	68.7	174.6	147.2	66.9	1.78
IV	33.5	66.5	168.9	142.6	64.8	1.73
V	33.0	67.1	170.5	154.7	70.3	1.80
VI	21.0	72.4	183.8	167.0	75.9	1.90
VII	23.8	70.9	180.2	156.2	71.0	1.87
VIII	24.8	70.0	177.9	162.4	73.8	1.87

weighted mean of all studies was 31.5 kcal/kg initial body weight/day.

Body weight was not stable during most of these tests. An average daily loss of 45.0 grams and 41.5 grams was observed during the studies where dehydrated foods and the liquid diet, respectively, were used. On the other hand, an average daily gain of 56.3 grams was seen in those individuals consuming the frozen foods. This provides a weighted mean of 24.0 grams weight loss per man per day.

The effect of this weight loss on the actual caloric requirement is difficult to assess since the composition of this weight loss has not been defined. A limited amount of data on individual test subjects indicates that the weight loss is not wholly attributable to a loss of body water. Available nitrogen balance data indicate that at least a portion of the weight loss consisted of protoplasmic mass. Assuming, therefore, that the weight loss was not solely water and did, in fact, represent a source of calories, a factor of 4 kcal/g (ref. 10) of weight change (either loss or gain) was used to adjust the measured caloric intake to the caloric requirement. This adjusted value or caloric requirement is expressed as kcal/day, or kcal/kg initial body weight/day and averaged 2334 kcal/day, or 32.7 kcal/kg initial body weight/day on a weighted basis. The lowest individual caloric requirement was 1782 kcal/day (24.7 kcal/kg initial body weight/day). The highest individual caloric requirement was 3101 kcal/day (43.5 kcal/kg initial body weight/day). Five test subjects that showed neither a weight gain nor loss averaged 30.1 kcal/kg initial body weight/day.

No predictive relationship has been noted between the different experimental environments and either caloric intake or requirement (table

TABLE IV.—*Summary of Caloric Intake and Requirement*

Dietary regime	Number of subjects	Initial body wt., kg	Average daily body wt. change g	Average daily caloric intake		Average daily caloric requirements [a]	
				kcal	kcal/kg wt	kcal	kcal/kg wt
Dehydrated foods	24	70.96	−45.0	2047	29.1	2227	31.5
Liquid diet	8	73.0	−41.5	2330	31.9	2496	34.1
Frozen food	8	71.39	56.3	2716	38.2	2491	35.0
Weighted mean	------	71.45	−24.0	2292	31.5	2334	32.7

[a] Caloric requirement obtained by correcting caloric intake data for observed weight change. A factor of 4 kcal/g of weight change was used (ref. 10).

TABLE V.—*Effect of Environment on Caloric Intake and Requirement*

Experimental group	No. of subjects	Altitude, mm Hg	Dietary regime	Daily caloric intake, kcal/kg	Daily calorie requirement, kcal/kg
VII	4	Ground level	Dehydrated	33. 6	33. 0
VI	4	700	Frozen	35. 4	32. 5
IV and V	5	380	Dehydrated	25. 5	30. 8
II	6	258	Dehydrated	30. 5	32. 3
III	4	258	Frozen	40. 9	37. 5
I	8	190	Dehydrated	28. 2	31. 5
VIII	8	700/200	Liquid	31. 9	34. 2

V). This is not unexpected since similar activity levels were used in all experiments and the temperature was maintained within comfortable, nonsweating limits.

Acceptability of the various dietary regimes was generally good. The liquid diet was the least acceptable, followed by the precooked dehydrated foods and the frozen foods. No attempt was made to rate the acceptability of the liquid diet. The major problems associated with that diet included the lack of taste (or variety), the lack of something solid to chew, and the presence of (to some individuals) an objectionable odor. It should be pointed out, however, that the liqiud diet was accepted by the test subjects.

The acceptability of the precooked dehydrated foods was evaluated on both an excellent, fair, poor scale (table VI) and a 9-point numerical scale (table VII) ranging from dislike extremely (value of 1 point) to like extremely (value of 9 points). Where possible, known dislikes of test subjects were avoided. Ratings of acceptability of the dehydrated foods at 700 and 190 mm Hg show that 65 percent of the items were rated as excellent, 32 percent as fair, and 3 percent as poor. Meats and beverages were rated lowest in terms of percent excellent. Numerical ratings at 258 mm Hg are similar, except that vegetables and meats were rated the lowest. Equating the overall ratings from both rating techniques shows similar results and indicates that the dehydrated foods were very acceptable to the test subjects. This agrees with data previously reported in reference 11 where it was noted that the dehydrated foods were well accepted, though slightly less than comparable fresh foods.

TABLE VI.—*Acceptability of Dehydrated Foods During Experiments at 700 and 190 mm Hg*

Item	RATING			Total items rated
	Excellent, percent	Fair, percent	Poor, percent	
Meats	58	41	0. 8	128
Vegetables	62	30	8	77
Fruits	62	34	4	171
Beverages	59	40	0. 7	134
Desserts	79	21	-----	247
Other	72	27	1	240
Average	65	32	3	-----

TABLE VII.—*Acceptability of Dehydrated Foods During Experiments at 258 mm Hg (9-point numerical scale)*

Item	Rating range	Average rating	Total items rated
Meats	7. 0–8. 8	7. 8	83
Vegetables	5. 1–8. 7	6. 8	114
Fruits	7. 0–9. 0	8. 4	43
Beverages	7. 3–8. 8	8. 0	41
Desserts	7. 8–8. 8	8. 2	85
Other	7. 8–8. 1	8. 0	158
Average		7. 9	

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One of the major reasons for low ratings was the production of excessive amounts of abdominal or intestinal gases during the altitude experiments. This was a common comment in regard to meat items and particularly those meat items that were highly seasoned. The high caloric milk drink was also included in this category. This problem was not unique to any phase of the experiment, but tended to persist throughout the test. Air-swallowing would not be the cause of this excessive gas since it should not be any greater at altitude than at ground level. Production of gas by microbial action seems to be the major cause since microbial metabolism will continue to produce a given volume of gas per unit of microbial metabolism. It should be remembered prior to selecting a dietary regime for space missions that a given volume of gas in the intestine will tend to more than double at a barometric pressure of 380 mm Hg and will be approximately 3.6 times larger at a total pressure of 258 mm Hg or 5 psia.

Rehydration difficulties were the next most cited reason for low acceptability, followed by an occasional item that did not taste the same as the label implied. It should be noted that these subjects were not trained tasters and that the tasting was being conducted in atmospheres vastly different from the one on Earth. Nonetheless, this is the type atmosphere to be encountered in space and the dietary regime must be adapted to it, not vice versa.

No ratings as such were obtained from those subjects consuming the frozen foods. The foods were uniformly well liked and, as witnessed by the caloric intake figures, heartily consumed. Only one problem with one individual was encountered, which again related to gas expansion and abdominal pain. In this instance, however, unlike the experience with the dehydrated foods, the difficulty was temporary and did not recur.

DISCUSSION

The caloric requirement data determined for man in a 1-g space cabin simulator would appear to be a reasonable approximation of the caloric needs of man in space. Specialized mission requirements such as strenuous and repeated extravehicular excursions or repeated and prolonged exercise to prevent cardiovascular deconditioning might exert a small influence on the data reported here. Pending the availability of data obtained in the weightless environment, the requirement of 2334 kcal/day, or more appropriately, 32.7 kcal/kg body weight, appears valid and should constitute a good guideline. Body weight, body surface area, or body weight raised to some exponential should be used in establishing caloric requirements for a given mission.

Based on the caloric data reported in this paper, oxygen requirements have been estimated. A factor of 4.825 kcal/liter of oxygen was used to make this calculation. Assuming that the weight change noted in these studies had a caloric value of 4 kcal/g, the oxygen requirement would be 484 liters/man/day, or 691g (1.52 lb). If the weight change had no caloric value, that is, if it were water, the oxygen requirement would be 475 liters/man/day, or 678 g (1.5 lb). At the other extreme, if the weight change were fat at a caloric equivalent of 9 kcal/g, the oxygen requirement would be 509 liters/man/day, or 726 g (1.6 lb). Expressed on a body weight basis, the oxygen requirement is approximately 10 g/kg body weight/day.

The different types of dietary regimes used in these experiments have their advantages and disadvantages relative to their use in actual space flight. The frozen foods, while very acceptable and more or less "normal," require freezer space, power for the freezer, power for an oven, and are reasonably heavy. This latter category is of importance, however, only if water is not being recovered onboard the space vehicle. In addition, these foods are vulnerable in the event of a freezer failure.

The dehydrated foods require special packaging for zero gravity rehydration, tend to produce a considerable amount of gas, and are somewhat less palatable. It would appear that these disadvantages can be readily overcome. The weight advantage of the dehydrated foods requires the availability of onboard-produced or purified water to be realized.

The liquid diet, while less acceptable than the other two, could be packaged in a dehydrated form. In this form it has the rehydration disadvantage and the weight advantage of dehydrated foods. It would appear, however, that the liquid diet would be quicker and easier to prepare and conceivably could be more palatable under very severe food preparation restrictions than the dehydrated foods. In addition, the liquid diet offers consistency of intake, a considerable advantage if one is concerned with the effect of the weightless environment upon metabolic processes.

No one dietary regime is the answer to all space missions. Close cooperation between the mission-oriented personnel and those interested in nutrition and metabolism can, however, provide an optimum dietary regime for diverse space missions probing the various facets of the space environment.

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Discussion: Dietary Regimes in Space Cabin Simulator Studies

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A dietary regime refers to a mode of management of diet, and a mode may be a method or a prevailing popular custom. The dietary regimes applied in the tests reported by Dr. Welch were some of both, mostly the latter.

While the food energy intake may have been reasonably well estimated, there is no indication of the output—urinary, fecal, or heat. Also there is some question as to whether the voluntary intake of certain foods is a completely valid indication of energy requirement for a specified performance. No information is given as to the proportionality pattern of protein-carbohydrate-fat in the diet—or the R.Q.—from which the relative derived energy could be determined day by day or from one condition to another. However, the value which Dr. Welch presents, 32.7 calories/kilogram is about the same as that commonly accepted for maintenance, that is, $93W^{3/4}$ or 32 cals/kg for a 70-kg man. (See ref. 1; the maintenance requirement (about $1\frac{1}{3}\times$basal) is given as $93\times24.6=2280=$ 32 cal/kg for "sedentary idle living.")

Dr. Welch does not mention individual variations. For missions of manned space flights of more than 20-day durations, it is most likely that dietary regimes are going to have to be tailored closely to the metabolic pattern of the individual astronauts and the individual variability of metabolic patterns for given dietary regimes will need to be established with reasonable degrees of precision if desired performance is to be realized. The most likely practical way to do this is by way of formula diet regimes. For example, formula diets could be devised for testing individual responses to oxygen and water demand by changing the proportions of fat and carbohydrate as illustrated in table I.

The values given are arbitrary but may be somewhere near the right order of magnitude. The *extra* water is added to make 1 gram of water per calorie so that the total water represents the total caloric value of each diet. The extra water is one key variable which could be changed readily.

This illustrates, I think, one approach to evaluation of dietary regimes for space cabin simulator study. The metabolizability of each of the dietary constituents will have to be determined by precise chemical and calorimetric methods; numbers taken from food composition tables or conventional factors are likely to be misleading for given diets or given individuals. Of course, all the nutrients will have to be balanced as well as protein, fat, carbohydrate, and water.

TABLE I.—*Illustrative Dietary Regimes for Testing Oxygen and Water Requirements*

[Total weight: Diet A+O_2+H_2O=3250 g
Total weight: Diet B+O_2+H_2O=3337 g]

Dietary Components	Amount consumed, g	Oxygen required		Metabolic water	
		g/g	Total g	g/g	Total g
Dietary regime A					
Protein	50	1.5	75	0.4	20
Fat	80	3.3	265	1.0	80
CHO	300	1.2	360	.6	180
Extra water	--------	--------	--------	--------	1840
Total	430	--------	700	--------	2120
Dietary regime B					
Protein	50	1.5	75	0.4	20
Fat	40	3.3	132	1.0	40
CHO	400	1.2	480	.6	240
Extra water	--------	--------	--------	--------	1860
Total	490	--------	687	--------	2160

REFERENCE

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COMMENTS

QUESTION: Dr. Welch, could you give a little more background on the data you presented?

DR. WELCH: With regard to intake, in the case of dehydrated foods we utilized data obtained from the Quartermaster Food Container Institute in which each one of the items was broken down as to total weight, grams of protein, grams of fat, and grams of carbohydrate. I fully realize that this is an estimate. We did utilize caloric data on a weight basis. I didn't present grams of fat, grams of carbohydrate, and grams of protein even though we had it.

With regard to the liquid diet, we used the bomb calorimeter; I fully realize that the number of calories that we get with the bomb may not represent the metabolic energy but it was quite close.

The R.Q. is really of little value because it indicates only what is going on in the lung at that particular time. Exercise, for example, will cause a change in the R.Q. Part of this change is undoubtedly metabolic; however, part of its is pulmonary as a result of hyperventilation.

As to individual variation, data were taken on each man but just not shown in the figure. This study was not a nutritional study, per se.

I believe the data are good. If taken to liters, values of 488 on the high side and 484 on the low side are obtained and we reported 475 to 590. When dealing with calories, these seem quite good.

DR. ENGEL: Dr. Welch, in these experiments, which in some cases went to 30 days, was there a trend toward attempting to maintain a caloric balance in these individuals or were they motivated to eat this amount?

DR. WELCH: I don't recall whether we had a trend in terms of weight. We did motivate them to consume, in the case of the liquid diet, a certain amount of the liquid diet per unit pound.

The other experiments were run on an ad libitum basis with the only deviation in this being that once a man had opened the package and dehydrated the food, he was urged to consume the entire amount.

The Appetite Factor

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Life began in the Archaic Sea and the electrolytes present in this sea set the conditions under which living systems can exist. These electrolytes include the cations sodium, potassium, magnesium, and calcium, and the anions chlorides, bicarbonates, and sulfates. When living systems left the Archaic Sea their external environment changed, but the conditions of life as set by the composition of the Archaic Sea did not change. To survive, living systems had to maintain, among others, the levels of the electrolytes in their external environment within narrow limits. The cells—the living elements in animals—have, in effect, remained aquatic. The animals' external environment became their *internal* environment, which is also known as the extracellular fluid. Basically, when we are feeding animals we are feeding these cells, and we must supply the essential nutrients to the cells in a form they can use without appreciably changing the levels of the electrolytes in their internal environment.

In nutrition, essential nutrients are transferred from the external environment to the cells. As an essential prerequisite there must be a desire for food. This is referred to as appetite or hunger.

Nutrition consists of:

(1) *Food-seeking behavior.* There are no restaurants in nature. Food-seeking involves locomotion, searching, exploration, pursuit, fleeing, and fighting.

(2) *Recognition of food.* Food must be differentiated from other objects of the external environment.

(3) *Selection of a balanced diet.* It is easily possible to select an improper diet from the available food supply in the external environment.

(4) *Recognition of toxins in food and their elimination.*

(5) *Eating.* The nutrients, as they exist in food, are largely unavailable to cells. Barriers have been set up to prevent undue changes in the composition of the intracellular fluids and to avoid the ingestion of toxins. These barriers are:

(1) *The mouth.* Only suitable foods are allowed entry into the gastrointestinal tract.

(2) *The pyloric sphincter.* Food is permitted into the intestinal tract at a rate which allows adequate digestion.

(3) *The intestine.* Certain nutrients such as iron and calcium are absorbed only in such amounts as are needed; the rest are excreted in the feces.

Much material from the body enters the intestine. It has been estimated that the dietary nitrogen has been diluted fivefold or more by endogenous nitrogen. Feces arise largely from endogenous sources rather than dietary. Consideration of the amount of feces as a factor in space feeding should include the possible role of the endogenous contribution to the contents of the intestine.

(4) *The cell membrane.* Only nutrients needed by the cells are permitted entry through the cell membrane; surpluses (except energy) are excreted, largely through the kidney.

To make this possible, elaborate biological equipment has been developed through the evolutionary mechanisms inherent in living systems. These parts are integrated by the brain through some 10 billion neurons, and through humoral factors that circulate in the blood. The brain acts as a control tower which receives information over the nerve tracts from the external environment. Eight cranial nerves participate in this process. This information is appreciated and integrated in the brain with information from the body, with responses directed toward the survival of the animal. It is possible to feed the wrong information to the brain and to deceive it, with resulting dire consequences. The importance of the brain is attested to by its protection by the skull—the toughest material known to biology.

As a result of the advances made in nutrition, it is now possible—or it soon will be possible—to formulate chemically defined diets so correctly adjusted to the needs of cells that the gastrointestinal tract can be short-circuited and the diet can be fed directly into the vein. The diet could be delivered with a tiny atom-powered pump from a plastic tank, which can be replenished at appropriate filling stations. This would render superfluous and antiquated the gastrointestinal tract, the exocrine pancreas, and other tissues that have evolved over hundreds of millions of years. If the delivery of the essential nutrients to the cells constitutes nutrition, then we have solved all our nutritional problems. But is this correct? Just what is expected from eating?

The long-range demands upon food are:

(1) Prevention of nutritional deficiency

(2) Provision of energy; the adipose tissues may store large amounts of energy as fat

(3) Maintenance of internal environment

(4) Growth, reproduction, and lactation

The immediate demands upon food are:

(1) Abolition of hunger, which may be a painful sensation

(2) Production of satiety, including the pleasure and gratification made possible by eating

(3) Sensory stimuli of foods which may be needed to initiate eating or to increase the intake of food

(4) Sensory stimuli which act on the gastrointestinal tract to prepare it for the digestion of food

(5) Sensory stimuli (handling) which aid rats in survival when subjected to stress

(6) Sensory stimuli go to the brain over the main sensory tract, the lemniscus, and also reach the reticular formation via collaterals, activate it, and help to maintain wakefulness. The sleeping animal has no desire to eat. Wakefulness is an essential preliminary for appetite. Sensory stimuli, such as the smell of coffee, activate the reticular formation, encourage wakefulness, and stimulate the desire to eat. Students studying for final examinations know that eating helps them to stay awake. People fall asleep during lectures, movies, or concerts, but not at the dinner table. After eating, animals become quiet or fall asleep. Human beings may or may not act in this way.

THE IMPORTANCE OF SENSORY STIMULI TO THE ASTRONAUT

The astronaut will be deprived of many sensory stimuli to which he has been accustomed—gravity, for example. We are beginning to realize the importance of stimuli to the nervous system. We read about the "terror of loneliness" in human beings subjected to a stimuli-free environment. Hence, food will probably be the major source of sensory stimuli to the astronaut. These include:

(1) Stimuli arising from thinking about food in anticipation of the pleasures of eating, provided that the food is tempting and highly acceptable. If the astronaut is thinking of a tempting morsel, it will give him pleasure and the secretions of his salivary glands will increase. If the food is not acceptable, thinking about it will not increase the flow of saliva. On the contrary, it may act to dry up salivary secretions.

(2) The sensory properties of food consist largely of: the flavors, odors, textures, colors, temperatures, and sight and sound of food, such as the crunching of toast during eating. Texture is important. So is the movement of the food in the mouth, especially if there are several

components, each having a different flavor. Many different sensory stimuli (flavors) are sensed during the mixing of the food.

(3) Stimuli from the act of eating arise from:

(a) Receptors that are activated in the teeth during chewing by touch and pressure

(b) Receptors that are activated in the muscles of the tongue as it moves around

(c) The activation of many receptors in the mouth through which the brain is kept informed of the shape and size of the food bolus without sight.

It would be a mistake to underestimate the importance of the act of eating.

Certain stimuli, when applied repeatedly, soon lose their effectiveness and animals fail to respond; this is known as habituation. Noise is an example of such a stimulus. The importance of food as a source of sensory stimuli is due to the multiplicity and variety of its sensory stimuli which may be reinforced by the internal chemistry; food tastes better with a fasting biochemistry than with a fed one.

Foods serve two purposes:

(1) As a food supplying the essential nutrients

(2) As a source of sensory stimuli which may be substituted for other sources of sensory stimuli which have been denied the astronaut

Reviewed in this light, the weight of the food no longer has the compelling importance it had when it acted only to supply the essential nutrients. When food serves both as a source of food and as a source of sensory stimuli, some weight allowance should be made to insure the necessary sensory properties of food. Food may be more important to the astronaut as a source of sensory stimuli than as a source of nutrients.

LOGISTICS AND NUTRITION

Logistics require the performance of the mission, including the return of the astronaut in good physical and mental health. First and foremost are the maintenance of the oxygen supply and, equally important, the elimination of such noxious material as carbon dioxide. Next in order of importance is the supply of water, without which life is possible for only a few days. Food is of least importance since life can continue for weeks without it, depending upon the supply of the fat that had been stored in the adipose tissue. One overall mechanism seems operant to insure the supply of oxygen (air hunger), water (thirst), and food (hunger). This mechanism consists of three parts:

(1) Need. This is expressed as appetite or drive

(2) Goal-directed behavior, the object of which is oxygen, water, or food

(3) Consummatory response leading to satiations and to the abolition of the need

Motivation is an important factor here. To what extent can motivation replace food in performance of urgent tasks? Both motivation and performance are greatly influenced by food. It has been asserted that motivation is worth 1000 calories of food for performance under survival situations.

ACCEPTABILITY

We learned from soldiers that "food is not food until eaten." It takes more than appetite to insure the ingestion of food. To be eaten, food must be acceptable, and this has little relation to the nutritional value of the food. Nor is it of particular importance to the astronaut that his food meets the standards for adequate nutrition set up by the National Research Council. Adequate nutritional standards have not been set up for astronauts, whose requirements may indeed be different. This might be especially true for calcium since weightlessness may act on calcium metabolism as it does in immobilization.

Acceptability is an evasive concept which is not simple: It is determined by the taste of food. Intrinsically, food tastes neither good nor bad. The taste of food is largely determined by conditioning and by the internal chemistry. Powdered milk had low acceptability among American soldiers; to them it tasted bad. The same powdered milk had the highest acceptability with similar soldiers who were starving in a German prison camp; there powdered milk had a delicious taste. The difference was not in the powdered milk, but in the internal biochemistry of the starving men.

SHOULD WE LEARN FROM PAST MISTAKES?

In World War II, hashes were common in combat rations because they fitted the filling machines, but the men wanted something they could chew, something into which they could "sink their teeth." The rations lacked desirable sensory stimuli and lacked "belly-filling" properties. The soldiers' evaluation of these rations was, "We could undoubtedly survive on these rations a lot longer than we'd care to live."

The rations had to be stable, and they were altogether too stable since the men would not eat them. The melting point of butter was too low for hot climates, so the melting point of the butter was increased by hydrogenation and the men used it to grease their boots.

When combat rations were tested in field trials, they were found acceptable, but they were not acceptable under combat conditions. Those who were conducting the field trials were largely measuring motivation, rather than acceptability. We must know what we are measuring.

MAN AND BEAST

Data obtained with animals are often applied to human beings. Before applying such information to human beings, it is advisable to determine experimentally whether the data obtained with experimental animals hold for human beings. Here are some examples of disparities:

(1) Methionine reduces the excretion of nitrogen in the urine of fasting rats and dogs; it does not do so in human beings.

(2) Fasting rats and mice increase their motor activity which is measured as running. Presumably these rodents gamble some of their precious energy reserves when they increase their motor activity on the chance of finding food. However, fasting human beings are more likely to decrease their activity to conserve their energy reserves because it will prolong their survival without food.

(3) Human beings work more efficiently on carbohydrates than they do on fats, but dogs work equally well on carbohydrates and fats.

(4) Rats use high fat diets more efficiently than high carbohydrate diets, but human beings do not use high fat diets as well as high carbohydrate diets. Nor are humans alike in this respect. When obese humans subsist on high fat diets consisting of 1000 calories, they remain in relative nitrogen balance and do not develop ketosis. Nonobese humans subsisting on the same diet develop severe ketosis and go into a marked negative nitrogen balance.

If it were possible to find suitable astronauts who are obese, their provision of food would be greatly simplified. An obese person with 20 kilograms of fat, which is not considered excessive, carries reserves of 184000 calories. This would provide over 2000 calories daily for 90 days. Part, or the major portion, of this energy could be used as a component of the astronaut's diet and it could be balanced with suitable foods rich in sensory stimuli in much smaller quantities than needed for the normal astronaut without fear of ketosis or excessive loss of body protein. Moreover, a large portion of the astronaut's food could be fat, which supplies maximum amounts of calories with the least weight without producing ketosis or marked negative nitrogen balance.

Discussion: The Appetite Factor[1]

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In the course of the past two decades, considerable progress has been made in our understanding of the mechanism of regulation of food intake, of appetite, and of satiety. At the same time, realization of the vast reaches of our ignorance, and of the fact that many of the often-repeated "common sense" generalizations in the area of hunger, satiety, and their abnormalities are but cliches which mask our ignorance, has grown correspondingly. After a long period of quiescence—from the pre-World War I period to the post-World War II era—research is now proceeding actively along several lines of attack: study of central mechanisms, particularly those based on mid-brain structures; study of gastrointestinal factors; interconnection of metabolic factors—particularly the metabolism of the adipose tissue—with neural and behavioral events; extensive examination of the various types of errors, inborn or acquired, which may lead to obesity or to anorexia and relevance of these to the normal physiology of regulation of food intake; study of the influence of environmental factors—both ecological and psychological—on food intake. In addition to the new interest in the application of modern operant conditioning techniques to problems of food intake, there is a renewal of interest in the analysis of human sensations of hunger, appetite, and satiety which had lagged since the middle nineteenth century. On such broad research activity rests the hope that progress will accelerate in this important and long neglected field.

DEFINITIONS

The terms appetite, hunger, satiety, regulation of food intake, limitation of food intake, obesity, overweight, anorexia, have all been used in a variety of senses and this semantic confusion has in turn often created apparent contradictions where basic agreement in fact prevailed. Words such as hunger, appetite, and satiety represent sensations, and as such, tend to take on highly subjective colorations. Studies in progress in the Department of Nutrition, Harvard School of Public Health, reveal great differences in the sensations of mild and extreme hunger in man as well as in the reasons for stopping eating. Nevertheless, we shall attempt to give a series of working definitions of the terms which will be used herein.

Appetite: the complex of sensations, up to a point pleasant, or at least not unpleasant, by which the organism is aware of desire for an anticipation of ingestion of palatable food. Specific appetites relate to desire for specific foods or nutrients.

Hunger: the complex of unpleasant sensations, felt after prolonged deprivation (during the "hunger state") which will impel an animal or a man to seek, work, or fight for immediate relief by ingestion of food (thus exhibiting "hunger behavior"). The passage from appetite to hunger is dependent on duration of dep-

[1] Much of the material presented herein appears in the textbook *Modern Nutrition in Health and Disease* by M. G. Wohl and R. S. Goodhart (Lea and Febiger, eds.).

rivation, rate of energy expenditure, and so forth.

Satiety: the complex of sensations which impel the organism to stop eating because hunger and appetite have been satisfied even though food is still available.

Regulation of food intake: the servomechanism or mechanisms whereby the body adjusts ingestion of food to requirement for homeostasis and for growth.

Limitation of food intake: the complex of sensations and factors which impel the organism to stop eating even though food is still available whether energy requirements for maintenance and growth have or have not been covered.

Obesity: excessive accumulation of body fat.

Overweight: weight in excess of normal range.

Anorexia: pathological absence of appetite or of hunger behavior in the presence of manifest energy needs.

CHARACTERISTICS OF THE REGULATION OF FOOD INTAKE

Regulation of Caloric Intake

Temporarily ignoring the conscious aspects, such as sensations of hunger, appetite, and satiety, let us examine the manner in which homeostasis is maintained and the expected pattern of growth achieved. The problem can be reformulated into the fourfold question: (1) Is there a regulation (or are there regulations)? (2) What is regulated? (3) How well is it regulated? (4) How is it regulated? In short, what are the mechanisms in terms of structure and function? This order will be followed in reviewing the available evidence.

Is there a regulation? In reference 1, Gasnier and Mayer first showed that this question is best answered not by considering the food intake, but by observing the constancy, within a given environment, of total body weight, water content, reserves other than water, nitrogen balance, and fat content. Their data on large numbers of animals carefully followed for long periods gave conclusive evidence that a regulation does exist.

What is regulated? In reference 1 it was further shown that three types of regulations could be defined:

(a) Biometric regulation. This is not, properly speaking, a mechanism but is a result of the very structure of the animal; it sets limits both upwards and downwards to energy exchange, the upper limit being the "summit" metabolism, the lower, the basal metabolism. The limits change with the physiologic state.

(b) Adaptation of intake to output: short term (day-by-day) regulation of energy intake. This is perhaps the most important mechanism. A number of studies in different animals have shown the high correlation between output—modified by cold, exercise, and so forth—and energy intake, as well as the sensitivity of intake of volume of food to changes in the caloric density of the diet.

(c) Correction of the errors in the short term regulation by successive compensations: long term regulation of reserves. If energy balance was achieved exactly each day, intake and output would be equal and in a plot of one against the other, all points would fall on the line bisecting the axes of coordinates. Actually, in such a plot, the points fall on a band spread on both sides of this line (ref. 1). The day-by-day regulation is thus not sufficient to insure constancy of body weight and reserves. Gasnier and Mayer showed, however, that the distribution of the points was not random but lent itself to the following conclusions. On a given day, the farther away the extra reserves are from the modal change, the greater the chances that during the next 24 hours (1) if the change is in the same direction, it will be small, or (2) if the change is in the opposite direction, it will be large enough to approach or pass the mode. There is thus a long term mechanism which, in effect, under constant environmental and physiological conditions tends to maintain the constancy of body weight.

How well do these regulations function? Four parameters have been defined to describe how well both the short term and the long term regulations function: precision, reliability, sensitivity, and rapidity (refs. 1 and 2). For the short term regulation, for example, the precision is inversely proportional to the difference between energy intake and energy output; the reliability is inversely proportional to the variability of the intake to output ratio; the sensitivity is inversely proportional to the dependence of the precision on the magnitude of intake; the rapidity is inversely proportional to the lag in adjustment of intake to output. The variation of such parameters as temperature, exercise, caloric dilution, state of hydration, changes in the nature of the diet, and so forth characterizes the extent to which regulatory mechanisms are able to respond to such challenges. For example, in adapted animals, as the temperature falls, both energy output and energy intake increase; the reliability of the short term regulation adjusting intake to output increases, its precision remaining the same (refs. 1 and 2). As regards the long term regulation, body reserves increase, the precision and reliability of the regulation increase, but the sensitivity and rapidity decrease with increasing metabolic intensity. The picture of the effect of enforced exercise on food intake is equally striking: the precision of the regulation is good within a wide range of activity. Below this range (in the "sedentary" range) and above it (in the "exhaustion" range) the precision deteriorates.

How do the regulations work? The answer to the question, "What are the mechanisms of these regulations?" is still tentative. We shall review briefly the anatomical support of these regulations and the possible modes of integration of these mechanisms. It should be unnecessary to note again that, when one speaks of mechanisms of regulation, the interval of time considered is all important. Short term studies demonstrate the influence of a multiplicity of factors on appetite and emphasize instability. Experiments of longer duration—no less than 1 day and preferably longer periods—emphasize stability. It is essentially with the mechanisms underlying this stability that we are concerned.

It should be equally unnecessary to point out at the outset that all investigators whose hypotheses are about to be reviewed have repeatedly acknowledged the weakness of any general theory of appetite founded on response to only one stimulus and none of them have attempted to enact such systems. The problem has been to identify the mechanism by which the metabolic state of the organism competes with such variable influences as taste, emotions, habits, and so forth, to permit long time homeostasis.

Regulation of Caloric Intake and Weight: Morphological Aspects and Possible Mechanisms. Anatomical Basis

Gastrointestinal tract

Haller was the first to suggest (in his *Elementa Physiologica*, in 1777) that hunger was a gastric sensation. In his chapter on the immediate cause of hunger, he stated that hunger sensations were due to the excitation of stomach nerves. For over a century and a half this theory was the one most generally accepted. It was only in 1911 that it was tested experimentally by Cannon and Washburn (ref. 3) who showed that hunger sensations appeared simultaneously with contractions of the stomach. The hunger contractions were further investigated by Carlson (ref. 4) who found that during starvation, the tonus of the empty stomach and the frequency and intensity of its contractions became progressively more pronounced, at least until the fourth day when the desire for food decreased. These gastric hunger contractions are relatively powerful; they occur in series of from 20 to 70 and last usually between half an hour and an hour and a half; they alternate with periods of quiescence. The contractions are seen in newborn babies before any food has been consumed. Their presence is general in land vertebrates, whether homeotherms or poikilotherms.

Hunger contractions are present even when there is some food in the stomach. The only time when the fundus does not exhibit them is immediately after a large meal. They occur after isolation from the brain and spinal cord, though at longer intervals and with less vigor. They are inhibited by a variety of stimuli; by the tasting or chewing of a palatable food, or even of an inert substance like paraffin wax, unless the contractions have become tetanic in nature; by stimulation of the gastric mucosa by ice cold water, acid, alcohol, smoking; by tightening of the belt; by vigorous muscular exercise; by sudden application of cold; by emotions such as fear or rage; by adrenaline; by glucagon; or by intravenous glucose given under conditions such that normal utilization takes place. Inhibition of gastric contractions can be brought about also by irrigation of the duodenum by glucose. That this inhibition persists when the stomach is denervated or in autotransplanted denervated gastric pouches has led to the postulation of secretion of a chalone by the duodenum or the liver. Interesting modifications of gastric tone take place in disease: for example, duodenum ulcer and diabetes cause an increase, pulmonary tuberculosis and vitamin B1 deficiency, a decrease.

Carlson (ref. 4) considered that the vagi were the main, if not the only, afferent pathways for the gastric hunger impulses and that the "primary hunger center" must therefore be the "sensory nuclei of the vagi" in the medulla (fasiculus solitarius). The existence of pressure- or tension-sensitive receptors in the stomach wall has been demonstrated.

The possible relation of intestinal phenomena to hunger has attracted some attention. The forward movement of food in the small intestine has been studied by a number of authors, in particular by Quigley (ref. 5). The character of the peristaltic movement has been shown to be dependent on the composition of the chyme. The small intestine, like the stomach, obtains its supply of extrinsic nerve fibers from two sources: a bulbar autonomic (parasympathetic) supply by way of the vagi and a thoracic autonomic (sympathetic) supply by way of the splanchnic nerves and the superior mesenteric ganglia. Stimulation of the vagi causes contraction or increased tonus in the musculature of the intestine; stimulation of the splanchnic nerves generally inhibits its tonus. Psychological states and stimulation of portions of the cerebral cortex may produce contractions or relaxation of the walls of the small and large intestines. Adrenaline, like splanchnic stimulation, inhibits intestinal movements; oxygen, organic acids, and bile increase them. The sensory fibers from the intestine are carried by the vagus and the splanchnic nerves.

Central nervous system

Autopsies of patients with hypothalamic obesity suggested a role for the hypothalamus in the control of food intake. Experimental work by investigators on both sides of the Atlantic eliminated the pituitary from consideration as the prime suspect in the development of adiposity. The work of Hetherington and Ranson (ref. 6) and Brobeck and coworkers (ref. 7) demonstrated that bilateral involvement of the ventromedial nuclei causes hyperphagia in the rat. It has since been shown that in that species, unilateral destruction of the ventromedial nucleus may cause very slow development of obesity. Hypothalamic obesity has been produced in the mouse by Mayer, French, Zighera, and Barrnett (ref. 8); in that species, bilateral involvement of the ventromedial area is necessary for even the slightest degree of hyperphagia to appear. Obesity follows superficial lesions of the base of the anterior hypothalamus in the monkey, and lesions caudal to the paraventricular nuclei in the dog. Conversely, Anand and Brobeck (ref. 9) found that in rats, bilateral destruction of more lateral parts of the hypothalamus is followed by complete cessation of eating. Teitlebaum and Stellar (ref. 10) have confirmed this finding, though they found that this inhibition may be temporary, with resumption of eating dependent on the nature and consistency of the food presented. Morrison and Mayer (ref. 11), noting that lesions in the lateral hypothalamus or subthalamus at the same rostrocaudal level as the ventromedial nucleus cause both aphagia and adipsia tried to see whether these two responses were separate consequences of the lesions. They found that the patterns of food or water exchange cannot be reproduced by deprivation of sham operated rats of either food or water. Daily water intubation facilitated the "escape" from inhibition of eating and drinking. Localization of "aphagic" and "adipsic" lesions did not completely coincide and their histologic location suggested that the median forebrain bundle was as important as the lateral area proper in the control of water and food intake (ref.12). Morgane (refs. 13 and 14) in a careful anatomical analysis of this phenomenon has concluded that lesions causing aphagia may interfere with at least two systems of fibers, of which the more important is lateral to the median forebrain bundle; only destruction of this system (and of the median area of the pallidum) causes an irreversible aphagia. Other areas have also been shown to interfere with the regulation of food intake; bilateral damage to the venromedial portion of the thalamus, to the rostral mesencephalic nuclei, to the temporal area of the amygdalum or the hippocampus cause hyperphagia. Destruction of the frontal area of the amygdalum or the hippocampus decreases food intake. Separation of the frontal lobes from their thalamic connections in rats, frontal lobotomy in man, and selective decortication in various types of animals also lead to hyperphagia.

Stimulation of various areas of the central nervous system has also proved rewarding. Larsson (ref. 15), for example, studied the results of electrical stimulation of the hypothalamus and the medulla and of intrahypothalamic injections in sheep and goats. He found that stimulation of the hypothalamus, just caudal to the optic chiasma backwards throughout the hypothalamus, lateral to the sagittal level through the columna fornix descendens and the mamillo thalamic tract resulted in hyperphagia. The most pronounced effect was obtained by stimulation of the region of the lateral hypothalamic nucleus, anterior to the columna fornix descendens or at the same transverse level as this tract. Rumination was seen on electrical stimulation of the same structures as gave hyperphagia. Mastication, licking, and swallowing could be elicited as single effects without the simultaneous occurrence of hyperphagia. These results were taken by Larsson to suggest that it is an oversimplification to speak of a mamillothalamic or an anterelateral hypothalamic "feeding center". Although electrical stimulation of both these areas, particularly the latter, causes hyperphagia, the fact that extramasticatory and licking movements as well as hyperphagia are obtained diffusely in other areas supports the conclusion that centers directly feeding behavior and centers having to do with motivation to eat rest on centers which are in part different.

Finally, before leaving the anatomical description of central nervous areas involved in the regulation of food intake, it might be noted that some experiments performed by Mayer and Sudsaneh (ref. 16), described as follows, suggest that the ventromedial area of the hypothalamus exercises some measure of control over gastric contractions.

Use of Behavioral Techniques to Define the Role of Central Neural Structures Involved in the Regulation of Food Intake

The use of the behavorial techniques developed by B. F. Skinner and his associates has made it possible to define better the role of central neural structures in the regulation of food intake. It is also opening a trail which may some day give a more precise metabolic and neurological basis to the concepts of hunger, satiety, appetite, and specific appetites. An early experiment was that of Anliker and Mayer which compared the feeding behavior of normal animals with that of animals with various types of hyperphagia (ref. 17). This clearly demonstrated that, as previously suggested by Brobeck (ref. 7) and by Miller, Bailey, and Stevenson (ref. 18), the ventromedial area appears to act as a "satiety" brake inhibiting constantly activated lateral "feeding" areas. (Similar techniques have permitted Rozin and Mayer (ref. 19) to study the characteristics of the regulation of food intake in the fish.)

Again on the basis of results obtained by behavorial techniques, Teitlebaum and Epstein (refs. 21 and 22) have suggested that qualitative effects on taste were necessary concomitants of the destruction of the ventromedial area or of lateral hypothalamic lesions. Animals with ventromedial hypothalamic lesions cease to be hyperphagic if presented with diets the consistency or taste of which they do not like. Under such conditions, they may eat less than normal animals. The significance of this interesting observation is difficult, however, to evaluate at present. Lesions performed with the stereotaxic instruments are notoriously complex and it may well be that Teitlebaum was studying the effect of the destruction of a number of anatomically contiguous centers; the fact that animals can maintain their weight when feeding themselves through a gastric fistula suggests that taste (if not exaggeratedly aversive) is not an essential component in the regulation of food intake although it obviously is one of the factors influencing food intake at a given time.

Another important behavioral technique which has contributed to our knowledge of central nervous areas involved in the regulation of food intake is that of Olds, who combined lever-pressing for food in the rat with autoexcitation of a number of central areas (ref. 22). The autoexcitation of certain areas (corresponding roughtly to parasympathetic nuclei) acts as an additional reward and leads the animal to a tremendous increase in the rate of lever-pressing. The autoexcitation of other areas (corresponding roughtly to the areas in which Hess had obtained stimulation of the sympathetic system) acts as a negative reinforcement and decreases rates of lever-pressing. The combination of Olds' autoexcitation technique with the use of an electric grid permitting the examination of the circumstances under which the drive to eat is particularly intense has allowed Morgane (ref. 23) to explore the role of the ventromedial area, the pallidum, the median forebrain bundle, and the lateral areas. His results seem to indicate that the lateral area should be subdivided into at least two subareas: an extreme lateral one, excitation of which leads to extreme rates of lever-pressing for food, to considerable hyperphagia, and to the crossing of the electrified grid to obtain food, even when the animal is fed; and the properly lateral area, excitation of which leads to some hyperphagia, even in fed animals but not to the crossing of the grid. These experiments, together with those on the effect of lateral lesions, do suggest the presence in the lateral hypothalamus of two systems of fibers, one having to do with purely quantitative aspects of the regulation of food intake (and presumably subject to ventromedial "satiety" inhibition) and one having to do with more qualitative aspects of appetite, the relation of which to the ventromedial area is still obscure.

PHYSIOLOGICAL MECHANISMS OF REGULATION

Gastric contractions as a basis or a component of hunger and of short term regulation of food intake

The views of Carlson on the relation between gastric pangs, hunger, and the regulation of food intake are summarized in reference 4. They constitute the oldest attempt to account experimentally for these phenomena. For Carlson, the consciousness of gastric sensations carried by the vagi is the kernel of the problem. Hunger is defined by him as "a more or less uncomfortable feeling of tension and pain referred to the region of the stomach". While he considers that an explanation of hunger pangs is an explanation of hunger, he does recognize that "many apparently normal persons experience in hunger, besides the gnawing pressure-pain sensation in the stomach, a feeling of weakness, 'emptiness', headache and sometimes nausea" but calls these states or symptoms "accessory hunger phenomena" because "they are not always present in hunger and their relative preponderance depends on the length of starvation and on some individual peculiarity in the person. It must be admitted, however, that in some individuals these accessory phenomena appear to overshadow, if not entirely to suppress, the pressure-pain sensations from the stomach." In turn, Carlson, struck by the fact that insulin hypoglycemia leads to gastric contractions and hunger feelings, postulated that blood glucose levels were involved in the occurrence of hunger.

The theory received wide, if temporary, acceptance. Although the existence of hunger pangs has been abundantly confirmed, accumulating facts led observers to doubt whether gastric movements provided a sufficient basis for Carlson's generalizations. For example, Adolph (ref. 24) showed, by diluting the ration of animals with inert material, that differences in the bulk of the diet—in spite of their effect on the stomach—had only a transient influence on food intake. Complete bilateral vagotomy, which abolishes the motor response to insulin hypoglycemia, does not prevent or even impair the augmentation of food intake produced by insulin administration. The existence of patients in whom bilateral vagotomy has been performed for the treatment of gastric ulcers enabled Grossman and Stein (ref. 25) to extend these findings to human subjects; they found that the sensations of hunger continued to occur after complete vagotomy. The sensations included feelings of emptiness and weakness. In those persons in whom epigastric pangs of distress associated with individual gastric sensations were a part of the sensation complex of hunger, vagotomy, by abolishing the contractions, eliminated that particular sensory component. Though the removal of this fraction of the sensory complex was recognized by the subject, it did not delay hunger or change the response to it. Vagotomy actually simply shifted the emphasis to the extragastric components, in particular the feelings of weakness and emptiness associated with the desire for food. Incidentally, the observation of Grossman and Stein appeared to disprove not only the essential nature of gastric contractions as a basis of hunger and regulation of food intake (the two concepts are not separated by Carlson) but Carlson's suggested mode of perception of these contractions as well. In two patients who had undergone sympathectomy persisting gastric contractions were no longer associated with a feeling of distress. Grossman and Stein concluded that the splanchnic nerves are the afferent pathways for the distress associated with gastric hunger contractions and that no such pathway exists in the vagus nerves.

With the decrease of the significance of hunger pangs, interest in their causation died down and stayed dormant for several decades. Scott and his associates (ref. 26) could find no correlation between blood sugar levels and the onset and prevalence of hunger contractions. Experimental work on the testing of the glucostatic hypothesis has revived interest in both hunger contractions and their control by showing the negative correlation between gastric hunger contractions and glucose utilization, by demonstrating the striking effect of glucagon in inhibiting gastric contractions and, finally, by indicating that gastric hunger contractions may be in part under the control of the ventromedial hypothalamic area.

It is legitimate to conclude from these studies, and from more recent ones on the nature and timing of hunger sensations in men, women, and children, that hunger pangs are an important component of the sensory complex identified subjectively as hunger. At the same time, in spite of the metabolic and neural concomitants of hunger contractions, available evidence makes it impossible to base a mechanism of regulation of food intake exclusively or even principally on its perception. It remains true, however, that any theory purporting to interpret the regulation of food intake which cannot account for the occurrence of hunger pangs is doomed at the outset.

Thermostatic Component in the Regulation or the Limitation of Food Intake

Brobeck (ref. 27), struck by the fact that the hypothalamus appears able to deal with a number of different stimuli which affect feeding behavior and to make suitable adjustments of food intake, hypothesized that a number of such stimuli may operate through their effect on the heat balance of the body. He accordingly advanced a thermostatic hypothesis, which postulated that "animals eat to keep warm and stop eating to prevent hypothermia". The actual experimental evidence for his view rested first of all on the observation that short term exposure to high environmental temperature is followed by reduction of food intake. Kennedy (ref. 28), however, has indicated that under experimental conditions not dissimilar to those in which Brobeck's animals were placed, dehydration and pyrexial tissue breakdown may have played a major part in the weight loss following an acute exposure to heat. Acute exposure to cold also caused depression of food intake at first. Working with hypothalamic hyperphagic rats, he demonstrated that in the long run—and as long as his animals stayed within the range of adaptation—they showed similar rates of weight gain at high and at low temperatures.

Another piece of evidence used in support of a thermostatic scheme is the fact that a change from a "high carbohydrate" to a "high fat" diet usually increases food intake and a change to a "high protein" diet usually decreases it. The specific dynamic action of protein is higher than that of carbohydrates which in turn is greater than that of fat. This was taken by Brobeck to indicate that modifications of intake follow perceptions of differences in specific dynamic action. It must be noted, however, that the specific dynamic action of a dietary mixture cannot be calculated by adding up the specific dynamic actions of its constituents if these were fed singly, but is usually lower and far less sensitive to changes in composition (within the usual range) than would be the case if the specific dynamic action were additive for the various nutrients. It had been repeatedly shown that in most strains, the effect on total caloric intake of changing from a high carbohydrate to a high fat diet is transient (though there are strains of animals which continue to eat more on a high fat diet, as do certain types of obese animals). Finally, there is no doubt that diets very high in protein do reduce the food intake of normal animals. The problem of the mechanism of this effect has been recently reexamined (ref. 29). The fact that the effect is as marked, at a protein level over 60 percent, in animals in which the ventromedial hypothalamus has been lesioned shows that the effect is not mediated through the hypothalamic "satiety" centers. Above the 60 percent level, and as the proportion of protein in the diet is further increased, food intake decreases in such a way that the protein intake remains constant, giving an appearance of a regulation based on protein intake. Inasmuch, however, as protein levels appear to have little or no effect in the 8 to 60 percent range (which encompasses the range of protein levels normally encountered by rats living on natural foods rather than semisynthetic laboratory diets) it seems doubtful that this interpretation is the correct one. It appears more likely that one is dealing there with a "safety valve" effect, which could indeed be based on an abnormally high specific dynamic action (or excessive blood amino acids, or other mechanisms) which limits food intake when more than a given amount of protein would be ingested but which does not come into play at lower levels. This safety mechanism would have to be situated elsewhere than at the ventromedial (satiety) centers. (Incidentally, it is possible that below a certain minimum intake of protein some other mechanism also comes into play to decrease hunger. In man, Dole and his coworkers (ref. 30) have obtained spontaneous reduction on diets excessively low in protein.)

Perhaps the most cogent experimental argument in favor of the existence of a thermostatic influence on feeding is the observation of Andersson and Larsson (ref. 31) that refrigeration of the preoptic area causes feeding in a fed goat. Cessation of feeding is observed in this animal even when fasted for a prolonged period when the preoptic area is warmed. The effect of cooling and warming on drinking behavior is the opposite of that on eating. While the effects demonstrated by Andersson and Larsson are clear cut, the fact that the differences of temperature used in the experiment are enormous (of the order of 10° C in the vicinity of the thermode, of 1 to 1.5° C at a distance of 6 mm) casts some doubt as to the applicability of the results under physiologic conditions. I feel that a thermostatic factor is an important component in the hunger satiety mechanism. They are inclined to believe that while progressive exposure to cold may have a facilitatory effect on feeding (over and beyond its effect on energy requirements) and exposure to heat, particularly if sudden, may have a clearly inhibitory effect on feeding, variation in heat balance is probably not the agency through which metabolic requirements influence food intake so as to insure caloric homeostasis. On the other hand, it appears that an elevation of body temperature may exert a safety valve effect (similar to that demonstrated for very high protein diets) which overrides any other factor which might promote feeding so as to prevent any further heat load on an already overloaded organism.

Souleirac's Theory of Regulation of Carbohydrate Appetite by Intestinal Absorption

Souleirac limited himself to the study of appetite for carbohydrate in rodents. However, his numerous publications later collected in book form deserve a somewhat detailed analysis. His work (ref. 32) has the original merit of being directed towards the quantitative account of a qualitative appetite, and thus provides facts which may eventually be used to integrate taste and calorie intake. Souleirac was struck by the observation that phloridzin, which according to Carlson increases gastric contractions, inhibited appetite for carbohydrate. Thyroidectomised and adrenalectomised animals, both of which present hypoglycemic tendencies, also show diminished appetite for carbohydrate. The observation led to a search for possible correlations between carbohydrate appetite and physiological characteristics. Using a self-selection method, Souleirac systematically examined the quantitative and qualitative variations of uptake of different types of sugar after removal of the anterior pituitary, thyroid, and adrenal glands, alloxanisation of the pancreas and administration of the corresponding hormones, anterior and posterior pituitary extracts, thyroxine, "cortine" and deoxycorticosterone and insulin. He concurrently studied the modifications of taste threshold for carbohydrates and the effect of the endocrine disturbances just listed on the intestinal absorption of carbohydrates. Similar studies were made after administration of adrenaline, ergotamine, pilocarbine, acetylcholine and atropine, after spinal section in the cerebral region and hypothalamic lesions, or after administration of glucose, riboflavin, and phosphate. The effects of cold and physical exercise also were examined. Estimations of blood glucose and of serum amylase were made after these procedures. Souleirac found that there was no correlation between either absolute blood sugar level or the level of serum amylase and carbohydrate consumption. On the other hand, he found that all hormones with an effect on carbohydrate metabolism modified the taste threshold for glucose, though the interpretation of the modifications was difficult. By contrast, the correlation between the taste for carbohydrates and the intestinal absorption of carbohydrates was clear cut. Any condition which increased intestinal absorption increased consumption and, conversely, if carbohydrate absorption was decreased, carbohydrate intake was decreased. For instance, injections of glucose depressed absorption of glucose and glucose intake; phloridzin and thyroidectomy decreased glucose absorption and intake; insulin and alloxan diabetes increased glucose absorption and intake. The only exception was provided by atropine, which slightly decreased the proportional absorption of glucose from the intestine but considerably increased the total. Souleirac explains the effect of atropine by the intense thirst it produces.

Although the facts invoked by Souleirac are clear enough as far as they go, it seems regrettable that no data are ever given on the calorie intake of the experimental animals, but only on the amount of carbohydrate solution ingested. The omission is all the more regrettable because the solid food available, cereals and greens, constituted a high carbohydrate diet. One would like to know also what the fluid (water) consumption in the different experimental situations was. Examination of the available information raises the question, which is not discussed by Souleirac, of how the organism detects the fact that carbohydrate is being absorbed. Souleirac observed that spinal section at the level of the sixth to seventh cervical vertebrae did not eliminate the response of the carbohydrate intake to endocrine stimulation, but then it would not interrupt splanchnic sensory connections. The increased intake after atropine treatment could conceivably lead itself to an interpretation based on the effect of the drug on the vagus. The fact that vagotomy and sympathectomy, which would seem to eliminate afferent impulses from the intestine to the central nervous system while eliminating hunger pangs, do not eliminate feelings of emptiness, weakness, and desire for food (ref. 25), makes it unlikely that the regulation of food intake is based exclusively, or even primarily, on awareness of intestinal absorption. A humoral or hormonal intermediary could, of course, operate independently of intermediary nervous pathways, but there is no indication of the existence of such a link with the higher centers.

Souleirac suggests that the effect of the hypothalamus on the regulation of food intake is mediated through intestinal absorption; excitation of the hypothalamus would bring about a diminution of carbohydrate absorption and consumption; the action of the hypothalamus would be antagonistic to that of the pituitary and the balance beween these organs would determine carbohydrate intake. While, in Souleirac's experiments, consumption of sugar solution increased after hypothalamic lesions, it is difficult to appreciate the significance of his finding that it cannot be compared with the increases also in food and water consumption which follow the operation. The incidental finding that unilateral lesions lead to increased carbohydrate consumption is of interest in the light of the fact that slow development of obesity follows the production of unilateral hypothalamic lesions in the rat.

Thus, the facts presented by Souleirac, although offering an undeniable challenge, do not appear to support the mechanism he wants to base on them. His observation that any modification of carbohydrate metabolism can affect appetite and even taste is in agreement with the postulation of the glucostatic theory. It appears doubtful, however, whether, strong though the appetite for carbohydrate (or protein or salt) may be, hunger and the regulation of food intake are simply summations of selective hungers and partial regulations. Such selective appetites do exist and can be extremely compelling; the "salt wars" are bloody illustrations of their strength. Yet, compelling though such appetites are, they do not appear to overrule the general regulation. Men and animals will, it is true, eat after satiety has apparently been obtained if the supplement offered is particularly appetizing or contains a nutrient of which they have been deprived. Yet no mammal will increase its food consumption from, say, a low-protein diet simply to satisfy a need for protein or a specific amino acid.

Glucostatic Component of the Regulation of Food Intake

The glucostatic mechanism in the regulation of food intake, proposed by Mayer and his coworkers in the early fifties (ref. 2) postulated that in the ventromedial (satiety) hypothalamic centers (and possibly in other central and peripheral areas as well), there existed glucoreceptors sensitive to blood glucose in the measure that they utilize it. This concept was based on the fact that the central nervous system is dependent for its function on the availability of glucose; that carbohydrates are preferentially oxidized, and are not stored to any appreciable amount, so that their depletion is rapid; and that in the interval between meals, there is an incomparably greater proportionate drop of carbohydrate reserves than of reserves of proteins and fat; only intake of food will replenish fully these depleted stores. Furthermore, carbohydrate metabolism is not only regulated by a complex edifice of endocrine interrelationships; it is, in turn, a regulator of fat oxidation and fat synthesis, of protein mobilization and breakdown, and of protein synthesis; thus, a mechanism of regulation of food intake based on glucose utilization could be—as it should—successfully integrated with energy metabolism and its components. Such a theory also permitted successful interpretation of the known effects of cold, exercise, diabetes mellitus, hyperthyroidism, hypothyroidism, and other metabolic changes, provided that the additional postulate was made that carbohydrate metabolism in the ventromedial area differed from that in the brain in general. In particular, it was postulated that the ventromedial area was highly glucoreceptive and that, unlike the rest of the brain, would show considerably heightened utilization. Such a theory could also account for such facts as the self-perpetuating effect of hyperphagia, which of itself causes a more rapid utilization of glucose (ref. 31).

Early experimental work designed to test the theory has often been misinterpreted and, apparently not infrequently, continues to be misinterpreted (ref. 32). Because of the (then) apparently insuperable difficulty in measuring glucose utilization in the ventromedial area and the postulate that, in general, ventromedial utilization must parallel peripheral utilization, an attempt was made by Mayer and Van Itallie to correlate hunger feelings (and later, by Stunkard, gastric contractions) with diminished peripheral glucose utilization in an easily accessible area, that is, the forearm. Utilization was measured by capillary-venous (or arteriovenous) differences (or "Δ-glucose"); in patients at rest, variations of blood flow were not taken into effect. It was found that, in general there was a satisfactory degree of correlation between small Δ-glucose and the appearance of subjective feelings of hunger and of gastric contractions. (That the correlation is far from perfect, even when carotid-jugular vein determinations are made, is emphasized in recent work.) It was also shown, in particular by Stunkard and Wolff (ref. 33), that whenever glucose utilization is proceeding satisfactorily, a slow intravenous glucose infusion in hungry individuals eliminates both the feeling of hunger and gastric contractions. In diabetics, and in hunger diabetes, glucose infusion does not affect hunger to a similar degree. While others at times have not observed the correlation between cessation of hunger and rises in the glucose utilization (ref. 34), they may have been operating under some of the conditions described by Van Itallie, Beaudoin, and Mayer (ref. 35) when peripheral glucose arteriovenous differences are not reliable indices of overall glucose utilization by the body, much less by the satiety mechanisms; such conditions include changes in circulation dynamics because of increase in blood flow, rapid rises in blood glucose, certain effects of insulin, and the presence of overriding dominant conditioning. Again, the peripheral arteriovenous differences, although still associated in the thinking of many workers with the foundation of the glucostatic theory, have never really held any direct significance in it and were used in the early work "merely to obtain more reliable information about the changes which take place in carbohydrate supply than is available from arterial or venous glucose alone".

It is interesting to note that Van Itallie and Hashim (ref. 36) have shown the reciprocal evolution of blood nonesterified fatty acid levels and arteriovenous glucose differences. While these authors point out that it is unlikely that nonesterified fatty acid levels per se act directly as a signal to the food regulatory centers, their work provides yet another indirect way to evaluate patterns of metabolic utilization and their possible correlation with the hunger-satiety balance.

Major developments which have recently appeared have entirely altered the status of our knowledge in this field by developing means of assessing, much more directly, hypothalamic events in the regulation of food intake rather than having to rely on mere statistical correlations. These include the effect of glucagon on hunger feelings and gastric contractions and the role of the ventromedial area in the regulation of gastric contractions, the elucidation of the mode of action of gold thioglucose, the demonstration of the special characteristics of the metabolism of the ventromedial hypothalamic area, and the determination of the electrical activity of the ventromedial hypothalamic area under the influence of variations of blood metabolites, glucose in particular.

Action of Glucagon: Hypothalamic Glucostatic Control of Gastric Hunger Contractions

Stunkard, Van Itallie, and Reiss (ref. 37) made the interesting observation that the injection of 2 milligrams of glucagon reproducibly eliminates gastric contractions (and hunger sensations) in human subjects. Their results demonstrated that the elimination of gastric contractions lasts as long as glucose utilization proceeds actively and ceases when glucose utilization is reduced, even though the absolute level of blood glucose is still well above the fasting level.

Stunkard also had the opportunity to observe a patient who had lost practically all of his brain cortex in an accident and was incapable of feeding himself (ref. 38). After 1 week of fasting, he exhibited almost continuous gastric contractions. A variety of treatments, including the infusion of amino acids and induction of pyrexia (by rolling the patient in an electric blanket), did not inhibit gastric contractions. The only treatment (with the exception of food) which proved effective in inhibiting gastric contractions was the administration of glucagon.

Mayer and his coworkers found that in rats, too, intravenous injections of glucagon inhibit gastric hunger contractions. The dose found to be 100 percent effective in a large series of animals was 75 micrograms. The inhibition starts between 45 and 60 seconds after the administration of glucagon. By the time inhibition takes place, the glucose in the blood has already risen considerably from the control fasting values and inorganic phosphorus has decreased, indicating active utilization. Blood glucose continues to increase as inorganic phosphorus returns to the fasted level and gastric hunger contractions appear.

Mayer and Sudsaneh (ref. 16) found that rats in which the ventromedial hypothalamic area has been destroyed show no significant difference in their pattern of fasting contractions from that seen in normal animals. The inhibitory response to epinephrine and to norepinephrine is normal. On the other hand, the intravenous administration of 75 micrograms of glucagon almost invariably fails to produce complete inhibition of hunger contractions in animals with lesions of the ventromedial nuclei whether the animals are allowed to become and remain obese, or whether they are reduced to their preoperative weight after demonstrating this hyperphagia. Response of these animals to prolonged exposure to cold is delayed, on the average, by 100 percent. The failure of the animals to respond to glucagon and the delay in response to prolonged exposure to cold are obviously not caused by refractoriness of gastric contractions as such. The finding may be interpreted as indicating that the ventromedial area does exercise a definite measure of control over gastric hunger contractions and does so in response to an increase in its glucose utilization. An anatomical basis for such a mechanism may be provided by the existence of the bundles of Schutz which seem to originate in the general area of the ventromedial hypothalamus and go down to the roots of the vagus.

Mode of Action of Gold Thioglucose

In 1949, Brecher and Waxler (ref. 39) observed a syndrome of hyperphagia and obesity in mice after a single intraperitoneal or subcutaneous injection of gold thioglucose. No mechanism was found by these authors to interpret this intriguing observation. The observation was confirmed by Marshall, Barrnett, and Mayer (ref. 40) who further showed that gold thioglucose caused extensive damage to the ventromedial hypothalamic area in varying degree to the supraoptic nucleus, the ventral part of the lateral hypothalamic area, the arcuate nucleus, and the median eminence. Marshall and Mayer (ref. 41) showed that there was minimal impairment of functions other than the regulation of food intake, unlike that which is observed with stereotaxic lesions. Gold thioglucose-obese animals, unlike animals made obese by stereotaxic lesions, will frequently mate and rear their young. As in stereotaxic hypothalamic animals, gold thioglucose-treated animals show impairment of satiety mechanisms as well as impaired reaction of the regulation of food intake to cold, exercise, and caloric dilution. Mayer and Marshall (ref. 42) later showed that gold thiogalactose, gold thiosorbitol, gold thiomalate, gold thioglycerol, gold thiocaproate, gold thioglycoanilide, and gold thiosulfate did not produce the brain damage which follows gold thioglucose administration. Neither were hyperphagia and obesity seen following such treatments, even though toxicity of such compounds is similar to that of gold thioglucose. It was also shown that in the rat, gold thioglucose caused lesions which were similar to those seen in the mouse. The fact that simultaneous administration of sodium thioglucose protects animals against hypothalamic damage is probably traceable to competitive inhibition. On the basis of these observations, Mayer suggested that the toxic gold moiety of accumulated gold thioglucose destroyed the ventromedial neurons specifically because of the affinity of these cells for the glucose component of the molecule, in accordance with the general proposal that glucose is a cardinal activator of the satiety center.

Recent work by Debons and coworkers (ref. 43), using radioautographic and neuron-activiating analytical techniques, confirms and considerably extends these conclusions. These authors first determined the gold content of the rostral, middle, and caudal portions of brains from controls. They found that some gold accumulated in the brain of all gold-treated animals with, however, notable differences in the localization of the gold. Animals treated with gold thiomalate failed to show any hypothalamic localization of the gold. Animals which received gold thioglucose but failed to become obese had a lesser total gold content of the brain, and the amounts of gold localized in the medial sections were less than in the case of the animals which developed the hyperphagic syndrome. In gold thioglucose-treated animals, radioautographic localization of gold activity was found consistently in four regions. The greatest concentration was in the hypothalamus, chiefly at the lateral angles and floor of the third ventricle. (Histologically, this region consisted of collapsed glial scar tissue and, in some instances, showed cystic changes.) There was also a second and discrete concentration of radioactivity in the midline dorsal and cephalad to the optic chiasma and immediately dorsal to the anterior commissure, a third in the caudal portion of the septum and ventralhypocampal commissure, and a fourth labeled area in the hindbrain in the midline at about the level of the vestibular nuclei in the floor of the fourth ventricle. The fact that gold thioglucose, but not thiomalate, administration leads to such localization, even though gold diffused throughout the brain in either case, was taken by the authors as a probability that the glucose moiety is responsible for the focal accumulation of sufficient gold in the hypothalamus to produce a destructive lesion which can result in hypophagia and obesity. Luse, Harris, and Stohr (ref. 44), in electron-microscopy studies of the early lesion, noted that gold thioglucose brought about initial changes in the hypothalamic oligodendroglia cells followed by focal neuronal degeneration. The authors suggest that the oligodendroglia cells, within certain areas of the central nervous system, share a high degree of specificity to glucose (ref. 45).

Debons and his colleagues (ref. 43) point out that while it is true that the foci of gold accumulation in the hindbrain, in the hypocampal commissure, and above the optic chiasm are at sites where lesions have been reported by Perry and Liebelt (ref. 46), this by no means proves the suggestion of these authors that such extrahypothalamic lesions indicate that gold thioglucose passes through deficient areas in the blood-brain barriers and is not selectively accumulated at "gluco-receptor" sites. Indeed, they add, in view of the extreme chemical specificity demonstrated for the gold thioglucose molecule, consideration must be given to the possibility that the sites of extrahypothalamic gold accumulation may themselves be glucoreceptive areas.

That there are, incidentally, a number of physiologic functions distinct from the regulation of food intake which must be dependent on the existence of glucoreceptors is suggested by a number of facts, some of them known for a long time. One example is the classical absence of a secretory gastric (hydrochloric) response to insulin after total vagotomy. Another striking illustration is given by the famous experiment of Zunz and LaBarre, confirmed more recently by Duner (ref. 47), that when the circulation in a dog's head was isolated from the rest of the body, with the nerve supply from head to body intact, hyperglycemia of the head resulted in hypoglycemia of the body.

Special Metabolic Characteristics of the Ventromedial Area

A number of recent experiments have emphasized the metabolic heterogeneity of the hypothalamus and the very special metabolic characteristics of the ventromedial area. Forssberg and Larsson (ref. 48), seeking to test the glucostatic hypothesis, reasoned that the hunger state must be accompanied by changes in the concentration of those compounds through which brain tissue, which cannot burn or store fat, can achieve, nonetheless, some energy storage (i.e., phosphagens: creatine phosphate and adenosine triphosphate). Rates of incorporation of glucose and phosphorus would be expected to be particularly affected in the ventromedial area if it was designed to be sensitive to the rate of utilization of glucose. To this end, these authors studied the incorporation of P^{32} and C^{14} glucose in three areas, one including the "feeding" and satiety areas, and two situated directly above the optic chiasm, the upper one cutting across the columna fornix descendens. The results showed that, in hungry rats, the sample which included the feeding area showed a preferential uptake of P^{32}, indictating an increased physiological activity over that in the fed state. By contrast, in the fed state, activity of the two control regions was enhanced while that of the feeding area was proportionally decreased. Experiments with C^{14} glucose showed the same type of response. In hungry rats, the region including the feeding area had a greater uptake of glucose, as compared to the control areas. While these studies demonstrated that various parts of the hypothalamus differ in their metabolic reactions, interpretation was difficult in that the experimental samples studies and compared to "control" areas included both the ventromedial and the lateral areas as well as other structures presumably not directly concerned with the regulation of food intake.

In a later study, Chain, Larsson, and Pocchiari (ref. 49) confirmed the difference in the fate of radioactive glucose in different parts of the rabbit brain, particularly the labeling of amino acids. Andersson, Larsson, and Pocchiari (ref. 50) extended the findings and mapped the incorporation of C^{14}-alanine, aspartic acid, glutamic acid, γ-aminobutyric acid, glutamine, and arginine in the hypothalamus of the goat, again demonstrating difference in metabolic reactions between various parts. Interpretation of these results, beyond the demonstration of heterogeneity of the hypothalamus, is again difficult.

Anand (ref. 51), studying glucose and oxygen uptake of various parts of the hypothalamus in the monkey, arrived at much more clear-cut results because of the better anatomical definition of his sample. He found that in the fed animals, there is a relative increase in the oxygen and glucose uptake per unit of nucleic acid activity by the satiety (ventromedial) region as compared with that of the feeding center. In the starved animal, the uptake of oxygen and glucose is less than that of the feeding region. In this experiment, the arteriovenous glucose difference was low in the starved animals and high in the ones which had been fed. Anand concluded that the results demonstrated an increase in activity of the satiety centers during fed states, which is accompanied by an increase in the uptake of glucose and is presumably determined by the changes in availability of glucose. He writes:

> . . . the medial regions are activated as a result of changes in the levels of the blood sugar produced by food intake, which subsequently produces satiety and abolition of further eating by inhibiting the lateral mechanisms. The electroencephalographic recordings from feeding and satiety centers under conditions of hyperglycemia (mentioned previously) lend further support to his (Mayer's) hypothesis, as the changes in the activity of satiety centers are more pronounced than changes in the activity of feeding centers.

Electroencephalic Determinations

Anand and his coworkers have evaluated in rats and monkeys the role played by changes in the blood levels of various nutrients on the electrical reactions of various hypothalamic areas (reported at the Conference on the Internal Environment and Alimentary Behavior, Brain Research Institute, UCLA, Feb. 1962). Electrodes were bilaterally implanted in the lateral, ventromedial, and various control areas of the hypothalamus. Still other electrodes were implanted in the cortex. Connections were brought through the skin at the back of the neck. Four to five days after the operation, hyperglycemia was produced by the intravenous injection of concentrated glucose solution. The consequent rise in blood glucose caused an increase in the frequency of encephalographic waves from the ventromedial (satiety) area from 6 to 7 per second to 9 to 10 per second. This treatment causes a drastic decrease in activity in the lateral (feeding) area, with reductions in potential by two-thirds or more being noted. The electrical activity of control areas in other parts of the hypothalamus was not affected.

Conversely, hypoglycemia (produced by intravenous injection of insulin) caused a reduction in frequency of ventromedial waves from 6 to 7 per second to 2 to 3 per second. Activity in the feeding center was increased.

Changes in blood amino acid concentration and blood lipid concentration did not affect the electrical activity of the satiety and feeding centers. Increase in glucose utilization following the consumption of a meal was similarly found to be associated with a doubling of the frequency of ventromedial pulsation and a decrease in the activity of the feeding centers.

Long Term Regulation of Food Intake and Body Weight

While the likelihood of the existence of a long term mechanism of regulation of intake and body weight, correcting the errors of the short term mechanism, comes out very strongly from the experiments of Gasnier and A. Mayer, the mechanism of such a regulation (the existence of which has since been postulated by a number of authors, in particular, Kennedy (ref. 52)) is still unclear. Experiments conducted in the Harvard Department of Nutrition indicate that the efficiency of food utilization by an animal which has once been obese and reduced is greater than before obesity had once taken place. This would suggest that, as postulated by Kennedy, the adipose tissue does play a considerable role in long term homeostasis and that perhaps the level of enzymatic activity within this tissue tends to be more self perpetuating than that of the fat content. It is, of course, possible that the long term mechanism works through short term components; more rapid uptake of nutrients, in particular glucose, could take place whenever the steric hindrance due to accumulated fat in the adipose tissue is relieved by fat loss; Quaade has pointed out some of the effects on heat load of the body caused by the insulation due to increased adipose tissue (ref. 53).

Hunger and Satiety Sensations in Adult Males

Monello and Mayer have recently studied hunger and satiety sensations of close to a thousand men, women and children. Part of the study relates to 200 males (relatively active salesmen) ranging in age from 22 to 61, with the largest number ranging from 22 to 51. The questionnaire method was used with the questions coming under 67 headings and the number of alternative answers under each heading varying from 4 to 6. While final evaluation awaits coding and computer use, the following general conclusions seem valid:

(1) There appear to be three major signals of hunger, which may occur as early as 2 hours following a meal. They are as follows:

(a) Specific physical sensations: gastric, mouth, throat, and head. While gastric sensations are an important signal, our work indicates that mouth, throat, and head sensations are far more significant than had been previously recognized

(b) Urge to eat and consciousness of hunger

(c) General sensations: restlessness and irritability being most frequent, with weakness and sleepiness not uncommon

(2) There is, in general, for the whole group—as one might expect—good correlation between the occurrence of the various types of sensations as the individuals proceed from satiety to extreme hunger.

(3) There is a considerable degree of individual variability as regards the very nature of the sensations, their timing, and the association of the sensations among themselves. Moods are equally variable; for example, at a given time after a meal, a fraction of the men will report no sensations of hunger and will feel contented; others, while not experiencing any sensations of hunger, will feel somewhat excited and restless; yet others experience various combinations of the sensations mentioned above and in addition may be restless or, in a small number of cases, sleepy; and so on.

A corresponding variability is encountered when "satiety" sensations and moods during and immediately following a meal are followed. It appears safe to assume that such sensations are a determinant of food habits, particularly as regards the spacing and relative size of meals and are in turn influenced by them. It seems important that we know the individual profiles of our astronauts and gage our feeding program for a particular mission not only in terms of caloric and nutrient requirements but also in terms of individual food preferences, and—as regards the way in which the food is going to be consumed—in terms of individual hunger and satiety patterns. After all, we are dealing with a small number of subjects who are relatively easy to assess as individuals; we should be able to devise the arrangement of meals and snacks which is conducive to maximum comfort for each. On long flights, where sensory deprivation may become a problem, the judicious use of food (apart from its nutritional properties) may do much to mitigate some of the psychological problems which may be anticipated.

CONCLUDING REMARKS

The existence of a regulation of food intake—perhaps mediated by a long term and a short term mechanism—which insures homeostasis is clear. In addition to properly metabolic influences, probably mediated through a glucostatic component acting on the ventromedial hypothalamic area, with a thermostatic component acting perhaps on another area (preoptic) as a "safety valve", and similar effects due to high protein (and perhaps amino acid imbalances, deficiencies, etc.) also acting on various areas, there are a number of other factors: gastric contractions (probably in part regulated through the hypothalamus), gastric distension, metering by mouth and pharynx, water balance, extremes of environmental temperature (acting above and beyond their effect on energy balance), and a host of psychological factors (taste, habits, and emotions) and social and cultural habits and pressures which at a given moment will influence the subject to increase and decrease intake. These various factors interact. For example, taste, may be in part dependent on the physiologic state (ref. 54). It seems to me—and I have studied a large number of forms of experimental and human hyperphagias and anorexias—that the wonder is not that there should be a great diversity of disturbances in the regulation of food intake, producing many different types of obesities and excessive thinness. The wonder is that in most animals and men, with feeding behavior subject to so many influences, the mechanism of regulation of food intake works so extraordinarily well.

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Gastric and Bowel Motility: Effect of Diet

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As has been pointed out there are advantages to putting one's subject in historical perspective. Let me therefore go back to a book published in 1903 entitled *The New Glutton or Epicure* (ref. 1). The author was Horace Fletcher, who insisted that our ills could be lessened by thorough and endless chewing, and so brought the word "fletcherize" into our language. A quote from his book may be of interest:

> One of the most noticeable and significant results of economic nutrition gained through careful attention to the mouth-treatment of food, or buccal-digestion, is not only the small quantity of waste obtained but its inoffensiveness. Under best test-conditions the ashes of economic digestion have been reduced to one-tenth of the average given as normal, and the ash accumulates in sufficient quantity to demand release only at the end of six-eight, or ten days, the longer periods of rest being the evidence of the best economic and health results.

And he appends a case report:

> A conclusive demonstration of thorough digestion in Mr. X's case was afforded to me. There had, under the regime above mentioned, been no evacuation of the bowels for eight days. At the end of this period he informed me that there were indications that the rectum was about to evacuate, though the material he was sure could not be of a large amount. Squatting upon the floor of the room, without any perceptible effort he passed into the hollow of his hand the contents of the rectum. This was done to demonstrate normal human cleanliness and inoffensiveness; neither stain nor odor remaining, either in the rectum or upon the hand. The excreta were in the form of nearly round balls, varying in size from a small marble to a plum. These were greenish-brown in colour, of firm consistence, and covered over with a thin layer of mucus; but there was no more odor to it than there was to a hot biscuit.

Unfortunately, these studies could hardly be called controlled, and possibly chewing does not fit in the rubric of motility. There have, however, been relatively few good studies on the effect of chewing on intestinal residue and the fecal wastes that are so much the concern of this symposium. Many years after Fletcher, a rather ingenious and little-cited experiment was described (ref. 2). Foods of different types were divided into chunks of equal quantity. One chunk was enclosed without further preparation in a little mesh bag; the other was thoroughly chewed, spit out, and then put in another mesh bag. The two bags were then tied to each other so that they would pass through the gut together and were swallowed.

On the basis of what the bags contained as they appeared in the feces, the different foods tested were divided into three classes. In one class, large residues were found in both bags. In another class, there were foods which disappeared completely from both bags. In between, there was a class which is perhaps the most interesting—namely, foods which disappeared if they had been chewed, but still present if they had not been chewed. Items in the first class included vegetables, potatoes, and certain kinds of fried meats. Items that disappeared whether chewed or not chewed were boiled eggs, boiled rice, fried cod, bread, and cheese. The intermediate group, which disappeared if chewed, but not if unchewed, consisted of roast chicken and stewed lamb.

Chewing may seem too simple an aspect of digestion to spend much time on, but I would argue that one should not adopt too supercilious an attitude towards this function. At least, purposeful and thorough mastication can hardly be harmful, and the same cannot be said concerning some of the dietary manipulations that have been proposed for feeding man in space. The only disadvantage to careful chewing is that it might lead to aerophagia, and hence might increase the volume of gas in the gut. (Incidentally, I would also consider aerophagia as a real disadvantage of the suggestion that astronauts chew gum for dental hygiene.) As opposed to chewing or other means of mechanically fragmenting food into small particles, pretreatment that alters the natural chemical composition of food may be distinctly harmful, particularly from the viewpoint of gastrointestinal motility.

A reasonable amount of knowledge exists concerning the nutritional value of food. At the other end, once food is absorbed and inside the body, many aspects of its eventual metabolic fate are known. Before the nutritional value of food can be made available to the body's metabolism, however, the food has to be ingested and then carried by gastrointestinal motility to its site of absorption. Concerning this aspect—the specific effect of various foods on motility—knowledge is relatively meager, although it is generally believed that the quality and quantity of a food may affect the motor functions of the gut (ref. 3). If a food is inimical to gastrointestinal motility, a variety of symptoms may ensue which as a rule are not serious in that they threaten life, but which may be sufficiently distressing to impair efficiency and morale.

The axiom that an army travels on its belly may be paraphrased into modern context by stating that an astronaut flies best on a comfortable belly; that is, the food given him should not make him a victim of indigestion.

When people complain of indigestion in this country, or of dyspepsia in England, they usually mean that they have sensations of upper abdominal discomfort, fullness, pressure, gas, cramps, nausea and bloating. The words "indigestion" and "dyspepsia" would imply that these symptoms are literally caused by impaired digestion and that the responsible mechanisms are deficient emulsification or enzymatic digestion of foods. As a matter of fact, failure of enzyme or emulsification systems rarely causes symptoms per se. In most instances when people complain of indigestion, it is a disorder of the motor function of the gut that is responsible. Cramps, "gas pressure", "lump feeling", belching, and bowel disorders are all manifestations of motility disorders, and our dietary regimen for the astronauts should be so designed as to avoid food factors that might derange normal motility sufficiently to bring about such symptoms.

One of the principal causes of indigestion as just defined appears to be gastric retention due to impaired evacuating mechanisms of the stomach. One must differentiate here between chronic gastric retention caused by an organic mechanical obstruction at the outlet of the stomach and the retention which is transient and expresses a disorder of motility. It is the latter which is considered herein; the mechanism that is responsible and the symptoms that are occasioned are exemplified by what happens when anyone eats too much, and, in particular, eats too much fat. Fats retard gastric evacuation by physiologic mechanisms, but the symptoms produced are uncomfortable enough: epigastric fullness, pressure, bloating, and possibly even nausea. If there is in addition some incompetency of the gastroesophageal barrier mechanisms, gastroesophageal reflux may attend this gastric retention, and the symptoms of heartburn are superimposed on the others.

The idea that gastric emptying is chiefly controlled by the pylorus, the "keeper of the gate," is untenable in light of present evidence. Gastric emptying is principally controlled by 2 factors: the pressures in the stomach, and the pressures in the duodenum. If the gradient between these pressures is flattened, gastric emptying is retarded. Thus, fats induce gastric retention by stimulating the duodenum to elaborate a humoral substance which depresses gastric motility. A variety of conditions involving the nervous system, as well as humoral factors, may also affect gastric evacuation, and in particular nervous tension, vertigo, and headache, most of which probably exert their effect by enhancing duodenal tone (ref. 4). Physical factors may also adversely affect gastric emptying time, and those who have been unaware of this have wasted considerable time in studying the absorption of foods given by mouth. For example, the effects of radiation were extensively studied in mice a number of years ago, and it was concluded that small doses of radiation grossly retard the absorption of various nutrients. Absorption was unquestionably retarded, but the reason was not so much intestinal damage as the fact that the radiation induced, among other things, gastric retention, and the foods which had been given by mouth simply failed to reach the absorbing surface in the usual time (ref. 5).

Transient gastric retention caused by the type of food eaten is of particular concern to us because of the idea that foods for space travel might be more easily packaged, more easily taken, and better digested and absorbed if they were chemically pretreated and broken down to some of their digestive products—protein to polypeptides and carbohydrates to dextrins or disaccharides, for example. Nothing could be worse, however, for the degree to which a food is broken down into smaller molecules before its ingestion, to that degree gastric retention and its attending symptoms are more likely to ensue.

In the duodenum there are, apparently, receptor mechanisms sensitive to osmotic pressure of the duodenal contents. These osmoreceptors respond to a wide variety of substances, and Hunt (ref. 6) has shown that gastric retention increases linearly with increasing solute concentration in the stomach. For a food of given caloric value, therefore, the osmotic activity increases, to the degree that it is predigested. Because of these considerations, I would strongly advise against the inclusion of any predigested foods, whether glucose, amino acids, peptides, or dextrins in formula diets. Incidentally, one would not feed fatty acids and glycerol instead of neutral fats would one? The astronaut will be much more comfortable if he is given foods as they naturally occur, although they may be physically uncomfortable; it will not increase the amount of food that he assimilates.

In the small intestine an analogous situation exists. Normally, to be sure, food is here digested and broken down into small and osmotically active constitutents, such as amino acids and glucose, but the absorption rate is so rapid as compared with the digestion rate that appreciable amounts of these osmotically active small molecules do not accumulate, and the intestinal milieu maintains isotonicity without difficulty. Should, however, food of unusual composition or amount enter the small bowel, its motility becomes deranged.

In discussing motility, it may be appropriate to define the terms more precisely, and, in particular, to point out the difference between motility and transit. Motility is usually considered to have three components: (1) tone, which determines the caliber of the bowel lumen in the face of various distending forces; (2) mixing waves, which essentially knead and churn the small bowel chyme; and, (3) peristalsis, a contraction which involves 1 to 2 centimeters of intestinal wall and moves downstream for variable distances. Although it is true that active peristalsis may cause rapid transit, peristalsis never can determine transit time per se. For example, a strong peristaltic contraction in the upper part of the small gut may tend to propel material downstream, but a high tone and active mixing waves in this lower area may act as effective brakes; and, the stronger the tone and the more active the mixing waves, the slower the transit, even though tone and mixing waves are expressions of motility. On the other hand, if the bowel is atonic throughout its length, it may take just one moderately forceful peristaltic wave to push material from one end of the gut to the other. In certain clinical conditions such as ulcerative colitis, for example, the patient has diarrhea even though his overall motility is much less than normal. Finally, material may move downstream even in the total absence of peristaltic waves, presumably because tone is higher and mixing waves more active in the jejunum than in the ileum (ref. 7).

The three components of motility normally interact so that the transport of chyme downstream causes no discomfort, and transit is neither too fast nor too slow. If, however, the intestine is rapidly distended, it reacts with forceful local contractions, tending to push its contents downstream more rapidly from the point of distention (diarrhea) and to retain them proximally (nausea and vomiting). One way of rapidly distending the small intestine is to introduce hypertonic material into it, for the intestine responds to such material by a copious and rapid outpouring of fluid in an effort to maintain isotonicity of its contents.

This phenomenon and the reactions that ensue can be illustrated by both experimental and clinical examples. By means of a technique devised by Fordtran (ref. 8) water and solute exchange rates across the gut wall of intact human subjects can be studied. By this means it can be shown that if a hypertonic solution of 900 milliosmoles per kilogram is infused at a rate of 15 milliliters per minute, the intestinal contents have already been diluted to an osmolality of 400 milliosmoles per kilogram at a point of 30 centimeters distal to the point of infusion, and to 220 milliosmoles per kilogram at a point 60 centimeters distal. In spite of compensating efforts by the intestine lower down, subjects so tested may have cramps, diarrhea, and at times even weakness. If xylose, a 5-carbon sugar that is about 50 percent absorbed, is ingested, water is partly retained in the gut, and again cramps and diarrhea, though of a lesser degree, may be produced (ref. 9).

Clinically, surgeons and internists worry about what is called the dumping syndrome, which may appear after the stomach has been anastomosed to the jejunum. The responsible mechanism is implied by the name: material from the stomach dumps through the artificial anastomosis into the small bowel at a concentration of nutrients and at a rate far above those which would be permitted by the normal route of gastric evacuation. As a result, fluids and electrolytes rush into the gut lumen; discomfort, cramps, distention, and nausea develop; and, as further consequences, the reduced blood volume brings about sweating, weakness, rapid pulse, and impending syncope.

Under abnormal conditions, this reaction of small bowel motility to an irritant—in this case hypertonic chyme—may be accentuated. Many years ago, in an effort to enhance the nutrition of a patient who had nontropical sprue, a disease characterized by impaired absorption of all substances including water and electrolytes, I fed the patient amino acids and glucose by mouth on the assumption that this might provide his small bowel with longer exposure time to food in a form all ready to be absorbed. Nothing could have been more disastrous. Even though the patient had normal gastrointestinal continuity, his gastric evacuation mechanism was not quite able to compensate for the extremely unnatural food administered, and presumably it allowed unusually hypertonic material to enter the small intestine. This organ, although its absorption was impaired, could pour out fluids and electrolytes, with the consequence that the patient had a diarrhea so profuse as to be reminiscent of cholera.

Why a discussion of what happens in sprue when we are talking about the nutrition of a healthy astronaut? The point is that the astronaut may be exposed to a variety of conditions which may not be ideal to normal gastrointestinal function. In several of the preceding papers it has been suggested that blood flow in the weightless state may be abnormal, and particularly abnormal with respect to its splanchnic distribution. Although experimental evidence on the point is limited, it is generally believed that impaired blood flow to the gut, particularly when that gut has just been filled with food, leads to deranged absorption as well as motility. Hence, if it is possible that the weightless state affects the circulation to the gut, it behooves us to be particularly careful not to feed the astronaut with artificial preparations which the gut may possibly not tolerate.

Emphasis has been placed on the reaction of the small intestine to a hypertonic solution because this is an example in which the sequence of events culminating in a motility disorder and distressing symptoms can be traced with a reasonable amount of knowledge. The intestinal tract of man, however, can misbehave in other ways which are more subtle and less easily documented. Thus, a peristaltic contraction at one point may be associated with a tonic contraction (i.e., a spasm) distally, this incoordination of adjoining gut segments presumably leading to pain and a variety of other abdominal symptoms. Such derangements of motility occur under ordinary life circumstances, and it is not easy to identify the responsible mechanisms except to suggest that they may be multiple and include phychic, physical, and dietary factors.

With respect to colonic motility, the concept of residue appears to dominate all thinking, but this is certainly an oversimplification. In the first place, high residue foods are not easy to define. If a food such as bran contains a great deal of undigestible material, this presumably leaves a residue in the colon, but the degree of bacterial action in the colon may reduce this residue so that the fecal bulk may not be as large as would be expected. Milk, on the other hand, contains no crude fiber or roughage in the sense that bran does; nevertheless, it is a relatively high residue food leading to considerable fecal bulk (ref. 10). Even an apparently low residue food such as white bread, if eaten almost exclusively and to excess, can cause loose stools, gas, and considerable fecal bulk (ref. 10).

Because of examples such as these, it is my belief that most discussions of fecal residues with respect to certain food items are based on hand-me-downs and a priori conclusions based upon in vitro analyses of foods. Residue, however, depends on several factors: the nature of the food consumed, the adequacy of the small bowel in digesting and absorbing that food, and, most important, the effect of the colonic flora on such residues of this food that may enter the colon. This last aspect of the problem has not been studied except in a most peripheral fashion.

The second problem pertaining to residues is that they are often equated with bowel function in the sense that high residue foods are believed to lead to frequent and possibly loose evacuations, and bland, low residue foods to the opposite. Although such correlations may frequently exist, they certainly do not exist invariably. Thus, ordinary barium sulfate used for X-ray examinations is certainly a high residue "food," but its constipating effects are well known. The same thing may be said of kaolin. On the other hand, when Fantus, Kopstein, and Schmidt (ref. 11) studied the effect of bran on intestinal transit, these times were not grossly affected and the total bowel evacuation rate was only slightly changed by an appreciable intake of bran.

Finally, it should be pointed out that one of the few careful studies that has been carried out on the colonic effects of residues indicated that residues do not stimulate colonic motility mechanically because of bulk, but rather because they offer hemicelluloses for digestion to the colonic bacteria, with the consequent production of volatile, short-chain fatty acids, which in turn irritate the colonic mucosa sufficiently to cause evacuation of stools (ref. 12).

The ingestion of hemicellulose-containing material is a reasonably sure way of providing colonic bacteria with a substrate, since the human small bowel does not digest these substances. Colonic bacteria, however, can ferment and produce lactic acid as well as short-chain volatile fatty acids from any carbohydrate material that reaches their normal habitat in the colon. (In this connection, it should be pointed out that numerous studies have shown that most of the human small bowel does not have an indigenous flora and is quite sterile except for bacteria that are intermittently carried down with food residues (ref. 13).) Currently, for example, there is great interest in the clinical syndrome of disaccharide intolerance, a condition characterized by inability to digest and absorb lactose or, less frequently, sucrose. In fact, many feel that milk intolerance is not an intolerance to milk proteins as much as it is due to impaired ability to handle lactose. Even normal carbohydrate tolerance may be overcome by eating carbohydrate in excess. Rubner's subject (ref. 10), when given an almost exclusive bread diet, had stools and symptoms suggesting that sufficient carbohydrate reached the colon for excessive bacterial fermentation to take place.

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The question may be asked "What has this got to do with the healthy astronaut?" No matter what strange diet is planned for him, it is true that we are not planning to feed him purely white bread and beer. The point is that from a clinical point of view the incidence of alleged milk intolerance in the population is fairly high. Recently, moreover, studies of lactose intolerance in the general population have yielded such high incidence figures that we must make our choice between two conclusions: (1) Either the tests are fallible or (2) borderline and subclinical lactose intolerance is fairly common. Two tests are used: One is a lactose intolerance test in which a lactose load is given by mouth and the blood level of one of its monosaccharide constituents, glucose, is measured thereafter. The second consists of obtaining a biopsy of the jejunal mucosa by means of a perorally passed tube and assaying the sample for its lactose content. In some test series, the incidence of abnormal results as determined by these two procedures is as high as 30 percent in what appears to be an essentially normal population. Perhaps our space travelers should have lactose tolerance tests as part of their physical examination, but a more sensible procedure would be to eliminate from their diet preparations with disproportionally high carbohydate concentrations.

Up to now, we have been discussing the indirect effect on motility of colonic flora acting by virtue of their utilization of food residues. At a recent meeting of the Gastroenterological Research Forum, it was noted that colonic bacteria may play a direct role in this respect (ref. 14). It is known that rodents in the germ-free state may develop a huge cecum, but the reasons for this are not known. According to this recent report, the small intestine may normally produce amines potentially able to affect the vasculature and the smooth muscles of the gut. Normally, however, colonic bacteria destroy these amines and negate their activity, but in the absence of bacteria, the muscular inhibition produced by the amines may lead to cecal distention. If this is true, then bacteria may affect motility much more directly than is generally appreciated.

Obviously one of the great and continuing unknowns is the role of the colonic flora, and, evidently, it must have further and intensive study. I would, however, like to question whether further intensive study of fecal bacteriology is indicated. Feces as passed by the anus contain variable amounts of dead bacteria, and the normal proportions of, for example, aerobes and anaerobes may not be indicated by analysis of material passed by the rectum. I would, therefore, strongly urge that those who study colonic bacteria in man obtain their samples from the cecum, and the ascending and transverse colons. This can be easily accomplished with the various tubes available today.

Whether weightlessness affects rectal evacuation is moot; apparently the record of defecation in space is incomplete. Irrespective of the effect of weightlessness, however, inactivity does affect intestinal transit and colonic evacuation. Clinically, it is quite apparent that the patient immobile in bed may get severely constipated. It is also apparent that artificial boluses, such as balloons, put into the intestine, move downstream much more rapidly if the subject is up and moving around than if he is lying quietly in bed. Presumably, it is the physical activity and motion rather than gravity which hasten the downstream passage of intestinal contents, but whether inactivity or weightlessness, the astronaut is exposed to both factors until large space capsules are made. Under current conditions, with the emphasis on short-term flights, I am sure that the most practical solution to the waste-disposal problem has been a constipated astronaut. Like other abnormalities of bowel motility, however, constipation tends to distress most people, and hence, for the future, when longer flights are planned, it is a state to which the astronaut should not be subjected. The diet of future astronauts should, therefore, be so designed to induce adequate roughage to promote normal evacuation.

The effects of weightlessness on motility and digestion are imponderable. Rather than speculate about these, I believe our terrestrial experience permits us to make certain recommendations concerning the diet of astronauts with the purpose of deranging gastrointestinal motility as little as possible.

(1) Fragmentation of natural foods into small particles may have certain advantages. This may be accomplished by purposely thorough mastication or, to the extent the palatability is not impaired, by mechanical pretreatment of foods.

(2) Excess fats should be avoided because of their effect in delaying gastric evacuation.

(3) Excess carbohydrates should be avoided because they may enhance fermentative activity of intestinal bacteria.

(4) This leaves protein as the principal staple of the astronaut's diet, and indeed there are few foods which are digested and assimilated as completely as, for example, a hard-boiled egg. It has been suggested that proteins may be gassy, but no objective evidence can be marshalled to support this belief. On the other hand, proteins do enhance the growth of so-called putrefactive colonic bacteria, and hence it must be admitted that gas production during high protein intakes, even though not excessive in quantity, may be particularly unpleasant in quality.

(5) Any form of predigested food is to be totally avoided. Its noxious effect is probably much more real than that usually attributed to spices.

(6) For long-term flights in the future, current attempts to induce constipation should probably be abandoned in favor of dietary manipulations that moderately promote bowel evacuation, particularly in view of the inactivity to which the astronaut will be exposed.

(7) These points, taken as a whole, indicate that the best diet, from the viewpoint of maintaining normal gastrointestinal motility, is one which in taste, composition, and character is a well-balanced diet such as might naturally be chosen on Earth; it should be modified only to the extent required by the practical limitations of space travel.

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Intestinal Flora

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Although certain pathogenic enteric bacteria such as the microorganisms now known as *Vibrio cholerae* and *Shigella dysenteriae* 1 (refs. 1 and 2) were described about the same time, the studies reported by Escherich (ref. 3) may be said to mark the beginnings of investigations of intestinal flora in the more general sense. Among other things, Escherich reported on the fecal flora of newly born infants and described the bacterium which bears his name, *Escherichia coli.* This species is the type species of the genus *Escherichia*, and this genus now has been conserved as the type genus of the family *Enterobacteriaceae.*

Since the early reports mentioned (refs. 1, 2, and 3) appeared, a vast literature has accumulated on the subject of the intestinal flora (and fauna) of man and lower animals both in health and in disease. While most of this work was very well done by highly competent investigators, the majority of the reports contained only qualitative data because of the technical limitations of the times. However, it should be emphasized that these early reports contained essential information upon which recent and current research is based; hence their importance should not be minimized.

In recent years, many investigations have been reported which deal with the intestinal flora of lower animals, both conventional and germ-free, and in the majority of these investigations quantitative methods were employed. A wide variety of subjects have been covered, such as the relationship of intestinal flora to resistance; the effects of changes in diet; and the effects of antibiotics, colicines, and bacteriophages on the flora and on antagonisms, to list only a few subjects and approaches (refs. 4 to 9).

However, literature containing quantitative data on the subject of the intestinal flora of the human, particularly the adult, appears to be very sparse. Hence, this report will, of necessity, be a summary of data reported in only a few papers.

Table I contains the data obtained by Haenel and Feldheim (ref. 10) from the examination of 50 fecal specimens from 21 healthy adults. They also examined 258 specimens from 94 patients suffering various disease conditions, other than diarrheal disease, and obtained results similar to those listed in table I except in cases of anacidity and gastrectomy.

Seeliger and Werner (ref. 11) recently gave an excellent report of extensive investigations into the intestinal flora of man, in which they employed a variety of media and methods, both aerobic and anaerobic. In the examination of 15 fecal specimens collected from a single adult, over a period of 6 weeks, these investigators reported the results which are given in table II in a modified form. Seeliger and Werner also studied the intestinal flora of five adults by aerobic and anaerobic methods. Their results may be summarized as follows.

Gram-negative microorganisms.—The aerobic and anaerobic bacterial flora is composed principally of rod-shaped forms. Gram-negative

TABLE I.—*Intestinal Flora Found in Examination of 50 Fecal Specimens From 21 Healthy Adults* (*ref. 10*)

Culture	Flora per g feces	Remarks
Bifidus group		
Gram-positive obligate anaerobes (undifferentiated)	Usually 10^9–10^{10}.	Numbers below 10^8 were not observed.
Acidophilus group		
Gram-positive (facultative aerobes-anaerobes undifferentiated).	Usually 10^5–10^8.	
Coli group	10^7–10^9	Numbers greater than 5×10^9 were not observed.
Enterococci	10^5–10^8	
Proteus	10^2–10^4	
Lecithinase-positive		
Clostridia	Generally $>10^8$	Occasionally absent.

TABLE II.—*Intestinal Flora Found in 15 Fecal Specimens Collected From a Single Adult Over a 6-Week Period* (*ref. 11*)

Culture	Average no. bacteria, million/g feces	*E. coli*, percent bacteria	*Klebsiella*, percent bacteria	*Streptococci*, percent bacteria	*Lactobacillus*, percent bacteria	*Bifidobacterium* and *Lactobacillus*, percent bacteria	Gram-negative anaerobes
Aerobic							
Mean	858	33.0	5.5	27.1	42.5	------	------
Maximum	70	7.3	5.0	14.0	4.0	------	------
Minimum	2150	88.4	36.5	53.5	55.6	------	------
Anaerobic							
Mean	2724	8.6	3.3	6.6	------	43.4	38.4
Maximum	1090	1.4	0.3	0.3	------	25.0	5.4
Minimum	5940	30.9	0.8	20.6	------	64.4	72.3
No. of specimens in which bacteria not detected	------	0	10	3	0	0	2

cocci, *Neisseria* (aerobic) and *Veillonella* (anaerobic), are abundant in the oral cavity, but occur infrequently in the lower intestinal tract. In adults the prevalence of Gram-negative anaerobes over *Escherichia* is in the order of 10^9 as opposed to 10^7 to 10^8 per gram. In addition to members of the family *Enterobacteriaceae*, *Alcaligenes*, *Pseudomonas*, and *Flavobacterium* occasionally are found. (*Aeromonas* and *Vibrio* species sometimes are present in fecal specimens.)

Gram-positive microorganisms.—Of the genera that are aerobic, the most common were *Staphylococcus*, *Streptococcus*, and *Lactobacillus* and of the anaerobes, *Bifidobacterium* species occurred most frequently. In adults the *Bifidobacteria* persist and frequently outnumber the anaerobic Gram-negative bacteria.

Spore-forming bacteria.—Seeliger and Werner found that normally these do not exceed 10^3 to 10^4 per gram. (*Clostridium perfringens* is almost universally present in the feces of men and many other animals (ref. 12); also, other *Clostridia* and some species of *Bacillus* may be found.)

Yeasts.—These were found in some specimens and of those that grow at 37° C *Candida albicans* occurred most frequently.

Some of the data reported by Seeliger and Werner (ref. 11) are summarized further in table III. Examination of the data in table III indicated that there was considerable variation in the bacterial counts from individual to individual, but the number of individuals examined was very small. Nevertheless, the results reported by Seeliger and Werner appear to agree quite closely with the data of Haenel and Feldheim (ref. 10) mentioned earlier and with data for man reported by Smith and Crabb (1961, quoted by Rosebury, ref. 8). In connection with the data given in tables III and IV, it is clear that both aerobic and anaerobic cultural methods are essential for an accurate estimation of the numbers of *E. coli* in fecal specimens, as mentioned by Seeliger and Werner.

Attempts to implant *E. coli* in man and other animals largely have been unsuccessful (ref. 11). Yet there is no doubt that some strains of *E. coli* do become implanted in humans and in lower animals and that this process begins within a few hours or days after birth. There are numerous reports in the literature which indicate that there are "resident" and "transient" strains of *E. coli* in the intestinal tract (refs. 9 and 13 to 16). The term "resident" as used here should not be taken too literally, since these resident strains are replaced by others from time to time.

In connection with the subject of implantation of *E. coli* strains, it is well to remember that all *E. coli* strains are not alike. On the contrary, there are thousands of different serotypes of *E. coli* and it is apparent that there are extreme differences, beyond serotypic differ-

TABLE III.—*Gram-Negative Aerobic and Anaerobic Bacteria Found in Fecal Specimens From Five Adults on Mixed Diets*

[Adapted from table 4, ref. 11]

Specimen	Aerobic bacteria [a]	Anaerobic bacteria
	E. coli [b]	*Ristella (Bacteriodes), Sphaerophorus, Fusiformis*
A		
(spec. 1)	2×10^7 (1×10^8)	$>2\times10^9$
(spec. 2)	1×10^7 (2×10^8)	--------
B	2×10^7 (1×10^7)	$>1\times10^6$
C	4×10^7 (3×10^8)	$>1\times10^9$
D	7×10^8 (7×10^8)	$>1\times10^8$
E	7×10^7 (7×10^7)	1×10^9

[a] Other enteritic bacteria did not grow with methods used.
[b] Data in parentheses were obtained by anaerobic culture methods.

TABLE IV.—*Gram-Negative Aerobic and Anaerobic Bacteria Found in Fecal Specimens From Five Adults on Mixed Diets*

[Adapted from table 6, ref. 11]

Specimen	*Staphylococcus*	*Streptococcus*	*Lactobacillus*	*Bifidobacterium*	Approx. ratio of *Bifidobacterium* to other bacteria (including Gram-negatives)
A (spec. 1)	3×10^5	([a])	([a])	2×10^9	1:1
(spec. 2)	1×10^9	1×10^8	6×10^7	4×10^9	3:1
B	1×10^7	5×10^5	2×10^8	9×10^8	3:1
C	([a])	([a])	([a])	8×10^9	5:1
D	([a])	4×10^5	5×10^7	1×10^{10}	5:1
E	([a])	1×10^8	1×10^6	1×10^8	1:12

[a] Bacteria did not grow with methods used.

ences, between them. Some serotypes when introduced may never be demonstrated in the feces. Some become implanted but may be detected in small numbers and may or may not be transient inhabitants. Others may replace existing serotypes and become "resident" strains. Some transient and some resident serotypes have the ability to spread easily from one person to another, while others lack this ability (refs. 17 and 18). The work of Spaulding and his associates (refs. 19 to 22) should be mentioned at this point, since their work by means of continuous culture methods appears to confirm, in general, the points mentioned.

It is known (ref. 11) that considerable change may take place in the intestinal flora in the absence of change in diet. Further, in reference 11 it is reported that diets that are rich in carbohydrates favor increases in the numbers of Gram-positive bacteria, especially *Lactobacilli* and *Bifidobacteria*, while diets with meats give rise to increases in the numbers of Gram-negative aerobes and anaerobes.

Nothing has been said about many other kinds of bacteria, *Mycoplasma*, and viruses which are known to occur in the intestine, at least from time to time. However, quantitative data on these microorganisms appear to be lacking.

Further, we have not mentioned the pathogenic forms such as the *Salmonella*, *Shigella*, enterotoxic staphylococci, and certain types of *Clostridium*. However, it is obvious that great care must be exercised in the selection, processing, packaging, and storage of all foods in order to be certain that pathogenic microorganisms are not present. Also, it is clear that the astronauts, as well as everyone in close contact with them, should be examined frequently to be as certain as possible that there are no carriers among them.

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Discussion: Intestinal Flora

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Although there are both flora and fauna living in intimate association with our skin, nares, larynx, trachea and bronchia, urogenital tract, and gastrointestinal tract, major interest and information has centered on the flora of the gastrointestinal tract. While other tissues and organs are not necessarily sterile at all times, their association with bacteria is usually minor excepting during gross infection. Much of the time they are sterile. Consequently the following report is concerned primarily with the microflora of the gastrointestinal tract. As recent summaries indicate, there are not enough complete data regarding the normal indigenous microflora of man's gastrointestinal tract. The data from experimental animals are much more numerous, but they don't seem to be qualitatively superior. The techniques used are laborious and it is difficult to correlate results from one laboratory with those from another.

Functions to be attributed to the action of the living microflora may be well documented in certain cases. In other cases there may be simply an implication from the fact that a researcher has found a difference between those animals which contain living microorganisms and germfree animals. If tissues of germfree animals are found to be different from those of classic animals, this is presumptive evidence that bacteria have a function in the stimulation, development and/or maintenance of host cells or tissues in an activated state. If these be essential functions then there is a symbiotic relationship between host and microflora. The host provides a constant temperature, water, food, waste disposal, and a relatively constant pH and atmosphere. The microorganisms may provide development of the defense mechanisms, changed morphological details, or nutritional benefits for the host.

When Pasteur contemplated the terminus of the half-century controversy of agriculture which culminated in the concept that bacteria are needed for nitrogen fixation in legume plants (reviewed in ref. 1), his knowledge of the tremendous capabilities of microorganisms in fermentation weighed more heavily than did his knowledge of specific microorganisms as the cause for certain diseases; he therefore expressed his belief that life without bacteria would be impossible. It was common knowledge that the intestinal tract was teeming with microorganisms, and he believed that during the evolution of vertebrates there was established a symbiotic relationship in which the host is dependent upon the microorganisms for the digestion of natural foodstuffs. Nencki answered the master of microbes: Since bacteria produce toxins, many bacteria are harmful and life should be possible without bacteria. This view was promulgated by Metchnikoff who believed not only that bacteria were responsible for many specific diseases and infections but also that the intestinal toxins they might produce would shorten the life of the man. He pointed out that vertebrate species which have a relatively short intestinal tract with relatively few microorganisms have a long life compared to those animals which have a long intestinal tract with many microorganisms.

Results of experiments by Kianizin (ref. 2) from 1894 to 1916 indicated that life was impossible when the water, air, and diet of dogs and rabbits were sterilized. Sucksdorff (ref. 3) found few bacteria in the intestinal contents of men fed sterile diets. Nuttal and Thierfelder believed that their experiments, in which animals were maintained in sterile conditions for 10 days, provided evidence that life is possible without bacteria. Their result was criticized by both Schottelius (ref. 4) and Kuster (ref. 5) who suggested that the increased weight was due to a filling of the gut. Similar results were obtained with invertebrates by Conte (ref. 6) and by Delcourt and Guyenot (ref. 7). These, plus the negative results of Schottelius during more than a decade of work and the disappointing results of Madam Metchnikoff with tadpoles, were all overcome by a series of dramatic, successful experiments in raising germfree chicks by Cohendy at the Pasteur Institute in 1912 (ref. 8) and with reproduction in axenic flies by Guyenot in 1917 (ref. 9). Life *was* possible without bacteria. This has been amply confirmed in a variety of laboratories, and colonies of mice and rats now in existence are in the 20th generation of life in the germfree state. We must interpret the results of Kianizin as we do the early germfree experiments: the prime cause of failure was a lack of understanding of nutrition.

What are the consequences to the indigenous microflora in a well-fed, isolated host? The pioneering experiments of this important study have been done by students of J. A. Reyniers. In 1941 Nelson placed a young conventional guinea pig in a sterile cage and gave it sterile food, water, and air for 1 year (ref. 10). During this time it exhibited autodisinfection to such an extent that only three species of microorganisms could be found. One of these was a mold which was not found inside the animal. The remaining organisms were one species of streptococcus and one diplococcus. This experiment was confirmed by Reback in 1942 with weaned rats fed an autoclaved diet in a nonsterile environment (ref. 11). These were found to have simplified flora. When he maintained weaned rats under sterile conditions, most enterococci were lost within 1 month. After 3 months no fission yeast or cocci, except lanceolate cocci, and almost no gram-negative rods were present in the feces. A gram-positive rod was the most abundant organism present. The intestinal flora of the white rat with complete anal block also becomes simplified. This work was reported by Wagner (ref. 12). The total microbial population was greatly diminished and the rats died within 10 days. One hypothesis, that death was caused by intestinal infection or toxins, was effectively denied by repeating the experiment with germfree rats. These died with similar clinical symptoms and during the same period as the conventional rats. These experiments and decontamination of rats having limited flora were reviewed by Luckey (ref. 1). Obviously more information is needed regarding the effect of long-term isolation upon the indigenous microflora.

INTESTINAL BIODYNAMICS

One vector of the biodynamics of the intestine which should be considered is the total space requirement, or the M-factor, of bacteria. If we consider that the volume of the average bacterium or coccus is about 1 cubic micron, or 10^{-12} cubic centimeter, then we are oriented to the fact that 10^{12} such organisms per gram would be 100 pecent of the volume. Some organisms, such as *Leptospira*, may be as large as 10 cubic microns and some may be as small as 1 or 2 tenths of a cubic micron. Table I gives numbers of intestinal microorganisms under different conditions. The usual total count of all microorganisms in human excreta is about 10^{10} bacteria per gram. Data obtained by adding known species of bacteria to animals which were germfree have been discussed under the heading of "gnotophoric animals" by Luckey (ref. 1). The population of *Bacteroides* in dibiotic rats is considerably greater than that in tribiotic rats with *Salmonella* as the third member of the biota. When *Streptococcus faecalis* or *Escherichia coli* was added to a germfree guinea pig the resulting total population was 10^9 per gram of contents. When *E. coli* and *Lactobacillus bifidus*

TABLE I.—*Bacterial Space or M-Factor in the Intestine*

[Data from various sources as reviewed by Luckey (ref. 1)]

Animal [a]	Material	Organism	Count, $\log_{10}$/g ([b])
Human	Colon and feces	All	11
Dibiotic rat	Cecum	Bacteroides u	4–5
Tribiotic rat	Cecum	Bacteroides u	2
		Salmonella t	8–12
Dibiotic guinea pig	Cecum	Str. faecalis	9
Dibiotic guinea pig	Cecum	E. coli	9.5
Tribiotic guinea pig	Cecum	E. coli	3–7
		L. bifidus	9
Dibiotic chick	Ileum	Str. faecalis	10.4
Dibiotic chick	Ileum	Cl. perfringens	9.2
Dibiotic chick	Cecum	Cl. perfringens	9

[a] Germ-free animals were inoculated with one microorganism (dibiotic) or two microorganisms (tribiotic).
[b] Data expressed as $\log_{10}$ of number of bacteria per gram of intestinal contents.

were added, the tribiotic guinea pig had a total count of 10^9 per gram and the number of *E. coli* was greatly reduced.

This variety of combinations of limited species added to germfree animals indicates that the total count of microorganisms in the lower intestine seems to be approximately 10^9 per gram. If we assume 10^{10} organisms per gram of material and the colon contents of man to be 1.5 kilograms, then the total number of microorganisms in our body would be approximately 10^{13}. Each one of these is leading what for it is a normal life: eating its full share of our food during its 20- to 60-minute lifespan, metabolizing the material we provide, and excreting products into our intestinal tract. The total impact of these guests which are continually at dinner is the major problem to be considered. If we assume that a microorganism can eat its body weight in 1 minute, then a rather simple calculation suggests that the bacteria in our tract process 1.5 kilograms per day; this happens to be the same as the total contents of the colon and is also approximately the amount of food we eat each day. A population of 10^{10} average-sized bacteria and 10^{11} *Bacteroides* per gram (see Gall et al., ref. 13) would suggest that 20 percent of the excreta is living bacteria (table II).

TABLE II.—*Colon Microflora Biodynamics in Humans Based on Average Number of 10^{10} Microorganisms per Gram of Intestinal Contents*

No. per g	10^{11}
No. excreted per day	10^{13}
Colon contents, g*	1500
Total microorganisms	10^{13}
Weight of microorganisms, g (also %)	20
Weight processed per day, g	1500

*Lower ileum and cecum included at 100 g each.

Metchnikoff believed that the ingestion of buttermilk prolonged life by changing the microflora of the intestinal tract to an aciduric flora. Torrey and Montu (ref. 14) showed that the presence of carbohydrate in a mixed flora encouraged lactic-acid organisms while a diet exclusively of meat decreased the number of lactic-acid organisms and tremendously increased *Bacterium welchii.* The concept that carbohydrate is required in the diet in order to maintain lactic microorganisms in the intestinal flora was verified by Porter and Rettger (ref. 15). (See fig. 1.) In starvation, another condition with little carbohydrate available in the gastrointestinal tract, the lactic-acid organisms were negligible. When carbohydrate was added to the diet or when a mixed diet was used, the lactic-acid organism became one of the most abundant groups of organisms. The gram-

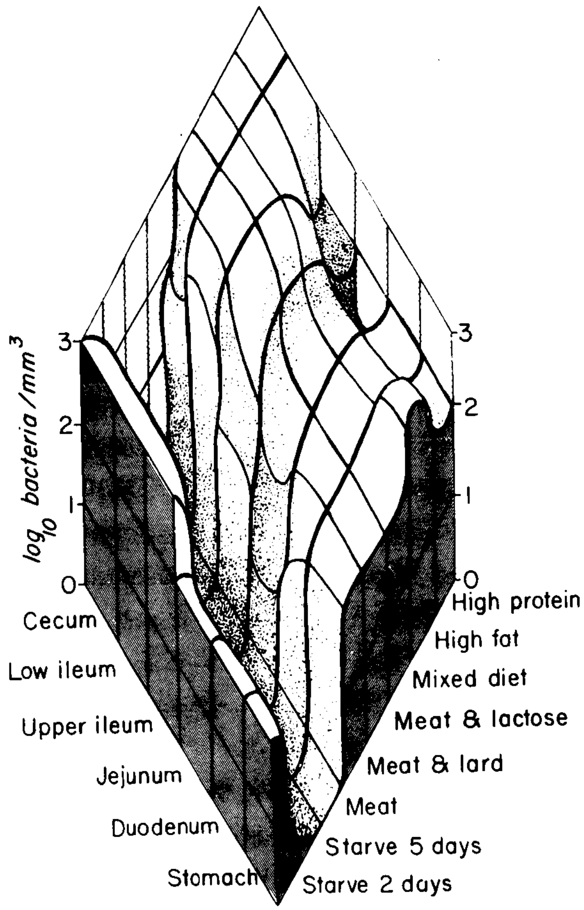

FIGURE 1.—Lactobacilli in rat intestine. The log of the number of bacteria per cubic millimeter is expressed on the ordinate. The abscissa on the left gives the part of the intestine from which the counts were taken. The abscissa on the right gives the diet fed the rats. Data of Porter and Rettger (ref. 15).

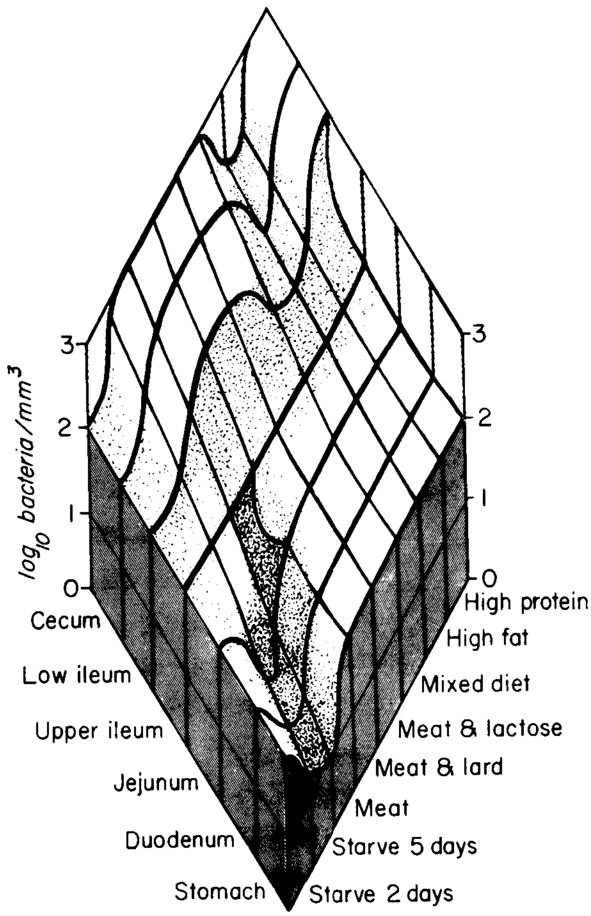

FIGURE 2.—Gram-negative microorganisms in rat intestine. See figure 1 for explanation. Data of Porter and Rettger (ref. 14).

negative organisms were less dependent upon the availability of free carbohydrate (fig. 2).

Another interesting study was that of Moore et al. (ref. 16), which is presented in modified form in table III. These data indicate that a very small amount of folic acid can be important in changing the microflora. It did not change the coliform count much but it did increase the lactobacilli and the enterococci by factors of approximately one million. When streptomycin or Sulfasuxidine was added, equally great changes were noted in the coliforms and very low changes were noted in the lactobacilli. When the potency is expressed as parts per million per log of change, it is noted that the vitamin is much more effective on a weight basis in changing the microflora than is either the sulfa drug or the antibiotic.

Workers at Chiba University at Japan have performed remarkedly clear-cut experiments showing the relationships of microorganisms to each other in vivo. In these studies, reviewed by Tanami (ref. 17) and Luckey (ref. 1), they inoculated germfree guinea pigs with two different microorganisms. In the first experiment presented herein (fig. 3) it will be noted that the two microorganisms, *Streptococcus faecalis* and *E. coli*, seem to be compatible in the intestine of the guinea pig and fill the gut to the capacity (10^9) according to the principles of the M-fac-

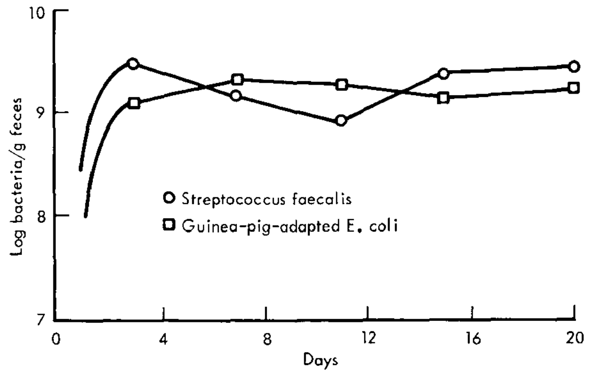

FIGURE 3.—*In vivo* association of microorganisms, inoculated *per os*, in the lower intestine of gnotophoic guinea pigs. The inoculum of *Str. faecalis* was considerably heavier than that of *E. coli*. Data of Tanami (ref. 17).

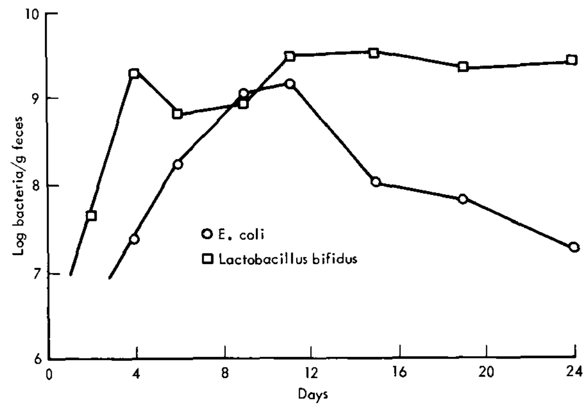

FIGURE 4.—*In vivo* antagonism of microorganisms inoculated into germfree guinea pigs at 20 days of age. Data of Tanami (ref. 17).

tor. Figure 4 illustrates the experiment in which *Lactobacillus bifidus* was inoculated into 20-day-old germfree guinea pigs in equal numbers with *E. coli*. It was noted that the lactobacilli increased most rapidly and filled the capacity. The *E. coli* grew more slowly. The apparent struggle for dominance was lost by the *E. coli*. Twenty-four days after inoculation only 1 percent of the total organisms was *E. coli*. In experiments in which the inoculum of lactobacillus was heavy and that of *E. coli* was light, the *E. coli* could not be found after 12 days. Preliminary experiments had shown that the guinea-pig-adapted strain was lethal for germfree guinea pigs. In another experiment (fig. 5), two strains of *E. coli* were introduced in equal numbers. The human-adapted strain disappeared rapidly and the guinea pigs died from the symptoms caused by the guinea-pig strain of *E. coli*. In a similar experiment guinea pigs were given 100 times as many organisms of the human strain as of the guinea-pig strain, and the guinea-pig strain disappeared within 4 days; no death occurred and no histopathology was noted. Thus it appears that there was definite antagonism between these organisms which could be to the detriment or to the benefit of the host depending upon other conditions.

In work of Phillips and Wolfe (ref. 18) it was noted that a symbiotic relationship existed between *Endamoeba histolytica* and two micro-

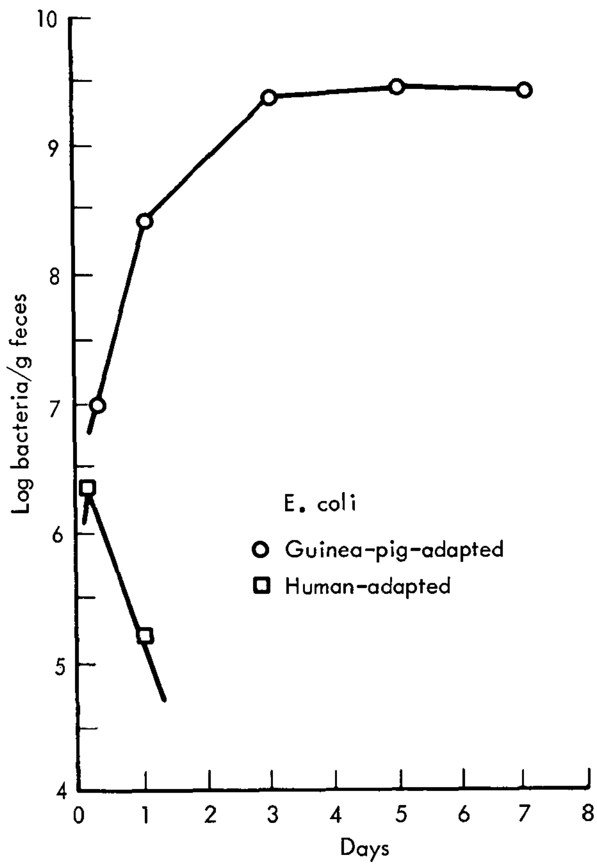

FIGURE 5.—*In vivo* antagonism of microorganisms inoculated in equal quantities into germfree guinea pigs at 20 days of age. Data of Tanami (ref. 17).

TABLE III.—*Effectiveness of a Vitamin, an Antibiotic, and a Sulfa Drug in Changing the Bacterial Population in the Intestine of a Chick*

[Data of Moore et al., ref. 16]

	Addition	Count as $\log_{10}$		
		Lacto-bacilli	Entero-cocci	Coli-form
	None	4	4	8
	5 ppm folic acid	10	9	9
	Do. +500 ppm streptomycin.	9	3	4
	Do. +10 000 ppm Sulfasuxidine.	10	6	3
Effective ratio	Material	ppm per log change		
1	Folic acid	1	1	5
200	Streptomycin	500	100	100
4000	Sulfasuxidine	10, 000+	3000	2000

organisms *Trypanosoma cruzi* and *E. coli*. Apparently *Trypanosoma* was needed for food of the amoeba *in vitro*, if not *in vivo*. Invasiveness for mammalian tissue did not appear to exist unless *E. coli* were present in some helpful capacity. The experiments of the Japanese workers suggests that guinea-pig-adapted *E. coli* alone could be the cause of the death of germfree guinea pigs. These results and others not summarized suggest that the germfree animal is a good host for nonindigenous organisms. The question raised is: What would happen to a host that had a simplified flora by virtue of prolonged isolation?

HOST MORPHOLOGY

The gross appearance of germfree animals is very similar to that of conventional animals. Even close scrutiny by handling does not reveal whether a chick is germfree or classic unless the olfactory senses are evoked. Then it becomes obvious that the intestinal microflora has a pronounced effect upon the odor of the host. Germfree mammals may be distinguished from classic mammals since the enlarged cecum of many germfree mammals causes a distention of the abdomen which is noticeable to the expert.

The effect of the microbial flora upon the organs and tissues of the host is readily divided into two parts. The first is represented by those organs removed from microbial activities: these include brain, bone, muscle, kidney, thymus, and endocrines. The second category contains those organs and tissues which are normally in constant contact with the microbial flora. Here three different categories of change are noted. The first might be termed the primary defense of the body. This is exemplified by the epidermis. Despite its contact with microorganisms there is no noticeable change in the features of the epidermis when germfree and classic animals are compared. Functionally, the bacterial clearing by the liver and spleen belongs to the first category as determined by Thorbecke and Benacerraf (ref. 19). In the mucosal lining of the gastrointestinal tract there are changes which suggest that similar changes would be noted in the dermis if bacteria penetrated the epidermis.

In the second category are those defense mechanisms which seem to be well developed in the germfree animals, but the organs or tissues simply are not functioning in defense. Examples of the second category are the phagocytes and antibody production. The data of Wagner (ref. 20) illustrate that germfree animals do not have antibodies to bacterial antigens; but when challenged, germfree and classic animals respond with about the same quantity of antibody. Thus it appears that the mechanism for production of antibodies is well developed in germfree animals but there has been inadequate stimulus to evoke a response.

The third class, or tertiary defense mechanisms, are those in which organs and tissues change morphologically upon contact. These must be given time to develop after contact with microorganisms. The lymphatic system is the prime example in this category. Apparently the epithelial lining of the sinuses and the cilia of the epithelium are in a similar category, according to Miyakawa (ref. 21).

When the germfree animal is inoculated or contaminated it will change within a few weeks to the morphological state of the classic animal.

Specific morphologic comparisons were summarized by Luckey (ref. 1). The circulatory system and the heart were identical; hemoglobin and red counts were similar. There was an increased number of lymphocytes in the classic animals, and the neutrophil count in the germfree guina pigs was higher than that in the classic guinea pigs. The number of monocytes was lower in germfree than in classic guinea pigs, but this was not true of rats. The respiratory system was macroscopically similar in the two groups. The pancreas was similar in the two groups. The small intestine was greater in length, thicker, and heavier in classic animals than in germfree animals. Histologically there were differences in the epithelial lining of the intestine. The liver was somewhat smaller in germfree birds than in conventional birds. The general appearance of the liver, kidney, ureters, and bladder and the color of the bile were identical in the two groups. The differences in the lymphatic system will be considered in more detail later.

The morphology of the cecum should be considered in more detail. While the ceca of birds were not different in germfree and classic categories, the cecum of mammals was enlarged in the germfree state. The work of Hudson and Luckey (ref. 22) illustrates the differences in the cecum size. (See fig. 6.) The weight of the cecum and its contents in the classic rats was about 2 percent of the total body weight. That of the SPF rat was statistically higher, being about 3.3 percent of the body weight. The weight of the cecum and contents of the germfree animals was much higher than either of these, approximately 15 percent of the body weight. While the weight of the cecum and contents drops rapidly following monoinoculation with certain microorganisms, the size and weight of the cecum wall do not change dramatically during this period. The primary action then is an evacuation of the cecum. This may be interpreted as a stimulation of the musculature of the cecum by material provided by the microorganism.

HOST PHYSIOLOGY

The growth of germfree mammals appears to be similar to that of classic mammals. In early studies the growth of germfree male rats was thought to be less than that of conventional rats. Gordon (ref. 23) has suggested that this was due to overcrowding in the early work. The growth rate of germfree chickens and turkey poults was slightly greater than that of classic animals. The work of Coates and Porter (ref. 24) suggests that this effect was due partially to the production of a toxin by intestinal microorganisms. Growth depression by the specific microorganism responsible, *Clostridium perfringens* (welchii) A, could be overcome by the administration of dietary antibiotics (Lev and Forbes, ref. 25). It might be noted here that most food poisoning due to bacterial action is thought to be caused by the production of toxins by bacteria in the food before it is ingested.

Although work in the second decade of this century showed that life was possible without bacteria, only in the past 15 years has it been shown that mammalian reproduction through

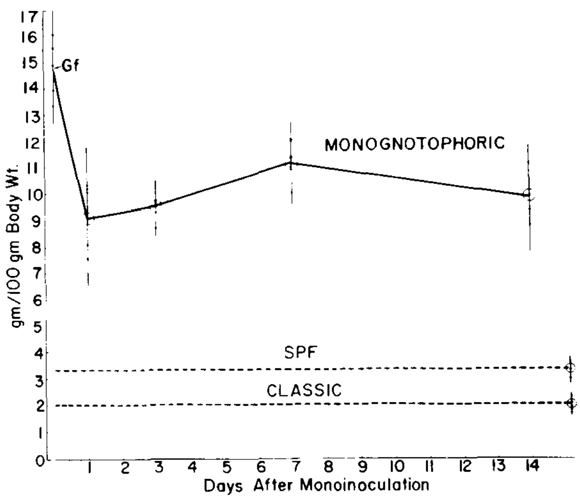

FIGURE 6.—Relative weight of cecum and contents in classic, SPF, germfree, and monognotophoric animals. Data of Hudson and Luckey (ref. 22).

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several generations is possible without bacteria. At the present time germfree chicks and quail have reproduced, germfree rabbits have been reared to the third generation, germfree guinea pigs are in their fifth generation, and germfree mice and rats are in the 20th generation according to M. Wagner (personal communication) at the University of Notre Dame. The data for rats and mice seem quite adequate; however, there is still difficulty with the enlarged cecum of the rabbit. If this becomes larger in proportion to the body weight than that of the germfree mouse, it can cause serious difficulties for the animals. When the cecum size reached 25 to 30 percent of the total body weight in germfree rats, it twisted and stopped the passage of food material through the intestine.

Of the variety of stresses that have been studied in germfree animals, that of anal blockage is of interest here. When the intestine was blocked at the ileocecal valve, activity decreased and no reproduction occurred; the rats became sick and eventually died. A similar reaction was seen in chicks (fig. 7) following anal pasting. This phenomenon is not uncommon in our country and has been thought to be a result of microbial infections. Seeing it here in germfree chicks, some of which died, is conclusive evidence that it is a physiological disease rather than an infectious disease. It has its prime cause in physiology and nutrition rather than infection. The anal blockage experiments of Wagner (ref. 12) confirm the general conclusion that death resulting from blocking of the intestine is not due to microbial toxins, infections, or invasion, but must be due to metabolic changes in the host.

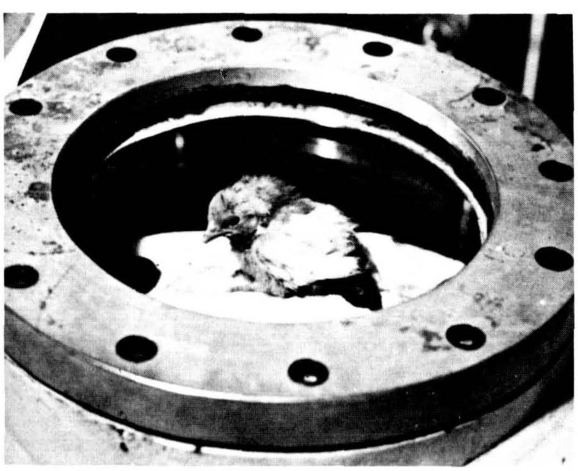

FIGURE 7.—Anal pasting in germfree chicks.

Radiation sickness in germfree animals appeared to follow a pathway similar to that in classic animals with the exception that infectious diseases did not complicate the experiment. Consequently, when doses near or below the LD–50 dose were given, the germfree animals lived longer in the experiments of Reyniers et al. (ref. 26) and McLaughlin et al. (ref. 27). When higher doses were used no significant difference was seen in the percentage of survival, and the general appearance and symptoms of radiation sickness were comparable. Similar results were reported by Wilson and Piacsek (ref. 28) in experiments with mice.

Although hemorrhagic shock appears to have an infectious-disease vector, Zweifach (ref. 29), Horowitz et al. (ref. 30), and McNulty (see Gyorgy, ref. 31) found no basic differences between germfree and conventional animals which were subjected to shock under similar conditions. Pathology of the dead animals was similar with the exception of the previously enlarged cecum of the germfree rats and general infection of the classic rats.

HOST NUTRITION

In all gnotobiotic experiments the diet must be sterilized. Experiments with colonies of germfree animals have been run satisfactorily with diets which were sterilized by gas (ethylene oxide), by radiation (either gamma-ray or electron-beam sterilization), or by steam heat. Other methods of sterilization such as filtration or dry heat and the feeding of sterilely raised material have been used only on a limited scale. Each of the methods can be used satisfactorily and each of the methods can be misused, causing a great variety of problems. Wherever comparisons are made, the classic animal must also be fed the same diet sterilized in the same manner.

It should be noted that although the diets used were sterile this does not mean they were free from bacteria. Small amounts of dead bacteria and their products exist in the diets. In one experiment where we were feeding a microbial fermentation residue as a source of unknown factor, the bacteriologist of the team believed contamination was present because large quantities of bacteria were seen in microscopic examination of fresh feces and the animals reacted to the microorganisims used with a good antibody response. However, no viable microorganisms were found to be present. One recent experiment of Pleasants et al. (ref. 32) has been run with a filtered, chemically defined, water-soluble diet.

If one considers the metabolism of germfree and classic animals, one might suspect that germfree animals require less food or possibly excrete less feces. This is apparently not true, as shown with rats (table IV). Kuster (ref. 33) reported a similar result with goats; Balzam (ref. 34) and Forbes and Park (ref. 35) found a similar effect with germfree chicks. Germfree and classic animals eat about the same amount per day and excrete about the same amount per day. And their food efficiency is comparable. The feces (table V) are somewhat more watery in the germfree rats than in the classic rats. Otherwise the gross composition seems to be similar when nitrogen and fat are determined on a dry-weight basis. The surprising fact, then, is that while biologically the excreta of the two groups of animals differ tremendously, there is no significant qualitative difference on a chemical basis other than the water content.

TABLE IV.—*Metabolism of Male Rats*

[3-week period]

	2 germfree	2 classic
Average age, days	165	146
Weight, g	221	324
Weight change, g	−0.5	0.6
Food, g/day	16.5	15.4
Feces, g/day	1.98	1.21

TABLE V.—*Rat Excretion Study*

[The collections were taken from one rat for each category for 3 weeks.]

	Germ-free	Conven-tional
Food intake, g/day/100 g rat	4.50	4.57
Feces, g/day/100 g rat	0.316	0.227
Water, percent	35	15
Nitrogen, percent dry	4.22	3.05
Fat, percent dry	4.58	5.58

A somewhat similar problem was posed by Babcock more than a half-century ago when he forgot to label data in the laboratory during a metabolism study. Babcock's dilemma has been modified here with human data (table VI). Columns A, B, and C represent the gross composition of body, food, and excreta of man, but the order is not designated. When one first looks at this data it is not too easy to determine which is excreta, which is food, and which is the body of man. In this case the carbohydrate is the giveaway. Since this was an American diet, it was high in carbohydrate: A is the food. Since the analysis of human total carcass by Forbes et al. (ref. 36) was done on a fat man, the high lipid in column B gives away the fact that this was the body composition. The feces are then delegated to column C. They are often higher in minerals and can be detected fairly readily on that account.

TABLE VI.—*Babcock's Dilemma*

[The columns of data are for food, feces, and total body composition in man, but not in this order. To obtain the correct order, refer to the text. Data from Starling's Textbook of Physiology, and Forbes et al. (ref. 36)]

	A	B	C
H_2O	64	60	66
Ash	1	5	5
Lipid	6	14	6
Protein	7	18	14
CHO (diff)	22	3	9

Babcock's dilemma is modernized in table VII, where columns A, B, and C are the vitamin content of body, food, and excreta of chicks without designation of which is which. Again it is difficult to distinguish between the columns. Column A gives data from the complete carcass analysis, column B is the diet fed the chicks, and columns C and D are the excreta.

The second part of this dilemma involves columns C and D. Both are excreta, one from germfree chicks and the other from conventional chicks. Again it is not easy to determine which is which, since some values are higher in column C and some are higher in column D. Actually column C is from germfree chicks and D is from classic chicks. It may be worthwhile to note that in both categories of bird some of the vitamins are higher in the excreta than they are in the diet. Since the biotin and folic acid concentrations were higher in the excreta than in the diet in the case of germfree chicks as well as classic chicks, this increase was not due to bacterial action and must represent bioincrassation. Bioincrassation is the concentration of relatively insoluble compounds within the intestine by the absorption of the more readily digestible components of the diet such as carbohydrate, protein, and fat. Bioincrassation is readily seen in mineral or tagged bacteria studies.

The overview of the vitamin requirement of germfree animals is simply that germfree chicks seem to require all the B vitamins and fat-soluble vitamins that classic chicks do. Germfree rats are shown to require biotin and possibly folic acid and vitamin K, which are not required by classic rats fed no drugs. There is a real discrepancy in the folic acid data but we cannot deny that McDaniel (ref. 37) produced a folic acid deficiency in germfree rats without the use of drugs. These qualitative differences in vitamin requirements of the rat suggest that the bacteria of the intestine produced vitamins which were utilized by the host, presumably without benefit of coprophagy. Since these experiments have not been run with restrained rats or with rats carrying tail cups, coprophagy is still a possibility. Coprophagy must be eliminated for the study of the intestinal synthesis theory, but it is a routine way for animals such as rabbits, mice, and rats to obtain a good supply of vitamins.

Miller and Luckey (ref. 38) first showed in gnotophoric animals the utilization of vitamins presumably produced in the gastrointestinal tract. (See fig. 8.) When the growth was limited by using only 100 micrograms of folic acid per kilogram of diet, the chicks weighed 100 grams at 3 weeks. When *E. coli* was added to germfree chicks the monoinoculated chicks grew considerably better than the germfree chicks. Folic acid analysis of tissues substantiated the fact that there was more folic acid in the gnotophoric birds than there was in the germfree birds. This is good indirect evidence that the folic acid produced by the *E. coli* was utilized by the gnotophoric chicks for growth

Table VII.—*Modern Dilemma*

[The vitamin content of chicks' excreta, food, and total body, but not in that order. The excreta of germfree chicks forms one column and that of classic chicks forms another column. Refer to the text to determine the proper heading for each. The data are given as γ/g on a dry-weight basis]

	A	B	C	D
Riboflavin	15	103	81	33
Niacin	155	92	90	135
Pantothenate	66	34	41	36
Biotin	0.2	0.4	1.8	2.3
Folate	18	2.8	16.9	8.5

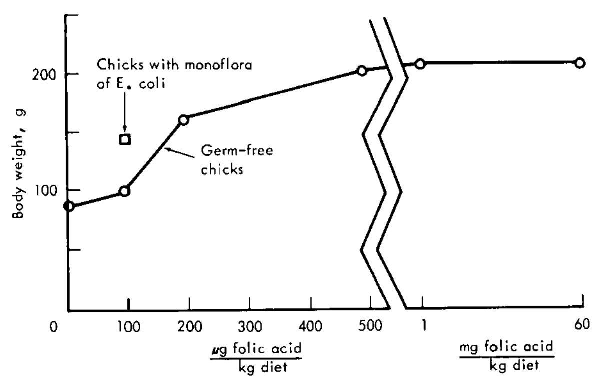

Figure 8.—Effect of *E. coli* on growth response of chicks to folic acid in the diet.

and for the body stores. The amount utilized was about 15 percent of the minimum requirement. This work was soon confirmed by Gustafsson et al. (ref. 39) in an experiment in which vitamin K deficiency was alleviated by adding specific microorganisms to germfree chicks (table VIII). Vitamin K deficiency in germfree animals could be alleviated by feeding vitamin K_1 or by inoculating with *Sarcina*, *E. coli*, or a full microflora. A variety of other microorganisms did not alleviate the deficiency.

Another difference between germfree and conventional animals is their reaction to antibiotics. Germfree animals react to low levels of antibiotics while classic animals react to antibiotics over a wide concentration range. Presumably, low levels of antibiotics act directly on the host while the higher levels have an effect upon the intestinal microflora. This work has been reviewed by Luckey (ref. 1).

It is not yet fashionable to include fiber as an essential nutrient; however, there is much evidence that fiber in the diet is conducive to well-being and fast growth in most species tested. This has been shown in the rat by Carlson et al. (ref. 40) and in crickets by Neville et al. (ref. 41). The cecum of the germfree rat decreased about 50 percent when 3 percent cellophane was added to the diet. Microorganisms function in some manner to reduce further the cecum size.

HOST CHEMISTRY

A summary of the survey of the chemical composition of germfree animals (figs. 9 and 10) illustrates that the differences in gross composition between germfree and classic animals are generally few. The cecal contents have more moisture in the classic chicks, and the nitrogen of the cecum is somewhat higher than in germfree chicks. Most values are not significantly different in the two categories. Such results are typical of vitamin analyses. Usually there is about one difference between germfree animals and classic animals for nine comparisons in which there is no difference. Thus far, these differences have not made a pattern which could be correlated with any meaningful morphological or physiological observation.

We have already noted that the vitamin concentrations in intestinal contents may be higher than in the diet. Another interesting phenomenon is the fact that germfree chicks fed a thiamin-deficient diet had a higher concentration of thiamin in their excreta than in their liver. Thus they were apparently excreting the vitamin which was causing their death by its deficiency.

The feces of germfree animals had proteolytic activity and were shown to contain trypsin and invertase by Borgstrom et al. (ref. 42) and Lepkovsky et al. (ref. 43). Trypsin and invertase were not found in feces from conventional rats; presumably the microorganisms inactivated these enzymes. The amylase content of the feces of germfree animals was slightly greater than that found for classic animals. Urobilin was not found in the feces of the germfree rats, while the bilirubin content was higher than that of classic rats, according to the data of Gustafsson et al. (ref. 44). Wagner (ref. 45) found no indole in the feces of germfree animals. When *E. coli* was added to the animals, indole was found in the excreta. The main sterol of germfree rat feces was cholesterol when the diet was a synthetic corn oil, according to Gustafsson et al. (ref. 46). Taurocholic acid was the only metabolite of cholic acid when Gustafsson et al. (ref. 47) fed labeled cholic acid to germfree rats. These findings suggest that the feces of germfree animals contain somewhat simpler metabolites than the feces of classic animals.

TABLE VIII.—*Vitamin K Study With Germ-Free and Gnotophoric Rats*

[Data of Gustafsson et al. (ref. 39)]

	Prothrombin activity, percent
Germfree	<10
Germfree + vitamin K_1 (25γ/kg)	100
Germfree + *Sarcina*	100
Germfree + *E. coli*	100
Germfree + *L. acidophilus*	<10
Germfree + Diphtheroid	<10
Germfree + Bacteroides (enteric)	<10
Germfree + full flora	100

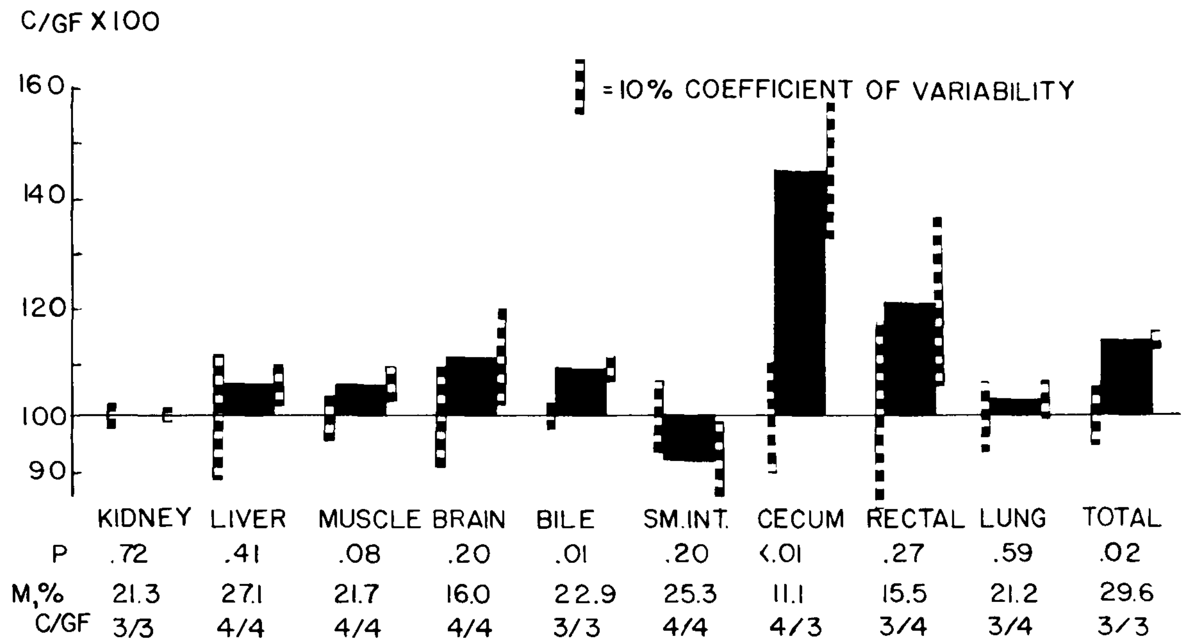

FIGURE 9.—Gross analysis of dry weight of 10-week-old white leghorn chicks. Averages for the germfree chicks are the base of 100 and the differences for the conventional chicks are represented by black bars. The coefficient of variability is given for the germfree at the left of the bar and for the conventional birds at the right of the bar.

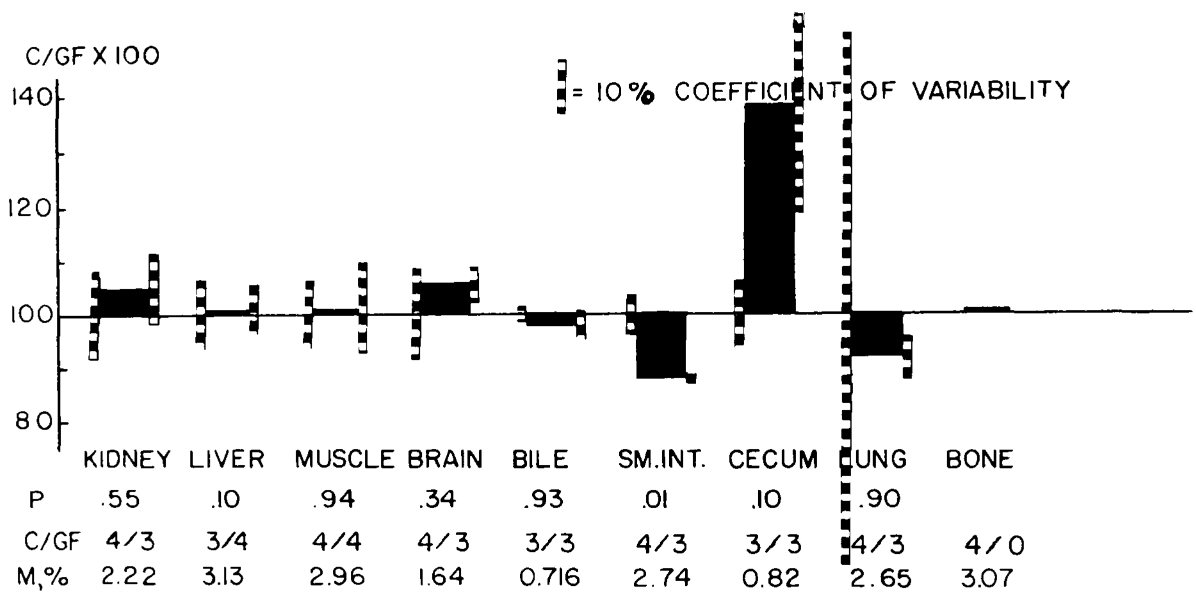

FIGURE 10.—Gross analysis of nitrogen content of 10-week-old white leghorn chicks. Averages for the germfree chicks are the base of 100 and the differences for the conventional chicks are represented by black bars. The coefficient of variability is given for the germfree at the left of the bar and for the conventional birds at the right of the bar.

DEFENSE MECHANISMS

The main anatomical differences that have been noted between germfree and classic animals are related to defense mechanisms. The finding of Glimstedt (ref. 48) that the lymphatic system of germfree guinea pigs was grossly underdeveloped has been amply confirmed by Gordon (ref. 23) and Thorbecke (ref. 49). Bauer et al. (ref. 50) found an increased development of lymph nodes in germfree animals which had been injected with *E. coli* antigen. The changes in the lymph node development following monoinoculation of germfree rats or mice are illustrated by the data of Hudson and Luckey (ref 22). (See fig. 11.) This rapid quantitative change is less dramatic than the qualitative change seen in the apex of the

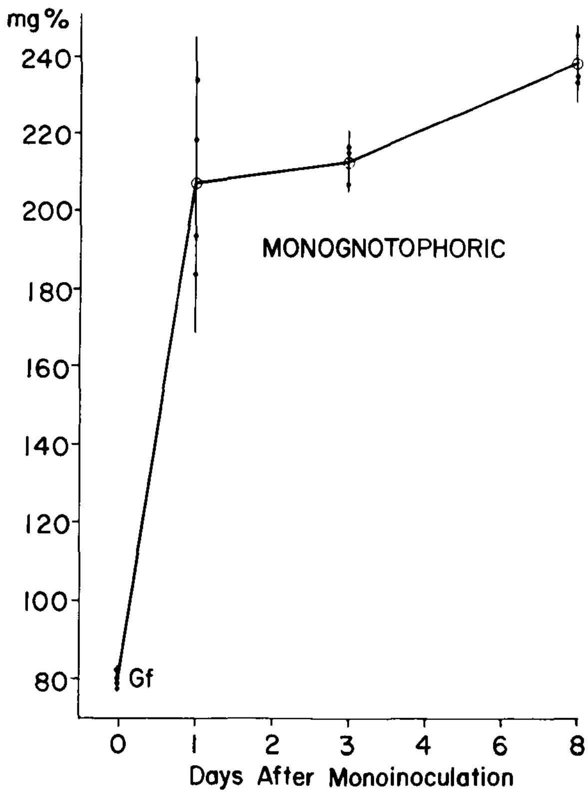

FIGURE 11.—Cervical lymph node development in germfree and monognotophoric mice at different times after monoinoculation. The ordinate is mg per 100 grams of body weight. Data of Hudson and Luckey (ref. 22).

cecum of the germfree rats which had been monoinoculated (fig. 12). The apex of the germfree cecum is generally clear. The classic animals show a well-defined apical aggregate comparable to a Peyer's patch. This aggregate develops in less than 24 hours as shown by the middle cecum in the figure. These changes in the morphology of germfree animals illustrate the impact of microorganisms. Similar qualitative differences have been noted by Miyakawa (ref. 21) in the sinus epithelium, which was grossly underdeveloped and contained no cilia in the germfree state. The classic animals had an epithelium which was multilayered and contained many cilia.

The paucity of leukocytes in germfree animals and the poor phagocytic response make these animals very susceptible to infection. Bauer and Horowitz (ref. 50) suggest slow macrophage digestion to be the major difficulty in phagocytosis by germfree mice. Germfree rats and mice often will die when taken directly from the germfree cage to the animal colony. If they are allowed to go from the cage to a protected environment for 4 days, practically none of them die when they are taken to the colony. Germfree chicks do not show this susceptibility; they may be taken directly from the cage to the animal colony. Surprisingly, germfree animals are effective in clearing injected particles or dead bacteria from the blood, according to the data of Thorbecke (ref. 49). The serum of germfree animals was found to have little germicidal activity as compared with that of conventional animals or gnotophoric animals containing a monoflora of *E. coli* (fig. 13). This work of Tanami and associates is interesting since it again shows that in the antagonism between *Lactobacillus bifidus* and *E. coli* the lactobacillus neutralizes the effect of the *E. coli*. Heterohemagglutinins, properdin, and complement are present in germfree animals. Specific antibodies are generally absent but they develop very rapidly and in quantities equal to those of conventional animals when challenged (Wagner, ref. 20).

Miyakawa (ref. 21) has shown that germfree animals do not develop anti-immune antago-

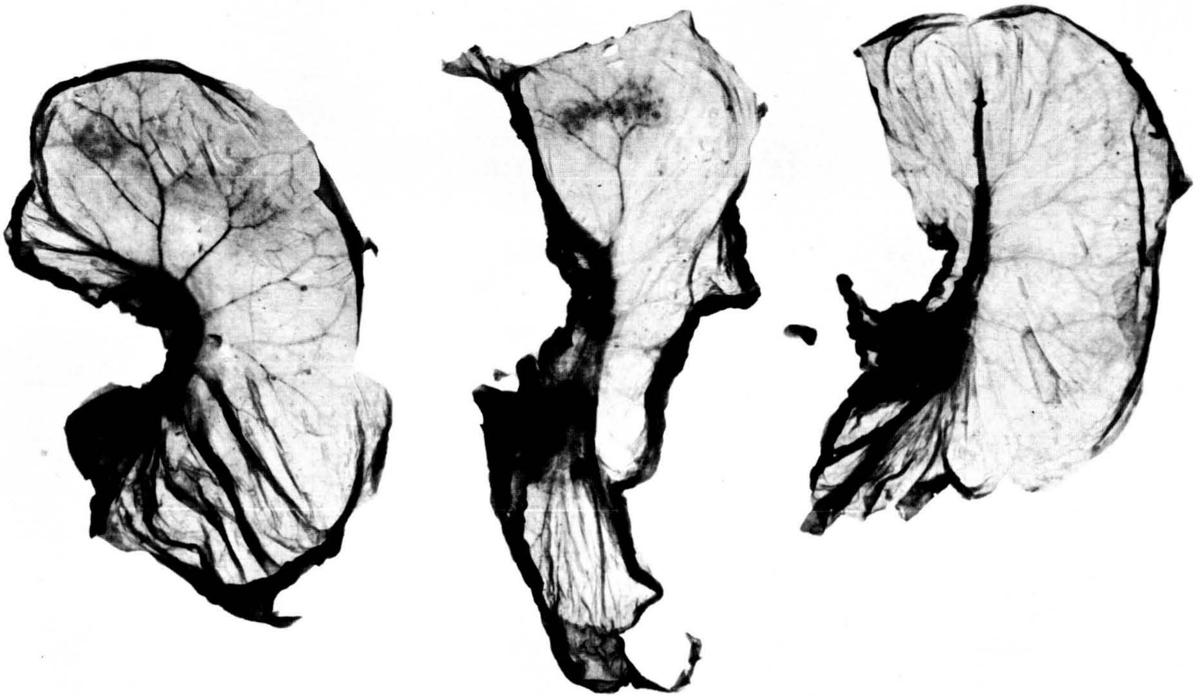

FIGURE 12.—Cecal apical aggregate. A large Peyer's patch (the circular spot in the upper corner) is seen at the apex of the cecum on the left which was taken from a classic rat. The cecum of the germfree rat, shown on the right, has no such aggregate. The cecum in the center shows a diffuse but well-developed aggregate. It was taken from a rat 1 day after monoinoculation of a germfree rat with *Streptococcus faecalis.* Data of Hudson and Luckey (ref. 22).

nism to heterotransplants. Thus skin grafts from different individuals and, indeed, from different species, have been accepted by germfree guinea pigs without serious default. Human tumor tissues were also shown to be viable in germfree guinea pigs. The endotoxin response in germfree animals was found to be different from that in conventional animals. Endotoxin was highly lethal in classic guinea pigs but not in germfree guinea pigs. This response was opened to question by Smith (ref. 51). Another difference between the two animal categories is the fact that blood vessels do not develop in granuloma tissue in germfree animals while they do in conventional animals. Presumably here is another case of an education process being required before the cells of the vascular system can be induced to penetrate the new tissue.

CONCLUSIONS

It is noted that the initial controversy over how essential bacteria are for the life of mammals cannot be clearly answered. The dilemma can be resolved only by defining "essential." If they are given special care and special diet, germfree animals can be reared through 20 generations. However, these animals differ from classic animals in morphology, nutrition, and chemical composition. The way in which they differ most is that the defense mechanisms are not well developed. The physiological responses which have thus far been measured are not materially different. Chemical analysis of the animals shows that there are fewer differences than there are likenesses. While each of these differences is meaningful, the general appearance of the germfree animal suggests that it is less complicated on a morphologic, histo-

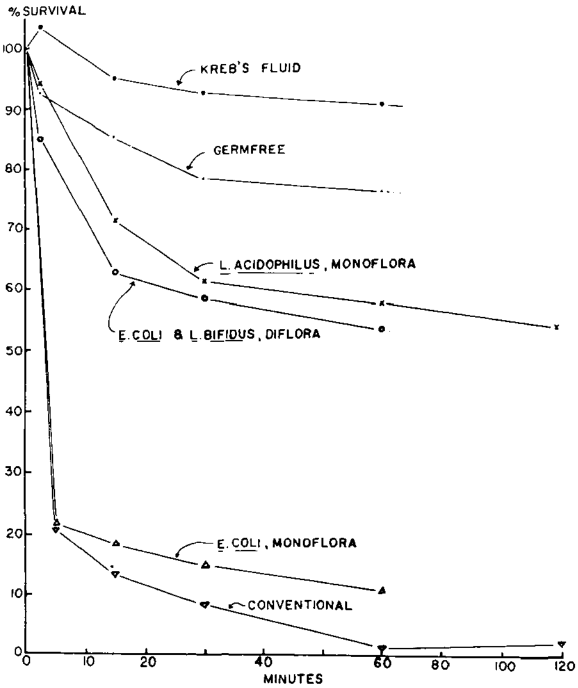

FIGURE 13.—Bactericidal activity of serum of guinea pigs held under different conditions as compared with that of Kreb's fluid. The ordinate gives the percentage survival of a culture of *Salmonella typhi.* Data of Tanami (ref. 17).

logic, and chemical basis than the conventional or classic animal. The excreta of germfree animals are remarkably different biologically from those of classic animals; chemically they are very similar when gross analysis is carried out. Vitamin analysis does not show consistent differences between the two groups. There is usually a greater complexity of metabolites excreted by the animals bearing bacteria.

Some defense mechanisms of germfree animals are well developed but need a stimulus to function. Others are not well developed, but in such cases contamination apparently imparts a rapid change to a state comparable to that of classic animals. Some of these reactions occur within 24 hours. The primary defense mechanisms such as skin and excretion show no differences between the classic and germfree animals. Blood-clearing mechanisms are primary factors by this standard. The secondary defense mechanisms are those in which structures are fully developed but do not function properly until the stimulus of the microorganisms initiates a response. Such is the development of antibodies. This is also seen in the untrained phagocytes which do not accumulate in a wound. The tertiary defense mechanisms are those in which a structure or function must be developed. This is typified by the apical aggregate of the cecum of germfree rats and mice. This develops very rapidly after contact with some microorganisms. Finally, germfree animals have naive heteroimmune reactions. It is not known whether these can be stimulated.

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Effects of Prolonged Bed Rest

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The Division of Research of the Lankenau Hospital, in collaboration with and supported by the Aerospace Medical Research Laboratories of the Air Force Systems Command, Wright-Patterson Air Force Base, has for the last 3 years been engaged in a series of studies aimed at defining the effects of prolonged bed rest and at determining how these effects may be eliminated or counteracted. The results of the first two phases of these studies have been reported in the form of technical reports (refs. 1 and 2). This paper, therefore, is merely a brief summary of these findings, which indicate that the changes observed during prolonged bed rest are not all due to inactivity, but that factors related to gravitational stress are also involved.

Findings obtained during prolonged bed rest may be relevant to the problems encountered during prolonged space flight, at least in one respect: the development of orthostatic hypotension as evidenced by impaired tilt-table tolerance. In the horizontal position in bed, the heart is not required to pump the blood against gravity from the subject's foot up to his head, as is the case in the upright position. Consequently, the cardiovascular reflexes which in the upright position maintain the blood pressure may not be stressed sufficiently in a subject maintained for several weeks in recumbent bed rest, resulting in a transitory impairment causing orthostatic hypotension when changing from recumbent to upright position.

In earlier studies (refs. 3 and 4), the subjects were allowed up for brief periods every day. The main difference between the earlier studies and our current studies is that our subjects are continuously confined to strict bed rest; at no time are they even allowed to raise their heads. All subjects are kept in a horizontal position and allowed to use one pillow only. The earlier studies indicated a variety of changes attributable to prolonged bed rest: Muscle wasting, negative nitrogen balance, demineralization of bones, increased urinary calcium and phosphorus elimination, kidney stones, urinary bladder infection, constipation, lowered basal metabolism, reduced blood volume, tilt-table intolerance, and markedly reduced physical work capacity.

In our studies, normal young men (Mennonite students, exceptionally well motivated) were confined to the horizontal position in bed for up to 63 days. Special tutoring service at the bedside enabled these subjects to continue their college education, while receiving a standard remuneration of $10.00 per day. The subjects were under constant surveillance, with around-the-clock nursing service. They were fed a measured formula diet prepared in the metabolic kitchen. Feedings and toilet functions were performed in the recumbent position. The metabolic collection periods were of 6-day duration. During an initial pre-bed control period, all subjects were trained by two 30-minute daily rides on the bicycle ergometer at 600 kilopond-meters per minute. Prior to the bed rest, and again at the end of the bed-rest period, tilt-table tolerance was determined, intravascular pressures being measured through arterial and venous catheters. Maximal O_2 uptakes were determined on the bicycle ergometer before and after bed rest.

In our first experiment, four subjects were studied before and after a 6-week period of bed rest. Bed rest caused a marked impairment of the tilt-table tolerance, and a marked reduction in physical work capacity, which barely returned to pre-bed rest levels following an 18-day retraining period. There was a twofold increase in urinary calcium output, but no consistent change in urinary nitrogen. Our subjects, who were free to move their arms and legs about, showed very little change in muscle strength, nor did the circumference of the extremities change appreciably. There was no appreciable change in pulmonary function in terms of vital capacity, or timed vital capacity; there was a slight drop in basal metabolic rate (BMR); there was very little change in body weight, and no consistent change in urinary excretion of catecholamines, 17-ketosteroids, or creatinine. The hemoglobin was reduced in most cases; whether this was entirely or in part due to the repeated blood sampling and catheterizations is an open question.

This initial experiment, then, confirmed the conclusions of previous studies that prolonged bed rest is indeed harmful to the individual's functional capacity. The next task was to determine whether all these changes are caused by inactivity as such, or whether some of them may be attributable to the absence of gravitational stress on a body maintained in the horizontal position. In the next series of experiments, therefore, four healthy young men were confined to prolonged bed rest as in the previous experiment, except that now two of the subjects worked for two half-hour periods a day in the horizontal position, using a bicycle ergometer set at 600 kilopond-meters per minute. This amount of work corresponded to an energy expenditure of about 500 calories. The other two subjects did the same amount of work on the bicycle ergometer in the sitting position. The rest of the 24-hour period all four subjects remained recumbent. We now observed that this amount of physical activity, whether it was performed lying down or sitting up, prevented any appreciable deterioration in physical work capacity, as measured by a comparison of the subject's maximal oxygen uptake before and after bed rest. Working in the horizontal position did not prevent the development of tilt-table intolerance, but in one of the two subjects working in the sitting position, no orthostatic hypotension developed. The other subject exercising in the sitting position had an impaired tilt-table tolerance unrelated to the bed rest, since he showed evidence of orthostatic hypotension both before and after bed rest. However, in all four subjects the increased urinary calcium elimination persisted in spite of the exercise. From this experiment we concluded that while the deterioration of physical work capacity in prolonged bed rest is caused by inactivity, the observed changes in tilt-table tolerance and urinary calcium output produced by horizontal bed rest are not caused by inactivity, but may be attributable to the effects of absence of gravitational stresses. In a further experiment, one subject worked for 4 hours daily in the horizontal position with the aid of the bicycle ergometer set at 600 kilopond-meters per minute, but, in spite of this, urinary calcium remained elevated.

It was postulated that the maintenance of a normal calcium metabolism may in some way be related to the forces of gravity acting constantly or intermittently upon the skeletal system. To test this notion, four healthy young men were confined to bed until the increased urinary calcium output had developed. They were then allowed to sit inactively for 8 hours a day in a wheel chair; the rest of the 24-hour period they were confined to horizontal bed rest. This lasted for a period of 3 weeks. This prevented the development of tilt-table intolerance in three of the four cases. There was a slight deterioration in physical work capacity, but the elevated urinary calcium persisted during the 3 weeks of inactive sitting.

From these studies it is apparent that the three major changes associated with prolonged, continuous recumbent bed rest (tilt-table intolerance, loss of physical work capacity, and increased urinary calcium elimination) are separable, and not all due to inactivity. The changes in tilt-table tolerance and urinary calcium output appear to be related to the absence of the normal stress of gravity acting on the body in the upright, ambulatory existence.

The practical conclusions of these findings, applicable to space medicine, may be as follows: One hour of exercise daily with the aid of a simple ergometer may be sufficient to maintain the astronaut at an adequate level of physical work capacity. The amount of urinary calcium loss encountered under those conditions for a period of a few weeks may not be of any practical consequence in terms of the overall calcium balance. At present there are no known ways of counteracting this. If inactive standing for a few hours daily should prove to eliminate the increased urinary calcium output, it might be worth considering subjecting the astronauts intermittently to a centrifugal force approaching the force of gravity by rotating him inside the capsule in such a position that the force will act in the direction of his feet. If such rotation could be accomplished by a device operated by the astronaut's feet with the aid of a pedal arrangement, he might at the same time achieve the exercise required to maintain his physical work capacity.

The development of orthostatic hypotension or tilt-table intolerance is by far the most serious problem, for this may threaten the astronaut's life. Every effort should therefore be made to arrive at a practical method of preventing the development of orthostatic hypotension which is likely to develop during prolonged space flights.

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Discussion: Effects of Prolonged Bed Rest

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The physiological effects of confinement have been mentioned frequently. In preceding papers, studies have been described concerning confinement and immersion, and brief mention has been made of zero-g conditions. Therefore, we are aware of the following changes which may occur (ref. 1):

(1) Body fluid distribution altered
(2) Diuresis
(3) N excretion increased
(4) Ca excretion increased
(5) Reduced energy expenditure
(6) Loss of muscle mass
(7) Weakness
(8) Impaired tilt-table tolerance

Rather than review any further the investigations on the physiological effects of confinement, this paper will present briefly some of the psychological aspects of confinement, particularly in relation to nutrition, using the term confinement not to mean total body immobilization but rather confinement to a limited space, that of a protective shelter (ref. 2 for winter trial; results of the summer trial, obtained by Ramskill and coworkers, are being readied for publication).

Two studies have been conducted at the Naval Medical Center in Bethesda in which 100 men at a time were maintained in a shelter 25 by 48 feet for a period of 2 weeks. One study was during the winter and the second during the summer period. In both studies the main item of diet was the Survival Ration Cracker, which John Browe of the New York Department of Health developed for shelters in that state.

Generally speaking, no major problems were encountered during the winter test, although a number of recruits suffered from upper respiratory infections which required medication. The temperature within the shelter rose to 83° F. during the first 6 days, but was reduced to 74° F for the remainder of the test by increasing the ventilation rate. With the relative humidity of the shelter varying from 40 to 60 percent, environmental conditions were actually quite comfortable. The first week of the summer test actually provided an extreme heat-stress experience (fig. 1). Although the weather in the Washington area was cooler than anticipated, temperatures during the first week were quite high. Dry-bulb temperatures in the shelter rose to a maximum of 92° F; this, combined with the high humidity, resulted in effective temperatures which reached 87° F. There were many nonspecific signs of heat stress, such as loss of appetite, apathy, subjective feelings of irritability, and, among some subjects, difficulty in concentrating. Two cases of heat exhaustion—characterized by dizziness, weakness, and, in one case, loss of consciousness—occurred on the seventh day. Heat rash was also very much in evidence.

Two techniques were used to study psychologic discomfort factors: one required the ranking of 21 discomfort indices; a second, yielded information on 13 of the 21 indices. Acuteness of discomfort and generality of discomfort are shown in figure 2 in which data from the winter trial are used. Food and lack of water for washing constituted the two leading sources of

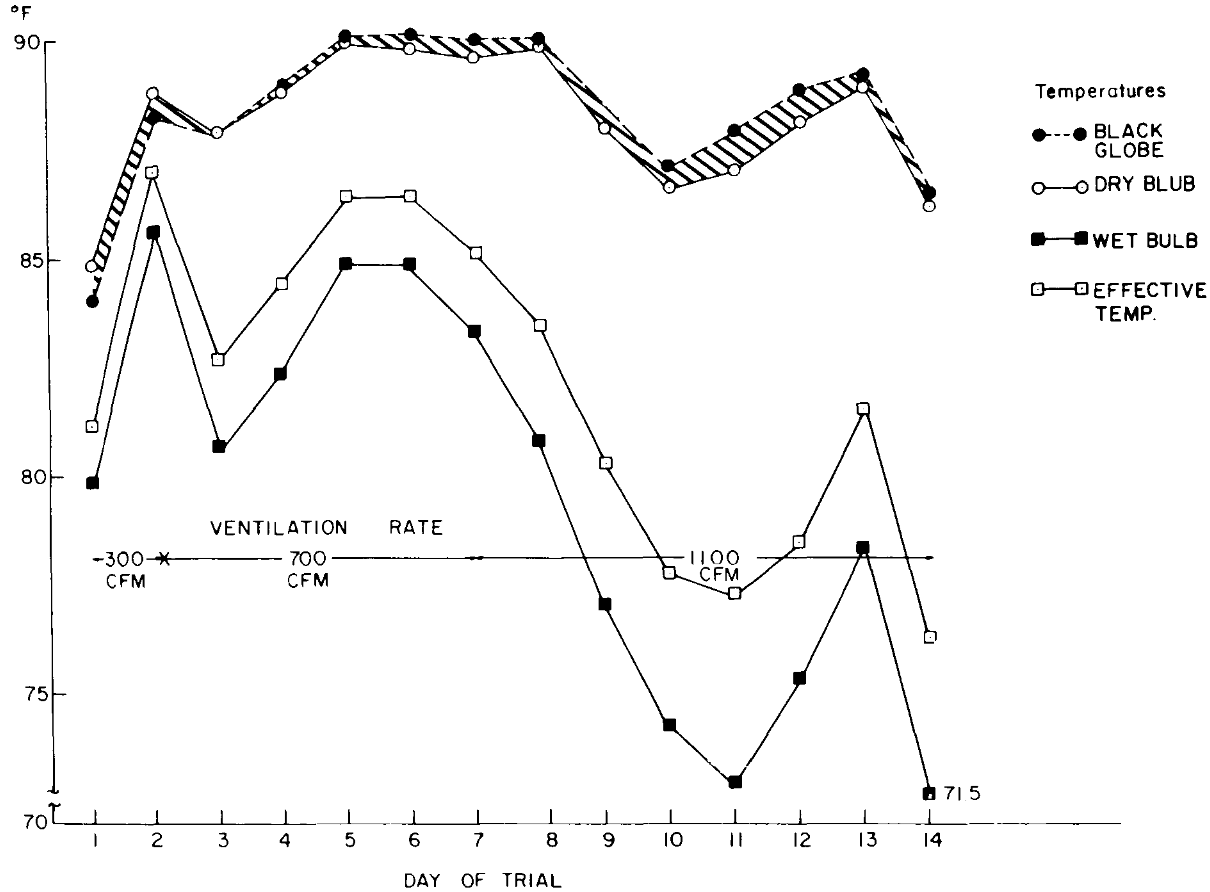

FIGURE 1.—Mean daily temperature within shelter during summer habitability trial. NMRC, Bethesda, Md.; August 1 to August 15, 1962.

discomfort; however, as will be noted, they not only constituted the leading sources of discomfort but were several scale points removed from the next most significant factors. The ranking technique alone does not permit determining whether the discomfort factors differ significantly from each other in terms of importance in producing psychologic discomfort. However, through computer analysis, it was possible to isolate those factors which cluster together in terms of importance. The circles indicate this. Even though food was the leading source of discomfort in terms of actual scale value, its ranking over lack of water in the hierarchy may be due to chance.

An analysis of the psychologic data in the summer trial is given in figure 3. Lack of water for washing remained a leading source of psychologic discomfort. However, food dropped to third place in acuteness and generality of discomfort. As might be expected, temperature and humidity, which were not of particular importance during the winter trial, became prime sources of subjective discomfort during the summer.

The debriefing interviews rather vividly reflected the shift in importance of discomfort factors. After the winter trial, the spontaneous comments of the subjects focused on food and, even when other topics were brought up by the interviewer, the conversation returned to the food. After the summer trial, spontaneous comments focused on a combination of heat, humidity, and dirt. The heat and humidity were oppressive to the extent that conscious efforts were made to avoid physical activity wherever possible. Considering the identical diet and the similarity of subject populations

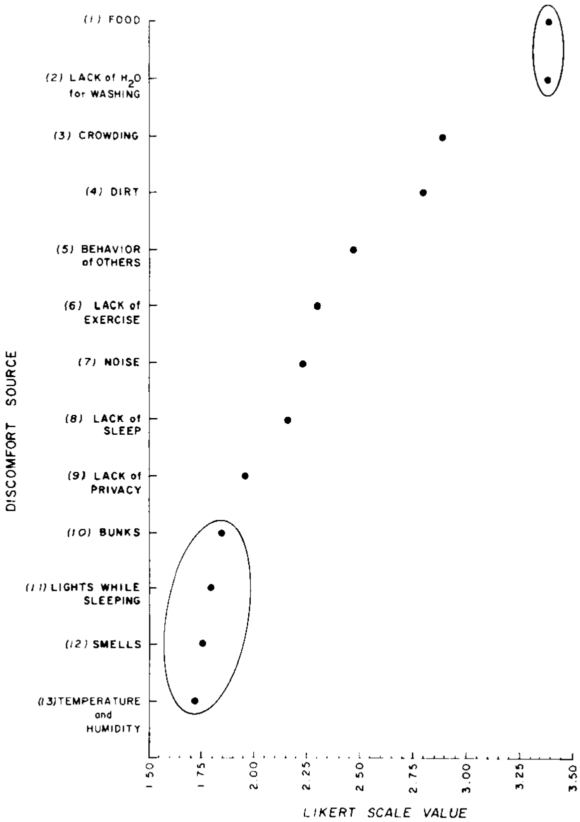

FIGURE 2.—Measure of acuteness and generality of discomfort. Winter trial.

in the winter and summer trials, the differences in response to food are quite interesting. While the data collected indicate that food acceptance was high in terms of actual intake, the subjects reported a general lack of appetite. For the group as a whole, it seemed that the crackers were considered unpleasant and unappetizing but not unacceptable.

I am not certain what this all means in terms of space flights. It suggests that the response to food depends somewhat on the other environmental stimuli. Perhaps on short space flights the form of the diet will not be too vital; that is, it need not be appealing as long as it meets the physiological needs of the astronaut. On long flights, the psychologic response to the form of the nutrients may be a major factor in the success of the mission.

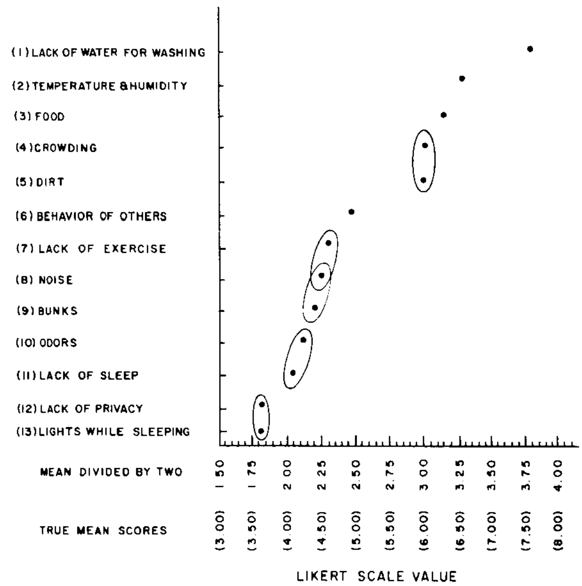

FIGURE 3.—Analysis of psychologic data obtained in summer trial.

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COMMENTS

DR. LACHANCE: Dr. Rodahl, please comment on the recent article in the Journal of Clinical Nutrition in which researchers at the Nutrition Laboratory in Denver observed two patients with different types of calcium stones who were fed high quantities of magnesium—I think somewhere in the vicinity of 300 milligrams per day; this was adequate to remove the formation of stones completely. When the patients stopped receiving the magnesium the stones recurred. I am wondering whether dietarily now we may have a remedy for our problem.

DR. RODAHL: We have found that as long as we can keep the urine acid there is no problem.

DR. HELVEY: In the closed circuits of the circulatory system where you don't have the positive hydrostatic head, it is irrelevant whether the patient is sitting or standing or lying because the amount of force necessary to circulate the liquid is the same in every case, is this not so?

DR. RODAHL: If you are concerned with the heart and elastic respiratory system in a man, the trouble is that as long as he is lying down there is no problem with the pulling of the heart and therefore the heart would work as a pump. But the trouble is that when he stands up, there is a pooling of the blood probably in the lower extremities and the difficulty is to bring this back for refilling of the heart. The arteries expand allowing the blood to pool in the lower extremities. Therefore, the filling pressure of the heart is inadequate to maintain the cardiac output and what happens first of all is that the pressure begins to fall and blood returning to the brain is inadequate. The patient faints.

DR. GRIFFIS: In your studies, Dr. Rodahl, have you tried to apply a horizontal position cycling at low frequency?

DR. RODAHL: We haven't done this. It might be very good.

DR. PARKER: The oscillating bed has been. There was, as I recall, a regression reduction in the amount of calcium excretion. The subjects were normal healthy individuals, however. In individuals who had poliomyelitis there is no effect on the calcium loss.

DR. MACK: We have done a very considerable amount of 2-week bed rest periods in which we have kept the patients very, very quiet and have done radiographic bone densitometry on certain parts of the body through X-rays and have found a loss in bone density which is aggravated as calcium intake decreases. We think that the level of calcium in the diet as well as other components of the diet are very important.

LT. COL. MCDOWELL: In response to Dr. Lachance's comment on the work being done on the effects of magnesium in patients who are chronic stone formers, I think it might be well to dispel any notion that they are claiming any panacea in the treatment of or prevention of renal stones. I think that the causes of the stones in the particular people studied are really not known and one should be very cautious. I would think it might be worth watching for such people in Dr. Rodahl's studies.

It might also be worth noting that other forms of magnesium have been tried before, but the important thing seemed to be the form in which magnesium was given; in this case I believe it was magnesium oxide.

DR. CRENSHAW: Dr. Rodahl, what is the ratio of calcium to phosphorus in your studies?

DR. RODAHL: I don't remember the number but the amount of calcium is between 1400 and 1700 milligrams.

DR. CRENSHAW: The point was that increasing the phosphorus ratio 2:1 might decrease the calcium excretion.

DR. RODAHL: This is true. However, in our case the same subjects were under control; they were up and about; there was some doubt of their being put to bed at the same time. There was a marked change, a 100 percent increase in calcium output. The phosphorus was not so markedly affected.

DR. LACHANCE: A study was made of three subjects after a period of bed rest. Using the valsalva method, fibrillation occurred enough times that it became a distinct risk. Dr. Rodahl, what is your experience?

DR. RODAHL: We had some problems with our early bed rest subjects. In one case actually, we had to work a couple of hours and almost lost a patient; so there is this tendency after prolonged bed rest to cardiac arrhythmia.

DR. VAN REEN: Dr. Rodahl, you indicated an excretion of some 12 grams of nitrogen per day. Since many people have increased their nitrogen excretion during bed rest or immersion, does this experiment include more protein intake?

DR. RODAHL: We have studied about 20 individuals lying in bed for many weeks and there was no marked change in nitrogen balance. There may be several reasons. In the first place we feed our subjects 72 grams of protein per day; this is divided into six different feedings. There may be the possibility that multiple feedings have a produce-bearing effect. There is some suggestion to this effect in animal work. Also, if early work in this field is studied, it shows that it isn't true to say that there is marked negative nitrogen balance during bed rest because in several cases the subjects were in marked nitrogen imbalance before the tests began. You have to be particularly careful to bring the nitrogen into balance before studies begin.

MR. WILSON: It is true that in 50 percent of normal healthy adults, taking a deep breath, closing the glottis completely, and bending down can produce arrhythmia and fainting. The maneuver used by pilots, however, is to maintain a partially open glottis. In this way there is a modified increase in interthoracic pressure. This has not caused arrhythmia or unconsciousness.

SESSION V

Waste Management

Chairman: ***Emil M. Mrak***

Chancellor, University of California, Davis

Waste management is one of the most important factors to consider in working out the total biological picture with respect to space travel. In addition to solid waste we must also consider liquid and the possibility of flatus.

The comfort of the individual and the possibility of using waste material for the benefit of the astronauts are indeed involved. This, of course, would depend on the mission, conditions, and length of the space flight.

Most certainly in developing foods for space flights we must do all possible to avoid including those that would be conducive to the production of flatus, and we should know what these are, the factors involved, and how flatus might be anticipated. Factors relating to the individual as well as to the food should be studied.

Solid waste management is indeed a difficult problem. Collecting and storing it on short-term flights is one problem, but on long-term space flights the possibility of reuse must be considered.

Liquid waste management and the collection of moisture, too, are matters of great importance. Can these materials be treated so that they can be reused? Can the humidity in the chamber be collected and used with ease and in line with this do we really know the water requirements of man under space flight conditions?

Several of these factors will be discussed in the following papers and I believe it will become apparent that we have a long way to go before all the problems in these areas come near to being solved.

EMIL M. MRAK

Flatus

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N65 18588

There are many recognized pathological causes of flatulence (refs. 1 and 2). This paper deals primarily with the flatus egestion in man which follows the ingestion of certain foods which have a wide reputation for the formation of gas. Specifically, in most experiments, 100 grams, dry weight, of California small white beans were used as an experimental meal to induce flatus production in human subjects. The flatus was collected by a rectal catheter attached to a portable chemical absorption tube arrangement worn by the human subject for 8 hours. The total flatus volume was calculated for 30-minute periods from the quantitative chemical absorption of carbon dioxide and the percentage composition of the gases—carbon dioxide, hydrogen, methane, oxygen and nitrogen—obtained by gas chromatography.

After a nonflatulent meal, the average human subject (fig. 1) will egest 20 to 50 cubic centimeters of flatus of relatively constant composition on an average of once per hour for 8 hours. After the same subject ingests the experimental bean meal, his flatus volume will continue to follow the same "normal" or baseline pattern for 3 to 4 hours after the meal. At this point, a rather dramatic rise in flatus volume—from 10 to 20 times the "normal" volume—begins to occur. This volume will peak at 5 to 6 hours after ingestion and then rapidly fall to a "normal" volume after about 7 hours. The flatus composition under nonflatulent conditions is primarily oxygen and nitrogen from swallowed air. However, during this peak period of flatus egestion, depending upon the individual, the principal components are hydrogen and carbon dioxide. The timing of this flatus pattern after a bean meal was very constant for the individual and surprisingly regular among 8 human subjects. This regularity

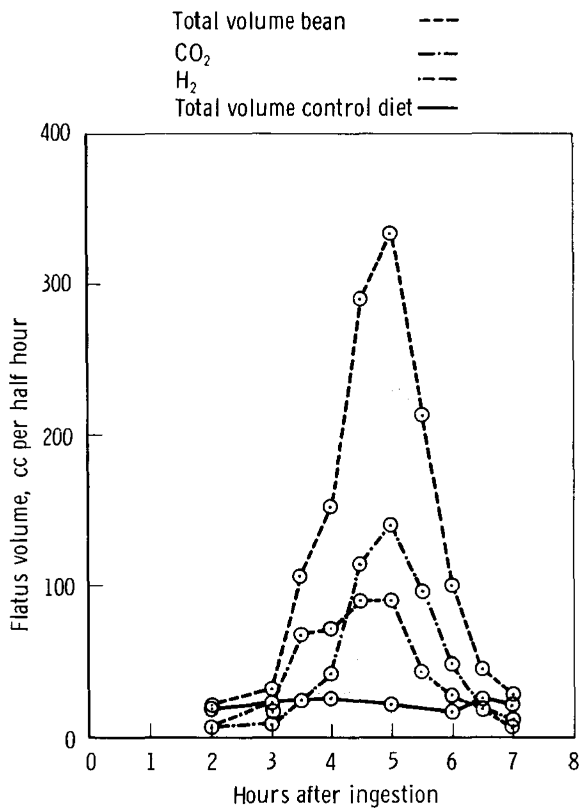

FIGURE 1.—Flatus composition.

suggests that the gas egestion of flatulence is timed by the regular progressive stages of the human digestive process.

There are individual differences in flatus composition. To date, one-half of our subjects produce methane and one-half produced no detectable methane, as indicated by gas chromatography. This agrees with Kirk's findings in his study of the effect of a diet of Brussels sprouts (ref. 3). The individual whose flatus appeared to contain no methane usually passed flatus composed of at least 50 percent hydrogen. The appearance of methane was usually at the expense of hydrogen, which in most cases was reduced to 20 to 30 percent. The presence or absence of methane probably reflects a difference in the intestinal microflora.

The total flatus collected from an experimental meal of beans varied among individuals. The total volume of flatus varied from effectively 0 to 1200 cc for the 3-hour period of peak flatus production for different subjects. Each subject, however, produced about the same volume of flatus each time he ate the experimental bean meal. Of special interest for further research was the subject who produced essentially no flatus on 100 grams dry weight of beans. When the weight of the experimental meal was increased to 150 grams, he produced the typical pattern of flatus production. For any one subject, if the weight of the experimental meal was doubled, the volume of the resulting flatus was more than doubled. The flatus volume relationship to weight of beans ingested is therefore apparently nonlinear.

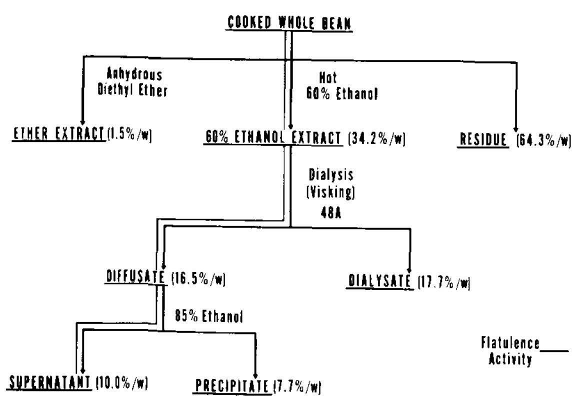

FIGURE 2.—Procedure to isolate biologically active factor.

Another individual variation is the time of occurrence of peak flatus production after ingestion of the experimental bean meal. This flatus peak varies from 5 to 7 hours after ingestion. Further, the length of the period of elevated gas egestion can vary from 1 to 3 hours. Both the timing and duration of peak flatus production probably depend upon the individual variation in stomach emptying time for the subject as well as the physical and compositional form of the meal.

ISOLATION OF THE FLATULENCE PRINCIPLE FROM DRY BEANS

While using the human assay technique to follow the flatulence activity, a systematic procedure (fig. 2) involving chemical and physical methods has been used to isolate the biologically active factor in a bean fraction representing less than 10 percent of the original weight, and yet this fraction retains the ability to produce flatulence in human subjects. The flatulence factor has been found to be successively extracted by hot 60 percent ethanol, dialyzable through reconstituted cellulose "sausage casing," soluble in 85 percent ethanol, and capable of passing through a Dowex 50 cation-exchange column. The molecular weight of the flatulence factor is less than 10 000 and perhaps even less than 6000. This active bean fraction still contains polypeptides and sugars such as stachyose, raffinose, and sucrose.

The fact that the flatulence factor is low in molecular weight and alcohol soluble indicates that the protein fraction can be isolated from any legume free from the problem of intestinal "upset." Samples of commercially available protein concentrate from the soybean have been tested by our human assay technique and found to contain only a trace of flatulence activity. These products were probably produced by the relatively simple process of basic extraction, isoelectric precipitation, and washing of the protein fraction. The disagreeable taste, color, and flatulence principle therefore remain in the "mother liquor." Thus, two flatulence-free products can be produced. One is a protein concentrate representing about 20 percent of the original dry bean weight, and, if the flatulence-free protein concentrate is blended back with the inactive extraction residue, soybean meal is produced representing a high nutritive value as well as 80 to 85 percent of the original weight of the soybeans.

UPPER BOWEL ACTIVITY ON BEAN MEAL

An accepted theory of flatus production has held that some principle in the bean increases the intestinal activity, thereby moving the contents along at such an increased rate as to reduce the absorption of gases. Using a transistorized frequency-modulated gastric radio, sensitive to intraluminal pressure, in accordance with the technique of Mackay (ref. 4), with the transmitter suspended in midileum, the intestinal activity was measured after a bean meal and after a rice meal. The pressure varied from 5 to 60 millimeters of mercury on both diets. The frequency of occurrence and the magnitude of the pressure waves were very similar on both bean and rice diets when recorded every 10 minutes from the time of ingestion for a period of 6 hours. The waves of greatest frequency and magnitude occurred about 4 hours after ingestion and might be classed as "hunger pangs," since they could be made to disappear by the ingestion of food, such as a candy bar. The similarity of the activity recordings on the two diets suggests that the flatus produced after the bean meal was not due to an increase in intestinal activity.

COOKING METHODS AND ADDITIVES FOR FLATULENCE REDUCTION

The Western Regional Research Laboratory has tested many "grandmother's" recipes as well as commercial samples which have been treated for the reduction of flatulence. Methods such as slow baking or high-pressure homogenization, and so forth, do not reduce the "intestinal upset" when the bean product is eaten. Food additives, such as sodium bicarbonate, castor oil, ginger or phosphates, do not reduce flatulence. To date, no method of preparation or chemical additive has reduced flatulence in our human subjects after ingesting a bean meal.

EFFECT OF DRUGS

The possibility that the principal gaseous components of flatus—carbon dioxide, hydrogen, and methane—are of microbial origin suggests that production of these gases can be controlled by drugs. Particularly attractive is the sterilization of the gastrointestinal tract of a human subject to whom a sterile bean meal can be fed to ascertain which of the "fermentive" component gases disappear from the flatus thus produced. In a similar experiment, a bean meal was ingested by a subject who had taken a quinoline-type drug prescribed for amebic dysentery for 12 hours prior to the experiment. The total flatus egested was reduced by 50 percent. But more interesting, the amount of hydrogen normally found in the flatus of this subject was significantly reduced, while the methane increased by 61 percent. Since the number of anaerobes has been found to increase in the feces by 150 to 400 percent on this drug, this suggests that hydrogen is produced by other than a common anaerobe.

FLATULENCE COEFFICIENT FOR DIET FORMULATION

Red kidney beans produce about as much flatus as the California small white variety. The same weight of dry lima beans by comparison produces about half as much flatus in our human subjects or 500 to 600 cc of flatus for the peak production period. However, a meal prepared from green frozen lima beans is nonflatulent.

Recently, we have begun to measure foods other than legumes. It comes as no great surprise that onions and white cabbage also are gas formers; yet they are less than half as potent as the standard experimental meal of California small white beans. The flatus egestion pattern of cabbage is similar to that of beans in that there is increased hydrogen during the peak period and a similar flatus volume peak occurs

5 to 6 hours after ingestion. These are preliminary findings using only one subject. The determination of a coefficient of flatulence for each of the extensive list of suspected foods must await the measurement of a significant number of human subjects.

THE ASTRONAUT

The most obvious answer to the flatulence problem is to send up and maintain an astronaut in a nonflatulent condition. From our experience with human subjects in an Earth environment if we extrapolate to a shirtsleeve cabin situation, a typical astronaut will pass hourly one 20- to 50-cc egestion of flatus composed of 10 percent carbon dioxide, 3 percent oxygen, 18 percent methane, 60 percent nitrogen, and 9 percent hydrogen. He might also have a different intestinal microflora, producing no appreciable methane or hydrogen. These values are only representative and for nonflatulent diets. The composition of flatus varies widely among individuals, becoming especially dynamic under flatulent conditions. For example, for the same subject during a 7-hour measurement period, the carbon dioxide composition can range from 10 to 82 percent, and then back to 10 percent by the end of the period. Hydrogen can vary from 0 to 50 percent, and methane from 0 to 40 percent. Proper formulation of the astronaut's diet will reduce the contribution of the intestinal gases to cabin contamination to a normal volume of 150 to 500 cc for a 24-hour period. A flatulent condition will not only add a tenfold to twentyfold increase in flatus volume but will increase the levels of carbon dioxide, methane, and hydrogen in the cabin atmosphere.

The astronaut may also be selected from that part of our population producing little or no methane or hydrogen and a very low level of hydrogen sulfide or other malodorous trace flatus constituents not yet identified. Further, since individual astronauts will vary in the degree of flatulent reaction to a given weight of food, individuals can be chosen who demonstrate a high resistance to intestinal upset and flatus formation.

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Discussion: Flatus

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On behalf of the Western Utilization Research Laboratory of the U.S. Department of Agriculture, Nielsen and coworkers at the Stanford Research Institute undertook the development of new laboratory methods for evaluating bean-induced flatulence. The expected composition of flatus was recorded: carbon dioxide, nitrogen, hydrogen, and methane. In vitro incubation of normal feces and colostomy residues resulted in the evolution of carbon dioxide and methane, but no hydrogen. However, gases arising from ileal dejecta contained hydrogen and carbon dioxide, but no methane. Reasoning that partial pressure relationships favor diffusion of methane and hydrogen from the intestinal lumen into the blood and, thence, the lungs, Nielsen examined the trace constituents of expired air. Long-path infrared spectrometry revealed measurable quantities of methane in the breath of some individuals (ref. 1).

With the support of the Idaho Bean Commission, Nielsen and his colleagues then designed sensitive chromatographic equipment capable of detecting hydrogen at concentrations as low as 4 parts per million. Hydrogen was thus found to be present in expired air at low levels or absent under normal conditions. Breath hydrogen concentration rose sharply about 3 to 5 hours after a bean meal, about the time that many subjects complained of gaseous discomfort (ref. 2).

At the University of California, we have continued this line of investigation. Recent data illustrate that pulmonary excretion of hydrogen and methane often exceeds rectal discharge of these gases originating in the bowel.

Normal subjects not given evocative foods have, over the course of a day, respiratory hydrogen levels ranging from nondetectable amounts (<4 ppm) to 20 to 30 ppm. In a small percentage of the populations we have studied, values may reach 60 ppm without known stimulation. Very frequently, small peaks are observed coincident with meals. Subjects vary from day to day but usually within their established categories of high or low hydrogren production. It is our impression that hydrogen values tend to be high in tense, active individuals, particularly in times of emotional stress, but we have not yet conducted systematic studies of this relationship.

Following consumption of beans at breakfast, breath hydrogen concentration is normal for about 4 hours, when a sharp elevation is noted. High production is usually evidenced for 1 or 2 hours, followed by a slow decline to normal. Peak concentration, as well as time and duration of elevation, vary among subjects and with amount of beans consumed. Elevation of expiratory hydrogen is correlated temporally with accumulation of flatus when this occurs, but high pulmonary exchange is often noted in the absence of egested flatus. Very preliminary data indicate that flatus hydrogen accumulation may be minimized by increasing physical work output, but whether this is due to decreased production or to increased pulmonary ventilation is uncertain. This point requires clarification relative to the special problems of space travel, because contamination of the cabin atmosphere would be diminished only in the first instance, even though personal comfort might be improved in either case.

Methane presents an entirely different picture. Respiratory levels are high in those subjects who have a large concentration in the flatus gases, regardless of flatus volume. Breath levels as high as 60 to 80 ppm have been recorded in a few subjects; about one-half of the population show levels above 15 to 20 ppm. In most subjects, methane content of expired air is nearly constant throughout the day. This gas does not appear to bear a cause-effect relationship to flatulence.

The temporal sequence of respiratory hydrogen suggests that gases are produced when chyme is presented in quantity to the ileum. These gases are presumably of bacterial origin, resulting from fermentation of unabsorbed nutrients. The amount of these substrates reaching the ileum depends on transit time (bowel motility), ease of digestion of foodstuffs and their availability to the digestive enzymes, and absorption rate. Discomfort from the gases evolved is probably dependent both upon the volume produced and the facility with which this volume is reduced by transfer across the intestinal membrane or expulsion as flatus. Thus, gaseous distress may be expected to vary with diet, the physical and emotional status of the subject, and the social environment.

It is apparent from our data that elimination of "gas-producing" foods from the astronaut's diet is insufficient to control the problem of waste-gas disposal.

Accumulation of gases will depend upon the number and characteristics of the crew, the size and leak rate of the capsule, and the duration of the mission. Our data indicate that hourly production of hydrogen and methane could range from negligible amounts to 16 and 23 milliliters, respectively, in normal individuals without stimulatory foods. One man might thus produce nearly 1 liter of these gases in 24 hours. The maximum acceptable concentrations of hydrogen (4.1 percent) and methane (5.3 percent) are based upon the explosive properties of these gases as neither shows biologic toxicity at these levels. However, hydrogen sulfide causes nausea and lacrimation at low concentration (maximum acceptable=20 ppm). Controlled combustion offers a possible solution to control of these gases, provided that sulfur compounds are removed initially and nitrogen is absent from the atmosphere, since these yield toxic oxides.

Ideally, we should identify the organisms that evolve hydrogen, methane, hydrogen sulfide, and other noxious volatile materials and develop techniques for their specific suppression. Immunization would be the method of choice; antibiotics are a poor second. We should also devote attention to maintaining in the intestinal tract conditions favorable to the growth of beneficial organisms.

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COMMENTS

Dr. Welch: What is the total volume of flatus produced per day in a normal type diet?

Dr. Murphy: There are a large number of figures in the literature on this total flatus per day and we are in agreement with them. The values run roughly from 100 to 500 cubic centimeters per 24 hour day.

Dr. Mrak: Did you use a hot-water extraction of lima beans?

Dr. Murphy: We have extracted with hot water, but the point is that exhaustive extraction will not remove all the flatulence present. It takes a little alcohol.

Dr. Block: Is it identified just where the flatulence is produced, whether it is in the small or large intestine? Is it a result of bacterial action producing different gases?

Dr. Calloway: I don't know of any other mechanism than bacterial action to account for hydrogen and methane. The temporal sequence of hydrogen production, the time when peak flatulence occurs, would suggest that gases are formed in the lower ileum. Methane appears to be a large bowel gas. It is possibly swept out as carbon dioxide and hydrogen pass down the colon.

DR. MASSEY: What kind of information do you think you would get through breath analysis if you had instrumentation to allow breath-by-breath analysis?

DR. CALLOWAY: By measuring breath gases, you cannot be completely certain whether the subject is also passing flatus. Many subjects very efficiently dispel gases as they are formed, through pulmonary exchange. We have never had a subject who produced flatus who did not also produce measurable amounts of these gases in the respiratory mixture, however. When hydrogen is present in the breath this means it has been evolved in the gut and I think that is significant physiologically. What you do with the information is a separate problem.

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Integration and Mechanics of Waste Collection and Processes[1]

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Waste collection and processing must be an integral part of any spacecraft life support system. The adaptability of the waste management subsystem to be integrated with other spacecraft systems is of significant importance and can be a major factor in the final selection. As a part of the NASA Langley Research Contract (NAS 1-2934), General Dynamics performed a study and survey of the industry to select a waste management technique. The techniques studied reflected the overall program objective of a completely integrated life support system capable of sustaining a four-man crew for 1 year with resupply at 90-day intervals. The major program objectives are as follow:

Fully Integrated System
Maximization of Reliability and Safety
Minimization of Weight and Power
Encompass Principles of Flight Type System
Maximum Advancement of State of the Art
Delivery of an Operating Life Support System Installed in a Test Bed for the NASA Manned Test Program

The following sections briefly describe the requirements for waste management in terms of the specific NASA Langley Research Center (LRC) contract criteria. The integration considerations are presented to show the broad interplay between a relatively simple system like the waste management and the overall spacecraft.

[1] Most of the information herein was made available through the NASA Life Support Project personnel at GD/Astronautics and GD/Electric Boat.

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WASTE-MANAGEMENT REVIEW

General

The techniques used to accomplish waste management must meet the basic crew requirements and in addition provide acceptable integration capabilities with the spacecraft and various subsystems. The techniques discussed in the following paragraphs are some of those investigated for the NASA–LRC life support system. The comments associated with these techniques are valid for this life support system and should not be considered as necessarily applicable to other spacecraft and life support system configurations.

System Requirements

A waste-management system must provide for the collection, treatment, and ultimate storage or disposal of waste material generated on a spacecraft. These wastes include the normal biological products of the crew plus those produced by various spacecraft subsystems. Table I is a summary of the wastes produced by the four-man crew and the life support system under consideration.

The major problems associated with a waste-management system of a zero-gravity spacecraft include: collection of feces, odor control, bacteria control, and prevention of toxic contamination of the cabin atmosphere. In addition, the system must provide the technique for the collection and transfer of urine to the water reclamation system.

TABLE I.—*Waste-Management System Requirements*

[Four Men]

Waste	Weight, lb/day	Tasks
Feces	1. 3	Collection, transfer, storage, and/or treatment.
Urine	13. 2	Collection and transfer.
Refuse:		
Unused food and packaging.	1. 6	Storage.
Personal hygiene wastes.	. 5	Storage.
Carbon from CO_2 reduction.	2. 5	Storage.
Solids in expendable filters.	Nil	Storage.

Techniques Investigated

Biological treatment

In the biological treatment of concentrated wastes, sufficient engineering data concerning loading rate, detention time, and degree of digestion during continuous operation are not available for precise design calculations of space-borne components. These factors are important since they dictate material balances and the size of the process equipment. Preliminary engineering requirements, however, can be determined based on known data.

The biological degradation of waste was considered unsuitable for the specific NASA–LRC mission for the following reasons:

(1) The process does not eliminate the need for other subsystems; solids must still be disposed of at the conclusion of processing.

(2) The process can stabilize only 40 percent of the organic waste during a reasonable time period.

(3) The process imposes very large weight, volume, and power penalties compared to other techniques.

Freeze-drying

Freeze-dying techniques for waste management require the use of water or urine and assume that there is an excess of water and that urine will not be recovered. The specific NASA–LRC mission objectives include the requirement for recovery of water from urine; therefore, freeze-drying techniques were not considered acceptable.

Freezer storage

The freezing of waste matter for storage and odor control is a feasible and competitive technique. Also, the freezer required to implement such a technique can be used for other purposes before it becomes completely filled with waste matter.

In case of freezer failure, however, another subsystem for storage and odor control must be available. Therefore, it may be desirable to use another technique for the primary storage and/or disposal of waste matter and use the freezing technique as a backup.

Thermal decomposition

Thermal decomposition of waste has the advantage of requiring no expendable materials. This technique, however, inherently requires high temperatures, and subsystems employing thermal decomposition have high power consumptions to maintain the required temperatures. For the requirements of this mission a thermal decomposition unit would require in excess of 600 watts of power for operation. This power requirement is substantially higher than the power requirements of other techniques.

Incineration

Incineration can be used to dispose of both feces and refuse. In this technique the waste material is heated and then ignited with oxygen. The effluent combustion gases are vented overboard. This technique leaves a small quantity of powdery residue that must also be vented overboard or removed for ultimate storage.

Jettisoning

Information on the jettisoning of wastes from a space vehicle is exceedingly sparse.

There are several problems associated with jettisoning of waste in space. These can be summarized as follows:

(1) No one has developed a device for jettisoning waste.

(2) Waste must be treated and "packaged" for jettison to prevent contamination of space. No work has been done on packaging techniques.

(3) Force of jettisoning may require counteraction by control rockets.

Storage

There are available several storage techniques for feces. The feces may be stored, treated or untreated. Pretreatment before storage may be by chemical additive, drying process, or freezing.

Summary

The preceding techniques are only a few of those which were considered for the treatment process. In addition to the treatment processes investigated, fecal collection devices have also been evaluated during the NASA–LRC life support system study phase. Table II presents the various collection methods and the treatment processes evaluated.

The results of these evaluations in terms of weight and power weight penalty with respect to mission duration are shown in figure 1. Although this particular figure points out the weight and power parameter of the combined techniques, the final selection must also consider reliability, maintainability, safety, and integration adaptability.

TABLE II.—*Techniques Studied for Fecal Waste Management*

Collection and handling	Treatment or storage
Air flow—manual transfer	Room temperature storage: vacuum dried, chemically treated, sealed container
Air flow into storage	Biological degradation
Air flow—water flush, mechanical pump transfer	Freezer storage Freeze drying Thermal decomposition
Manual collection and transfer	Incineration Jettisoning

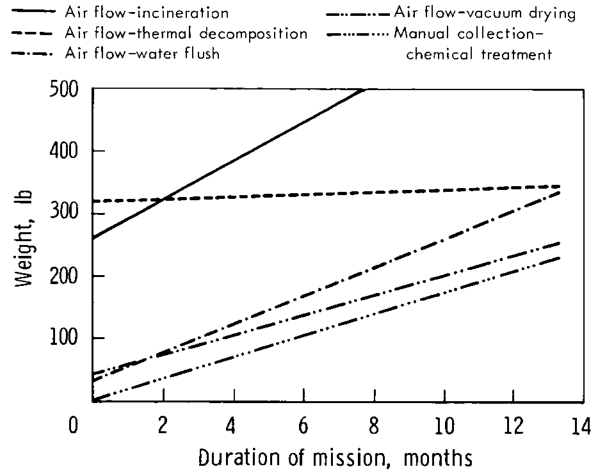

FIGURE 1.—Waste-management comparison techniques.

The most significant point of the data presented in figure 1 is the slope of the lines representing the various combinations. The 1-year mission, as defined by the specific spacecraft model, is best satisfied from the weight standpoint by the manual-collection and chemical-treatment technique. The air-flow thermal-decomposition technique because of the low expendables would become competitive in terms of weight at about 18 months. An 18-month mission, however, may have different mission and design criteria than the one being considered here. The difference might be the inclusion of a food-management system designed to use man's metabolic waste as a nutrient for algae, thus eliminating the thermal-decomposition technique from consideration.

Figure 2 shows schematically the waste-management system selected for the NASA–LRC program (air flow collection and waste heat vacuum drying). The feces are collected in a semipermeable plastic bag. A blower is used to draw cabin air through the bag and an activated charcoal canister, the flow of air providing a means of directing the feces to the bottom

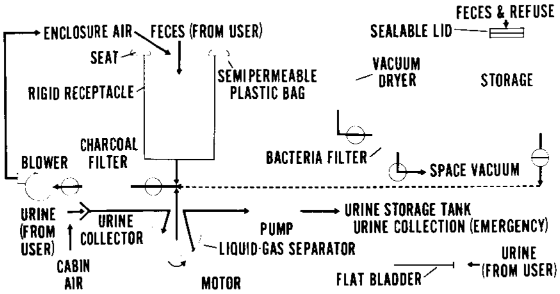

FIGURE 2.—Waste-management system.

of the bag under zero-gravity conditions. After defecation the bag is removed and placed in a chamber where it is exposed to waste heat and the vacuum of space for drying. It is then stored in a sealable container for ultimate removal during the resupply operation. The waste-management technique also provides a means of collecting urine and transferring it to the urine-collection tank of the water-management system. The urine transfer must be accomplished in zero gravity; therefore, a liquid-gas separator is provided.

SYSTEM INTEGRATION

General

So that the specific integration factors associated with the waste-management system can be fully appreciated, the overall life support system integration approach is presented.

There are numerous considerations both external and internal to the life support system that are closely associated with the selection of the life support system. These considerations must be reflected in the various subsystem specifications, which include all interface requirements of the subsystems.

Table III presents the major factors that must be considered. Those items shown in the first column are basic system criteria. The listings shown in the second column are those factors which tend to have the greatest integration potential. The following paragraphs briefly describe the significance of the potentially high integration considerations shown in table III.

TABLE III.—*Considerations Which Affect Life Support System Selections*

Basic system considerations	Potentially high integration consideration
Mission date	Power supply and power constraints
Mission duration	Waste heat availability
Crew size	ISS heat loads
Crew metabolic rates	Spacecraft wall thermal characteristics
Mission objectives	Orbital parameters and spacecraft orientation
Resupply interval	Spacecraft configuration
Zero gravity capability	Resupply techniques
Booster payload capacity	Crew safety and emergency procedures
Resupply vehicle payload capacity	

Power Supply and Power Constraint

The type of auxiliary power supply and the amount of power available for the operation of the life support system are essential in the evaluation and selection of all life support system techniques. The specific considerations of the auxiliary power supply as used in the evaluation and selection of the life support system are:

(1) Power weight penalty: 290 lb/kw

(2) Total power available to life support system: 2.5 kw (max)

(3) a.c. three-phase 400 cycles, 115 to 208 volts

(4) d.c. 28 volts

Waste Heat Availability

In addition to the regenerative heat exchanges within the individual life support system processes to reclaim waste heat, the auxiliary power supply waste heat provides significant integration possibilities. The quantity and temperature of the auxiliary power source waste heat is exceptionally high and is available from the coolant loop used in the radio-isotope power supply. The following information on coolant loop conditions at the discharge of the auxiliary-power-source regenerative heat exchanger is used to integrate the waste heat source with the life support requirements.

(1) Coolant temperature: 401° F

(2) Minimum coolant temperature after heat exchange: not critical

(3) Depending upon temperature of waste heat required, total q, Btu/hr, can vary significantly

Life Support System Heat Loads

The heat generated within the spacecraft cabin by subsystems other than the life support system can most efficiently be removed by an integrated heat transport loop which satisfies all the spacecraft thermal requirements. The total electrical power available for the subject mission is 5 kilowatts including the life support power requirements.

Spacecraft Wall Thermal Characteristics

The thermal characteristics of the cabin wall, when exposed to the incident energy of the space environment and to the varying internal heat loads, are essential in evaluating and selecting the technique for thermal and humidity control.

The preliminary cabin wall thermal characteristics used for the thermal control evaluations are:

(1) Mean radiant internal temperature of the cabin wall is within ± 5° F of the cabin air temperature

(2) Cabin internal wall temperature is above the cabin air dewpoint

(3) Maximum heat loss through the wall is equal to the four-man crew metabolic heat

(4) Inside surface convective film coefficient equals 1 Btu/hr ft^2 °F

Orbital Parameters and Spacecraft Orientation

The orbital parameters have a significant effect upon the design and analysis of the thermal control system. The orbit and orientation of the spacecraft dictates the environment in which the space radiator must function. The specific considerations used in the evaluation of the thermal control system are:

(1) Orbit altitude: 250 n. miles.

(2) Orbit inclination to the solar vector: 30°

(3) Orbit eccentricity: zero

(4) Vehicle cylinder axis normal to the solar vector

(5) Rotation of vehicle (cylinder) about its axis: zero

In addition to thermal control problems, the orbital parameters have some effect upon the life support system evaluations from the standpoint of emergency resupply time.

Spacecraft Configuration

The internal configuration of the spacecraft with respect to volume, number of compartments, and crew duty stations is a guiding factor in the evaluation of competitive life support system techniques. The volume of the spacecraft has a direct bearing on the gaseous stores, thermal control, and atmospheric control. The number of compartments has the same effect as the volume but, in addition, lends itself to evaluation of various techniques of the emergency life support system operation. The crew duty stations and crew location during off-duty hours have to be a consideration in the analysis and selection of various life support system functions.

The following factors were used to integrate the aspects of the spacecraft configuration into the evaluation and selection of the life support system.

(1) Total cabin volume: 4150 ft^3

(2) Upper compartment volume: 2305 ft^3

(3) Lower compartment volume: 1755 ft^3

(4) Airlock volume: 90 ft^3

(5) Upper compartment: living and control station quarters

(6) Lower compartment: research laboratory

Resupply Techniques

The resupply techniques for the life support system, in addition to the normal weight and volume constraints, must be compatible with the zero gravity and vacuum of space environment. The specific life support system functions which require resupply must be analyzed and selected, not only on the basis of performing a desired function, but also on their ability to integrate with reasonable resupply techniques.

Crew Safety and Emergency Procedures

The analysis of the complete life support system must consider each component or subsystem selection on the basis of crew safety. The companion problem associated with adequate crew safety is the ability of the integrated subsystems to provide modes of emergency operation consistent with a high probability of mission success.

The specific considerations used to maintain high safety standards for the integrated life support system include the following:

(1) Instrument monitors and alarms
(2) Physical design criteria (pressure, temperature, and environment)
(3) Dual modes of operation
(4) Redundancies
(5) Dual function design
(6) Emergency resupply reaction time

Waste Management Integration

The preceding paragraphs have briefly summarized some of the major life-support-system

TABLE IV.—*Waste-Management-Integration Chart*

General interface	Specific interface
Thermal control	Waste heat from the auxiliary power supply for feces vacuum drying unit or from the FC–75 heat transport loop
	Transfer of heat by cabin air from the vacuum drying unit to the simulated radiator
	Integral blower heat transferred to the simulated radiator
Atmospheric control	Odors associated with fecal collector to activated charcoal or toxin burner
	Air loss due to vacuum drying operation
	Odors associated with storage containers to toxin removal devices or toxin burner
	Storage for spent filters, and carbon from the Bosch Reactor
Water management	Urine transfer to water reclamation storage tanks
	Overall water balance considering fecal water loss
	Storage of waste water residue, liners, and evaporators
Food management	Storage of leftover food
	Storage of used food packaging
	Biological specimen freezer used for food and as a temporary waste storage backup
	Transport container for food is actually waste storage container
Personal hygiene	Debris and refuse from body and sanitation unit
Power supply and constraint	Blower for air flow feces collector (intermittent)
	Use of waste heat for the vacuum dryer to minimize power
Waste heat	Waste heat from the auxiliary power supply to minimize drying cycle time
Orbital parameters	Emergency resupply time
Spacecraft configuration	Provide for privacy
	Vacuum source for feces drying
Resupply	Capacity of waste management system to satisfy short-term occupancy of six crew members
	Design criteria of maintainability and replacement for expendables
	Return of waste from spacecraft to resupply vehicle
	Resupplied waste containers used for food storage during transfer from Earth
Safety	Emergency collection and storage for 17 days
	Isolation area for collection and storage to minimize toxic contamination
	Manual overrides of system functions
	Bacteria filters
Internal to the waste management	Instrumentation and control
	Feces transfer from collection unit to drying and storage units
	Storage container integrated with feces collection blower to minimize odors during waste storage
	Expendable supply storage (paper wipes, bags, chemicals)
	Urine collection device (air flow or centrifugal)

integration parameters. The specific integration factors which influence the selection of the waste management system are shown in table IV. The 34 factors noted are typical of the interplay between the spacecraft complex and the waste management system. Some of the factors have only a minimum effect on system selection while other factors, such as crew acceptance, are extremely important. In broad terms, the waste management system has some influence or is influenced by all the other life support subsystems.

CONCLUDING REMARKS

The life support system, of which waste management is a part, is a system which is very compatible with integration and because of this the individual subsystem evaluations must constantly consider this factor. Without major emphasis on system integration the resulting life support system would be no more than a collection of interdependent subsystems, each one performing its independent function without regard to the overall objective of an integrated life support system.

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Liquid Wastes and Water Potability in Space Vehicles

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Although the problems of feeding and nutrition in space vehicles are both important and fascinating, they do not seem truly difficult of resolution. The problems of water supply and waste management, on the other hand, are exceptionally critical and far from being solved. Indeed, they may be the factors that control the size and weight of the vehicle or the duration of the mission.

It has been stated, for example, that the weight of dehydrated food will be only about 0.6 kilogram per man day, but the metabolic water requirement will be about 2.5 kilograms or 2.5 liters per day, that is, four times the weight of food. Consequently, it will be desirable, if not absolutely essential, to reclaim and reuse waste water in space vehicles. We know that food can be neatly packaged in advance, stored in cabinets and containers, and readily prepared for appetizing and nutritious meals. However, the handling of human wastes will depend largely on the actions of the astronauts. Furthermore, it is apparent that reliable hardware and techniques for waste disposal remain to be developed.

It is the intent of this paper to explore some of the ramifications of wastewater reclamation in space vehicles and to describe some of the criteria that control the treatment of urine and other wastewaters.

BOUNDARY CONDITIONS

In assessing the problems of wastewater management and reutilization, it is desirable to establish certain boundary conditions or limitations to the study. Accordingly, the following logical assumptions have been made:

(1) That the flight duration will exceed 15 days but not 6 months, and that it will involve three men or more. For shorter flights and fewer men, sufficient fresh water can probably be carried aboard, and waste water can be stored. For periods longer than 6 months, processes more complicated than those described in this paper may be indicated.

(2) That feces will be kept separate from urine, packaged, disinfected, and stored. For voyages in excess of 6 months or for colonies on the Moon or Mars, it may be desirable to utilize feces in photosynthetic processes.

(3) That zero gravity will prevail, except briefly during takeoff and landing; that is, that these boundary conditions apply to space vehicles and not to colonies on the Moon or Mars.

(4) That occupants will be free to move about the cabin and to operate simple water-recovery apparatus; that is, a shirt-sleeve regime will prevail.

(5) That weight will be a controlling factor but that power will be ample for the operation of simple functions.

(6) That dehumidifying equipment will be provided to condense all excessive cabin moisture and make it available for reuse.

WATER QUANTITIES

The quantities of water consumed by a man vary widely, depending on the level of his activity, temperature, diet, body weight, and so forth. The following average values from Hawk and his coworkers are quoted by Breeze (ref. 1), and by Wallman and Barnett (ref. 2) as:

Water intake	*ml/day*
Drinking water	1200
Water used for rehydrating food	1000
Water oxidized from food	300
Total	2500
Water output	
Urine	1400
Feces (water content)	100
Respiration and perspiration	1000
Total	2500

From the foregoing table it can be readily seen that if all urine is reclaimed and if the water of respiration and perspiration is recovered by dehumidification apparatus for drinking water and rehydration of food, the water oxidized from food exceeds that stored with the feces by 200 ml per day. Hence, the total water available in the cabin will increase daily and may become a problem of ultimate disposal or storage.

In addition to the water taken internally, man needs water for personal cleansing, laundry, and perhaps cabin cleansing. In a prolonged voyage with zero gravity, bathing and cabin cleansing will probably be limited to sponging operations but a centrifugally operated washing machine for the cleaning of clothing should be easy to develop. Ingram (ref. 3) has estimated these supplemental water needs at 5.5 to 8.5 liters per day. This water is capable of reclamation along with that from urine, respiration, and perspiration. Indeed, the carbonaceous content of washwaters may be advantageous in the biological stabilization of urine.

WATER QUALITY REQUIREMENTS

Standards of water quality have been published by the U.S. Public Health Service (ref. 4) and the World Health Organization (refs. 5 and 6). These standards are summarized in table I. In the case of the WHO, standards have been published for international control and also for the European nations. Table I shows the stricter standards.

Some consideration should be given to the rationale under which these standards were established. In all instances, they are extremely conservative. They are designed to protect children from fluoride and nitrates. They protect aquatic life and gold fish in aquariums with respect to chromates and copper. They meet the threshold limits of taste in the case of copper, iron, zinc, and manganese. In short, they are standards of excellence, but not criteria of human health or limits for the maintenance of a healthful condition of man in space. They should definitely not be applied blindly to the determination of water quality to be met by reclamation systems in space. In many instances, short-term exposure to concentrations considerably in excess of the USPHS or WHO standards would produce no measurable detrimental effect.

It is especially important to note that the USPHS and WHO standards apply mostly to mineral constituents. Only in the case of carbon chloroform extract and phenolic compounds do true organic substances enter into the determinations. The USPHS and WHO standards were formulated largely on the basis of natural waters and their possible contamination by mineral wastes from industrial processes. They certainly did not envision the quality of water reclaimed directly from human wastes. For this reason the USPHS Drinking Water Standards should not be applied blindly, as several investigators have done, to the quality of reclaimed water acceptable for space travelers.

CHARACTERISTICS OF WASTEWATERS

Analyses of the water that may be recovered from the sponge baths of astronauts, from cabin cleansing, from the laundering of clothing, and

TABLE I.—*Drinking Water Standards*

Determination	USPHS	WHO
Bacterial:		
Coliform bacteria, per 100 ml	1.0	[a] 0.05 [b] 1.0
Physical:		
Turbidity, silica scale units	5	------
Color, cobalt scale units	15	------
Odor, maximum threshold number	3	------
Chemical, mg/liter:		
Alkyl benzene sulfonate	0.5	------
Ammonia	--------	[a] 0.5
Arsenic	[c] 0.05	[a] [b] 0.2
Barium	[c] 1.0	------
Cadmium	[c] 0.01	[a] 0.05
Calcium	--------	[b] 200
Carbon chloroform extract	0.2	------
Chloride	250	[a] 350
Chromium (hexavalent)	[c] 0.05	[a] [b] 0.05
Copper	1.0	[a] 3.0
Cyanide	0.2	[a] [b] 0.01
Fluoride	[c] 1.6–3.4	[a] 1.5
Iron	0.3	[b] 1.0
Lead	[c] 0.05	[a] [b] 0.1
Magnesium	--------	[a] 125
Magnesium + sodium sulfate	--------	[b] 1000
Manganese	0.05	[a] 0.1
Nitrate, as NO_3	45	[a] 50
Phenolic compounds	0.001	[a] 0.001
Selenium	[c] 0.01	[a] [b] 0.05
Silver	[c] 0.05	------
Sulfate	250	[a] 250
Total solids	500	[b] 1500
Zinc	5.0	[a] 5.0
Radiological, pc/liter:		
Radium-226	[c] 3	------
Alpha emitters	--------	[a] [b] 1
Strontium-90	[c] 10	------
Beta emitters	[c] 1000	[a] [b] 10

[a] WHO European Standards of 1961.
[b] WHO International Standards of 1958.
[c] Mandatory. Others are recommended by USPHS.

from the condensate from dehumidifying operations have not been reported in the literature. It may be assumed, however, that such waste waters will contain sebaceous excretions, sweat, detergents, and condensates that in combination will resemble domestic sewage with respect to biological oxygen demand (B.O.D.), total organic solids, C:N:P ratios, and other parameters of organic and mineral pollution. Such waste waters should be amenable to biochemical treatment.

The other major waste water is urine, for which the approximate constituents are shown in table II. Note especially that the total solids, or residue on evaporation, exceed 4 percent or 40 000 mg/liter, as compared with the USPHS recommended limit of 500 mg/liter or a more rational limit of 1500 mg/liter. Expressed otherwise, the dissolved solids in urine exceed those of sea water. Note also that the levels of sodium, potassium, chloride and sulfur are too high to meet the USPHS limit for total dissolved solids. With respect to trace elements, however, no problem is involved, because in every instance the trace mineral output of urine is acceptable by rational or USPHS standards. Nevertheless, the mineral constituents of urine give us an important clue to the treatment that will be required. It is evident that biological methods alone such as activated sludge, trickling filters, or algal ponds will not be sufficient for treatment because they will not remove the dissolved mineral solids. It will be necessary, therefore, to utilize an evaporative process, electrodialysis, an electrolysis fuel cell, or some similar method for separating water from the dissolved mineral solids in urine.

In examining organic solids in urine, it is noted especially that urea accounts for about 50 percent of the total dissolved solids; that other nitrogenous compounds such as amino acids, creatinine, hippuric acid, and uric acid are significant; and that lipids and organic acids account for important fractions. Indeed, many of these organic compounds are volatile enough to appear in the condensate from evaporative processes or the effluent from electrodialysis units.

TABLE II.—*Approximate Average Constituents of Urine*

[after Altman, ref. 7]

Determination	mg per day	mg per liter	Rational limit
Water	1 400 000	------------	------------
Total Solids	60 000	[a] 43 000	1 500
Inorganic:			
Calcium	230	164	200
Magnesium	45	68	125
Sodium	4 200	[a] 3 000	500
Potassium	2 380	[a] 1 700	500
Bicarbonate	140	100	------------
Chloride	7 000	[a] 5 000	500
Sulfur	1 120	[a] 800	500
Phosphorus	840	600	------------
Trace elements:			
Aluminum	0.077	0.055	------------
Arsenic	0.023	0.016	0.05
Copper	0.035	0.025	1.0
Fluoride	1.54	1.10	1.5
Iron	0.49	0.35	1.0
Lead	0.028	0.02	0.1
Manganese	0.049	0.035	0.1
Nickel	0.21	0.15	--------
Selenium	0.035	0.025	0.05
Silicon	9.10	6.5	------------
Tin	0.013	0.009	------------
Zinc	0.36	0.26	5.0
Organic:			
Urea	30 000	[a] 21 400	------------
Other N-compounds	4 700	[a] 3 360	------------
Amino acids	2 100	[a] 1 500	------------
Creatinine	1 600	1 140	------------
Hippuric acid	350	250	------------
Uric acid	140	100	------------
Bilirubin	50	36	------------
Creatine	56	40	------------
Indican	70	50	------------
Imidazole derivatives	170	121	------------
Purine bases	42	30	------------
Miscellaneous	140	100	------------
Lipids, carbohydrates, and misc. organic acids	2 320	1 650	------------
Carbonic acid	190	136	------------
Citric acid	800	570	------------
Formic acid	60	43	------------
Lactic acid	210	150	------------
Oxalic acid	35	25	------------
Reducing substance	1 000	715	------------
Miscellaneous	25	18	------------
Vitamins, metabolites	50	36	------------
Hormones	100	71	------------

[a] Excessive.

TREATMENT PROCESSES

Considerable attention has been directed at processes for the recovery of drinking water from urine. The work prior to July 1962 has been summarized by Slonim, Hallam, Jensen, and Kammermeyer (ref. 8). The most promising systems use some form of distillation, with vacuum distillation being operationally most advanced. With all such processes, however, it is necessary to provide additional treatment of the condensate because it contains volatile organic constituents of urine. Some of these compounds produce undesirable tastes. The aftertreatment may consist of filtration through ion-exchange resins or activated carbon, both of which become exhausted and must be replaced periodically.

Dr. Konecci has stated that we should search the literature and rely heavily on the experience gained by others, even in generations past. Sanitary engineers have had many decades of experience in the treatment of municipal and industrial wastes. Perhaps we should explore some of the systems that have been efficacious in such operation.

It would seem logical, for example, to stabilize the organic constituents of urine prior to distillation by means of oxidative processes that convert organic compounds to mineral solids. For this purpose, sanitary engineers normally employ the activated sludge process, trickling filters, or oxidation ponds. All of these systems, however, rely heavily on gravity forces and indeed it is difficult to envision how they could operate in a zero-gravity condition.

It appears, however, that no one has given consideration to an ancient method of stabilization of organic solids, namely intermittent and unsaturated percolation through fine-grained media such as soil. After a bed of such media has been ripened, seeded, and acclimated to a given organic waste, it will function effectively to convert carbonaceous and proteinaceous substances to oxidized end products such as carbon dioxide, carbonates, nitrates, sulfates, phosphates, and water.

An advantage of percolation through fine-grained porous media is the fact that it is not dependent on gravity because capillary forces will control. It will be necessary, however, to provide pressure to force the waste water into the column and to follow each injection of waste water with compressed air to assure an aerobic atmosphere in the interstices. Considerable knowledge is available on two-phase flow through porous media, but the application of this process to the stabilization of urine remains to be developed. Tentatively, it is estimated that a column 20 centimeters in diameter and 1 meter long would be more than adequate for a crew of three.

Consideration must be given to the fact that stabilization of organic matter utilizes oxygen and produces CO_2, both of which are critical factors in space travel. Let us examine the magnitude of the oxygen utilization. If *all* of the urea in urine were converted to nitrates, CO_2, and water without any biosynthesis of protoplasm, the oxygen requirement would be approximately twice the weight of the urea, or about 64 grams per man day, which equal to 2 gram mols of oxygen or 45 liters per day at standard temperature and pressure. The oxygen demand for man's respiration, however, is in the order of 610 liters per day, as reported by Breeze (ref. 1); hence, the complete oxidation of the organic solids in urine would add only 7 percent to the oxygen demand. The CO_2 production would be even less significant, because the respiratory quotient for oxidation of urea is only 0.25.

CONCLUDING REMARKS

From this brief dissertation, it is apparent that considerable work needs to be done to determine many of the factors related to the recovery of waste water in space vehicles. Attention should be directed especially to the following matters:

(1) Establishment of realistic criteria or standards for the necessary quality of water recovered from urine.

(2) Research in the oxidation of urine by intermittent percolation through fine-grained media, especially in the absence of gravity.

(3) Development of apparatus and procedures to assure effective oxidation of urine in columns of fine-grained media.

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Discussion: Liquid Wastes and Water Potability in Space Vehicles

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It was clearly shown in the preceding presentation that urine is a primary problem in the water management cycle in spacecraft. This will be true, according to Dr. McKee's assumptions, for flights lasting up to 6 months. After the 6-month period, feces must be placed back into the cycle, and other complex problems in handling and reusing the water supply will demand attention.

This problem of urine reuse or recycling into the potable water supply is believed to have been solved long ago by the ancient Norse. According to this theory, the warriors, prior to battle, would eat an intoxicating variety of mushroom. The urine produced was collected and drunk. Soon the Norse would begin to roar and rant and, going "berserk," would rage into battle. Although the process met with frequent success, it hardly seems the water reclamation system of choice for men trying to accomplish delicate missions in space.

Dr. McKee presented a list of constitutents of urine. This list can be expanded to at least 183 materials which have been identified in normal urine. Of these, many have biologic activity at concentrations which might be attained in the recycling of urine. As an example, mercury is excreted in normal urine at levels approaching 100 gamma per person per 24 hours. The total nitrogen content of urine is 10 to15 grams per person per 24 hours, of which urea comprises approximately 85 percent.

The nitrogen content of the recycled water will be very important, since the body is poisoned by accumulated nitrogen and one of the main functions of the urinary system is the excretion of excess nitrogen. The problem of nitrogen removal may be susceptible to attack by chemical precipitation of urea or by catalytic treatment of ammonia at 1650° F. Here, weight and energy considerations become important.

Some difficult problems in recycling urine which might occur aboard a spacecraft would be caused by materials in the urine which are nonionic, volatile, and not readily adsorbed on carbon. Of the 20 or more different methods which might be used in treating urine, I think the most likely would involve distillation and adsorption. Another problem which might develop in a spacecraft is an imbalance in the production and composition of urine as a result of the very severe regimen imposed on the astronauts during flight. In addition, should an astronaut become ill, this might upset the balance considerably by producing new urinary products, difficult or impossible to remove by the spacecraft water reclamation system. We may, therefore, have to think about means for detecting physiological changes in the astronauts and then determine whether we can treat abnormal urine or whether it would have to be segregated and stored.

Dr. McKee has pointed to the advantage of having an excess of water in the spacecraft materials balance, which results because some water is produced from food. However, in the closed system of spacecraft ecology, once it is necessary to grow food aboard the spacecraft, the "excess" water must be used, with other waste products, for this purpose by photosynthesis or other means. Then, if the spacecraft leaks at all, a water shortage will develop.

I would like to comment specifically on the percolation method for treating urine described in the preceding paper. This method ought to be one of the treatment means investigated and might play a significant role as a component in an integrated system. However, some of the problems which might develop would include changes in or sloughing of the bacterial slimes that would be present and active in the filter media. The formation of crystals which might tend to clog the medium and the production of gases other than carbon dioxide, oxygen, and hydrogen might present other problems.

In the event that a biological system fails or suffers serious alteration during flight, the entire mission may be lost. If the biological system is designed as a single unit, all the eggs are in one basket. I believe it would be desirable to divide this basket, so to speak, into many small baskets, or modules. If difficulty develops in one of these modules as a result of chemical changes, nutritional changes, or mutation, it can be flushed out and reinoculated from the others. This approach might prove fruitful for any application made of the percolation method or for algal photosynthetic gas-exchange systems.

Dr. McKee is certainly correct in stating that the recycling of water is going to be one of the major problems in sustaining manned spacecraft flight. He put the problem in proper perspective when he demonstrated the relative importance of water solely from the standpoint of its daily required weight compared with the weight of other spacecraft life-support necessities.

SESSION VI

Long-Term Flight Nourishment Sources

Chairman: ***Allan H. Brown***
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Definitions of "long term flight" seem to be numerous. In a previous session, it was indicated that short term flights were of 14 days' duration or less; long term flights were of 90 to 120 days' duration. This is a rather arbitrary distinction, based on the capabilities of particular vehicles, but it is a convenient distinction. However, in terms of nutritional requirements, I would interpret short term flights as meaning those in which no food intake is needed.

It was surprising to learn from a preceding paper that on very short missions, approximating 24 hours or less, food intake actually reduces the performance. Presumably, one of the reasons for feeding was morale and this is a most important reason. Therefore, the acceptability of the food ought to be paramount.

The technique in designing food for short term missions has been largely one of free programing of the astronaut, according to the specifications of the average man, and then assuming that the particular astronaut will conform to these specifications. We have been much concerned about the exact requirements, the caloric, vitamin, and protein requirements, but what data are these estimates based on except ground-based data on average men? Even the basal metabolic rate turns out to be very much in doubt.

So, what we have been doing, as I see it, is trying to predict on the basis of data we don't have, namely data taken in flight in a weightless state and in a suit, what kind of nutrition would optimize an astronaut's performance.

It would seem that perhaps if we could provide the astronaut with some ad libitum feeding, rather than to force-feed him, we might get better performance. Now, of course, I realize that this means providing food at less than maximum density and it also suggests that probably some food will be left over. It seems to me that we have certain concepts for improving machines, but nothing which applies to man. There are certain safety margins which are applied to electronic equipment which, as far as man's food intake is concerned, do not seem to be given consideration. I suggest that, in general, the philosophy of overbuilding a system to improve performance could, with profit, be applied to the man part of this machinery complex.

For purposes of this session I would define operationally a long mission as one in which it is advantageous to regenerate certain of the components in order to recycle some of the components of the system. I would not define this in terms of so many days, weeks, or years. This can be the regeneration of the drinking water, of the oxygen, or of the food, and perhaps of other components.

Although transit time to the Moon and even to Mars may eventually be rather short, the total mission time is very different from the transit time. The total mission time is always going to be long if we expect the astronauts to make any studies when they reach their space objective.

Also, the payload cost will be high; even though new sources of energy are found, it seems extremely unlikely that the payload cost will ever become negligible. Therefore, there is reason to consider the regenerative system.

The emphasis in this session is on the viral regenerative systems. This method is not the only way to recycle, even food, but it is receiving a good deal of consideration.

ALLAN H. BROWN

N65-18591

Combined Photosynthetic Regenerative Systems[1]

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Application in space of photosynthetic regenerative systems goes back in concept to at least 1951. It derives from a proven model, the biological world. However, the biological world developed in a very large area and volume. In space the environment of the human is necessarily restricted within some confining structure. The problem is to miniaturize and reconstruct in small volume some approach to the balance of the biological world. The question is whether such an approach will prove feasible when compared with simple use of expendable materials and with other possible regenerative systems.

At one time it was common to discuss the problem at hand as that of the closed ecological system. I found, however, that this terminology implied an all-or-none character. To the contrary, the operations to be performed are partially separable. Table I shows the proximate human material turnover. These are old and tired textbook figures, but they are good enough to identify the regenerative operations in order of magnitude: (1) recovery of water, (2) regeneration of gases, (3) provision of food, and (4) removal of solid wastes. This paper is limited to operations (2) and (3).

It is of interest that the three methods which have been seriously studied have a common denominator, an initial input of energy for electrolysis of water (table II). This may be followed by the Sabatier reaction, using H_2 to reduce CO_2 to methane (or other reduced carbon). The methane presumably would be dumped overboard. The method does not provide regeneration of reduced carbon to a form available as human food. However, it does appear to provide a potentially compact and reliable means of regeneration for gases. A second method would utilize the synthetic metabolism

TABLE I.—*Approximate Human Turnover*

Input, g/day:	
H_2O	2200
O_2	860
Food (dry)	520
Output, g/day:	
H_2O	2540
CO_2	980
Solid waste (dry)	60

TABLE II.—*Principles of Three Regenerative Methods*

Electrolysis:

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

Reduction: Sabatier reaction

$$4\ H_2 + CO_2 \rightarrow {}^{a}CH_4 + 2\ H_2O$$

Hydrogenomonas:

$$6\ H_2 + CO_2 + 2\ O_2 \rightarrow (CH_2O)^{a} + 5\ H_2O$$

Photosynthesis:

$$2\ H_2O \rightarrow 4\ (H) + O_2$$
$$4\ (H) + CO_2 \rightarrow (CH_2O)^{a} + H_2O$$

[a] Approximate form of reduced carbon.

[1] Taken in large part from a paper, *Use of Algae for Support of the Human in Space*, in *Space Research IV* (P. Muller, ed.), "Proceedings of the Fourth International Space Science Symposium," Warsaw, 1963.

of the bacterial genus *Hydrogenomonas* to reduce CO_2 to cellular material, presumably available as human food. Possibilities and limitations of this approach are under study.

A third regenerative process (table II) is based upon use of the photosynthetic process. Here the splitting of water classically has been called a photolysis; in recent theory it is treated more nearly as a biochemical electrolysis. Since H_2 is not produced as such, the inevitable dangers inherent in H_2+O_2 gas mixtures are avoided. The technical miracle of the process is that safely, quietly, and separated only by submicroscopic dimensions, there are produced compounds at least as reduced as H_2 and at least as oxidized as O_2. The end result in the green plant is the evolution of O_2 and the reduction of CO_2 to organic materials.

In table II all equations are written in approximate fashion adequate to provide comparison of methods. They are not sufficiently accurate for detailed discussion of any of the methods described. We now proceed to such discussion of the photosynthetic process.

We do not have, and cannot expect in the foreseeable future, the facility to use stable photosynthetic machinery to grind out a simple and defined product. Rather, we must use the machinery as it is used by the plant to produce more total plant material. In theoretical studies of photosynthesis, investigators have sought to isolate the process from other cellular metabolic processes. This has been accomplished with partial success over short time periods. Over long time periods we can use only the overall operation which I shall call photosynthetic metabolism.

Photosynthetic metabolism of the green plant is shown diagrammatically in figure 1 with partial breakdown into unit processes. The photochemical cycle is certainly more complex than depicted since it requires two separable photochemical events. It results in eventual evolution of O_2 (details of mechanism unknown) and production of energy-loaded biochemical currencies of reduced pyridine nucleotide and high-energy phosphate. From CO_2 and fixed nitrogen all other syntheses of cell materials now may proceed. Among various plants there is a great range of variation in distribution of final product between the three major groups of organic compounds. A large part of this variation arises from two simple biological principles: (1) that working machinery is largely protein and (2) that larger organisms have proportionately less working machinery and proportionately more skeletal material. In plants skeletal material is the carbohydrate, cellulose, not digestible by the human.

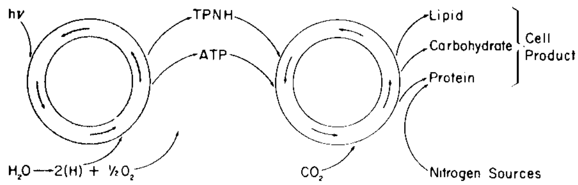

FIGURE 1.—Simplified diagram of algal cell synthesis.

As we proceed from a microscopic alga to the small duckweed to the large corn plant to the giant sequoia, there is a progressive reduction in the proportion of working machinery and a progressive increase in cellulose. In the same series there is also a progressive decrease in manageability of the plant. For these and related reasons, it should be no surprise that the algae have received the most intensive examination for use in a photosynthetic regenerative system.

Let us examine the photosynthetic metabolism of *Chlorella*, chosen as a typical alga. As in other microorganisms, the business of metabolism is the construction of more cellular materials to produce more cells. *Chlorella* accomplishes cell synthesis with such a remarkable conservation of organic material that about 95 percent of the total carbon and nitrogen removed from the medium is recoverable in the cells produced. Hence, we may predict overall metabolism from cell composition. The procedure, a simple inversion of the methods used to describe overall animal metabolism, is illustrated in table III. From elementary analysis, taking oxygen by difference, we may express the total organic cell product as an empirical formula. Writing down the reactants and products gives an equation which can be balanced to

TABLE III.—*Overall Metabolism of* Chlorella

Elementary analysis: 48.7% C; 7.5% H; 9.4% N; 6.4% ash

Derived formula for organic composition: $C_{6.0}H_{11.1}O_{2.7}N$

Equivalent weight: 140.7 (organic)
149.0 (total cells)

Equation for cell synthesis:

$$0.5\ (NH_2CONH_2)+5.50\ CO_2+4.55\ H_2O \rightarrow C_{6.0}H_{11.1}O_{2.7}N+6.68\ O_2$$

Equivalents calculated for 100% recovery [a]:

CO_2/O_2 (AQ)	=0.82
CO_2/cells	=0.82 liter/g
O_2/cells	=1.00 liter/g

[a] Recovery means carbon recovered in harvested cells divided by carbon taken up as carbon dioxide.

describe photosynthetic metabolism. The equation allows estimation of equivalents between CO_2 uptake, O_2 production, and cell production.

Algal metabolism is potentially versatile and under metabolic constraints may vary widely. In fact, we have been especially concerned with variations in metabolism. Such studies have led to unfortunate misinterpretation. When managed in steady-state culture and limited only by light intensity, the composition of *Chlorella* is remarkably constant.

As confirmed experimentally, equivalents between gas exchanges and cell production allow the performance of a culture to be estimated rather precisely by simple measurement of cell production rate. The assimilatory quotient (A.Q.), written as a CO_2/O_2 ratio, is close to matching the usual human R.Q. The value of the algal A.Q. may be raised by alternate use of ammonia as a nitrogen source or lowered by the use of nitrate. This facility for control of the CO_2/O_2 quotient is a special consequence of the high protein composition. Similar facility is not found in most higher plants in which the total product is much lower in protein. For present space capsules we have heard references to leak rates so high that concern for the CO_2/O_2 ratio and, indeed, attempts at any regenerative system for gas exchange, would be absurd. If it is at all proper to give attention to regenerative systems for long missions, one must assume that leak rates of enclosures will be reduced to such a point that they will be small compared to the gas exchange of human occupants. Presumably, there will always be some residual leakage which will give rise to loss of O_2 faster than loss of CO_2. To be effective, a regenerative system will require a CO_2/O_2 quotient *less* than that of the human.

An important characteristic of algal metabolism not shown in table III is the efficiency of the process. Efficiency of total cell synthesis in two species of *Chlorella* has been measured as the heat of combustion of cells produced divided by the absorbed visible light energy. The results submit to statement of a *maximum* efficiency close to 20 percent, a respectable value in view of the multiple steps required.

I have discussed the photosynthetic exchanger largely in terms of gas exchange. Without exchange of O_2 and CO_2 we cannot regenerate food. Significance of the algal product as food for the human will be discussed separately. It would be reasonable to expect that the algal product can be made to provide some significant fraction of the nutritional requirement for the human.

Up to this point, the photosynthetic exchanger looks so favorable that one must inquire why it is still so far from a shelf item and why even its feasibility is in question. The major difficulty is that it has not easily submitted to miniaturization. I shall suggest some reasons for the difficulty.

As a form of energy, light is peculiarly hard to manage. (For example, we cannot store it at all.) Efficient power transfer to a photochemical reaction has special restrictions. A photochemical system is tuned or frequency-specific while our best light sources are rather wide band generators. Among photochemical systems, photosynthesis is remarkable in that it can use a frequency band which contains even as much as 40 percent of the energy in the whole solar spectrum. But there is one difficulty more serious than any of these. It lies in the necessary gradient which always attends light absorption and in a special characteristic of photosynthetic machinery.

Figure 2 shows a typical relation between rate of cell synthesis and rate of input light energy to an algal cell. The specific growth rate k (a

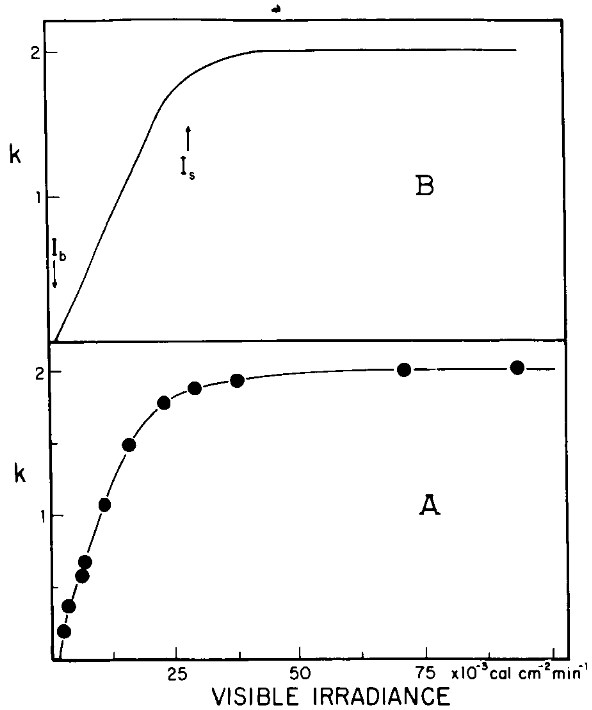

FIGURE 2.—Specific growth rate k as a function of irradiance. (A) Experimental data obtained on a thin suspension of *Chlorella* in a steady-state device and with filtered tungsten light. (B) A simplified curve used for discussion. I_b, irradiance to maintain basal metabolism of the cells; I_s, irradiance at which growth rate becomes light saturated.

first order reaction constant in days^{-1}) is plotted against incident visible irradiance for experimental data (A) and diagrammatically (B). Up to a value of irradiance, I_s, growth is limited by rate of light energy income and proceeds at close to maximum efficiency. Above I_s growth becomes light-saturated and efficiency decreases with further increases in irradiance. The difficulty is that I_s has such a low value (in fig. 2 at about 1/20 of full sunlight). The plant chloroplast maintains a pigment system (antennae) with a high capacity for collecting light quanta. At high irradiance it absorbs light at a rate faster than the photochemical products can be processed into cellular material. This high light absorption is a sensible arrangement for the plant. It is an extreme disadvantage to our applied problem of compacting a photosynthetic exchanger.

We can examine the problem in terms of figure 3. The curves describe a simple Beer's Law decay in irradiance, I, in any culture in which cx represents the quantity of algae per unit of irradiated surface. A cell at the front surface absorbs light at a rate proportional to incident irradiance, I_o, but it works only at a rate proportional to I_s. The total light absorbed is measured by the area under the curve. The fraction of absorbed light used with maximum efficiency is measured by the (shaded) area below I_s. By increasing the incident irradiance we can increase the productivity of a culture, but only with a penalty of lowered efficiency.

This argument has been presented in a simplified and intuitive fashion. It ignores a number of second-order effects with which our laboratory has been concerned. However, we are here concerned with the principles rather than

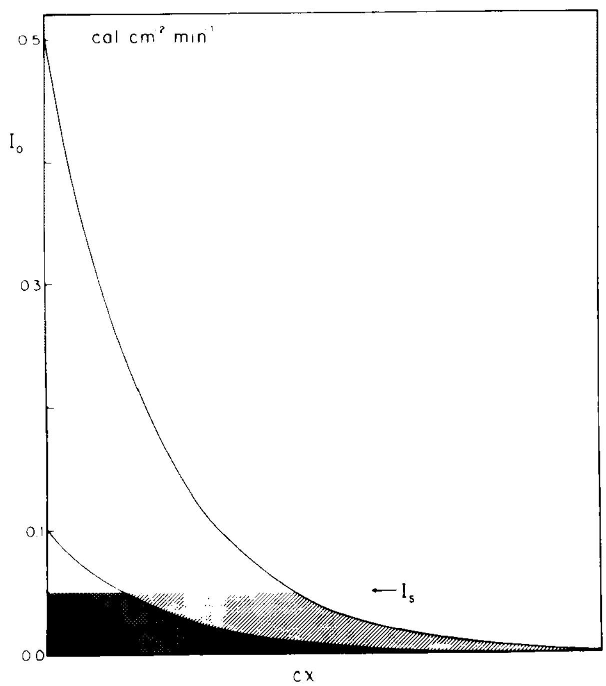

FIGURE 3.—Irradiance in an algal suspension as a function of cx, the quality of algae per unit area of irradiated surface. The two curves describe different values of I_o, the incident irradiance. I_s is defined as in figure 2.

with the details. When developed mathematically as the Bush equation, the argument allows prediction of the production rate of any algal culture at a given irradiance. Figure 4 presents the relation between production rate and incident visible irradiance using parameters which are reasonable but not necessarily correct. Approximate agreement between the curve and reported experimental values should not be taken seriously because of admitted uncertainties in validity of some of the experimental values.

The intent of figures 3 and 4 is not one of presenting reliable relations between production rate and culture irradiance. The intent is to call attention to two essential features of design criteria. The first is that the most important design consideration is attainment of a very large illuminated surface area as viewed by the algal culture. Because of ultimate concern for minimum volume, many workers have been led to think in terms of production rate per unit volume. It is far more instructive to consider production rate per unit illuminated area as the primary criterion. Thereafter, the problem becomes one of achieving minimum culture thickness x in design and maximum cell concentration c by attention to culture medium.

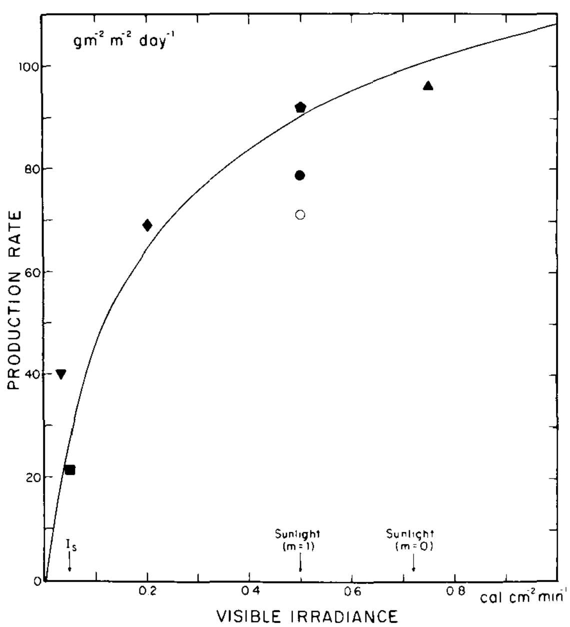

FIGURE 4.—Production rate per unit area of illuminated culture surface plotted against incident visible irradiance. The curve is that predicted by the Bush equation using reasonable values. The points represent reported experimental values.

A second design feature evident in figure 4 is that there is a necessary relation between power requirement and surface area. Reduction in surface area (and hence in volume) can be accomplished by higher incident irradiance, but only at a penalty of decreasing efficiency and increasing power demand. Even if we have a wealth of power, efficiency still is a concern for a low efficiency means an increased heat loading and increased gear for heat dissipation.

There are valid arguments for and against concerted effort toward practical development of an algal photosynthetic exchanger. One can point to large gaps in our knowledge of the metabolism and nutrition of algae and their nutritional usefulness to man. However, one can also assert that the unknowns and difficulties are more apparent than with other regenerative systems simply because efforts have been pushed further. Algal cultures can be managed reliably over long periods of time and offer many inherent advantages. At the same time, attempts at compacting to minimum weight and volume have not been notably successful. There have been numerous attempts at small-scale and pilot-plant models. These have started with some chosen premises, selected one of several possible light sources, and proceeded to examine performance of the design chosen. As a result we have a sizable body of information, largely buried in reports. But we have had no rational development which leads to design principles and thence to solid evaluation.

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Discussion: Combined Photosynthetic Regenerative Systems

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In the preceding paper a thorough exposition was given of the problem of survival for man in an environment which is lacking in the nutritive support to which he has become accustomed on Earth. The model for supplying man with his requirements for existence is based upon that which is both common and successful on Earth. In simplest terms, what is proposed should be considered a potentially balanced system, with men supplying the needs of plants and vice versa. The energy to power the system is to be supplied in the form of light. This kind of system works and is proven. Our present existence precludes debate on that particular point.

The only question is to determine to what degree our ingenuity will permit the simplification and compression of the plant-man interdependence to a size which is manageable, either for space travel or for a Moon or planetary base. In such a compression and concomitant simplification, one is forced to exchange the inefficient, very stable, and inexpensive natural environment of Earth for the necessarily more efficient, but less stable and very expensive, climate of a closed capsule—a capsule, by the way, in which ecological stability is purchased by the expenditure of relatively large amounts of energy and which is predicated on meticulous attention to the maintenance of the optimum metabolism of both plants and men. Any serious deterioration in the metabolism in either of these two components will obviously result in the loss of the whole system. Superior biological engineering as an adequate compensation for the checks and balances of this still uncrowded planet is absolutely critical for the survival of both members in a closed capsule.

A source of frustration to biological scientists being asked to assist in designing space machinery is the frequent inability of the engineers to understand the complexity and variability of the organisms which are to become parts of this operational system. The engineers on the other hand have been asked to provide hardware to support organisms about which our knowledge is remarkably primitive in spite of centuries of study, and for which vital data are either lacking or, if present, are seriously debated. It is exceedingly difficult to translate biological data into operational systems. This is a built-in problem in doing the things we wish to do in space, and neither the biologists nor the engineers need apologize for it. However, it is incumbent on both to understand the needs and limitations of the other. In no case is this more true than in the attempt to construct a photosynthetic regenerative system and in the procurement of tentative designs for an apparatus which will function efficiently and safely for long periods. It is imperative that we have a reasonable mechanism for reconciling the conflicting requirements of both the engineer and the biologist.

No attempt will be made herein to provide the details and to suggest decisions that must be made in arriving at the design for any tentative photosynthetic gas exchange unit. The additional problems which attend the use of the algae byproduct of a gas exchanger for the nutrition of the astronauts would require an exhaustive treatment. (See ref. 1.) Instead, this paper is concerned with a few of the problems to be faced in determining what must be done to provide a functioning apparatus. How successful bioengineers prove to be in synthesizing a system from the facts at hand will determine the size of that system, and, in turn, will dictate the minimum length of the mission it will be feasible to support by biological regeneration. First, some of the options available in selecting appropriate organisms should be mentioned; and, second, certain engineering requirements stemming from this choice must be examined. This can give an overall view of the problems we face in beginning to think about the construction of flight systems.

Dr. Myers has presented some cogent reasons for the use of the alga, *Chlorella*, as a highly efficient photosynthetic plant—a plant which is comprised primarily of working machinery rather than dead cellulose. This working machinery can be employed as a component of a manageable apparatus which can serve as a source of food as well as oxygen. One must keep in mind that much of the data that have been presented with regard to the stochiometry of the critical reactions performed by the alga are based upon actively growing, rapidly metabolizing organisms which are reproducing at almost their maximum growth rate. When conditions are changed so that the growth rate is less than maximum, there are certain metabolic shifts which may, for brief periods of time, or even for long sustained periods of time, modify the overall chemical syntheses in which the cell is engaged (ref. 2). This change may be better visualized if we examine the structure of a few of these small plants which show visible changes in the cells under differing culture conditions.

The organism in figure 1 is *Chlorella mutabilis* Shihira and Krauss, one of many species of the genus (ref. 3). It has a chloroplast which, instead of being large, cup-shaped, and parietal as in many species of the genus, is actually disk-shaped and not conspicuously parietal. The species does, however, demonstrate the major involvement of the cells with photosynthetic machinery. Along with the photosynthetic machinery, each cell contains all the elements of metabolism and reproduction to allow for a complete life cycle as long as a satisfactory environment is provided.

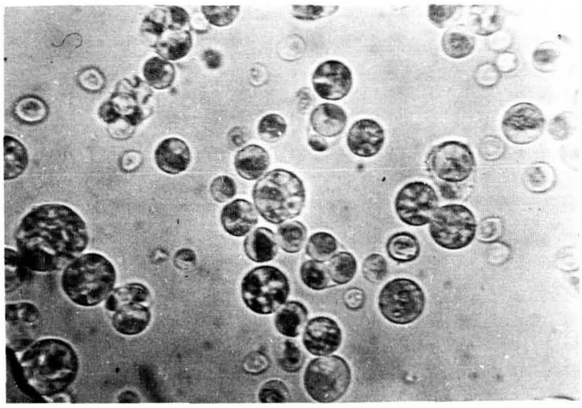

FIGURE 1.—Cells of unicellular alga *Chlorella mutabilis* grown on inorganic medium at an illuminance of 400 foot-candles. (×1350)

As can be seen in figure 1, this genus has a very simple life cycle. Small, newly released "daughter cells" grow rapidly to become large "mother cells". These in turn form from 2 to 128 "daughter cells", often called autospores, which are liberated when the mother cell wall ruptures. Several cells in figure 1 are about to divide. The process of small spherical cells becoming large cells and then subdividing does not involve any sexual phase and is one of the simplest reproductive systems existing in the algae. Although the external appearance of the growing and reproducing cell appears to change primarily in size, there are great but subtle differences in the internal biochemical apparatus. That the cells do change during their life cycle has been clearly demonstrated for pigment and nucleic acid concentrations, photosynthetic and respiration rates, vitamin levels, and in sensitivity to thermal extremes. This capacity for change is also manifest in the many responses that the cells make to changes in their environment (ref. 4).

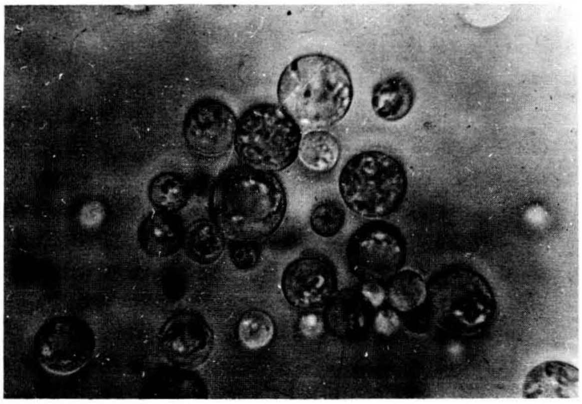

FIGURE 2.—Cells of unicellular alga *Chlorella mutabilis* grown on organic medium in total darkness. (×1350)

Figure 2 shows the same species as in figure 1 except that it has been cultured for some time in darkness. Its adjustment to lack of light has been to convert to an entirely different metabolism associated with the loss of all green pigment and the production of cells which are almost transparent. This is a healthy rapidly growing culture that has been cultured on glucose in darkness for only a brief period of time. The organisms are colorless and when recovered from the medium after centrifugation, appear to the naked eye as a white, odorless paste.

The algae will vary in chemical composition depending on the way in which they are grown. Normally most species of *Chlorella* are about 60 percent protein, with fat and carbohydrates comprising most of the remaining 40 percent. It cannot be too strongly emphasized that this differs with the species and the conditions under which they are grown. Many examples can be found of the things that happen biochemically when these organisms are grown under different conditions of nutrition or in various physical environments.

One further example should suffice to illustrate the differences in species of *Chlorella* as well as the responses of these species to their surroundings. The alga in figure 3 has recently been isolated from sea water and is being named *Chlorella anitrata*. It has been established that nitrate is toxic to this species. It grows normally at a very high rate in media in which nitrogen is supplied as ammonium, but if nitrate is present in the solution, the organism is badly damaged, its growth rate is reduced and it becomes gigantic in size.

The same organism but grown on ammonium nitrate is shown in figure 4. Similar modifications can be obtained with other species by other manipulations of the medium. A large number of species are now available, each of which has characteristics which may, or may not, be advantageous in a closed system depending upon what conditions are imposed upon it. Much depends on what the nitrogen source is going to be. More depends on the rates of growth that are desired, the kind and intensity of light, the temperature, the agitation rate, and so forth. Many options exist with regard to organisms and to the way in which they may be cultured. The genus *Chlorella* is varied and the species within it are versatile, and, as we are beginning to learn, mutabile. Furthermore, there are other genera which possibly may match a given engineering specification better than *Chlorella* does. However, the existing knowledge concerning them is far less than our knowledge of *Chlorella*.

With some background concerning the nature of the photosynthetic organisms available to us it should be profitable to recall certain engineering considerations which will be significant in the use of such algae in a man-plant system. Figure 5 gives the electromagnetic energy spectrum from within which photosynthetic

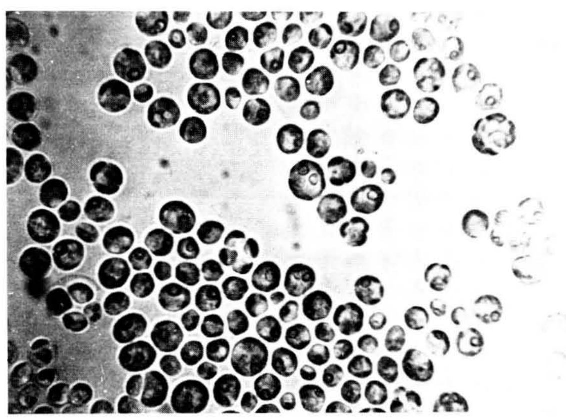

FIGURE 3.—Cells of the unicellular alga *Chlorella anitrata* grown in light on an inorganic medium containing nitrogen supplied as NH_4Cl. (×1350)

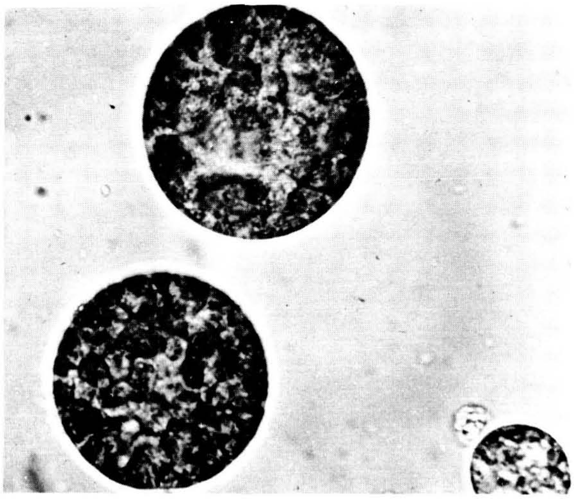

FIGURE 4.—Cells of the unicellular alga *Chlorella anitrata* grown in light on an inorganic medium containing nitrogen supplied as NH_4NO_3. (×1350)

organisms obtain the necessary energy for life. This is a very complete compilation (from ref. 5) and we are concerned with only certain aspects of it. This figure gives the solar energy distribution outside the Earth's surface and is approximately the range that can be expected in the photic zone around the Earth, Moon, and, even, Mars. On very long space trips the amount of light received by a traveling spacecraft, or by a space station, is progressively less as the space ship travels away from the Sun. Even on Earth, a fair amount of energy is filtered out before it reaches the surface of the planet. However, when dealing with electromagnetic energy, the plant is not only receiving the useful energy for photosynthesis, which occurs in the same range as human vision but is also absorbing radiation which is not compatible to life. Both ultraviolet and infrared radiation may be destructive—the first through direct

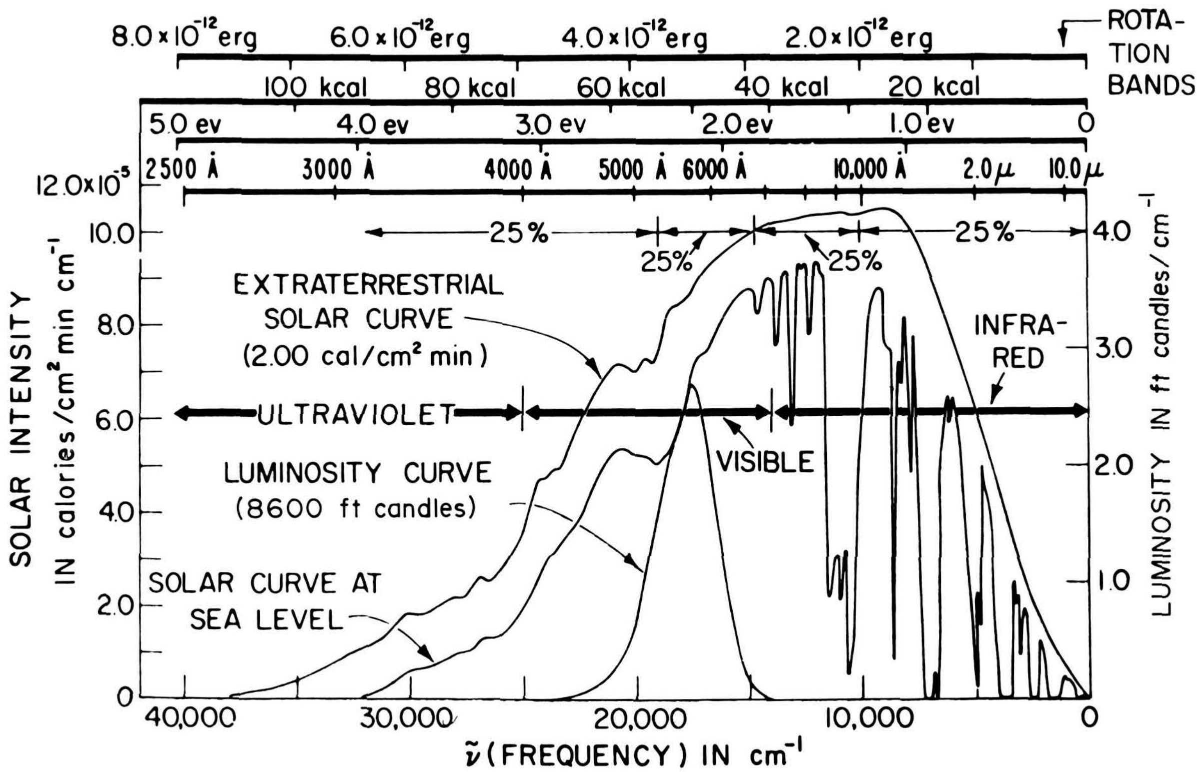

FIGURE 5.—The frequency distribution of solar radiation (ref. 5).

effect on nucleic acids and the second by simple elevation of the temperature. The design of apparatus, using either solar energy or the energy from artificial light sources, must include a certain degree of screening to remove damaging ultraviolet radiation and some method of cooling to permit the organism to grow in a favorable temperature range.

The approaches to both screening and trapping the energy of this spectrum for algal photosynthesis have been many and the literature is filled with solutions. They employ two basically different methods. The first is a solar energy converter using the natural light which is presumably free in space and is available whenever the spacecraft is not in a planetary shadow. The second method requires the use of generated electrical energy (which may be powered by a nuclear reactor as Dr. Teller mentioned in a preceding paper) that will provide illumination either through incandescent lamps or fluorescent tubes or panels.

Figure 6 illustrates one form of solar energy converter on a very large scale. This is a Japanese plant for growing algae. It covers about a tenth of an acre and produces large amounts of algae. Although it is still an inefficient system compared to laboratory apparatus, it has the advantage of producing algae at efficiencies which are above those for conventional crops of higher plants. The harvesting apparatus for extracting algae from the nutrient solution, which is found in the buildings behind the vats, constitutes a large portion of the installation and is always a problem whether in

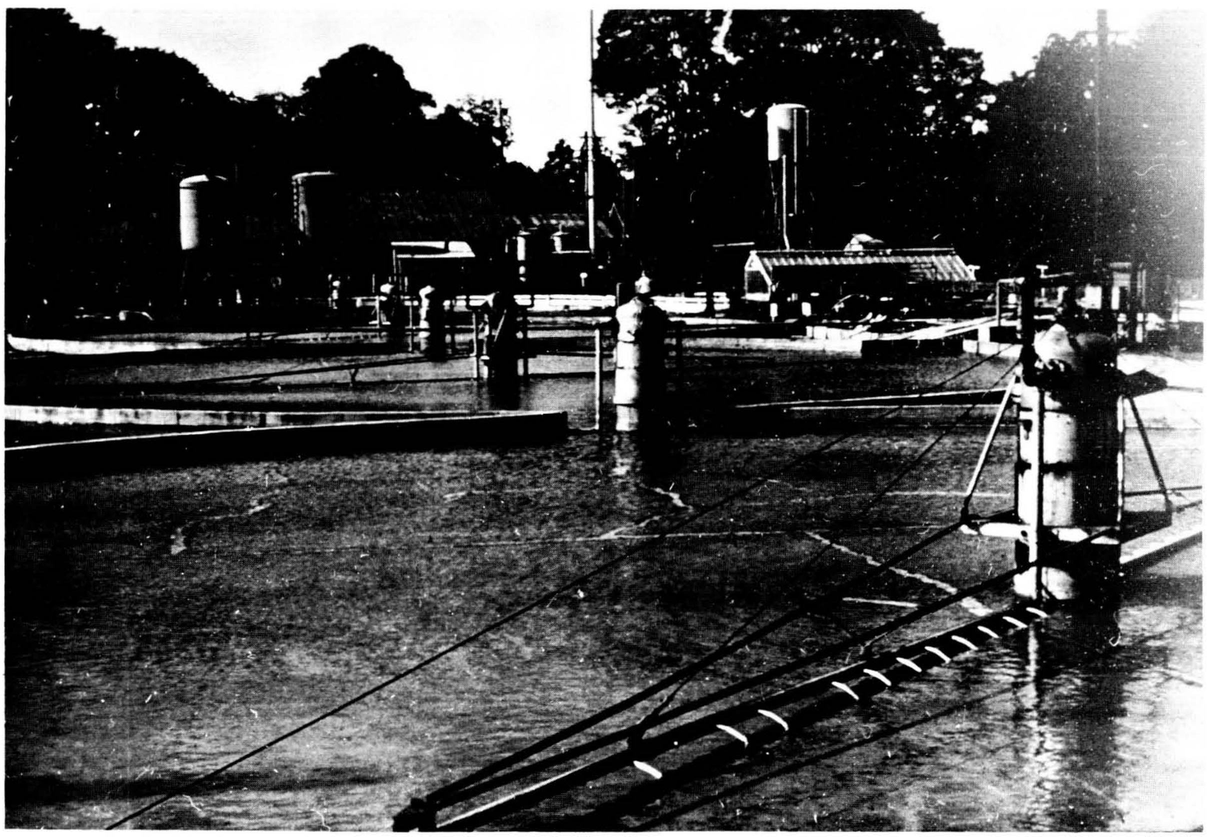

FIGURE 6.—The large algal culture plant at the Microalgae Research Institute, Tokyo, Japan.

solar or artificially illuminated cultures. Something approaching this type of installation might be useful in an extraterrestrial base. However, such a system is much too extensive to be employed in the cabin of a spacecraft.

Figure 7 is a diagram of a much smaller but more sophisticated apparatus that has been used for routine culture of algae for experimental purposes (ref. 6). It is not intended as a prototype for space hardware, but does include the elements which must be included in any flight gas exchanger. The chamber for the culture of algae is inside an aluminum box in which there is a device for illumination. It also includes various monitors for determining how fast the culture is growing and for determining the rate of gas production. For a relatively small culture of algae, a significant amount of hardware is required. There has been no attempt to miniaturize this apparatus and consequently there is a much greater amount of supporting equipment per unit of culture than might ordinarily be expected. In view of the fact that, in terms of the components this may be termed a prototype, it should be useful to consider the major elements of this design which we call the "Recyclostat".

The algal culture occupies a relatively small space in the center of the illuminated box. It is contained in a cylindrical glass chamber equipped with air- and medium-inlet ports at the bottom and with a harvesting port at the top. It is illuminated either by fluorescent lamps or, if the experiments should require a very great illuminance, by iodine vapor incandescent lamps. The temperature of the chamber is held at any desired level by the presence of a water-cooled heat exchanger upon which it rests. Whenever high light intensities are used, water filters are required to remove as much infrared as possible. The heat developed when the illuminance is less can be controlled by the heat exchanger. Refrigeration devices serve to cool the water filters and to provide coolant for the heat exchanger in the base which supports the culture.

A necessity in any automatically controlled device is the presence of a monitoring system. In our Recyclostat, a photodiode, absorbing primarily in the infrared, has been employed as the sensing element to measure the density of the algal population. The growth of this culture is transmitted to the recording system in units of diluent medium required to keep the population constant. The investigator can tell at a glance how the culture is performing. The data can readily be converted to growth rate per 24 hours.

A critical matter in producing algae is a system for harvesting. This has been solved in the Recyclostat by a filter system. Aliquots of the culture are pushed out of the culture chamber by air pressure as fresh medium is added. The algae are recovered on a plastic millipore filter. The nutrient solution is collected and returned to the culture apparatus. This permits recycling of the medium so that there is no water loss. The Recyclostat is designed to grow algae on the recycled medium for an extended period of time with only the exhausted nutrients replenished from outside (ref. 7).

Culturing algae in an apparatus like this is not difficult so long as fresh sterile medium is permitted to flow through the culture and no effort is made to close the system, recycle it, and preserve the water. As soon as the additional requirement of recycling is added, the engineer is faced with a major problem of preventing the introduction of bacteria into the culture. In the Recyclostat preservation of sterility is accomplished by means of bacterial filters installed in the medium return-line just after the point at which the cells are harvested.

The results of experiments performed in this device thus far are of considerable interest. They are especially revealing in that they provide an hourly record of growth in the culture and show the fluctuations which are encountered in the growth rate. Figure 8 gives the growth of a culture grown in the Recyclostat over a period of just 24 hours at an illuminance of 1600 foot-candles. During the course of the growth of the culture there were significant fluctuations in cell production. Projections of growth rate and yield based on some of the high readings which can be obtained over short pe-

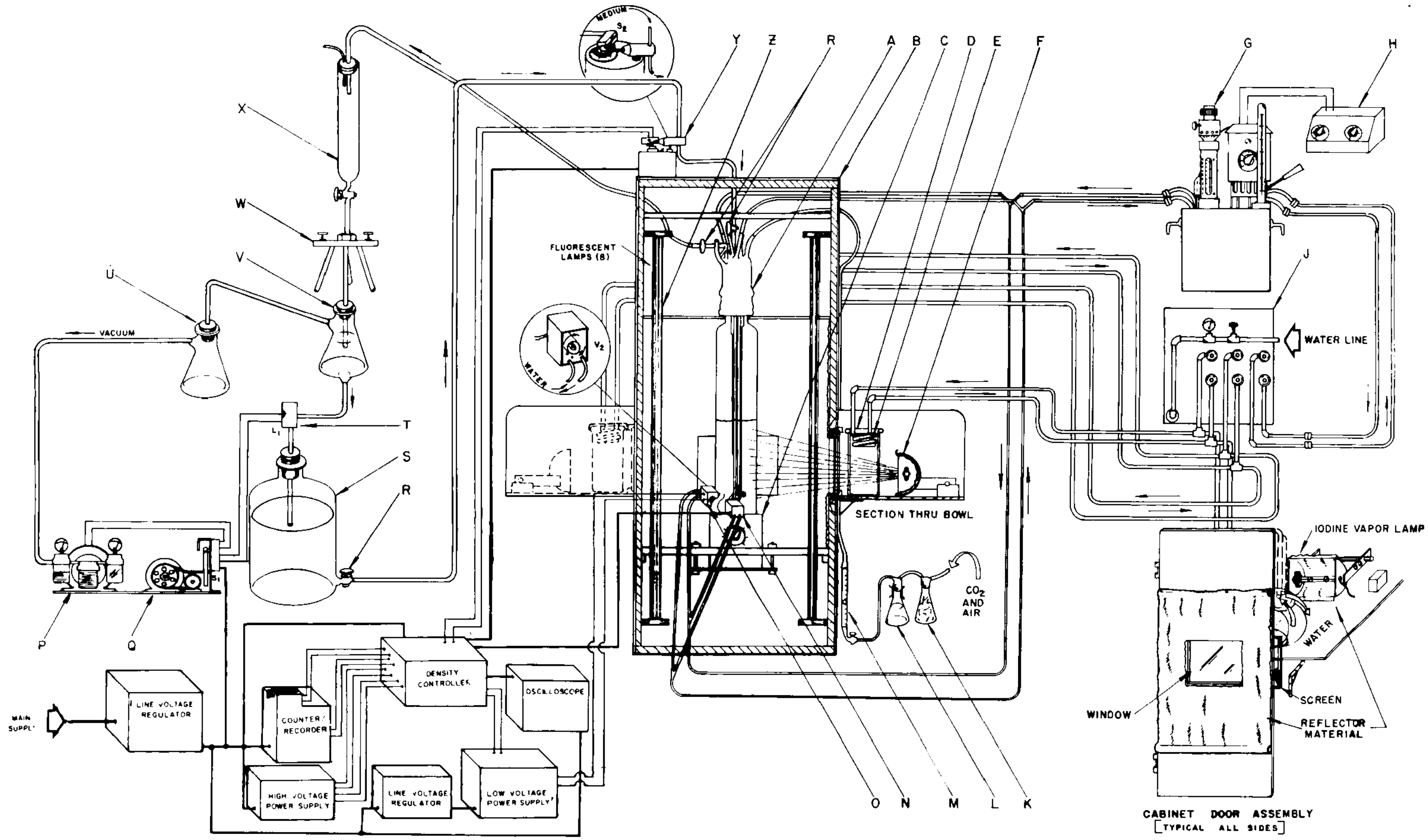

FIGURE 7.—A diagrammatic representation of the Recyclostat, a continuous culture apparatus for algae. The system provides for sterile culture, harvest, and recycling of medium which is continuous and automatic. A—Culture chamber (including top and bottom as one callout); B—cabinet; C—electric stirrer; D—water filter; E—cooling coil; F—high intensity "Quartzline" iodine vapor lamp; G—temperature regulator; H—potentiometer; J—water cooler; K—gas filter, cotton; L—gas filter, water; M—flow meter; N—Photo Duo Diode; O—reference lamp (V_2); P—vacuum pump; Q—timer; R—stopcocks; S—recycled medium reservoir; T—solenoid (L_1); U—vacuum trap; V—intermediate supernatant reservoir; W—membrane bacterial filter; X—overflow receiver; Y—flow inductor; Z—fluorescent lamp.

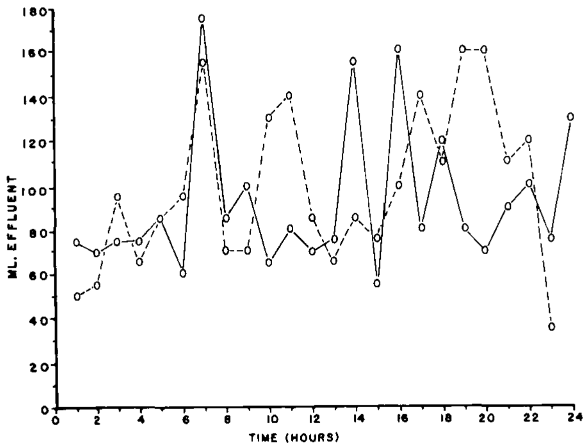

FIGURE 8.—Growth of *Chlorella* in Recyclostat showing hourly fluctuations of growth in terms of milliliters of medium required to keep population constant per liter of culture.

riods of time, might be quite different from those obtained if the lower rates were selected.

Not only are these fluctuations obvious for short-term experiments, they were also present during long experiments. Figure 9 shows the same fluctuations. This plot was obtained by averaging three experiments conducted during periods of 12 days each. There was a clear periodicity in the growth of the culture. So far as can be determined, all cellular requirements such as the nutrients, favorable temperature, and light were held constant, but still there were major fluctuations in growth. This was quite disturbing, because there are no satisfactory explanations for the fluctuations that are encountered.

In summary, it should be clear that strong engineering support is essential if we are to provide a reliable design for a photosynthetic regenerative system. Improvement of the reliability of very long term experiments is needed so that accurate predictions can be made of what can be done in a realistic flight apparatus. A photosynthetic regenerative system is indeed feasible. How feasible it will be depends on a thorough understanding of both of the organisms which are to be components of the space capsule. One cannot but reflect on the amounts of time and energy that are being directed toward further research on the human component, although we have centuries of medical research behind us and large amounts of data. A start has been made in developing our knowledge of the algae, but there is a definite need for a similar order of magnitude in research about the algal component of the space capsule. Such an effort must be made if any degree of reliability is to be assumed in the ability of the alga to support the man.

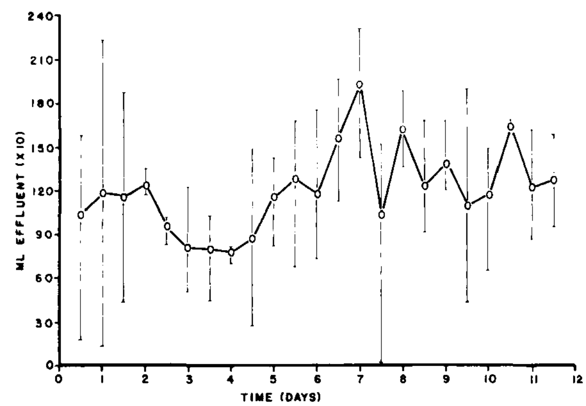

FIGURE 9.—Growth of *Chlorella* in Recyclostat showing daily fluctuations of growth in terms of milliliters of medium required to keep population constant per liter of culture. The curve shows averages of determination for three 12-day experiments.

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Animal Food for Astronauts

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Those nutrients which are needed by the animal as specific chemical substances, such as essential amino acids and fatty acids, vitamins, and mineral salts, make up but a small part of human food and can be taken into space as pills. The bulk of human food is regarded as fuel to supply the energy for the formation of ATP (the biological energy currency) and the production of heat.

ANIMAL ENERGY UTILIZATION

The nutritive content of food as fuel may be expressed as food energy. Assuming that the astronaut's food (as fuel) has to come from animals, can we speculate what types of animals should be taken with him? To show a basis for such speculation, we have to discuss some principles of energy utilization for the production of animal substance.

The chemical energy of a food is measured by its *heat of combustion*, that is, the heat produced when it is burned in a calorimeter, usually in a bomb under 25 atmospheres of pure oxygen. A considerable part of the chemical energy of the ingested food leaves the animal as chemical energy in feces, urine, and methane. The rest is called the *metabolizable energy*.

In animals that are just maintained (that is, without net gain or net loss of body substance), all the metabolizable food energy appears as heat. In growing or lactating animals, however, up to 30 percent of the metabolizable food energy may be found as chemical energy in produced body substance, milk, and so forth.

The following scheme illustrates the situation and defines net energy:

- Food energy (heat of combustion)
  - Digested energy
    - Net energy (chemical energy in increase of body substance, milk, etc.)
      - *1 g protein = 5.7 kcal*
      - *1 g fat = 9.5 kcal*
      - *1 g glycogen = 4.2 kcal*
    - Heat increment (calorigenic effect of food)
    - Chemical energy in urine and methane
  - Chemical energy in feces

If food intake is expressed in terms of metabolizable energy, then the result is either net energy or heat, and we can formulate as follows:

Energy in animal product (as fuel for man) = Metabolizable energy in animal food − Animal heat production

To facilitate generalizations on food utilization, the heat production of the animal can, theoretically, be regarded as the result of two components:

(1) The heat which the animal presumably would produce at the cost of its own body substance if it were fasting. This, if expressed per unit time, is usually called the *basal metabolic rate*, a term originally defined for human beings but, somewhat more loosely, now generally applied also for animals in post-absorptive condition and resting at a comfortable environmental temperature. In animals, resting cannot usually be as strictly maintained as in man. The present discussion is limited to the range of environmental temperatures within which temperature changes do not affect the metabolic rate. For a more thorough discussion extending to low environmental temperature, see reference 1.

(2) The difference between the rate of animal heat production and its basal metabolic rate is known as the *heat increment* or the *calorigenic effect of food*. By an error in the translation of a name chosen by Rubner, "Spezifisch dynamische Wïrkung," this effect is often called in English "Specific Dynamic Action" (SDA), even though the effect is neither specific nor dynamic.

EFFICIENCY OF FEED UTILIZATION

The success of animal production in terms of energy utilization is measured by the *total efficiency*, defined as the quotient of the chemical energy in the animal's product and the chemical energy in the corresponding feed which may be expressed as total, as digestible, or as metabolizable feed energy.

The *total efficiency* depends on the composition of the ration and on the ratio of basal metabolic rate and rate of feed intake.

The *partial efficiency* characterizes the suitability of the feed. It is the quotient

$$\frac{\Delta G}{\Delta I}$$

of a change in gain and the corresponding change in feed intake.

To find the relation of the total and partial efficiency, gain may be formulated as follows:

$$G=e_p(I-M) \tag{1}$$

where

e_p = partial efficiency
I = intake of feed energy
M = maintenance requirement

Therefore,

$$\frac{G}{I}=e_p\,\frac{I-M}{I}=e_p\left(1-\frac{M}{I}\right) \tag{2}$$

The maintenance food prevents the loss of body substance equal to the basal metabolic rate B. If for simplicity's sake, we assumed the same partial efficiency e_p for gain and for maintenance, then

$$B=e_pM \text{ or } M=\frac{B}{e_p} \tag{3}$$

This result introduced into equation (2) leads to

$$\frac{G}{I}=e_p\left(1-\frac{1}{e_p}\frac{B}{I}\right)=e_p-\frac{B}{I} \tag{4}$$

To get a rough approximation on the efficiency of good farm animals, we may assume that their rate of gain is about equal to their basal metabolic rate and that their partial efficiency for the metabolizable energy is about 60 percent. In this case, $B=G$; therefore,

$$\frac{G}{I}=0.3\quad 2\frac{G}{I}=e_p\quad \frac{G}{I}=e_p\frac{G}{I}$$

That is, the total efficiency of the metabolizable energy is 30 percent.

BODY SIZE AND EFFICIENCY OF ENERGY UTILIZATION

The ratio $\frac{B}{I}$ in equation (4) is the reciprocal of what may be termed the relative food intake $\left(\frac{\text{Rate of intake of food energy}}{\text{Basal metabolic rate}}\right)$.

Neither the partial efficiency (criterion for nutritive content of feed) nor the relative food intake is related to body size. Therefore, the efficiency of energy utilization is independent of body size (ref. 2). As early as 1908 Rubner (ref. 3) found such a rule in the special case of doubling the birth weight with an efficiency of 35 percent, and Mayer (ref. 4) formulated the total efficiency of rat growth as a function of age by the following equations:

For male rats: $e_{tot} = 0.81 - 0.346 \log t$

For female rats: $e_{tot} = 0.78 - 0.388 \log t$

where

e_{tot} = total efficiency of energy utilization

t = time after weaning

RELATIVE RATE OF PRODUCTION

If energy utilization is a critical limitation of space travel, then astronauts should be trained as vegetarians. But if energy is abundant, as in fact Dr. Teller has suggested in explaining his "Project Moses" (providing water on the Moon), then one may consider producing animal substance for human food in space. In this case one may ask what type of animal should be taken along to Mars or Venus? This discussion is limited to one aspect of this question: Would large or small animals be more suitable?

As previously mentioned, efficiency of energy utilization is essentially independent of body size and, assuming an abundant energy supply, this efficiency is not important for selection. Important, however, is the load which has to be hauled into space. Therefore, the relative rate of production of human food (which may be measured in calories of chemical energy) per unit mass of the animal, becomes important criterion for the suitability of animals for space animal husbandry.

This relative rate of production as a function of body size may be estimated as follows:

The basal metabolic rate of large and small animals is on the average $70 \times W^{3/4}$ kilocalories per day, where W stands for body weight in kilograms and $W^{3/4}$ is the metabolic body size. (For space travel, body weight becomes variable and practically meaningless, and we should therefore speak of body mass, which for simplicity's sake we may express in terms of body weight at the Earth's surface with the gravitational acceleration of 978 cm/sec^2.)

If we assume that large and small animals are built and composed similarly and also behave similarly (isometric animals behaving isokinetically), then the rate of formation of body substance is proportional to the basal metabolic rate and therefore to the metabolic body size or the ¾ power of body mass.

The relative rate of production in this case is proportional to the metabolic body size divided by the body mass $\left(\frac{W^{3/4}}{W} = W^{-1/4}\right)$, that is, to the reciprocal of the fourth root of body mass. We may also say that the time necessary for a given relative production of body substance increases directly in proportion to the fourth root of body mass.

For the sake of simplicity we neglect changes in body composition and calculate, for example, the duplication time of animal mass. The results of such calculations were based on the weight of a newborn calf furnished by Brody (ref. 6 p. 400) and a calf's birth weight duplication time reported by Rubner (ref. 7). The duplication time ranges for several hypothetical micro-organisms and animals are shown in table I.

Table II shows a somewhat different type of calculation for adult animals, rather than young animals, assuming that in the mature animals the rate of production of body substance measured in kcal of chemical energy is equal to their basal metabolic rate.

TABLE I.—*Duplication Time of Birth Weight*

[$dw/dt = 0.041\ W^{3/4}$; $t_{dupl} = 18.6\ W_o^{1/4}$]

Birth weight, W_o, kg	Duplication time, t_{dupl}		
	Days	Hours	Minutes
10^{-15}	3.3×10^{-3}	0.079	4.7
10^{-12}	1.9×10^{-2}	.46	28
10^{-6}	.59	14	------
10^{-2}	5.9	------	------
1	19	------	------
10	33	------	------
100	59	------	------

TABLE II.—*Rate of Animal Production Compared With Body Weight*

Animal	(1) Body weight, W kg	(2) Production rate, 70 $W^{3/4}$, kcal/day	(3) Production rate per kg, (2)/(1), kcal/day/kg body weight	(4) Total animal weight to produce 7.4 Mcal/day, 7400/(3), kg	(5) No. of animals to produce 7.4 Mcal/day (4)/(1)
Cattle	500	7400	14. 8	500	1
Sheep	50	1310	26. 2	283	6
Rabbits	5	235	46. 8	158	32
	1	70	70	106	106
Rats	. 25	24. 8	99	74	296
Mice	. 025	4. 4	174	42. 5	1700

Note in column (3) that the rate of production per kilogram of body weight ranges from 14.8 kcal/day for cattle to 174 kcal/day for mice. Especially interesting for space-flight nutritionists is column (4). To produce 7.4 megacalories of human food, which is abundant for two men but may suffice for three, a steer of 500-kg body weight has to be hauled into space. The same amount of food is furnished by 296 rats which weigh 74 kg or by 1700 mice with a weight of only 42 kg.

When weight is important, the astronauts should eat mouse stew instead of beef steaks.

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Discussion: Animal Food for Astronauts

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Under conditions existing on Earth, Dr. Kleiber's concept of efficiency of production per unit of space would certainly support his conclusion that "mouse stew" can be produced more efficiently than beef steak. Yet the significance of the effects of various foods upon morale, and performance cannot be ignored. We are all aware of the effects on troop morale of the unpalatable C and K rations of World War II, even though the diets were nutritionally adequate. The importance of acceptability of food cannot be ignored, since complete nutritional adequacy is only one measure of a food's value. The importance of acceptability and satiety cannot be completely evaluated, because of its influence upon morale, and thereby performance. Consequently, the question of mouse stew versus beef steak may become a point of morale and performance instead of merely one of efficiency. It could well be that in space flight we may need to sacrifice somewhat in efficiency in order to achieve morale and performance.

A second unanswered question is how various animals may respond to the conditions of stress imposed by space flight. An interesting study by Smith and Kelly (ref. 1) deals with the effects of chronic acceleration upon growth and body composition. The authors devised a centrifugal device that subjects chickens to chronic acceleration for various periods of time and gives significant information on the effect of increased gravity upon various physiological responses and ultimately upon body composition. Short periods of mild acceleration of 1.5 g or less enhanced growth. Under such conditions, the birds showed improved appetites and there was no special tendency to seek feed and water when the centrifuge was stopped momentarily.

At higher fields of gravity (about 3 g), where the birds' movements become restricted, food or water deprivation may become a factor. However, this is not the only factor, since acceleration-adapted (3 g) birds die after 6.3±0.4 days when deprived of food and water, whereas control birds survive 12.8±0.4 days under the same conditions. Similarly, birds becoming sick from acceleration per se die within a few hours or days, suggesting that acceleration has a pronounced effect upon their physiological responses.

The same authors then made detailed analyses of the bodies of the birds subjected to the various conditions. A summary of some of the data is given in table I. Results are given in terms of the soft tissues only, although data on all body parts were obtained. The data demon-

TABLE I.—*Composition of Control and Accelerated Birds—Soft Tissues Only*

	Dry matter, percent	Fat, percent
Female:		
Centrifuged	24.5±0.5	1.95±0.36
Controls	32.6±2.7	12.12±3.34
Male:		
Centrifuged	24.5±0.3	2.25±0.68
Controls	30.3±1.5	8.80±1.81

strate that the control birds have more dry matter and more fat. The increase in dry matter appears to be mainly if not entirely due to the change in fat content. Acceleration obviously had a marked influence upon composition.

An interesting and consistent change in relative shank mass has been observed in the birds subjected to centrifugation. The shank mass of the accelerated birds averaged about 40 percent greater than that of the controls. Detailed studies have shown that the increase in shank mass was not due to differences in bone size or to edema, since the water content of accelerated birds was similar to that of control birds. Obviously, acceleration could conceivably greatly influence both composition and relative body proportions.

The work on chronic acceleration merely serves to illustrate the effects upon composition of altering gravity. Naturally, little is known about the influence of subgravity upon body composition or relative body proportions. Not only may subgravity influence the composition of man and lower animals, but the severe degree of confinement in space flights may have a profound effect. One of the great unanswered questions is the effect of such conditions upon different species, including man. It could well be that the exacting scientific approach of Dr. Kleiber based upon our existence upon Earth may be altered by the acceleration to which space travelers, both man and other animals, are first subjected followed by existence at subgravity conditions.

We need ask ourselves two basic questions: (1) What are the long-range effects of acceleration? and (2) What are the long-range effects of subgravity? Only scientific research and experience in space will answer these questions. The relative efficiency of mouse stew and beef steak could well be influenced by the altered environment found in space.

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Plant Systems as Long Term Flight Nourishment Sources

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In man's effort to accomplish successfully space voyages of long duration, one of the major problems is providing adequate nutrition for the astronauts. One possibility is to have all the food required for the duration of the trip packaged in dehydrated and/or liquid form. An alternative plan is to utilize certain selected plant forms growing within the confines of the space unit as components of a balanced ecology. It is hoped that the plants would provide the basic caloric requirements, and most or all the essential vitamins, amino acids, and minerals. The plants chosen should possess maximum capabilities for satisfying, via recycling processes, man's requirements for oxygen and food. Ehricke (ref. 1), in a systems analysis of manned flights to Venus and Mars, has calculated the weight saving which would be accomplished by a successful closed ecological system. This weight differential could be the limiting factor for long-term space missions, since the weight of a nonregenerative system increases more or less linearly with time of mission.

Various regenerative systems, physiochemical and biological, have been suggested and investigated for O_2 production, CO_2 removal, water cycling, and nutritional support in closed systems. This paper will be limited to considerations of the nutritional aspect of plant systems and, in particular, to multicellular (broadleaf) plants.

MAN'S DAILY NUTRITIONAL REQUIREMENTS UNDER SPACE SIMULATED CONDITIONS

Recent investigations of Welch (ref. 2) and associates have provided significant data concerning nutritional requirements of human subjects confined in space-cabin simulators. These experiments, reported in a preceding conference paper by Welch, have been for periods of 2 to 4 weeks and under different atmospheric pressures and compositions. The foods used were liquids, liquids reconstituted from lyophylized solids, and, in some instances, liquids amplified with vitamin concentrates. The general nutritional requirements (obtained by Welch) of these subjects are shown as follows:

Energy, cal	2334
Food (4.3 cal/g dry), g	54. 2
Approximate composition:	
Proteins, g	104. 8
Carbohydrates, g	395
Fats, g	58

Data are not available on the amino acid, vitamin, and mineral constituents, but it may be assumed that the dietary selection was sufficient to provide in excess of the minimal daily requirements of the subjects.

SELECTED PLANT SYSTEMS AS A FOOD SOURCE FOR LONG TERM SPACE MISSIONS

With the establishment of man's general food requirements we come to the primary objective of this discussion—a consideration of the potentialities of plant systems in providing man's nutritional requirements on extended space missions. Most of the investigative work in this field has dealt with the microscopic green plants (algae). Since other papers will cover this phase of work, only comparative references will be made to the algal forms. McDowell and Leveille (ref. 3) have presented a somewhat complete review of nutritional investigations of the algae and emphasize the fact that the most important dietary contribution of algae would be "calories, the heaviest component of any dietary regime wherein part of the diet requires premium transport." The authors also point to the necessity of "more algae for more investigators to study" in order to evaluate fully its potentialities as a food source.

Investigation of higher (broadleaf) plants as nutritional sources for space missions, in comparison with the algal forms, is in its infancy. Some research is being directed toward the nutritional potentialities of certain fungi and bacteria (*Hydrogenomonas*), but, at present, sufficient data for comparative performance are not available.

A literature survey (ref. 4) of the broadleaf plants has been made to determine those species possessing desirable characteristics as components of closed ecologies. Three species were selected for investigation: Chinese cabbage (*Brassica chinensis*), endive (*Cicarium endiva*), and tampala (*Amaranthus gangeticus*). The report of this investigation contains data relating to: (1) photosynthetic gas-exchange rates and ratios, (2) chemical and biochemical assays, (3) growth rates and so forth, but no definitive data pertaining to nutritional studies. Compositional data of these plants grown under artificial light of 2000 foot-candles and normal atmosphere are presented in table I. Vitamin content of the leafy components of the plants is presented in table II, and the amino acid content is presented in table III. Pyridoxine (B_6) and pantothenic acid values were not provided for either of the three plants and none of the values were listed for tampala. Tables II and III also list, respectively, the vitamin and amino acid contents of *Chlorella pyrenoidosa* and *Spirodela polyrrhiza*. It is reported that the sulfur amino acids are lacking in the algae. The fact that certain vitamins or amino acids may be present in submarginal amounts would not negate the choice of the plant because of the availability of supplements at practically no weight penalty.

FEEDING EXPERIMENTS WITH *SPIRODELA POLYRRHIZA*

For experimental feeding with *Spirodela polyrrhiza*, plants were grown in Hoagland's modified nutrient placed in large sealed lucite tanks. Carbon dioxide was kept at concentra-

TABLE I.—*Nutritional Values*

[Data obtained from ref. 4]

Content	Endive			Tampala			Chinese cabbage		
	Leaf	Stem	Root	Leaf	Stem	Root	Leaf	Stem	Root
Moisture, percent, fresh tissue	92. 8	85. 7	95. 8	82. 3	86. 6	92. 6	91. 7	87. 7	93. 2
Ash, percent, dry weight	16. 4	6. 7	20. 5	10. 6	8. 1	15. 0	13. 3	9. 8	20. 0
Protein, percent, dry weight	28. 0	15. 6	38. 0	26. 0	15. 0	23. 0	23. 0	22. 0	41. 0
Carbohydrate, percent:									
Dry weight	42. 2	41. 1	41. 7	42. 2	41. 9	41. 5	40. 2	41. 9	38. 0
Water soluble	24. 6	63. 7	33. 1	17. 6	42. 3	29. 5	40. 1	43. 8	16. 7
Alcohol soluble	23. 5	45. 9	34. 1	7. 1	28. 7	21. 7	30. 2	40. 6	14. 8
Fiber, percent, dry weight	10. 8	11. 6	12. 4	8. 3	18. 7	15. 1	7. 9	21. 9	18. 5
Lipid, percent, dry weight	6. 3	2. 0	4. 5	2. 5	5. 5	4. 6	5. 7	2. 8	2. 7

TABLE II.—*Vitamin Content of Plants*

[mg/100 g dry]

Plant	Pyridoxine	Thiamine	Riboflavin	Niacin	Panto-thenic acid	Ascorbic acid	Carotene	Calories
Chlorella pyrenoidosa [a]	0. 053	0. 35	3. 70	19. 86	3. 44	13. 96	(Ade-quate)	-----
Spirodela polyrrhiza [b]	1. 74	. 40	2. 62	12. 50	3. 58	10. 80	31 000	370
Endive	-------	1. 16	2. 00	6. 70	------	182	50 000	330
Tampala	-------	-------	-------	------	------	242	69 265	-----
Chinese cabbage	-------	1. 67	2. 00	------	------	135	69 880	400
Man's daily requirement (63 kg.) [c]	1. 95 mg	1. 57 mg	1. 80 mg	20 mg	Required	75 mg	5 000	3000

[a] Reference 3.
[b] Rosner-Hixson Laboratories (Chicago).
[c] Reference 5.

TABLE III.—*Essential Amino Acid Content*

[g amino acid/16 g N]

Plant	Phenyl-alanine	Methio-nine	Leucine	Valine	Lysene	Isoleu-cine	Threo-nine	Trypto-phan
Chlorella pyrenoidosa [a]	1. 92	0. 59	3. 22	1. 81	5. 09	1. 39	1. 58	1. 53
Spirodela polyrrhiza [b]	6. 05	. 41	3. 80	1. 86	2. 00	1. 51	1. 35	. 19
Endive [c]	------	8. 68	7. 75	------	9. 28	4. 90	5. 60	------
Tampala [c]	3. 16	6. 86	9. 60	------	8. 96	5. 53	5. 48	------
Chinese cabbage [c]	. 55	3. 31	6. 62	. 26	8. 51	3. 64	4. 00	------
Man's minimal requirement, g/day [d]	1. 10	1. 10	1. 10	. 80	. 80	. 70	. 50	. 25

[a] Reference 3.
[b] Rosner-Hixson Laboratories (Chicago).
[c] Reference 4.
[d] Reference 5.

tions of 1 to 8 percent and oxygen kept below the 20 percent level by intermittent flushing with nitrogen. The plants were harvested at intervals, washed in dionized water, lyophilized, milled in a ball mill, sealed and stored in tinned cans, and placed in a deep freeze at –20° C. The plants were shipped to the Rosner-Hixson Laboratories (Chicago) for chemical and nutritional evaluation. Because of the limited supply of test material only a few pilot nutritional experiments have been performed. Chemical analyses data (obtained by Rosner-Hixson Laboratories) are shown as follows:

Protein (N×6.25), percent	33. 00
Fat	5. 29
Fiber	4. 87
Ash	13. 00
Carbohydrate (by differential)	39. 15
Carbohydrate (determined)	28. 90

This composition along with the results of analyses for vitamins, minerals, and amino acids indicate the possibility of (1) feeding *Spirodela polyrrhiza* as the sole source of nutrients in sustaining the life of an animal and (2) failing in this, of being able to supplement *Spirodela polyrrhiza* with minor additions of other nutrients to accomplish the same purpose.

Because of the limited supply of presently available test material, and because part of this supply must be held in reserve for stability studies on composition, only pilot or single animal tests were conducted in most cases. The following results reported by Rosner-Hixson Laboratories are therefore inconclusive and supply was exhausted.

(1) *Spirodela* as the sole source of food:

(a) One weanling male albino rat died on the 11th day after consuming a total weight of 49 grams of dry *Spirodela* (duckweed). The rat lost weight during the test period and, from behavior involving abnormal wasting of food, it would appear that duckweed is quite unpalatable or is deficient in some vital nutrient. After 6 days on test, the rat's abdomen appeared distended. Autopsy findings indicated irritation of the gastrointestinal tract as evidenced by hemorrhages in the stomach and intestinal lining.

(b) One weanling male rat was fed duckweed moistened with water to reduce possible unpalatability due to dustiness. The animal died on the fifth day, showing the same gross pathology as in case (a). In addition, blood, bilirubin, and protein were found in the urine.

(c) One weanling male rat was fed duckweed moistened with corn oil to reduce dustiness. The animal died on the sixth day showing the same gross pathology as in cases (a) and (b).

(d) Two weanling male mice from two separate colonies were fed duckweed as the sole source of food plus 0.9 percent sodium chloride added to their drinking water. After 3 and 4 days, respectively, the mice were dead, having consumed adequate amounts of drinking water but none of the duckweed.

In the laboratories at the USAF School of Aerospace Medicine (unpublished data obtained by Wilks) four adult male albino mice were fed on *Spirodela* as a sole source of food for a period of 31 days. The food was prepared by mixing dry *Spirodela* flour with paraffin (80 percent flour, 20 percent paraffin by weight). There was a slight weight loss during the first week but this was regained later. All four animals appeared healthy at the end of the experiment, which was terminated at 31 days when the food supply was exhausted.

(2) *Spirodela* as a nitrogen source:

(a) Two weanling male rats were fed the AOAC (Association of Official Agricultural Chemists) ration for determining biological availability of nitrogen shown as follows:

Spirodela, percent (equals 1.44 percent N)	29.0
Salt mixture XV, percent	1.2
Vitamin mixture, percent	1.0
Cottonseed oil	6.5
Sucrose	62.3

At the end of the 4-week test period the N.E.R. values (nitrogen efficiency ratios, grams gained per gram of nitrogen consumed) were found to be 8.6 and 7.4, respectively, for the two rats. These values approximate the nitrogen availability of a protein source such as peanut flour.

(b) One rat from (a) was continued on test but changed at the end of 4 weeks on ration 1 to ration 2 containing double the concentration of duckweed, namely, 58.0 percent. After 6 weeks on ration 2, during which period the rat gained in weight (83 grams) and consumed a quantity of food equivalent to 271 grams of duckweed, the animal was sacrificed, and various organs and tissues were removed and submitted to a pathologist for histological examination. Gross pathology yielded negative findings, but histopathology indicated calcified areas in the kidneys.

(c) One weanling female rat fed ration 2 containing 58.0 percent duckweed for 4 weeks gave the same N.E.R. value (9.3) as with ration 1. Hemoglobin was determined and found to be normal—15.0 grams per 100 milliliters. The animal was then sacrificed, and various organs and tissues were removed and submitted to a pathologist for histological examination. Both gross pathology and histopathology yielded negative findings.

(d) One weanling male rat fed ration 3 containing 43.5 percent duckweed for 4 weeks gave the same N.E.R. value (9.0) as with rations 1 and 2. (This ration actually was fed at the same time as ration 2 as insurance against the 58 percent level yielding unsatisfactory results.)

(e) One weanling male rat fed ration 4 containing 87 percent duckweed for 4 weeks gained only 18 grams on 11 grams of nitrogen consumed for a poor N.E.R. of 1.6.

(3) *Spirodela* as a source of vitamin D by bioassay:

Using three and five rachitic rats, respectively, at two different times, the results of the A.O.A.C. bioassay for vitamin D indicate that this vitamin, if present at all, is present in amounts below 67 U.S.P. units per pound.

The following indications may be drawn from biological studies conducted to date.

(1) *Spirodela* is unsatisfactory as the sole source of food when supplied in a dry state.

(2) *Spirodela* is a fair nitrogen source, on a par with the protein in peanut flour.

(3) Proper supplementation of *Spirodela* may permit its use at high levels, ranging between 50 and 90 percent.

COMPARISON OF PLANT SYSTEMS TO PROVIDE THE OXYGEN AND CALORIC REQUIREMENTS OF ONE MAN

From the available data on oxygen production and carbon dioxide fixation, and the fixation of 2400 calories of energy, a comparison of the performance of the plant systems is presented in table IV. These data are not intended to represent maximum performance but are based upon experimental data now available. The picture might be altered somewhat if all factors for each plant were optimized. The fixed-energy column is the electrical energy equivalent of man's caloric requirement. If the four representative species exhibited the same efficiency in the conversion of electrical energy into food energy (calories), the energy requirements would be identical. If the endive and Chinese cabbage were light saturated at the indicated level of 2000 foot-candles then they appear less efficient than the algae and duckweed. These garden vegetables would require a greater illuminated area as shown, and as a consequence the total light-flux requirement would be increased. The total energy requirement is also shown. The need for ancillary equipment such as harvesting devices, gas separation, gas spargers, cooling, and so forth is indicated in the last column. This requirement will be higher for the algal system and least in the garden vegetable system.

A review of the literature points to the fact that more data are needed on the vegetable plants relating to maximum growth rates, light saturation levels, atmospheric composition, and pressure before valid conclusions can be stated concerning comparative performance of various plant species.

SYSTEMS CONTROL

Liquid suspensoid systems, such as the algae, will apparently be more complex from an engineering standpoint, but the various growth parameters should be more amenable to automated control. Algae will problably require more time-consuming and complex processing for preparation of acceptable foods than the other plant types. The success of the algal sys-

TABLE IV.—*Basic Requirement of Plant Systems for Nutritional Support of One Man*

Plant	"Fixed" energy, kw/day	Total electrical energy requirements, kw/day	"Standing" crop, g	Total mass of system kg	Illuminated area, m^2	Ancillary equipment
Algal	2. 79	139	240	100	10–12 (3500 ft-c) at plant surface.	++++
Duckweed	2. 79	139	800–900	100	6–8 (10 000 ft-c) at plant surface.	++
Endive	2. 79	1085	1950	100	78	+
Chinese cabbage	2. 79	666	1573	100	48 (2000 ft-c) at plant surface.	+

tem depends upon successful integration of plants and machinery to a much higher degree than the broadleaf systems. Physiologic effects, a priori, of sub g and zero g would seem to favor the algal system. The technical requirements for culture of broadleaf plants would probably not extend beyond the efforts of practical horticulturalists.

With the broadleaf type of plant system the gaseous exchange occurs via the gaseous environment, and would not require the complexities of dissolving and separating the respiratory gases in the liquid component of the system. Harvesting and processing the raw plant material into acceptable food would probably be relatively simple with the broadleaf type of plant.

CONCLUDING REMARKS

Some general concepts based upon limited experimental data relating to the potentialities of plant system as a source of nutrition for man in sealed environments have been presented. Research on the nutritional aspect of components of bioregenerative systems has demonstrated their feasibility as a means for providing man's caloric requirements. Much remains to be done with regard to selecting any one or more species of plant as the primary nutrient source in a closed ecology. More information is required for quality control of production, processing of food products, supplementation for essential deficiencies, and so forth. Much can be accomplished if the system can be made to provide man's caloric requirements. Essential vitamins and certain amino acids and minerals could be added as supplements if needed. Both pure cultures and "clean" cultures must be assayed for any toxicologic properties. Steady state and maximum reliability performance must be established and maintained for extended periods. Atmospheric pressure and composition must be compatible with the ecologic components, and the respiratory and photosynthetic quotients must be such as to maintain stability of the partial pressures of the atmospheric components.

Nutritional systems must be assayed in animal and human experimentation and, finally, under space-simulated conditions. Volume, mass, space performance, and manpower requirements must be carefully analyzed in cyclic (physicochemical and biological) and noncyclic processes before the most dependable long-term space system can be realized.

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Discussion: Plant Systems as Long Term Flight Nourishment Sources

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The ecosystem approach to man's logistic problems in space travel is a very appealing one to the biologist and especially to the limnologist. Before the turn of the century (1887), Stephen A. Forbes presented an inspired paper, "The Lake as a Microcosm," (ref. 1), to the Peoria Scientific Association. In this classic work, Forbes emphasized the tremendous sensitivity of any biological components of lakes to changes in any other part of the system, and at the same time considered the lake more or less as a closed system. Today, when we must consider closed systems in space, attention must be given to high sensitivity of the organisms involved. With an unlimited supply of solar energy, a really balanced system could recycle carbon and other elements and provide both food and oxygen for the space traveler. The preceding paper provides information on what might be expected from selected higher plant systems as energy sources, and reviews the nutritional content of five plants. Dr. Wilks deals with *Spirodela polyrrhiza* (L.), the largest of the four genera of duckweeds.

The *Spirodela*, which was grown in lucite tanks, would serve as an adequate nitrogen source for weanling rats, but would not maintain them as a sole food source. As the proportion of duckweed was increased to 87 percent of the ration, the nitrogen efficiency ratio fell. This drop may be due to decreasing the proportion of other constituents in the diet or to some toxic or imbalanced component of the duckweed. If growth and survival result from supplementary methionine in the diet, then either a nutritional imbalance may be indicated or the methionine may be serving to reduce a toxic effect. If methionine does not prevent mortality in the rats, then toxicity or other nutritional imbalance is a more likely possibility. In summary, the author demonstrated that *Spirodela* was inadequate as a sole food source for weanling rats, but served as a fair nitrogen source when supplemented with vitamins, sugar, and oil.

These interesting conclusions point to several areas where further discussion of the experimental techniques and approaches is appropriate. Dr. Wilks has indicated the inadequacy of the test-animal sample size because of a limited supply of duckweed. The selection of weanling rats as subjects seems unfortunate, since young rats, because of incomplete development of intestinal flora, might be particularly ill-equipped to grow on a duckweed diet, although two adults appear to have survived on it. Extrapolation of rat-human requirements is obviously tenuous but not easily circumvented in pilot studies. Certainly a long period of experimentation with human subjects would be essential before any plant food system is launched.

The culture methods are incompletely described but may provide a clue to the low production of the duckweed available as test material. The botanical literature provides a surprising wealth of information on the morphology, biochemistry, and physiology of the Lemnaceae as well as a host of other possibilities for space salads. Light quality (refs. 2, 3, and 4) and periodicity (ref. 5) affect flowering as well as the properties of the vegetative plant body. Studies indicate that chemical compounds or elements can be used to offset specific effects of lighting. The addition of copper, for example, makes *Lemna perpusilla* respond as if subjected to a short day length (ref. 6). The growth problem is further complicated by an interaction between crowded cultures and day lengths (ref. 7). Seager (ref. 8) observed that in ponds both *Spirodela polyrrhiza* and *Wolffia papulifera* were found to flower only under very specific chemical conditions. The sensitivity of duckweed to environmental factors was further evidenced by Kandeler (ref. 9), who was able to induce flowering with ultraviolet light of NaOH treatment.

Some imbalances in normal vegetative growth may result from changes in the delicate balance of the nutrient solution in which specimens are grown. These changes take place with aging, nutrition, and density of the culture. Boron deficiency, for example, has been shown to produce accumulation of starch in *Lemna minor* (ref. 10). This results in a reduction in protein content in favor of soluble nitrogen and an increase in dry weight from a greater than normal development of cell-wall material. Similarly, uptake of growth substances by the same species of duckweed is very dependent upon the pH of the external solution (ref. 11). In any event, culture conditions should be well defined and reproducible to assure a product of uniform nutritional value.

Attention should also be given to known antimetabolite action such as the antithyroid property possessed by the family Cruciferae (ref. 12) which includes the Chinese cabbage, *Brassica chinesis*. Despite extreme experimental variation in cultural conditions, striking differences between species exist in the phenolic constituents of 18 duckweed species (ref. 13). Such compounds might be important in the mortality of test animals.

For more definitive work, pure cultures of the plants should be used. Single fronds can be sterilized and maintained indefinitely under aseptic conditions (ref. 14). This provides generic uniformity and can yield a generation time per frond of about one-half day. Both winter conditions and dense cultures are conducive to turion formation by duckweeds (ref. 15). This is the resting stage which sinks to the bottom and would have to be avoided to maintain growing cultures. The danger of endophytic or epiphytic contamination by bacteria, fungi, or symbiotic algae may occlude experimental results by producing various metabolites or antimetabolites. Further, careful scrutiny must be made of all microorganisms carried into space, and the use of axenic cultures would make this task easier.

The problem of selecting a plant system was discussed briefly by Dr. Wilks from the point of view of ancillary equipment requirements and the assumption of a 2 percent conversion of electrical energy into available caloric energy. If this assumption had any validity in nature, we would not be likely to find the tremendous diversity evident in the plant kingdom.

If rats are unable to exist on duckweed alone, one might conclude that man will need to use another plant or, perhaps better, a mixed salad. In selecting the best plants, we might first look at the vegetable choices of human populations which have lived on a largely vegetarian diet. In most cases they utilize a variety of plants. Careful sorting and analysis should probably yield plants whose nutritional properties are much superior to those currently under study, and a combination of plant species might be easier to keep in balance than a single species. When the plants have been selected, it will be necessary to determine exactly how optimum growth rates can be achieved and sustained.

One of the most advanced experimental methods for attaining optimum conditions is the use of response surfaces described by Box (ref. 16). Although developed for purely chemical experiments, the approach has been used in other research areas and appears extremely promising in arriving experimentally at what are optimum growth conditions. Box has wisely noted that the experimenter is the one who must decide what space is to be explored; the statistician can assist only in indicating how it can best be accomplished. A sophisticated experimental design will yield little information if the most important variable has not been included.

As a limnologist, I have recently used this approach in attempting to achieve an optimal nutritional level for algae in Castle Lake, California (fig. 1). Productivity, as measured by carbon 14 assimilation, is considered a function of the three nutrient variables (fig. 2), the molybdenum, potassium, and sulfur concentrations that are now limiting the basic fertility of the lake (ref. 17). The graph of this function would be a surface in 4-space; that is, each point on the surface has four coordinates, three for the three elements, and one for the productivity value (fig. 3). The productivity value is derived from the slope$\times 10^{-3}$ of each response curve as measured by carbon 14 assimilation. If a mathematical expression for the function were known, the location of the maximum point or points on the surface could easily be found because they would equal zero. Although a mathematical expression for the function is not known, it can be approximated in the region of several experimentally determined points by fitting a polynomial expression by the method of least squares. An easy way to find the approximate location of the maximum is to determine a few experimental points, fit a first-

FIGURE 1.—View of Castle Lake, California, looking east towards Mount Shasta. Castle Lake is located at an elevation of 5200 feet in a glacial cirque basin and has been under intense limnological investigation since 1959.

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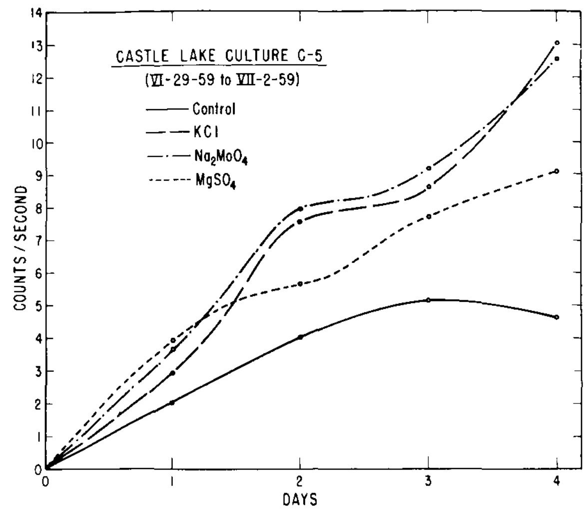

FIGURE 2.—Stimulation in the rate of photosynthetic carbon fixation (as measured by C^{14} uptake) of the natural phytoplankton population in Castle Lake, California. Cultures were incubated *in situ*.

degree polynomial, and then make further investigation in the direction of maximum increase. Once the maximum has been approximately located, it can be surrounded by several experimental points in order to fit a polynomial of high enough degree to be a good approximation to the actual function. The more variable the response surface, the higher the degree required. By setting the partial derivatives of this higher degree polynomial equal to zero, the maximum can be located with precision. The arrow is therefore a vector and the numbers define its direction. This kind of problem lends itself nicely to computer solution.

The importance of simultaneous investigation of a number of variables in plant systems can scarcely be overemphasized. The optimum level of one nutrient is often affected by both the concentration of other nutrients and by a variety of environmental factors. Today's space biologists and engineers have a formidable task, but, fortunately, tools for solution of these complex problems are for the most part available. It seems that if engineers can learn to understand better the problems of biologists and biologists can appreciate the problems faced by engineers, solutions to our problems of space travel will come at a much faster rate.

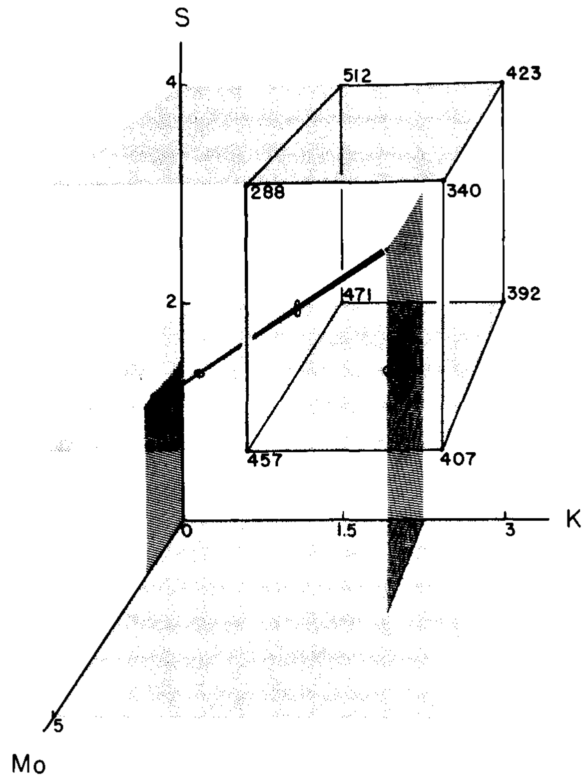

FIGURE 3.—A three-dimensional factor space of a Castle Lake culture experiment indicating the positions of eight experimental points. The response to K, Mo, and S additions, as measure by C^{14} assimilation, is indicated at the corners of the box. The calculated direction of maximum increase in response is given by the arrow.

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Algae Systems

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The Army Medical Research and Nutrition Laboratory does not now have an active program in the field of algae system study and thus the data given herein are not new. These data are given in more detail in reference 1. The scarcity of algae available to nutritionists for study is a major problem and we have been unable to convince ourselves sufficiently of its importance to our primary Army mission to investigate this problem in any significant way, either by undertaking mass culturing ourselves, or by urging any expenditure of Army medical research funds for contracts. Existing data, which I will review, suggest that the bottlenecks exist in the areas of growing and processing algae. Our laboratory's capabilities, for example, include nutrition but not food technology. Thus, while we can, and will, offer assistance in assessing the nutritional value of promising algal material furnished us, we feel the major responsibility for the growth and processing of algae must rest with those agencies having space as a mission.

Despite widespread interest in growing algae, very few sources can provide large enough quantities of algae for feeding studies. Consequently, few feeding studies have been conducted. In part, this represents the reluctance of nutritionists, and especially investigators contemplating costly human feeding studies, to use algae from sources where growth and processing conditions are uncontrolled, secret, not easily reproducible, or not adaptable to use in space.

Implicit in this hesitation to conduct feeding studies is the fact that nutrient composition varies with growth and processing conditions. Chemical analyses indicate that algae, with minimal supplementation, should be an excellent food. *Chlorella pyrenoidosa*, as ordinarily grown, has an apparent composition (on dry-weight basis) of 40 to 60 percent protein, 10 to 20 percent fat, 5 to 10 percent ash, and approximately 20 percent carbohydrate. The composition can be altered by (among other things) control of the composition of the nutrient medium, the light intensity, age of culture, temperature, and so forth. Tremendous variation in proximate composition is possible.

While data are available on how to achieve specific compositions in laboratory-sized ventures, more data are needed for large-scale production methods.

As to vitamins and trace minerals, the adequacy of micronutrients is of little importance in the decision for or against the use of algae in space, since the weights or required supplements would be small and could be provided easily by resupply from Earth.

Using algae supplied to us from other laboratories, we have performed chemical analyses, and have conducted feeding studies in animals and human subjects; the resultant data have been published in references 1 to 5. This review will concern chiefly feeding studies, from our laboratory and elsewhere.

Most studies reported in the literature on food value of algae have been concerned with the protein content. Leveille and Sauberlich (refs. 3 to 5) in our laboratory have presented data on the protein value and amino acid deficiencies of various algae for growth of rats and chicks. The data show that all the algae tested were far inferior to either the casein or soybean protein controls used for the rat and chick studies.

In one series of experiments, in which algae protein diets were supplemented with seven amino acids given simultaneously, a significant increase in weight gain occurred. The effects on PER (protein efficiency ratio) or on feed efficiency were then noted when a single amino acid at a time was omitted from the mixture. In subsequent experiments, only the amino acids shown to be limiting were added, and then the other amino acids were added one at a time or in combination. Without going into more detail, the following conclusions can be stated. As measured by weight gain and protein efficiency ratios or feed efficiencies, the algae fed are deficient in methionine for the rat and chick. The mixed algae tested proved deficient in glycine when fed to chicks; this is of importance particularly if chickens are used as an intermediate food source in the chain. *C. pyrenoidosa* also appears to be deficient in histidine (in addition to methionine) for the rat. While these results are in accord with chemical analysis of amino-acid content of the various algae it is to be noted that the food consumption of animals receiving algae was much lower than that of controls eating soybean or casein as the protein source. Among all animals in a given group receiving algae, regardless of the amino-acid supplements fed, food consumption was essentially equal. Thus, the comparisons of protein efficiency ratios and feed efficiencies may be of value in relative terms, within groups, even though of less value in establishing the "absolute" biological value of algal protein.

Japanese investigators (refs. 6 to 16) have contributed greatly both in (1) culture techniques and (2) nutritional studies. In a representative experiment in rats they reported that when dried green algae was the source of protein the weight gain was only 66 percent of that for a skim-milk diet. Digestibility (coefficient of absorption) was only 57.5 percent.

Lubitz (ref. 17), has reported a considerably higher digestibility coefficient for the protein of dried *Chlorella pyrenoidosa*, yet the weight gains for the *Chlorella*-fed rats were also much less than those fed egg or casein, and food consumption was less.

Cook (ref. 18) has reported interesting studies of sewage-grown algae fed to rats. Here, too, the protein efficiency ratio was low. The PER was increased by boiling the algae (results with other cooking methods were not as good as boiling, and also resulted in lower food consumptions). Both low food consumption and low digestibility were considered responsible for the rather low weight gains observed.

The digestibility of algae will be discussed further after reviewing the human feeding study conducted by our laboratory. Human studies have been relatively scarce.

Over 4 years ago Powell, Nevels, and McDowell (ref. 2) conducted a short feeding study in young adult male volunteers (fig. 1). We fed a mixture of *Chlorella* and scenedesmus obtained from Japan. This was fed in increasing amounts over a 6-week period, substituting the algae into a basal diet at levels of 10 grams, then 20, 50, 100, 200, and 500 grams per man

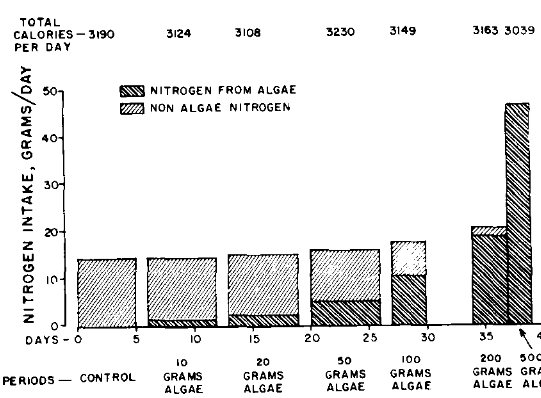

FIGURE 1.—Amount of nitrogen supplied by various amounts of algae fed to young men over a 6-week period.

per day. Many recipes were tried in attempts to disguise the bad taste. Algae (in amounts up to 25 grams per normal serving) was most nearly acceptable when added to gingerbread, chocolate cookies, and chocolate cake, but the taste of algae was dominant and unpleasant and the cake and cookies became olive drab in color. All subjects tolerated diets supplemented with algae in amounts up to 100 grams per man per day. Even early in the study, however, some gastrointestinal symptoms (abdominal distention, associated with increased eructations and flatulence) appeared. At feeding levels above 100 grams per day the algae was very poorly tolerated because these symptoms increased along with nausea and, in some subjects, diffuse abdominal pain, vomiting, malaise, and headache. Surprisingly, there was no diarrhea; instead, stools became bulky and dry, and sometimes bowel evacuation caused rectal pain. One subject had persistent vomiting at the 200 gram level and had to discontinue in the study. Only two of four subjects attempting to consume 500 grams of algae as the only food source per day for 2 days were able to ingest the full amount, but not without symptoms.

Physical examinations failed to show abnormalities other than those associated with the gastrointestinal tract. All laboratory tests remained within normal limits. All symptoms disappeared within 2 days after return to a normal diet.

The cause of the gastrointestinal toxicity is not known. No bacterial pathogens could be cultured from the material as received; furthermore, the material was autoclaved prior to feeding. Whether heat-stable bacterial enterotoxins were present is not known; the algae had not been grown or handled under sterile conditions. Gastrointestinal symptoms observed during the feeding levels up to and including 100 grams per day were most pronounced at the beginning of the periods suggesting that tolerance to the algae might be developed. Longer feeding studies would permit this to be tested, and would also permit digestibility studies. Accurate digestibility data were not possible in this study because of the short periods and the marked gastrointestinal symptoms at the higher algae feeding levels. Stool excretion data suggest poor digestibility for all macronutrients (table I). We concluded that algae in this form (heat-treated, dried algae) can be tolerated as a food supplement but further processing will be necessary if algae is to be useful as a major food source.

Vanderveen et al. (ref. 19) have suggested that any toxicity, and perhaps the poor acceptability and digestibility, associated with algae might be due to the presence of bacteria contaminating the growing algae. This could arise from the presence of toxins or only a small number of microbial bodies in the final product. Furthermore, since the populations (both as to number and kind) of bacteria will vary in different algal cultures grown under unsterile conditions, a true evaluation of toxicity, as well as nutritional value, can be made only on algae grown under sterile conditions. If no problems were encountered with ordinary algal cultures this would not be a necessary practical consideration; however, the facts seem to point to the

TABLE I.—*Representative Fecal Excretion Data for One Subject*

Period	Wet stool weight, g/day	Dry stool weight, g/day	Ash, g/day	Fat, g/day	Nitrogen, g/day	Carbohydrate, g/day	Total calories/day
Control	195	49	6.3	6.2	5.6	1.8	257
Algae:							
50 g	284	74	8.3	7.5	7.1	13.8	401
100 g	282	85	8.6	6.7	8.8	14.6	476
200 g	393	136	12.5	15.3	15.2	22.2	806
500 g	529	217	19.6	20.8	22.4	36.4	1272

desirability of further study of algae grown and processed under sterile conditions.

There are no good data available to determine the extent to which acceptability and toxicity may be related. Does the generally poor acceptability of algae represent the presence of toxic materials? When algae can be grown and processed to yield acceptable material (from organoleptic and gastrointestinal tolerance points of view) there will still remain the need for extensive short and long term toxicity studies in several animal species before long-term feeding can be considered for man.

Epidemic poisonings have occurred in animals drinking water from lakes whose surfaces were covered with the toxic "waterbloom" of certain blue-green algae. To our knowledge no such toxicity has been associated with green algae. Nevertheless, since the nature and origin of blue-green algal toxins are poorly understood, the fact that such epidemics occur indicates the need for careful study of any algae used for food.

Not only should possible toxicity and nutrient content be studied, but it should be determined whether some components of algae might impose additional nutritional requirements. For example the highly unsaturated lipids in algae (and perhaps branched chain fatty acids) might alter the vitamin E requirement; there is evidence to suggest this in some work on chicks.

There is some suggestion, particularly in the work from Japan, of a relationship between the acceptability and the digestibility of algae, in that extraction of the chromagens, such as the carotenes, chlorophylls, and xanthophylls, with solvents leaves a partially decolorized product which is both more digestible and bland in taste and odor.

Evidence favors the view that the poor digestibility of algae is due to its tough cell wall which is resistant to mechanical, thermal, and chemical attack. The algal cell wall is notoriously hard to rupture for analysis, even in the laboratory. Electron-microscopy studies of fecal specimens have shown that the cellular membrane often remains intact when dried algae is consumed. The digestibility of algae should be improved by rupture of the cell wall prior to feeding, or by giving the animal a dietary source of enzymes that would help digest the cellulose cell wall. The latter approach was studied by Leveille, et al. in our laboratory using rats.

The experiments may be briefly outlined as follows. Of six enzyme preparations used, two would appear to enable the rat to digest algae protein at a rate comparable to that of casein, particularly if one takes into account the fact that approximately 20 percent of the total nitrogen of algae is not protein nitrogen. Shefner et al. (ref. 20) have reported more basic studies on the chemical composition of the algae cell wall, and on the polysaccharides of the cell contents that may not be digestible by human digestive enzymes. They found the algal cell wall a highly complex structure. The variety of basic carbohydrate residues recovered from algal material (both cell wall and contents) leads them to conclude that it is "unlikely that a single highly purified enzyme would be able to cause extensive degradation." They have sought for, and found, potentially useful mixtures of cell-wall degrading enzymes in natural sources, such as the snail and sea urchin (or in bacteria of these marine animals' digestive tracts) in which algae constitute a normal part of the diet. These interesting studies should continue and tests of enzymes so obtained should be extended to whole animal experiments, as they suggest.

These studies involving the digestibility of the complex carbohydrates in algae point up a view we wish to emphasize. Heretofore, most of the few algae-feeding experiments (other than taste and acceptability tests) have been directed toward assessing the growth-stimulating effect of algae (due to micronutrients), or toward studying the digestibility and biological value of the protein. However, used as a food in space, algae's most important contribution would hopefully be calories, the heaviest component of any dietary requirement wherein part of the diet requires premium transport. If, in supplying adequate calories, algae provides protein of good biological value, essential fatty acids, minerals, and vitamins, so much the better. Thus, although eventually it will be necessary to establish the biological value of algae protein for man, of first importance are studies that would lead to improve acceptability of algae and improved availability of all the contents of the algae cell (carbohydrate, fat, and protein as well as micronutrients), chiefly because of the calories algae can supply.

We have alluded to the many gaps in our knowledge throughout this brief review. In summary, we need more algae for more investigators to study. Many strains need to be grown, under various environmental conditions that are well-controlled, carefully described, and reproducible. Chemical analyses for nutrients need to be correlated with strains of algae and the conditions of growth. The same applies to processing methods; indeed, the greatest problem at present lies in the development of processing methods that will yield algae that are acceptable and digestible. Is it necessary to grow algae under sterile conditions or will clean culture conditions suffice? With proper processing, what fraction of the total nutritional needs of man can be supplied by algae? What intermediate food producers are best used in the food chain between algae and man? What are the toxicities, if any, associated with a given level of processed algae in the diet over a long period of time, and if they constitute a problem, how can this be corrected? In a closed ecological system, will "blind alley" compounds accumulate in the system and require special chemical or physical treatment (e.g., high-temperature incineration) to return to the useful cycle? Is a processing method based on organic solvent extraction practicable in space?

Even if the answers to these questions result in a bioregenerative system too complicated or cumbersome for space vehicles, a system employing algae, at least in part, seems inevitable for "fixed" bases, for example, on the moon or an orbiting space station.

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Study of Effects of Carbohydrates on the Body Under Stress and Fatigue

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The influence of nutrition on the capacity for physical work has been the subject of several extensive reviews (refs. 1 to 3). A belief that performance is in some way related to the foods consumed has led some enthusiasts to pursue the hope that a special state of muscular capacity might be achieved by the intake of certain diets (ref. 4). Such an optimistic view may be unwarranted. Although theoretical considerations favor the feeding of calories in order to maintain the blood sugar level and to provide fuel for the working muscles, and also favor special intake of vitamins because of their participation as coenzymes in energy-yielding reactions, research has failed to demonstrate an unequivocal effect of these substances on work capacity. Indeed, the demonstration with rats (ref. 5) that running capability is increased significantly during starvation, despite the relatively low levels of blood sugar coincident with food deprivation, leads one to question seriously the role played by diet in the performance of hard physical work.

Therefore, experiments have been undertaken to determine the influence of nutrition on performance in order to clarify the relationships between body metabolism and performance capabilities. These studies have been directed toward determining the influence of prolonged physical work on metabolism, with particular emphasis on the development of special dietary supplements to prevent fatigue and to improve work capability. Additionally, preliminary studies have been undertaken to evaluate the utilization of body energy reserves during periods of food austerity, as well as to develop methods for enhancement of the use of the body energy stores.

EXPERIMENTS WITH ANIMALS

Preliminary evaluation of dietary effects on performance was obtained through studies with dogs. Six to eight animals were used for each test. The results to be described were obtained through experimentation with male, pure-bred beagle dogs, approximately 2 years of age and weighing 8 to 12 kg. The performance tests followed a common plan of exhaustive treadmill running at a speed of 3.6 mph, the grade varying between 9° and 13° of incline. Maximal work capacity has been expressed as energy expenditure measured in kilocalories.

The experiments were undertaken for three purposes:

(1) To compare metabolism in sedentary and working animals with a view toward determining those responses which are likely to be associated with physical work.

(2) To evaluate the immediate effect of specific nutrients on work capacity and to ascertain the effect of recency of food intake on performance.

(3) To evaluate metabolism and performance in relationship to the level of blood sugar.

Early evidence of the relative ineffectiveness of carbohydrate supplements on work performance was obtained through a comparison of the effects of a carbohydrate supplement and a water supplement during exhaustive work. Experimental dogs were provided with either no supplement during treadmill running, or with water, or with carbohydrate pellets consisting largely of sucrose and dextrose and administered in an amount equal to 0.5 percent of body weight. The results are summarized in table I. While carbohydrate supplements tended to elevate the respiratory quotient and to minimize the decline in blood sugar during work, there was no obvious improvement in work capacity. The average total energy expenditure of animals without supplements was 1191 kilocalories; with carbohydrate supplements total energy expenditure was substantially similar, 1299 kilocalories. In contrast, animals given water during work showed a significant increase in performance, 2141 kilocalories, and a tendency to maintain their blood sugar at nearly normal levels.

Further studies of the influence of carbohydrate loading were undertaken. Animals were examined for their maximum work capability at 2, 4, 6, 17, and 120 hours after the last meal, which consisted largely of carbohydrate. The results are summarized in table II. During the first 6 hours following the intake of food, the average work capacity was 720 kilocalories; 17 hours after the last meal, work performance was 2200 kilocalories; 5 days after the last feeding performance capacity was increased to 4100 kilocalories. In these last tests, somewhat surprisingly, the blood sugars at the termination of work were 100 mg per 100 ml, or approximately 20 percent higher than the levels measured just prior to exhaustive treadmill running.

TABLE II.—*Relationship Between Work Capacity and Recency of Food Intake* [a] *in Dogs; Water Was Provided Ad Libitum During Work*

Time after last feeding, hr	Work capacity kcal [b]
2	850 ± 250
4	600 ± 275
6	700 ± 300
17	2200 ± 219
120	4100 ± 300

[a] 200 g Purina Chow
[b] Mean value ± standard deviation.

To investigate further the relationship between food intake and performance capabilities, animals were offered, during work, one of the following special nutrient supplements: water, milk, or aqueous solutions of either (a) carboxymethyl cellulose, (b) corn oil, (c) phospholipids, (d) lactalbumin, (e) glucose, or (f) water-soluble vitamins. With the exception of the supplement containing the cellulose derivative, the concentrations of protein, sugar, fat, vitamins, and phospholipids were similar to those found in milk. The results of these tests are shown in table III. Supplements of milk, corn oil, vitamins, phospholipids, and cellulose derivatives decreased performance approximately 40 percent; supplementation with glucose or lactalbumin was neither beneficial nor detrimental.

TABLE I.—*Effect of Water or Carbohydrate Supplementation on Work Capacity of Dogs*

	No supplement	Carbohydrate (52.4 ± 7.2 g)	Water (1520 ± 172 cc)
Work capacity kcal	1191	1299	[a] 2141
Respiratory quotient	0.77	[a] 0.85	0.77
Max. rectal temp., ° F	105.4	105.7	[a] 104.2
Δblood glucose, mg/100 ml	[a] −39.3	−20.2	−14.5
Δblood lactate, mg/100 ml	−.1	.8	−.7
Δblood acetone, mg/100 ml	.9	.5	1.3

[a] Differs significantly from both other treatments, $P < 0.05$.

TABLE III.—*Effect of Nutrient Intake During Treadmill Running on the Work Capacity of Dogs*

Nutrient	Percent change in work capacity[a]
Milk	−61
Corn oil	−38
Water-soluble vitamins	−37
Plant phospholipids	−40
Carboxymethyl cellulose	−60
Glucose	<1
Lactalbumin	4

[a] Compared with capacity when only water was consumed.

The apparent ineffectiveness of carbohydrate supplements on performance capabilities has been of special interest, and additional tests have been undertaken to evaluate the factors regulating the blood sugar level during work. Specifically, the level of blood sugar has been examined during physical work with and without starvation.

The effect of food deprivation combined with hard work is shown in table IV. During the first day of fasting, the level of blood sugar measured at rest was 86 mg per 100 ml; following treadmill running of 6 to 10 hours' duration the level declined to 47 mg per 100 ml. In contrast, on the third and fifth day of fasting the level of blood sugar measured at rest was 72 mg per 100 ml and 69 mg per 100 ml, respectively; during those periods, long sustained work did not further lower the level of the blood sugar.

TABLE IV.—*Blood Sugar in Dogs Following Prolonged Work[a] During Fasting*

Day of fast	Resting blood glucose, mg percent	Postexercise blood glucose, mg percent
First	86±6.0	47±5.6
Third	72±2.3	67±20
Fifth	69±7.0	64±15

[a] Of 6 to 10 hours' duration.

Additionally, studies were undertaken to follow the blood sugar level during various periods of work. These results are shown in figure 1. In general the level of blood sugar tended to decrease systematically to 40 mg per 100 ml until a cumulative energy deficit of approximately 1200 kilocalories had been attained, but thereafter the level of the blood sugar tended to rise. In conjunction with these studies, the overall body metabolism was examined at rest and during prolonged physical work. A comparison of the responses of sedentary animals with those of active animals is shown in table V. Although the level of blood sugar was depressed in the physically active animals, the urinary nitrogen and acetone excretion were uninfluenced.

The results of the above investigations have led to a serious reevaluation of the nature of the metabolic substrate utilized during prolonged work. In effect, substantial degradation of body protein and fat was anticipated during the prolonged running tests, and significant increases in the blood ketones as well as in the urinary nitrogen and creatinine were ex-

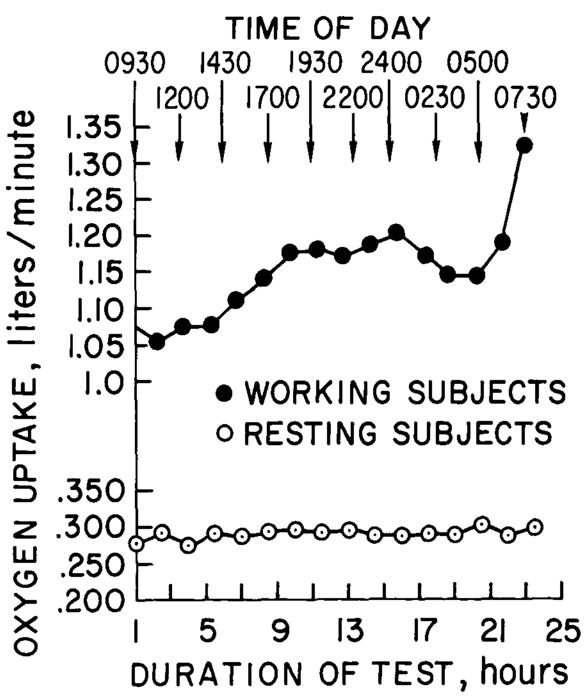

FIGURE 1.—Effect of work with ad libitum water intake on the blood glucose level.

TABLE V.—*Physiologic Characteristics of Work, Blood Chemistry, and Urinary Excretion in Postabsorptive Dogs*

	Sedentary, 20 hr [a]	Active, 12 hr [a]
Energy expenditure, kcal/min	0. 50±0. 04	[b]3. 35±0. 3
Gross energy expenditure, kcal	600±30	[b]2100±210
Heart rate/min	90±15	[b] 235±12
Respiratory rate/min	25±4. 0	[b] 210±15
Venous O_2, cc/100 ml blood	16. 0±1. 0	15. 9±0. 8
Oxygen debt	None	None
Blood glycogen, mg/100 ml	2. 2±1. 5	2. 8±1. 6
Blood glucose, mg/100 ml	72±5. 0	[b] 55±6. 0
Blood fructose, mg/100 ml	3. 3±0. 9	2. 8±0. 6
Blood pyruvate, mg/100 ml	2. 1±0. 5	2. 0±0. 4
Blood lactate, mg/100 ml	3. 0±1. 5	4. 0±0. 8
Blood acetone, mg/100 ml	2. 0±0. 7	3. 0±1. 4
Urinary NPN, g	2. 2±0. 7	1. 9±0. 6
Urinary urea N, g	1. 7±0. 4	1. 5±0. 5
Urinary creatinine N, mg	75±32	57±13
Urinary acetone, mg	12±5. 0	18±7. 8
Urinary sodium, meq	22±3. 0	24±3. 0
Urinary potassium, meq	12±2. 5	[b] 18±2. 5
Urinary phosphorus, mg	195±44	183±30

[a] Mean value ± standard deviation.
[b] Differs significantly from value obtained with sedentary dogs, $P \leq 0.01$.

pected. However, the results have failed to confirm this hypothesis. Therefore, it is postulated that carbohydrate is formed and utilized even during undernutrition; that the relative constancy of the blood sugar level during fasting with hard work and, again, the tendency of the blood sugar to increase during prolonged work are due to de novo synthesis of sugar. Finally, since no important variations in nitrogen metabolism have been observed, it is postulated that sugar may be synthesized from fat precursors.

EXPERIMENTS WITH HUMANS

A program has been undertaken with human subjects to test further the hypothesis of glucose synthesis. As a preliminary measure, investigations have been carried out to test the feasibility of walking for periods up to 24 hours, the time needed to develop an experimental situation suitable for studies of carbohydrate synthesis.

Studies are in progress with 20 male subjects, varying from 22 to 40 years of age. After 3 months of intensive physical conditioning, they are tested on the treadmill for periods of 24 hours or until the onset of exhaustion. The pace varies between 2.5 and 2.7 mph and the degree of incline is varied between 0° and 2° in order to attain a workload which is one-third of each individual's maximal work capacity. Additionally, each subject is tested during a 24-hour period of rest. All tests are conducted in the postabsorptive state. The physiologic characteristics of the tests are shown in table VI. Generally, heart rate and rectal temperature during work are 104 and 38.1° C, respectively. Blood lactic acid levels remain normal.

The oxygen uptake, the level of blood sugar and fatty acids, and the pattern of urinary excretion have been examined. Figure 2 shows the relationship between the duration of the test and the oxygen uptake. In general, the oxygen uptake measured at rest was relatively constant. During work, however, oxygen uptake tended to rise during the first 10 hours from 1.07 liters/min to 1.20 liters/min. The level of blood sugar declined during the first 9 hours and thereafter was relatively constant (fig. 3). Two points are

TABLE VI.—*Average Physiologic Responses at Rest and During Work in 13 Human Subjects*

	Treadmill walking	Resting
O_2 uptake, liters/min	1. 151	0. 288
Percent of peak effort	32	8. 0
Heart rate/min	104	61
Rectal temp., °C	38. 1	37. 1
Serum lactate, mg/100 ml	13. 0	10. 5

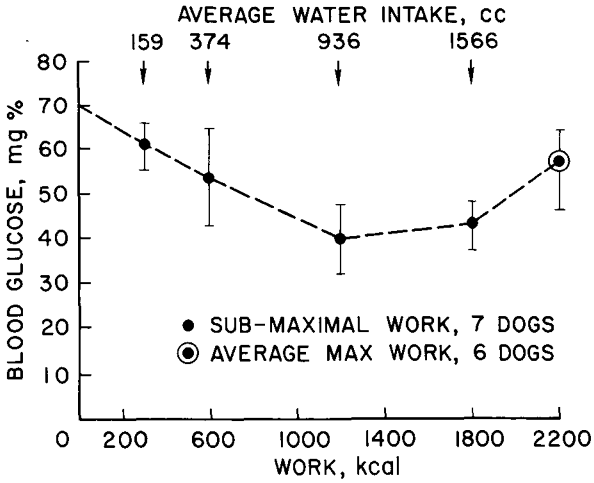

FIGURE 2.—Mean oxygen uptake at rest and during work in 13 human subjects.

noted in regard to the level of blood sugar. First, the level of sugar in the working subjects was only 10 mg per 100 ml lower than that observed in the resting subjects, despite the substantially greater energy deficits incurred during work. Second, we have noticed a tendency of the blood sugar to rise terminally after approximately 22 hours of treadmill walking. Serum free fatty acids also showed a tendency to rise (fig. 4). During the first 10 hours of work, the level of fatty acids increased from 0.65 m q/liter to 2.6 m q/liter.

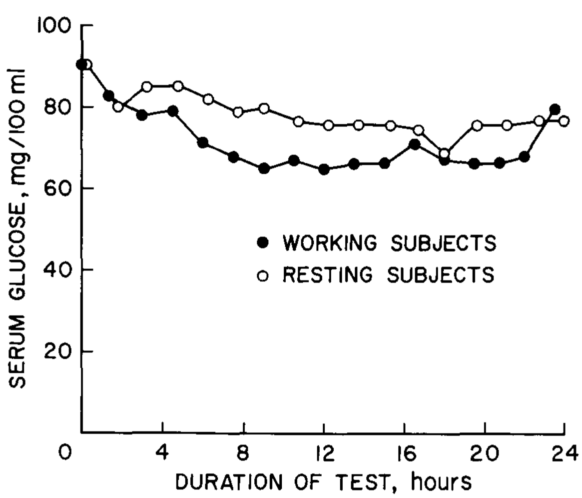

FIGURE 3.—Mean blood sugar at rest and during work.

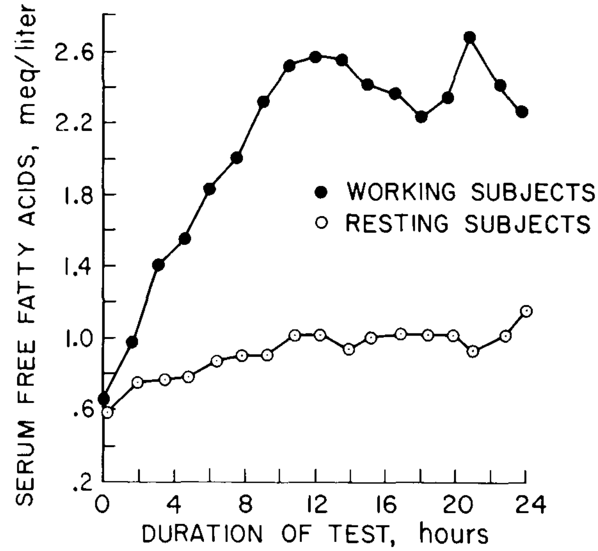

FIGURE 4.—Mean serum free fatty acids at rest and during work.

A preliminary examination of the blood and urine for nonprotein nitrogen content has shown that physical work does not increase protein breakdown in the body. Further biochemical tests are in progress to measure ketone-body production and to evaluate protein catabolism more fully.

Additional studies are being planned to test the hypotheses that (a) the relative constancy in the blood sugar level after 10 hours of treadmill walking is attributable, in part, to glucose synthesis which, accordingly, would be reflected in the body glycogen reserves; (b) the increased oxygen uptake shown during work is related to carbohydrate synthesis, particularly to the conversion of fats which are relatively poor in oxygen into oxygen-rich carbohydrates; and (c) increases in serum fatty acids are associated not only with the mobilization of lipids (palmitic and oleic) from the fat stores, but also with the production of short-chain (C_2 to C_7) fatty acids which may serve as direct precursors for carbohydrate synthesis. Furthermore, more sensitive psychological tests are being developed in order to assess the influence of progressive exhaustion and lack of sleep on reaction time, short-term memory, steadiness, and problem-solving ability and to correlate these with changes at the biochemical level.

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COMMENTS

DR. HELVEY: I am very much interested in the mechanism of this rise of the blood sugar content. Might it be that there is an irritation of the calamus scriptorious of the fourth ventricle liberating some reserves otherwise not acceptable in the liver?

DR. YOUNG: At the present time we are administering adrenalin. Presumably, if there is any liver glycogen there, it should be observed in the increase in blood sugar. These tests are only in process now and we have no data.

MR. ALLEN: What is being depleted in 24 hours of work?

DR. YOUNG: We do not measure body composition. We measure nitrogen excretion and there appears to be no unusual amount of nitrogen excretion so that must leave fat.

DR. JOHNSON: Were these men on a prescribed diet before these tests were given? If so, how long and what diet?

DR. YOUNG: We had no way of controlling the diet. We did provide a series of menus and make recommendations as to what they should eat but these individuals were from private contractors and private citizens and ate more or less what they wanted.

DR. VORIS: How many hours post-absorptive were tests made?

DR. YOUNG: The subjects ate at 7:00 in the evening. We started at 8:30 or 9:00 in the morning, so about 13 hours elapsed. They had no food during the day.

QUESTION: What was the approximate average weight loss during the course of the experiment?

DR. YOUNG: It varied from zero to as much as 5 pounds.

QUESTION: Did the subjects eat during the experiment?

DR. YOUNG: No, they had as much as 5 liters of water. We provided water and 5 grams of salt.

SESSION VII

Novel Nutrient Sources

Chairman: ***Gerald F. Combs***
Professor, Department of Poultry Science
University of Maryland

Formula diets offer several advantages over more conventional foods in meeting the nutritional needs of man in space flights up to 90 days. Such a diet in the form of a rehydrated liquid formula could (1) reduce the manipulations and time required for inflight feeding, (2) permit dispensing of food without removal of suit components such as gloves, (3) make it possible to feed through tubes inserted in the helmet, (4) simplify storage problems, (5) minimize fecal production, (6) provide great flexibility of manipulating nutrient levels for nutritional studies under space stresses, and (7) permit ready modification of dietary intakes to compensate for different requirements arising from any cause (individual differences, environmental changes, etc).

Granted formula diets do not permit great variety, but at the same time they need not be monotonous in the extreme as they may be varied in flavor and color and even texture without difficulty. Moreover, active individuals have been maintained on such diets in liquid form for 90 days at M.I.T. with no adverse physical effects nor any measurable change in psychological state. Further efforts should permit development of diets which are quite acceptable and could include bite size pieces as well. Such diets need not be highly purified or expensive. They are suitable for the incorporation of specific supplements, such as certain high-energy nonfat compounds which may permit a further reduction of the weight of food required to furnish the same amount of metabolizable energy. This approach also is ideal for insuring that each mouthful of diet is nutritionally complete and, at the same time, logistically efficient.

There is quite a difference between insuring nutritional adequacy and in doing this most efficiently without supplying excesses that may greatly influence the problems of specific requirements, metabolic stress, and waste disposal. More information is needed in order to appraise the specific needs, limitations, and variation between individuals in order to obtain more exact nutrient specifications. For this, metabolic studies are needed and formula diets containing constant known nutrient levels are almost essential.

Also, it would appear that the direct supplying of food from Earth to orbiting capsules will be sound for some time as equipment for meaningful regeneration of body wastes into a primary food source may not justify its weight displacement until the capacity for lift-off is less critical. At best, these would provide a very limited variety of foods of limited palatability, until a more extensive system can be established on a lunar or other planetary base. Accordingly, the availability and use of logistically efficient complete diets will be of great value.

GERALD F. COMBS

Chemical Synthesis of Proteinoids: Part 1[1]

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N65-18596

Food may be regarded as predominantly a set of carbon compounds which have been selected by processes of Darwinian evolution. The ultimate method of preparation of such chemical substances may well be chemical synthesis. To deny this possibility is tc ignore the accomplishments to date in the chemical synthesis of rubber, of polyamide fibers, of the hormones oxytocin and vasopressin, and so forth. In the field of food components, chemical synthesis already dominates the commercial production of vitamins. We, therefore, are into the area of chemical synthesis of foods far more perhaps than is generally realized. This emphasis was made by McPherson in two papers in 1959 and 1961, the latter being titled "The Synthesis of Food" (refs. 1 and 2).

Our awareness of the potentiality in synthesis of food arose from research on molecular evolution (ref. 3). The perspective which has been developed is covered in reference 4. In these studies, synthesis is used in the rigorous chemical sense, rather than in the sense of artificial assemblage of food components, synthetic or natural.

In order for chemical synthesis of food to be of interest sociologically it must, of course, be inexpensive. To be suitable for use on prolonged missions, food synthesis must meet another prime requisite, that of simplicity of operation. The economical synthesis of vitamins, referred to earlier, is in nearly every case extremely intricate organic chemistry and not at all suitable for execution, for example, in a space vehicle. The few amino acids which are used in supplementation can also be more economically synthesized than isolated, but their fabrication requires many steps of intricate organic chemistry; the application to space nutrition is hardly more thinkable than for the vitamins.

One can, however, now visualize syntheses simpler than the production, one at a time, of the many vitamins and amino acids, as these are now carried out industrially. Not only are these food components now made one at a time, but the production of each amino acid or vitamin requires many steps and much processing.

The simultaneous synthesis, which we refer to as *pansynthesis*, of 8 to 14 amino acids has been demonstrated to be a relatively simple process operationally. Mechanistically, from the viewpoint of the organic chemist, it must be very complicated, but operationally it is very simple. This kind of synthesis seemed more attainable following the finding that, under simple appropriate conditions, one could panpolymerize all of the 18 amino acids common to protein to yield polyamino acids—protenoids (ref. 5). These are nutritionally active (ref. 6).

[1] Contribution no. 034 of the Institute for Space Biosciences. Aided by Grant no. NsG–173–62 of the National Aeronautics and Space Administration.

This kind of investigation emerges from serious laboratory efforts to discipline theories of the origin of life (ref. 3). Such a background seems logical when we entertain two premises: (a) that the first organisms were chemically similar to contemporary cells and (b) that the first organisms would use, as food, substances chemically similar to those of which they where composed (ref. 7). The appropriate conditions are dry amino acids at the outset and a sufficient proportion of neutral α-amino acids. The polymerization of non-α-amino acids is well known, but this statement was not applicable to α-amino acids until the special conditions were discovered (ref. 5).

As a practical solution to the problem of space nutrition, the state of the art in synthesis of amino acids and proteinoids is not far advanced. We are not ready to substitute for a diet of roast chicken, potato salad, and apple strudel one of proteinoid, sugary condensation products of formaldehyde (ref. 4), and Hoffman LaRoche vitamins. The possibilities of chemical, nutritional, and engineering investigations through the approach of pansynthesis are no longer, however, merely blackboard speculation.

The salient features of the state of the art for proteinaceous compounds may be outlined as follows. Many syntheses of amino acids from simple gases are now known. The most recent of these and two of the earliest are shown in table I. The two columns on the right indicate the production of four proteinogenous amino acids by electric discharge in gaseous mixtures of methane, hydrogen, water, and ammonia (ref. 8). As the columns on the left show, vapor phase thermal reactions of methane, ammonia, and water yield products readily hydrolyzable to amino acids (ref. 9). These syn-

TABLE I.—*Amino Acid Compositions Produced Thermally in the Presence of Silica and by Electric Discharge*

[Basic amino acids are not listed because they have not yet been fully studied. Some amino acid analyses of thermal products showed peaks corresponding with lysine (or ornithine) and arginine.]

Amino acids	Thermal synthesis, percent (ref. 9)			Electric discharge synthesis, percent [a]	
	Silica sand 950° C	Silica gel		Spark discharge	Silent discharge
		950° C	1050° C		
Aspartic acid	3.4	2.5	15.2	0.3	0.1
Threonine	0.9	0.6	3.0	--------	--------
Serine	2.0	1.9	10.0	--------	--------
Glutamic acid	4.8	3.1	10.2	0.5	0.3
Proline	2.3	1.5	2.3	--------	--------
Glycine	60.3	68.8	24.4	50.8	41.4
Alanine	18.0	16.9	20.2	27.4	4.7
Valine	2.3	1.2	2.1	--------	--------
Alloisoleucine	0.3	0.3	1.4	--------	--------
Isoleucine	1.1	0.7	2.5	--------	--------
Leucine	2.4	1.5	4.6	--------	--------
Tyrosine	0.8	0.4	2.0	--------	--------
Phenylalanine	0.8	0.6	2.2	--------	--------
α-NH_2Butyric acid	0.6	--------	--------	4.0	0.6
β-Alanine	([b])	([b])	([b])	12.1	2.3
Sarcosine	--------	--------	--------	4.0	44.6
N-Methylalanine	--------	--------	--------	0.8	6.5

[a] Recalculated from the results obtained by S. L. Miller (ref. 8).
[b] β-Alanine peak obscured by other unknown peak.

theses have been carried out in beds of silica gel, silica sand, alumina, and volcanic beach sand. For three of these, the results are different; silica in either form gives similar results. Variation in the balance sheet with temperature is apparent. The first column indicates that amino acids are obtainable through synthesis carried out at 950° C in vapor phase reaction through silica sand. The second column refers to experiments at 950° through silica gel; the first two columns show results which quantitatively are quite similar. The third column is at 1050° C. A greater variation in quantitative proportions is observable. The remarkable aspects of this pansynthesis are (a) that at least 14 of the 18 amino acids common to protein are syntheized by this process simultaneously, and (b) all 14 are amino acids common to protein. No others are found.

The four amino acids which are missing are tryptophan, histidine, cystine, and methionine. Tryptophan would have to be sought separately; such experiments have not been done. Histidine is blanketed on the amino acid analyzer by ammonia which is present in large proportions as one of the reactants. No cystine or methionine should be expected because of the fact that no sulphur compound has been used in the experiment reported here. Although basic amino acids are also formed, proportions have not yet been determined. The total yield is very low. It is not calculable for vapor phase reaction until further criteria are applied but the unused gases could be recycled according to typical engineering concepts. Unwanted products could be converted to simple gases and run through a cycling process. The range of possibilities by varying solid support, temperature, and so forth, needs to be extensively investigated, but is obviously open to control.

This brief discussion of the synthesis of amino acids was included because this a fundamental and prior problem in the context of some of the objectives of space nutrition.

Part of the background thinking about panpolymerization of amino acids is presented in figure 1. Many who are familar with amino acids would expect by heating amino acids above the boiling point of water to obtain the dark, unworkable mass such as is seen in the tube on the left. Such a result, in fact, is well documented in the literature (ref. 10). If, however, one heats dry amino acids containing sufficient proportions of dicarboxylic amino acids at 170° for periods such as 6 hours, a light colored product results. It is soluble in dilute alkali and can be reprecipitated by salting out, a method classically used for the purification of proteins. The polymer contains some of each of the 18 common amino acids. It has many of the properties of protein (ref. 3). Yields are typically 10 to 40 percent, higher figures being obtained by the addition of various phosphates. Copolymerization with aspartic acid can be employed with any number of amino acids from 1 to 20 or more. One can extend this operation to the nonproteinogenous amino acids. Extensive decomposition does not occur; in fact, 100 percent of amino acids can be recovered from mod-

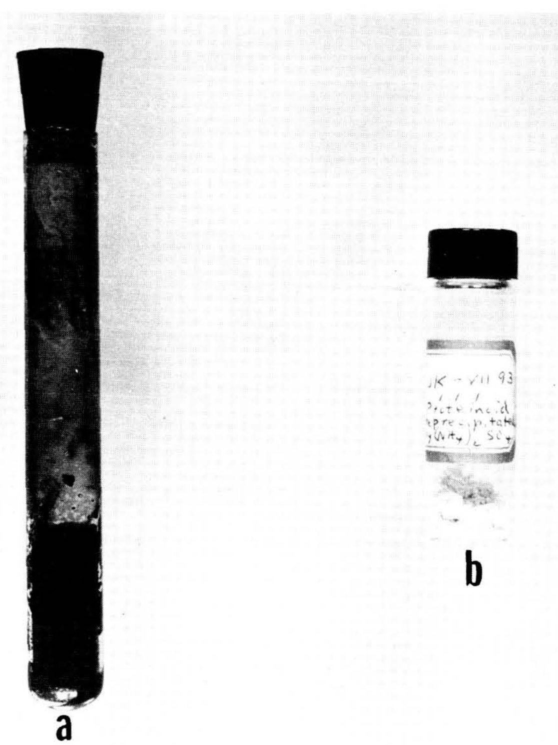

FIGURE 1.—Amino acids. (a) Heated above the boiling point of water. (b) With sufficient aspartic acid and glutamic acid, heated above the boiling point of water and purified by salting out.

erately purified proteinoids (ref. 11). These reactions have now been repeated in many laboratories.

The degree of polymerization yields products in the range of molecular size of proteins (ref. 6). Proteinoids of mean molecular weights between 3500 and 8500 are easily obtained. The synthesis and characterization of the proteinoids have been examined extensively (refs. 3, 6, and 12).

One salient structural feature is a very low degree of branching (ref. 13). Two properties of most pertinence here are (a) the proteinoids are split by proteolytic enzymes (ref. 6) and (b) nutritive quality.

We first learned that proteinoids could be used instead of peptone by *Lactobacillus arabinosus* and by *Proteus vulgaris*. The former has amino acid requirements resembling those of man. Another principal inference from this work is that very complex compounds can arise in a very simple way. The proteinoids are, in our view, as complex as the proteins or perhaps a little more complex. In a nutritional context they can be viewed as synthetic generic protein.

In figure 2 are chromatograms of hydrolyzates of three separately synthesized proteinoids. These are by the automatic amino acid analyzer, using the analysis of Spackman, Stein, and Moore (ref. 14). The areas under the peaks correspond approximately to the proportions of individual amino acids, except for proline. Only the similarities and differences in pattern need be noted. The differences in each case are in the phenylalanine content. The central analysis is from a 2:2:1-proteinoid. The reaction mixture consisted of 40 percent aspartic acid, 40 percent glutamic acid, and 20 percent of an equimolar mixture of the 16 other amino acids. This dry mixture had been heated to 170° C for 6 hours, then hydrolyzed under conditions that are used for hydrolyzing proteins, and then analyzed in the usual fashion.

The analysis of the first of the hydrolyzed proteinoids is the same except that phenylalanine was omitted. The analysis shows that no phenylalanine is in the polymer, but all the other amino acids are present in essentially the same proportions in the two syntheses.

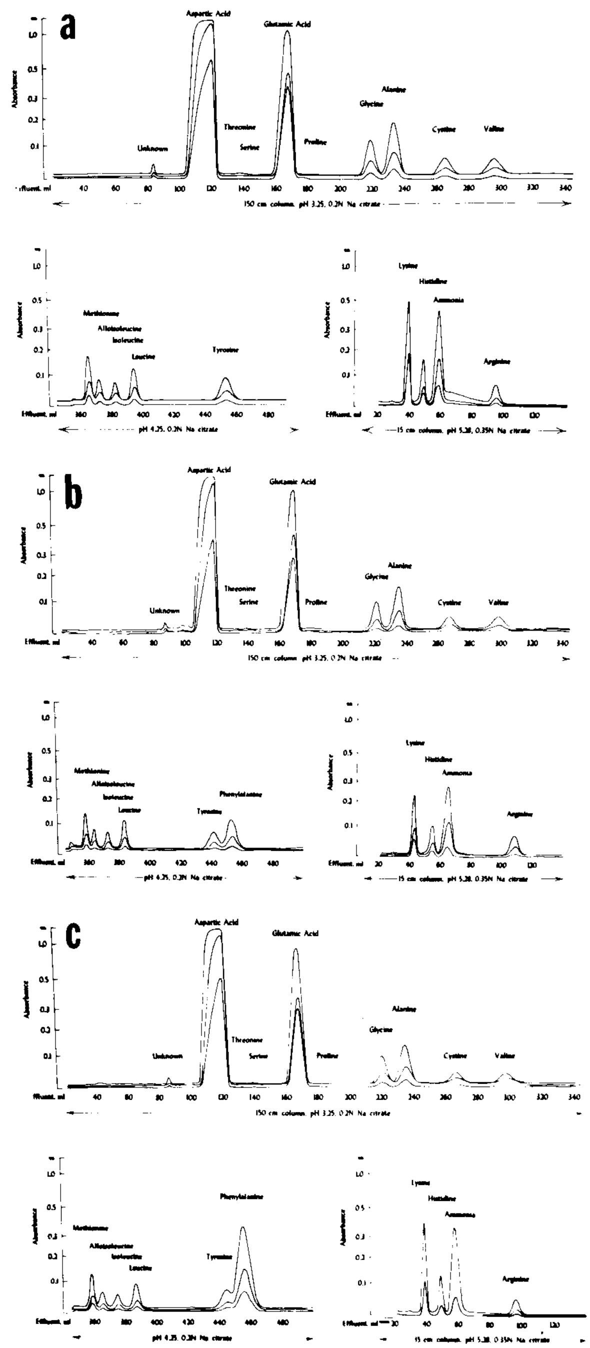

FIGURE 2.—Chromatograms of hydrolyzates of proteinoids. (a) 2:2:1-proteinoid reaction mixture lacked phenylalanine. (b) Standard 2:2:1-proteinoid. (c) Standard 2:2:1-proteinoid with 3½ times as much phenylalanine in reaction mixture.

This pair of patterns calls to mind the kind of situation that Abderhalden, Mendel, and others sought in proteins in nature in order to learn about the contributions of individual amino acids to protein nutrition. This comparison offers the possibility of feeding amino acids in peptide bound polymers with systematic omission of individual amino acids. Information would thus be gained from bound amino acids rather than from free amino acids. Some of the defects of studies employing free amino acids have been pointed out by Rose (ref. 15).

The third chromatogram shows the analysis of the hydrolyzate of a 2 : 2 : 1–proteinoid which was prepared under the same circumstances as the standard proteinoid except that three and one-half times as much phenylalanine was used in the reaction. One may see the larger proportion of phenylalanine in the proteinoid. Many similar studies demonstrate that the proportion of any amino acid in the thermal polymer is regularly related to the proportion of that amino acid in the reaction mixture. Proportions are, therefore, to a considerable degree controllable. Comparisons of the proportions of other amino acids show that the syntheses are highly reproducible. This kind of result has come as a surprise to many, although not all, chemists. This surprise may be understood on the basis that, erroneously, heating has been often regarded as brutal treatment for amino acids and, secondly, that no precedent existed for simultaneous chemical polymerization of as many as 18 monomers. Much evidence has accumulated that the amino acids regulate their own sequences (ref. 3) as well as their composition, but this result is outside the area of our immediate concern.

Figure 3 indicates another mode of producing proteinoids through the Leuchs anhydrides of

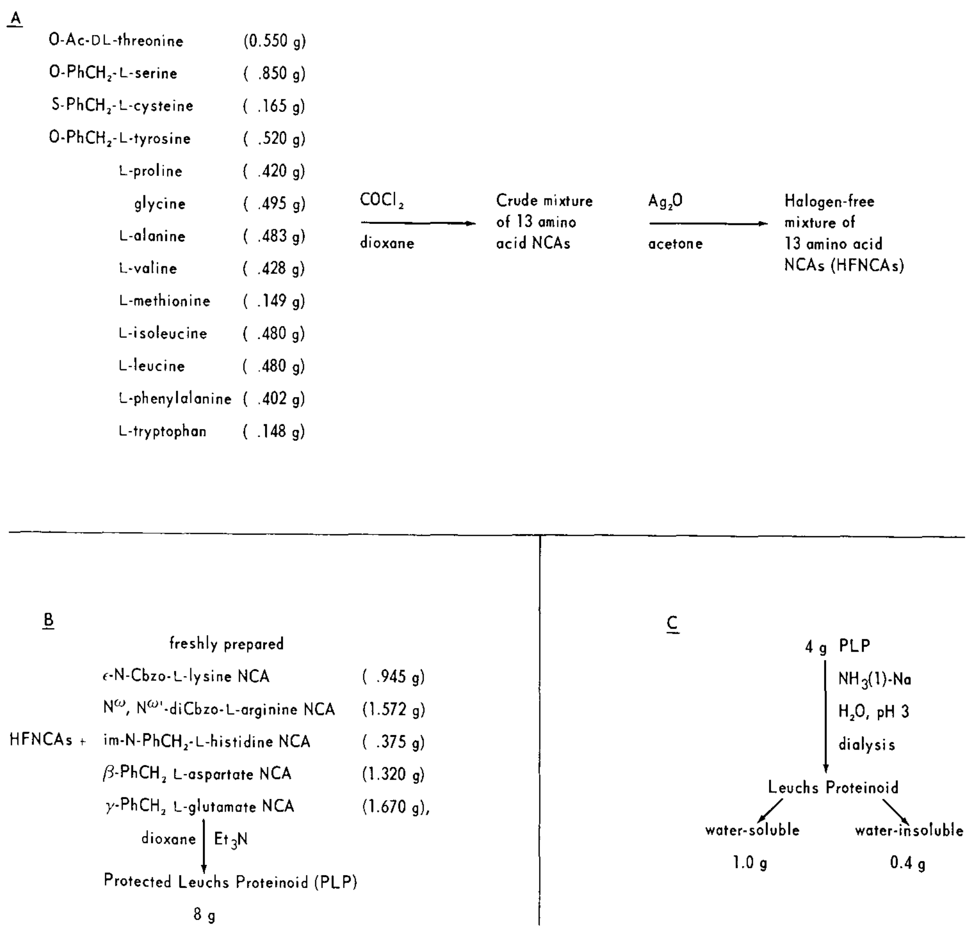

FIGURE 3.—Flow sheet for a synthesis of Leuchs proteinoids.

the amino acids. This kind of synthesis is far from simple. It requires blocking of the reactive side chains of nine of the amino acids and then removal of the blocking groups, following polymerization. The amino acids are not substantially racemized in this synthesis, however, and the proportions are less subject to internal control than are the proportions in thermal proteinoids. This synthesis can simulate exactly a natural protein in proportions of individual amino acids.

In figure 4 are, again, a controlled pair of Leuchs proteinoids which show identical patterns except for histidine which has been omitted from one of the polymers. In both this and the thermal type, proportions of otherwise nutritionally limiting amino acids, such as lysine, can be increased. For the objective of nutritional investigation, the thermal proteinoid and the Leuchs proteinoid each has its own features. They may be most valuable when used comparatively. Composition, as is indicated, can be controlled chemically and evaluated nutritionally. For the objective of space nutrition, the Leuchs proteinoid may be of particular investigative interest for missions requiring an optimally balanced nutritional polymer of amino acids. The thermal proteinoid should be more interesting for studies underlying chemical regeneration and studies aimed at prolonged missions. The proteinoids have acceptable taste, either raw or roasted; they taste somewhat like grilled fish.

Much more might be said about potential problems in the application of this relatively new knowledge to utilitarian objectives. Some of the problems are common to both chemical and biological regenerative systems. The pragmatic emphasis, I believe, is to recognize that many difficult problems can be visualized and that possibly many problems are not yet defined, but we have open experimental avenues that can be traversed.

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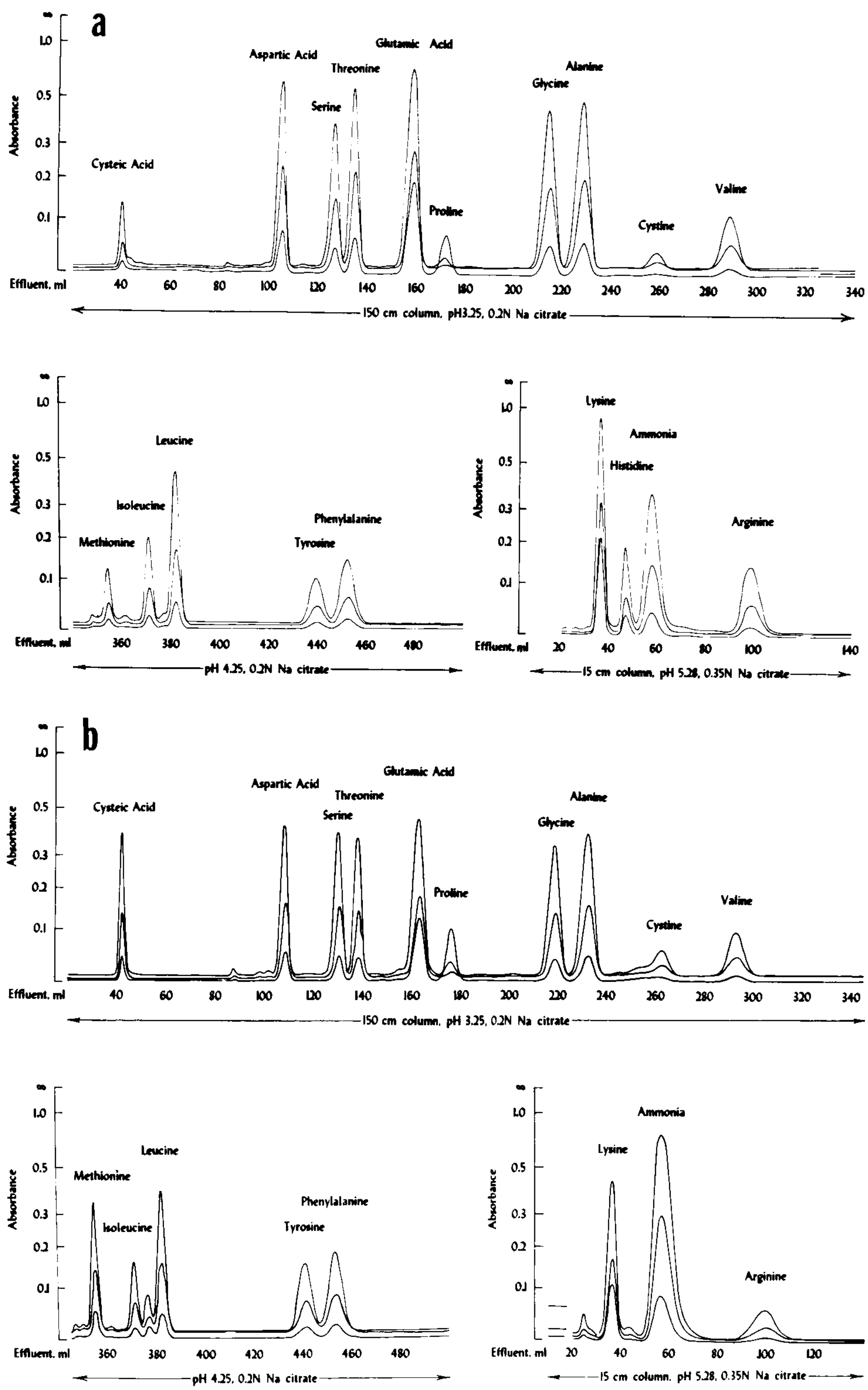

FIGURE 4.—Leuchs proteinoids. (a) All common amino acids. (b) Lacking histidine.

COMMENTS

Dr. McPherson: The pansynthesis of amino acids and the production of proteinoids represent a major breakthrough having consequences far beyond the relation to space flight possibilities. Heretofore, the production of a synthetic diet has involved the preparation of 18 to 22 individual amino acids—each by a long and laborious synthesis. It was necessary to blend these in the optimum proportion, and incorporate them into polymers by yet to be developed methods, or to produce polypeptides by laborious synthesis. These long and laborious methods have now been short-circuited.

An analogous situation existed in the early studies on synthetic rubber. Chemists in the 1920's thought that it might be necessary to build up polymers one unit at a time—monomer to dimer to trimer, and so forth—adding each unit by a separate reaction. The actual synthesis turned out to be much simpler. All that was necessary was to emulsify the monomer with Ivory soap and water and add a little persulfate and a high-molecular-weight mercaptan. The polymer was formed quickly, and engineering production became feasible.

It is interesting to speculate on the long-range possibilities of synthetic food from the perspective of history. The discovery of agriculture 9000 years ago gave the basis for all that we call civilization. The world population 9000 years ago may have been 1 million with such keen competition for hunting and fishing rights that the Earth was overpopulated for the people then living. Today the population of the Earth is 3 billion, an increase by a factor of 3000. Everyone is aware of the problem of population pressure. One possible effect of population pressure is accelerated research and development of synthetic food that may usher in a new era of civilization.

Dr. Scrimshaw: One point has not been developed—the potential usefulness of the proteinoids or, indeed, of any usable synthetic source of nitrogen. Only part of the protein requirement need be supplied as essential amino acids; the remainder may come from nonessential amino acids or even ammonium citrate. If the proteinoid did nothing more than supply usable nitrogen for the synthesis of nonessential amino acids in the body, the weight of protein to be taken along could be cut by as much as 80 percent. If, in addition, even an unbalanced but constant pattern of essential amino acids is supplied, this pattern could be balanced by a very small weight of essential amino acids brought along for the purpose.

Similarly, the recycling of urinary nitrogen to produce glycine, ammonium citrate, or some other simple but biologically utilizable nitrogen source could reduce the food supply problem if either the essential amino acids in synthetic form or food containing them in concentrated form were carried. The experiments of Swendseid Harris, and Tuttle ("The Effect of Sources of Non-Essential Nitrogen on Nitrogen Balance in Young Adults." J. Nutrit., vol. 77, 1962, pp. 391–396) as well as our own, indicate that the proportion of essential amino acids in egg and other animal protein is much higher than is required by the human adult and can be diluted with simple nitrogen-containing compounds without reducing the capacity to meet the protein requirement of the adult.

Chemical Synthesis of Proteinoids: Part 2

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As was pointed out in the previous paper and in a 1960 publication (ref. 1), proteinoids have many properties of natural proteins. In the earlier studies it was shown that proteinoids can replace peptones in broth cultures of *Lactobacillus arabinosus* (ref. 1), a fact which indicates that the peptide linkages of proteinoids are susceptible to the attack of bacterial proteases. Furthermore, it has been demonstrated that such proteolytic enzymes from the digestive tract as pepsin, trypsin, and chymotrypsin are also able to split proteinoid (refs. 1, 2, and 3). The hydrolysis rate, however, is rather slow compared to that of an equivalent amount of casein (ref. 1).

We found that a certain improvement of the proteolyzability of proteinoid could be achieved by oxidizing proteinoid with performic acid (ref. 2), pretreatment of proteinoid with 8 M urea, and heating of proteinoid in aqueous solution. Oxidizing proteinoid with performic acid resulted in an increase of the hydrolysis rate of proteinoid using trypsin, pepsin, and papain as hydrolyzing agents. Pretreatment of proteinoid with aqueous 8 M urea solution results also in an increased proteolyzability. In particular, the effect of trypsin is improved. The highest proteolysis rate could be obtained by first heating proteinoid in solution. A temperature of 80° C and a heating period of 1 minute was sufficient to increase the proteolyzability remarkably. Pepsin especially reacts much more readily with proteinoid.

Later we tried to accumulate information on the proteolyzability of proteinoid in vivo as well as on the utilization of thermal amino acid polymers. Preliminary experiments in vivo have been carried out to answer the question as to whether or not amino acids stemming from proteinoid can be incorporated into tissue proteins of rats (refs. 4 and 5). In those trials proteinoids have been used, which were prepared from hydrolysates of the yeast *Torula utilis* producing both radioactive methionine and cystine from S–35 sulfate.

In the experiments to be reported here, so-called "methionine"-proteinoids were used; that is, proteinoids were prepared from purified amino acids including S–35 methionine.

These preparations have been used in the feeding experiments after separation into a water-soluble and water-insoluble fraction. In most of the feeding trials we have carried out, the water-soluble fraction of a 2:2:1 "methionine"-proteinoid was applied by stomach tube twice a day over a range of 7 days to male rats weighing 80 to 100 grams. The diet consisted of 86 percent maize, 10 percent skimmed milk powder, 3 percent of a mineral mixture, USP XIV, and 1 percent of a mixture of vitamins essential for rats. Several organs and tissues have been checked for total radioactivity and for radioactive methionine.

About 60 percent of the total radioactivity was not absorbed from the intestine and appeared in the feces when the water-soluble fraction was fed. Nearly 37 percent of the total radioactivity passed the intestine wall and was found in the tissues and in urine. The highest amount of absorbed radioactive material, however, was accumulated in the liver and the blood as demonstrated in table I.

TABLE I.—*Distribution of Radioactivity After Application of Radioactive Proteinoid*

	Recovered radioactivity, percent	
	Range	Average of 10 animals
Liver	14.78–16.25	15.11
Blood	5.07– 6.23	5.82
Brain	1.74– 2.50	2.19
Skin and hair	1.22– 1.46	1.34
Kidneys	1.26– 1.82	1.45
Digestive tract (tissue)	0.25– 0.63	0.40
Rest of body	6.89– 7.48	7.25
Feces	57.53–66.89	60.03
Urine	3.14– 4.36	4.08
Digestive tract (content)	1.50– 6.72	2.23
Air	0.06– 0.20	0.10

Table II represents the distribution of radioactivity in the protein and the nonprotein fraction of the different organs and tissues. The results indicate that methionine stemming from thermal proteinoid can be incorporated into tissue proteins of rats. The highest content of radiomethionine could be found in the blood proteins. After dissection, no abnormal alteration of the organs could be found by histological examination carried out by Dr. E. Greuel.

TABLE II.—*Distribution of Radioactivity in the Rat Body*

	Radioactivity recovered from carcass, percent		
	Nonprotein fraction	Protein fraction	Total
Blood	8.43	24.41	32.84
Skin and hair	------	------	12.08
Liver	7.68	1.44	9.12
Brain	5.72	1.90	7.62
Kidneys	1.87	1.61	3.48
Intestinal tissue	2.09	2.18	4.27
Rest of body	10.27	20.32	30.59

Furthermore, the water-insoluble fraction was administered to male rats of the same weight range. The conditions of these experiments were also the same as those described for the water-soluble fraction. About 80 percent of the recovered radioactivity was found in the feces; however, more radioactivity could be observed in the urine, while tissues were less radioactive. The blood proteins showed a relatively much higher amount of radioactivity. These results are summarized in tables III and IV.

TABLE III.—*Distribution of Radioactivity After Application of Radioactive Proteinoid*

	Recovered radioactivity, percent	
	Range	Average of 10 animals
Blood	0.90– 1.68	1.45
Brain	0.38– 0.48	0.42
Skin and hair	0.20– 0.42	0.30
Liver	0.21– 0.36	0.26
Kidneys	0.07– 0.23	0.15
Digestive tract (tissue)	0.03– 0.12	0.10
Rest of body	0.54– 0.99	0.93
Feces	78.61–89.50	87.34
Urine	6.84– 9.12	8.40
Digestive tract (content)	0.38– 1.20	0.50
Air	0.09– 0.21	0.15

TABLE IV.—*Distribution of Radioactivity in the Rat Body*

	Radioactivity recovered from carcass, percent		
	Nonprotein fraction	Protein fraction	Total
Liver	35.62	7.55	43.17
Blood	4.17	12.45	12.62
Brain	4.98	1.27	6.25
Kidneys	1.06	3.08	4.14
Intestinal tissue	1.93	0.81	2.74
Skin and hair	------	------	3.40
Rest of body	9.42	14.26	23.40

Other experiments with nonradioactive proteinoids, which have been carried out over a period of a month, gave no evidence that proteinoids have any toxic effect on rats.

It should be emphasized that these experiments are a beginning, and many gaps in knowledge exist. Improved results will certainly be obtained because procedures for the preparation of proteinoids with better proportions of essential amino acids are available, and, also, we now have individual fractions of proteinoid.

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High Energy Nonfat Nutrient Sources

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Previous papers have outlined the problems of feeding man in space and to some extent have discussed possible ways of providing maximum nutrition in the smallest possible weight and volume. In general, these methods have included the use of freeze-dried foods, formula diets, and closed-cycle-recovery systems of one kind or another. All of these methods, however, have one thing in common—they are all based upon the use of naturally occurring nutrients. Therefore, diets based upon them are limited in their composition by certain physiological limitations.

For example, the maximum caloric density that can be obtained is limited by the maximum amount of fat that can be incorporated in the diet without physiological dysfunction. If, however, one is not limited to the naturally occurring nutrients, a new set of rules may prevail, and diets of greater nutrient density may become possible.

It was to test this possibility that a program was initiated with our group some 6 years ago, first under the sponsorship of the Air Force, and for the last 2 years with the sponsorship of the National Institutes of Health. From the first, we concentrated on the energy component of the diet. Energy was selected for several reasons. First, of all the components of the diet, energy can be supplied by a variety of compounds, while other physiological needs require relatively specific structure. Second, the satisfaction of the energy need occupies the greatest part of the diet.

Two general experimental approaches were used: first, to consider known compounds which could possibly supply metabolic energy, but were not usual dietary compounds; second, to attempt to design and synthesize compounds that could be useful in supplying dietary energy.

Of the many compounds examined, two were selected as models for these studies. The first of these, 1,3-butanediol, is a commercially available material, while the second, 2,4-dimethylheptanoic acid, was designed and synthesized in our laboratory to be used as a dietary energy source.

The 1,3-butanediol is a four carbon straight chain dihydroxy compound. It is miscible with water and liquid at room temperature. It has been used very extensively in the plastics industry, and more recently it has been proposed for use as humectant in tobacco. Originally, it was prepared from petroleum. Today it is synthesized and available in carload quantities at about 18 cents per pound; it is a very cheap material.

About 1949, reports concerning this compound began to appear in the literature, almost entirely in the German literature. The Germans were particularly concerned with its use in the drug and cosmetic industry, and, during the war, apparently as a possible food source. Fisher (ref. 1), for example, describes a very low acute toxicity, reporting an oral LD–50 of about 20 cubic centimeters per kilogram.

Meyer (ref. 2) fed the material at low concentrations for three generations in rats and found no effect on growth, reproduction, or fertility. Much of this work was summarized by Bornman (refs. 3 to 5) in which he concluded that, from all the data available to him at that time, the compound was not toxic.

It is interesting to note that 1,3-butanediol, of all the family of butanediols (the 1,4; 2,3; and 1,2 compounds), is relatively nontoxic. All of the others are very toxic.

Subsequent to this work, Schussel (ref. 6), another German worker, reported that of a whole series of polyols that he investigated in feeding tests, 1,3-butanediol was best tolerated. Furthermore, he reported that concentrations of lower than 20 percent in the diet appeared to stimulate growth. Moreover, it was Schussel who first said that the use of compounds such as 1,3-butanediol may provide a new base for nutrition.

In our laboratory we have confirmed the low toxicity of 1,3-butanediol (BD). Furthermore, we have estimated the gross energy density of the material at 7.5 calories per gram. Using an animal growth technique which we have developed, we have estimated the metabolically available energy as 6 cal/g in animals that have been adapted to the compound for at least 1 week prior to the test. This is an important point which will be discussed later.

The initial feeding studies attempted to duplicate some of the earlier German work. The results of one such test are shown in figure 1. In this particular test, 20 percent BD was added to a 35 percent fat diet. During the first week of the test there was a significant growth depression in animals fed BD. Following this first week, the animals gained weight almost equivalent to that of animals on the control diet. The important point is that there was a growth depression occurring in the first week during which the animals appear to adapt to the compound. Following this adaptation period, the animals grow at a rate equivalent to that of animals on the control diet.

In examining food intake of these animals, it became evident that simultaneous with this growth depression, there is a depression of food intake. Therefore, it was assumed that the growth depression was a function of reduced food intake. To test this hypothesis (that the depression of food intake was responsible for the depression in weight gain) a feeding experiment was performed, the results of which are shown in table I. In this experiment, animals were pair-fed relatively high fat diets containing various amounts of BD. As might be expected, food intakes were equivalent throughout the test.

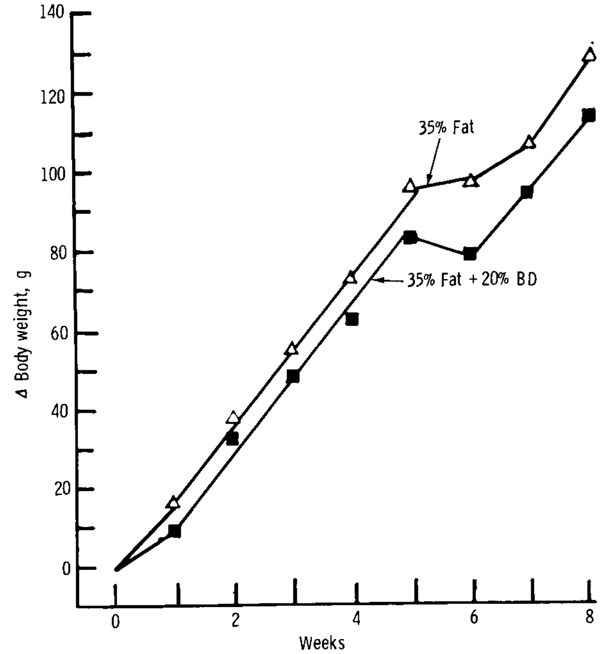

FIGURE 1.—Growth of rats fed diets ad libitum containing 35 percent fat or 35 percent fat supplemented with 20 percent 1,3-butanediol.

However, since it was the food that was pair-fed and not calories, there was an increase in the calculated caloric consumption with increasing BD in the diet, assuming BD to have a caloric density of 6 cal/g. This was confirmed by the observation that body weight increased with increasing calculated calorie intake. Finally, there was little difference in food efficiency during the test. Since weight gains were similar when food intake and calories were equivalent, it was concluded that the depression in weight gain observed during the initial feeding of butanediol was a function of decreased food intake.

TABLE I.—*Effect of Paired Feeding of Graded Levels of 1, 3-Butanediol (BD) as a Carbohydrate Replacement in a 25 Percent Fat Diet*

Group	Food consumption, g	Calories consumed, cal	Body weight gain, g	Efficiency, percent	
				Food	Caloric
10% Fat	320	658	51.3	16.0	7.8
25% Fat	319	775	63.9	20.0	8.2
25% Fat+5% BD	320	794	71.5	22.3	9.0
25% Fat+20% BD	320	842	70.5	22.2	8.4

There is, however, always a disadvantage with pair-feeding tests in that they tend to penalize the control animals by restricting their food intake. To obviate this objection, a similar experiment was performed in which the animals were tube-fed isocaloric amounts of diets with and without BD. The results of these tests are shown in table II.

In this test, all animals received the same amount of protein and calories during the last 3 weeks of the test. At the end of the last 3 weeks (last column) all of the animals gained essentially the same amount of weight indicating again that the decrease in weight gain observed upon the initial feeding of butanediol was a function of a reduction in food intake. There was, however, some decrease in the weight gain of animals fed butanediol during the first week of the test, again demonstrating this adaptation phenomenon.

The reason for this depression of food intake during the initial feeding of BD is unknown to us at this time. It is possible that it is a function of poor absorption of the compound during the initial phases of feeding which in turn may reduce the absorption of other components of the diet. Some support for this explanation may be obtained in the works of Hess and Kopf (ref. 7), who observed that 1,3-butanediol, when given orally, retarded the absorption of drugs. If this is true, there must then be some adaptive mechanism which permits better absorption of the compound in the period after the first week of feeding.

In terms of the metabolism of butanediol, a number of workers had postulated that 1,3-butanediol (BD) is oxidized to betahydroxybutyric acid, a pathway that seems reasonable when looking at the structure of butanediol.

TABLE II.—*Weight Gains of Rat Pairs Intubated With Equal Volumes of Isocaloric and Isonitrogenous Liquid Diets*

Diet	Average body weight gain [a] per week, g				Total weight gain, g	
	1st wk	2d wk (9 rats)	3d wk (9 rats)	4th wk (9 rats)	in 4 wk	in 2–4 wk
30% Fat	16±2 (9 rats).	22±2	17±0.8	18±2	73	57
30% Fat +20% BD	8±2 (10 rats).	24±1	17±0.8	16±0.9	65	57
Water intubated control [b]	27±3 (10 rats).	29±4	29±3	27±4	112	85

[a] Mean and standard error.
[b] Fed stock diet ad libitum.

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It occurred to us, therefore, that if we fed very large amounts of BD, we would expect to find an increase in the ketone body concentration in the serum of the rat, and, if it were high enough, we would hope to find a ketonuria as well.

In addition to the question of the metabolic pathway of BD, the long-term effects of feeding relatively large amounts of the compound also needed examination.

For these reasons, a 30-week test was performed in which diets containing various levels of fat, protein, and BD were fed to male rats. The experimental variables of this test are shown in table III. Generally, the protein in these experiments varied from 11 to 36 percent of the calories. Fat varied from 22 to 83 percent of the calories while BD varied from 22 to 36 percent of calories. Carbohydrate varied in these diets from essentially 0 up to 61 percent of the calories. At the end of the 30 weeks of the test, liver, serum, and urine were collected. Assays for ketone bodies, liver phosphohexose isomerase, glucose, cholesterol, and liver glycogen were performed.

TABLE III.—*Experimental Variables*

Protein, percent:	
20 percent casein	18
33 percent casein	28
40 percent casein	36
Fat, percent	10–60
1,3-Butanediol	20–30
Calories, cal/g	4. 0–6. 7
Protein, cal/g	11. 1–36. 8
Percent of calories:	
Protein	11–36
Fat	22–83
1, 3-Butanediol [a]	22–36
Carbohydrate	1–61

[a] Based on an estimated utilizable calorie value of 6 cal/g.

The characteristics of diet used in this study are shown in table IV. There are three points of importance. The first is that the BD was added in every case to a 30 percent fat diet. Second, there are at least three diets in which the carbohydrate was included at 5 percent or less in the diet. Third, during the course of the experiment, it became obvious that variations in protein from as low as 10 percent to as high as 36 percent of the diet had no effect on any of the parameters studied. Therefore, in order to simplify the presentation of these results, they are presented as combinations of groups fed similar levels of fat and BD. No specific effect of the presence or absence of carbohydrates in the diet was observed.

TABLE IV.—*Characteristics of Diets Used in 30-Week Study* [a]

Diet	Fat, percent	1,3-butanediol, percent	Protein, percent	Carbohydrate, percent
1	10	------	18	62
2	10	------	36	42
3	30	------	18	42
4	30	------	36	22
5	30	20	18	22
6	30	20	36	2
7	30	20	36	------
8	30	30	18	12
9	30	30	28	------
10	50	------	18	22
11	50	------	36	2
12	60	------	18	12
13	60	------	18	11
14	60	------	18	6
15	60	------	28	------

[a] Dry basis.

With one exception, no significant difference in growth of any of the groups was observed at the end of 30 weeks (fig. 2). The one exception to this was the group that was fed the diets containing 30 percent BD. At no point did this group match the growth rates of the other groups. These data were corrected for the first week growth rate depression which has been observed in every experiment. The calculation of nutrient efficiency, caloric efficiency, and food efficiency also demonstrated no significant difference at 4 or 30 weeks with the exception again of the animals fed the 30 percent BD diets.

The metabolic parameters are shown in figure 3. The effects of increasing levels of dietary fat are shown by the solid lines. There was an unexpected increase in phosphohexose isomerase activity in animals fed diets containing 50 percent fat. Since the changes in serum glucose and liver glycogen were consistent with this variation, it did not seem likely that these were

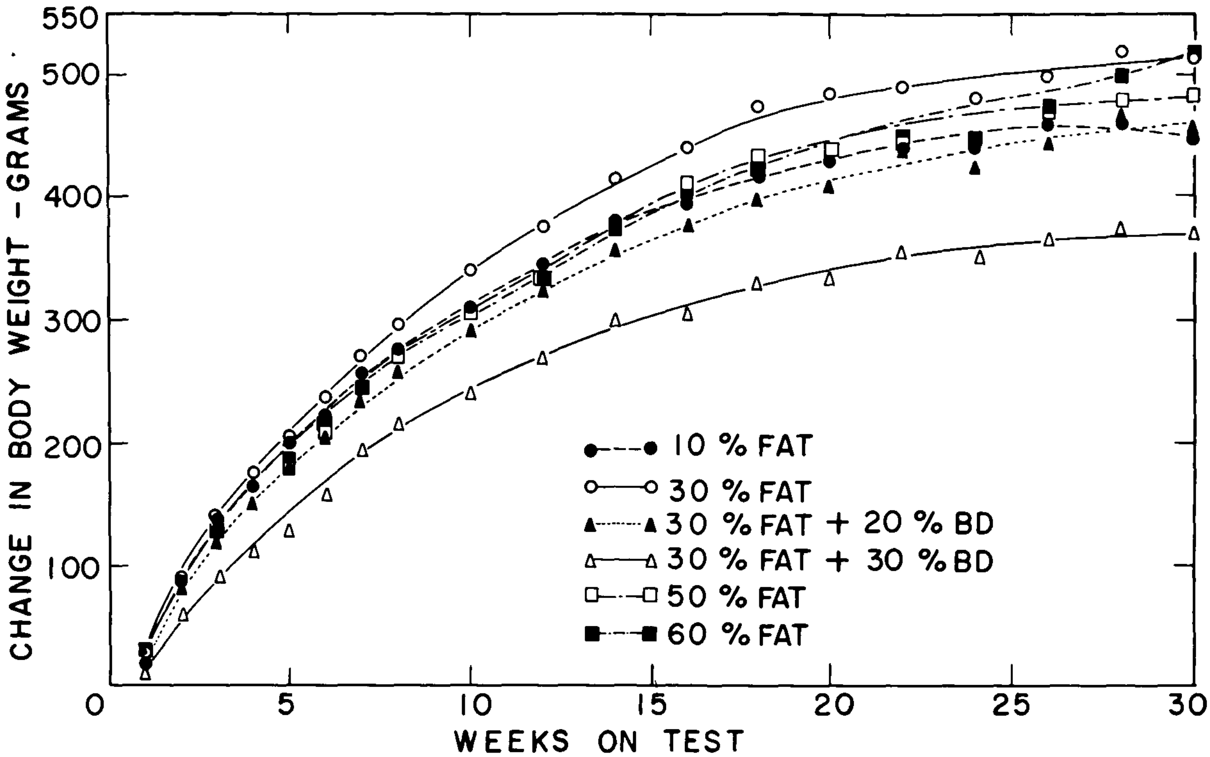

FIGURE 2.—Growth of rats fed diets ad libitum containing various levels of fat and 1,3-butanediol.

the results of analytical error. Whether this represents an unknown exotic effect of 50 percent fat diets in this experiment or represents an unknown variable or artifact in this group is unknown. We suspect that the latter is correct.

The addition of BD to these diets is shown by the dashed lines originating from the 30 percent fat group because this was the level of fat to which the supplements were added. Liver phosphohexose isomerase increased sharply with increasing amounts of dietary BD. Glucose changes, however, were not nearly so consistent. At 20 percent BD, there was a decrease in serum glucose, while at 30 percent, glucose increased. Similar responses were seen with liver glycogen, where there appeared to be a decrease at 20 percent supplementation and a rise at 30 percent.

The influence of the various diets on the ketone body concentration of the serum and urine was of particular interest in this study (fig. 3). With increasing amounts of fat in the diet, serum levels increased up to 50 percent dietary fat. At 60 percent dietary fat there was a very drastic and severe drop. In the urine, a similar increase in ketone body levels was found, sharply at 50 and 60 percent dietary fat.

The sharp decrease in serum ketone levels at 60 percent fat may be a function of increased clearance of ketone bodies at this serum level. Some support for this may be found in the fact that there was a significant increase in urine volumes of the animals fed 60 percent fat diets. However, and this is the most interesting observation of the experiment, the addition of BD to the 30 percent fat diet resulted in a tendency for the ketone body serum levels to drop and, concomitantly, no changes in the urine levels.

If BD was metabolized to betahydroxybutyric acid, one would expect to find some increase in ketone body levels at the 30 percent dietary level. In addition, both the 50 percent fat diets and the 30 percent fat—30 percent BD diets should provide approximately the same amount of ketone bodies if the BD was metabolized to betahydroxybutyric acid. Since an increase in ketone body levels was found when the 50 percent fat diets were fed and since no

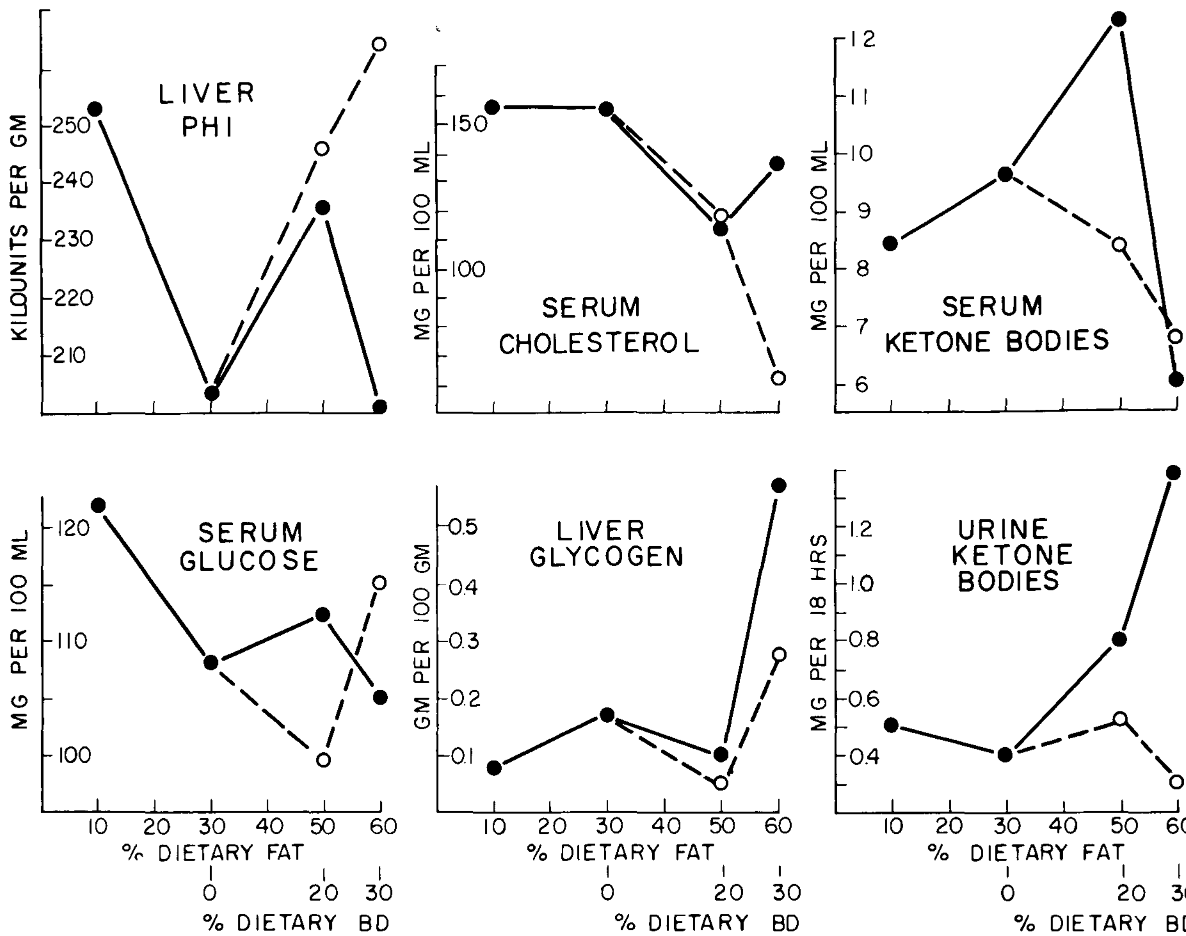

FIGURE 3.—Various metabolic parameters in rats fed diets containing various levels of fat and 1,3-butanediol for 30 weeks.

increase was found when butanediol was fed, some doubt must be cast on the postulate that BD is metabolized to betahydroxybutyric acid. If this hypothesis is not valid, the question of how BD is metabolized still remains to be answered. At the present time we are studying this problem. We have managed to obtain the compound labeled in the 1 and in the 4 position, and are in the process of performing a number of studies with these labeled compounds.

The feeding of BD has a number of interesting corollary effects. With increasing amounts of fat in the diet, there is a tendency for serum cholesterol to increase slightly (fig. 3). When, however, butanediol is added to the 30 percent fat diet, there is a consistent decrease in serum cholesterol levels. In fact, with 30 percent BD, serum cholesterol level is less than half of the level at 30 percent dietary fat.

Whether this decrease in serum cholesterol levels is accompanied by an increase in liver levels of cholesterol or whether there is an inhibition of cholesterol synthesis in the liver is not known. It might be pointed out that, in these diets, there is no added cholesterol.

The second compound investigated in this program was 2,4-dimethyl-heptanoic acid (DMHA). This compound was designed to circumvent the ketosis resulting from the accumulation of two carbon fragments obtained when high fat diets are fed. We postulated that the addition of methyl groups in the 2 and 4 positions of a fatty acid would result in the formation of three carbon propionate fragments upon beta oxidation rather than the two carbon acetate fragments obtained during the oxidation of the more usual fatty acids.

Using the pure material, a number of acute toxicity tests were performed. These tests gave an estimated acute LD-50 of about 5 grams per kilogram. This is a value quite similar to that obtained for other short chain or medium chain fatty acids.

To study the metabolism of the compound, it was decided to synthesize DMHA labeled with C-14 in the alpha methyl group. In this way we required only a relatively small amount of material to study its metabolism. The response of the rats fed the labeled DMHA was compared to rats fed an equivalent amount of propionate labeled in the 3 carbon.

In these experiments, the animals were trained to consume all their ration in 1 hour. Objections can be made that trained fed animals are not the same as ad libitum fed animals. For the purposes of this test, however, this technique allowed a more reasonable calculation of metabolic distribution of the compound.

At the time of the experiment, the animals were placed in metabolism cases and fed their respective diets. Collections were made of carbon dioxide, urine, feces, and spilled food. The animals were re-fed at 24 hours in those experiments lasting 48 hours. At 12 and 48 hours animals were sacrificed and liver, carcass, and epididymal fat pad were assayed for activity.

The cumulative amount of label appearing in the respired air expressed as the percent of ingested activity is shown in figure 4. It is apparent from these data that the oxidation of 2,4-DMHA does not occur at the same rate as propionate. At 48 hours, only 80 percent of DMHA is oxidized completely, the remainder appearing in the urine. The distribution of 2,4-DMHA in a number of body compartments is shown in figure 5. While it might appear that 2,4-DMHA is not as efficient a precursor of liver glycogen, one must remember that the oxidation of 2,4-DMHA occurs at a much slower rate.

Another way of getting at this problem of the efficiency of a material as precursor of a metabolic product is by calculating the ratio of the specific activity of the precursor to the specific activity of the product. When this ratio is calculated for the alpha methyl carbon of

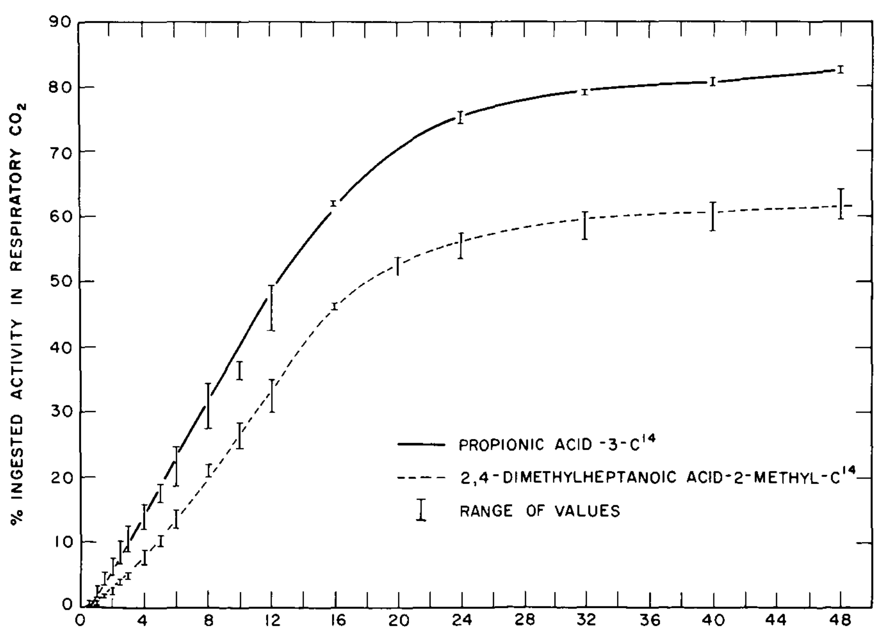

FIGURE 4.—Cumulative percentage of recovery of ingested activity in respiratory carbon dioxide.

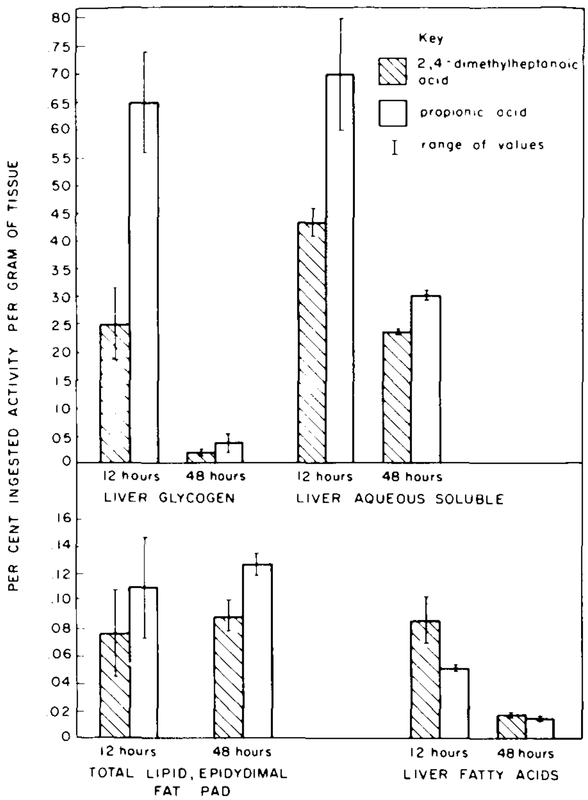

FIGURE 5.—Percent ingested activity from propionate 3-C^{14} and 2,4-dimethylheptanoic acid-2-methyl-C^{14} in lipid-soluble and non-lipid-soluble fractions of the rat.

DMHA and for carbon 3 of propionate no difference between the two was found (table V). This indicates that DMHA is about as efficient a precursor of liver glycogen as propionate. Moreover, one might also interpret these data as meaning that propionate is an obligatory intermediate in DMHA metabolism, confirming the original hypothesis.

As indicated earlier, 20 percent of the activity of DMHA was found in the urine. About 60 percent of this was in the form of 2,4-dimethylpimelic acid, the omega oxidation product of 2,4-DMHA. A significant amount of the

TABLE V.—*Radioactivity in Glycogen From Propionate and 2,4-Dimethylheptanoic Acid (DMHA)*

Compound tested	Animal number[a]	Liver glycogen, percent	Sp. act. glycogen / Sp. act. compound
Propionate	1–12P	5. 95	0. 945 × 10^2
	2–12P	5. 45	. 715
	4–12P	5. 82	. 777
	5–48P	2. 52	. 165
	10–48P	1. 85	. 067
DMHA	5–12D	4. 04	1. 290
	7–12D	3. 08	1. 060
	10–12D	3. 42	. 664
	4–48D	2. 36	. 143
	6–48D	2. 17	. 090

[a] The 12 or 48 in animal number refers to duration of experiment in hours.

betahydroxy derivative of 2, 4-DMHA was also found, indicating that the compound was first of all being beta oxidized, but secondly that beta oxidation was inhibited to some extent. Whether this inhibition is due only to the presence of the alternating methyl groups, or whether it is a function of the short chain length combined with the presence of the methyl group is not known at this time. This is currently under investigation.

In conclusion, data have been presented on two compounds which are not normally considered to be dietary nutrient sources. Whether these compounds per se ever prove useful is, at the moment, immaterial. The important point is that a concept has been presented that postulates the possibility that compounds capable of being utilized for energy by the animal can be designed and synthesized. The compounds we investigated thus far are considered to be models. At the present time, we are attempting to use them in an effort to gain more information about the processes of energy metabolism so that potentially more useful compounds may be designed.

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Use of Formula Diets

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The first formula diet available—one for which none of us can claim any credit—is mother's milk. In each mammalian species, the mother secretes a milk which is the formula diet for its young up to the time that the young or the child is able to eat other foods. Milks of different animals vary markedly in composition. Each is presumably well suited for the growth and development of the particular species. The modifications of cow's milk to produce good formula products for infants have really provided the introduction to the more recent development of formula diets for other uses.

Under conditions of stress or in special situations, a formula diet can be extremely useful, since it can provide a tailor-made combination of the types and amounts of nutrients needed to furnish optimal nutrition in each particular situation. It can also insure complete nutritional adequacy. Some present day uses of formula diets are as follows:

- Infant formula products
- Tube feedings
- Weight control diets
- Ulcer diets
- Diets providing adequate water along with food
- Diets for long-term care of special subjects in the hospital
- Diets for metabolic studies

Cow's milk is probably an ideal formula diet for the young calf. With suitable modifications and additions, it is an excellent basic material for many of the formula diets:

For *infant formulas*, carbohydrate must be added, the type of fat may be changed, and various vitamins and minerals may be included to meet better the nutritional requirements of the human infant.

For use in *tube feeding*, the level of fat may be decreased for better gastrointestinal tolerance, and the level of protein increased to provide therapeutic needs with limited total food intake.

Formulations used in *weight control* require a concentrated diet, providing adequate levels of protein and of all other essential nutrients, with restricted calories.

For subjects with *peptic ulcer*, an unsaturated vegetable oil in the formula can replace the saturated butter fat and cholesterol of the Sippy diet, while other additions improve the overall nutritional value of this diet.

Other special formulas may supply the *water requirement* of the subject along with the food, may supply fats which are more readily utilized in subjects with malabsorption, or may supply a high proportion of polyunsaturated fatty acids for medical or other reasons. It is hoped that a review of some of these formula diets will assist in the evaluation and design of formula diets for space travel.

INFANT FORMULA DIETS

In table I are shown the compositions of cow's milk and human milk, cow's milk as originally modified for infant feeding (by adding carbohydrate), and some proprietary infant formula products with levels of nutrients closer to those of human milk.

TABLE I.—*Composition of Cow's Milk, Human Milk and Infant Formula Products*

	Cow's milk	Human milk	Infant formulas			
			Modified cow's milk	Products		
				1	2	3
Composition, percent:						
Protein	3. 3	1. 2	2. 7	1. 5	1. 7	1. 5
Fat	3. 7	3. 8	2. 8	3. 7	3. 4	3. 6
Carbohydrate	4. 8	7. 0	7. 8	7. 0	6. 5	7. 2
Ash	0. 72	0. 21	0. 6	0. 34	0. 38	0. 25
Caloric distribution, percent:						
Protein	20	7	16	9	11	9
Fat	51	51	38	50	47	48
Carbohydrate	29	42	46	41	42	43
Minerals:						
Overall level	High	Low	Intermediate	Low	Low	Low
Low in	Iron, Cu		Iron, Cu		Cu, I	I
Vitamins:						
Added	D		D	12	6	9
Low in	C, E	D	C, E		E(?)	

The levels of protein and ash in human milk are much lower than those in cow's milk and provide a lower solute load to the kidneys of the infant. Adding carbohydrate and water to milk reduces protein and ash levels sufficiently to permit ready handling of the solute load by the kidney of the young infant. In many of the formulas now available for infants, levels of protein and ash closer to those of human milk are used, as seen in Products 1, 2, and 3.

Human milk also provides a good source of vitamin C, vitamin E, and linoleic acid, whereas cow's milk contains low levels of these nutrients. In many formula products, fats which supply more linoleic acid are substituted for milk fat; and vitamins and trace minerals are added to compensate for losses in processing and the "dilution" of milk solids with added carbohydrate and fat. Some of the infant formula products are *complete* formula diets, on which many infants in the United States now start their lives.

In addition to providing for the requirements of normal infants, formula diets are also available for infants with special nutritional requirements because of allergy, metabolic defects, or premature birth. For example, soybean, protein hydrolysate, or meat formulas can be used for allergic infants. Formulas with carbohydrates other than lactose or galactose are available for the galactosemic infant; and a complete formula low in phenylalanine is available for the phenylketonuric infant.

TUBE FEEDING FORMULATION

Feeding of patients who are comatose, have broken jaws, or cancer of the throat or esophagus can best be accomplished by tube feeding. Early tube feedings made from milk and eggs or other mixtures were often not well tolerated, or were not complete nutritionally.

The composition of a tube feeding mixture especially designed to provide liberal amounts of protein, a low level of fat (to assure better gastrointestinal tolerance), and all necessary vitamins and minerals is shown in table II. In order to provide the nutrients at the concentrations desired, this product can only be supplied as a powder and mixed with water prior to use. If a liquid formula with these concentrations of nutrients were heat-sterilized, it would form a solid gel.

TABLE II.—*Composition of Tube Feeding Formula and of Nutritional Diet Supplement*

[Per 8 fluid ounces]

	Tube feeding formula (Sustagen)	Nutritional diet supplement (Tribute)
Calories	360	280
Protein, g	22	14
Fat, g	3.2	9.3
Carbohydrate, g	61	35
Minerals	Complete	Complete
Vitamins	A and D—recommended allowances; B vitamins—therapeutic	All—recommended allowances

The formulation of a specially designed formula diet which is available in liquid form as a nutritional diet supplement is also shown in this table. The levels of protein and of calories in this product are not as high as those in the tube feeding preparation, but it still supplies practically twice as much protein, and 75 percent more calories than does milk. Added vitamins and minerals make this a complete diet, providing both nutritional and therapeutic support for patients.

PEPTIC ULCER FORMULA DIET

For many years the Sippy diet has been used in the treatment of peptic ulcer patients. The purpose of this milk-cream mixture was to afford relief to the patient by buffering gastric acid, soothing the ulcerated lining, and decreasing gastric motility; unfortunately, such a diet is quite low in protein, iron, ascorbic acid, and other essential nutrients and is very high in fat, as shown in table III. In recent years the Sippy diet has been implicated in the very high incidence of cardiovascular disease in peptic ulcer patients. Briggs et al. (ref. 1) found a 36 percent incidence of myocardial infarcts in ulcer patients, in the United States, who had been treated with the Sippy diet, as compared with 15 percent in ulcer patients who had not received the Sippy diet, and 15 percent in nonulcer patients.

The formulation of a modified diet for the ulcer patient is also given in table III. This has all of the beneficial characteristics of the Sippy diet, without its nutritional inadequacies: It contains a lower level of fat than the Sippy diet, as a vegetable oil, and more protein. This is desirable from a nutritional standpoint; but since some of the therapeutic effectiveness of the Sippy diet and its slow gastric emptying had been attributed to its high fat content, research was required to see whether these changes would affect the usefulness of the diet. Studies were therefore carried out on the effect of the level and type of fat, in a milk base diet, on gastric emptying time in the rat.

TABLE III.—*Composition of Ulcer Dietary and Sippy Diet*

[Per 6 fluid ounces]

	Ulcer dietary (Quell)	Sippy diet (half milk-half cream)
Composition, g, and caloric distribution (percent)		
Protein	10 (20)	6 (9.5)
Fat	10 (45)	22 (78.0)
Carbohydrate	17.5 (35)	8 (12.5)
Calories	200	254
Minerals	Complete	Inadequate: Iron Cu
Vitamins	Complete	Inadequate: C E

Homogenized mixtures of skim milk, lactose, and different levels of various fats were made for these studies (table IV). The liquid formulas contained 4, 8, or 12 percent fat, and all contained approximately 3 percent protein. The carbohydrate level was varied to keep the total solids constant. Fasted rats received 2 milliliters of diet by stomach tube and the levels of solids and fat remaining in the stomach were determined after 1 and 2 hours. A brief summary of the results of one of these studies comparing milk fat (cream) and corn oil in these diets is shown in figures 1 and 2. With milk fat, the levels of solids (fig. 1) remaining in the

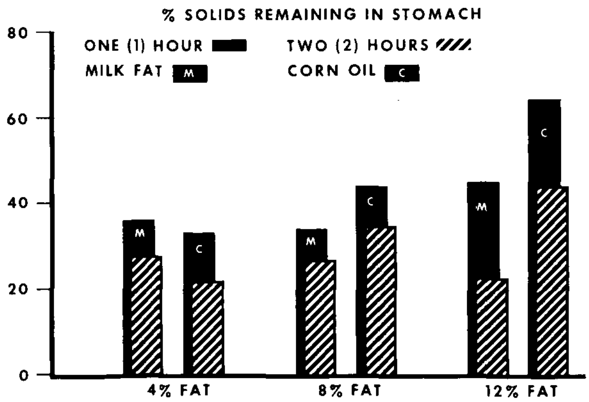

FIGURE 1.—Percentage of solids remaining in stomachs of rats fed formulas containing milk fat and corn oil.

stomach of the rats given 4 or 8 percent fat mixtures were not markedly lower than when the 12 percent fat mixture was given. With corn oil, however, there was a marked increase in gastric retention as the level of fat was increased, and the dietary solids found in the stomach after 2 hours with 12 percent cream were no higher than that with 4 or 8 percent corn oil.

Figure 2 shows the percent of the administered fat remaining in the stomach. As the level of dietary fat was increased, the percent of the milk fat retained in the stomach after 2 hours decreased, while that of the corn oil increased.

A more detailed description of this work and comparisons of other fats are described by Harkins, Longenecker, and Sarett (ref. 2). These studies show a relationship between retention of fat and fatty acid chain length. In general, diets containing from 4 to 8 percent fat as vegetable oils were retained as well as diets containing 12 percent fat as cream. On this basis, an ulcer diet providing only 45 percent of the calories as fat (or 5.6 percent in the liquid product) was formulated.

Studies have also shown that this dietary effectively heals restraint-induced ulcers in rats (ref. 3). Ulcer scores were 3.7 to 4.1 in animals given water, 1.6 to 1.8 in animals given the Sippy diet, and 1.9 to 2.2 in animals given this formulation. Milk gave a score of 3.2.

Nutritional studies showed that this formulation supported excellent growth in rats—as good as was found with a nutritionally complete 20 percent casein diet (table V). With the Sippy diet, rats grew poorly; when this was fortified with vitamins and minerals, growth was better, but caloric efficiency was still low and liver fat

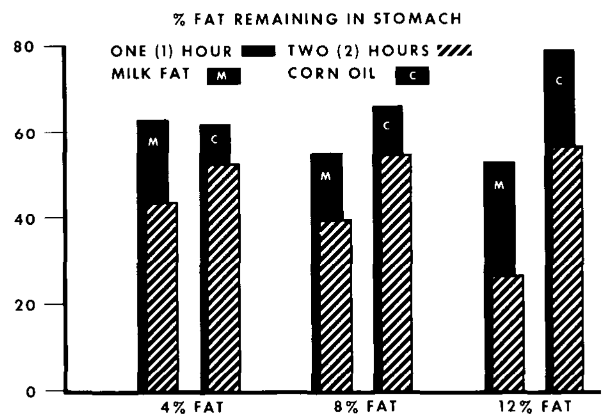

FIGURE 2.—Percentage of fat remaining in stomachs of rats fed formulas containing milk fat and corn oil.

TABLE IV.—*Composition of Liquid Test Diets*

Composition	Fat content, g/100 g			Source of nutrients
	Low	Moderate	High	
Fat	4	8	12	Milk fat (cream); vegetable oils; and triglycerides.
Protein	3	3	3	Milk pro'ein from skim milk powder.
Carbohydrate	13	9	5	Lactose as lactose and from skim milk powder.

TABLE V.—*Nutritional Value of Ulcer Diet*

(a) Overall value

Diet	Weight gain, g/4 weeks	Caloric efficiency, g gain/1000 cal	Liver fat, percent
Ulcer diet	145	100	4.4
Sippy diet (milk-cream)	66	48	6.2
Sippy diet (milk-cream plus vitamins and minerals)	97	57	14.8
Casein control diet (powdered, 20 percent protein)	135	105	3.2

(b) Protein efficiency

Diets (10 percent protein)	Weight gain, g/4 weeks	Protein efficiency, g gain/g protein
Ulcer diet	83	3.0
Casein control diet	87	3.1

levels were quite high. Protein efficiency of the ulcer formulation was approximately the same as that of the casein control.

Clinical studies have since shown that the buffering of gastric acidity by this formulation is as good as is obtained with the Sippy diet. There is also much less postprandial hyperlipemia, and plasma cholesterol levels are lower than with the Sippy diet.

FORMULA DIETS FOR METABOLIC STUDIES

Formula diets have recently come into widespread use in metabolic studies by many clinical investigators. In 1935, Holt et al. (ref. 4) used formula diets to study the absorption of various fats in infants. About 10 years ago, Olson et al. (ref. 5) showed that formula diets were convenient and useful in carrying out well controlled metabolic balance studies. Ahrens and coworkers (ref. 6) also found formula diets useful in providing different types and levels of fat and carbohydrate in the diet for carefully controlled metabolic studies.

A low protein formula diet made from evaporated milk, corn oil, and dextrose was introduced by Feinstein et al. (refs. 7 and 8) for use in weight loss by obese subjects. Although this diet was low in protein and nutritionally incomplete in some respects, it undoubtedly served as an additional stimulant to the present use of formula diets, especially in weight control.

FORMULA DIETS IN WEIGHT CONTROL

Formula diets have had their greatest impact and largest use (other than in infant feeding) for weight loss and weight control by obese persons. The composition of the first of these, introduced in the fall of 1959, is shown in table VI. This dietary for weight control, providing 70 grams of protein, 900 calories, and the Recommended Daily Allowances of vitamins and minerals per quart, was designed to assure adequate nutrition, with virtually no loss of essential body tissue during weight loss. Many studies on the nutritional value of this product were carried out in animals in short- and long-term experiments prior to clinical testing. Before describing the earlier studies, it may be pertinent to show the results of two studies comparing nutritional values of a few of the approximately 150 competitive products which rapidly appeared on the market after this dietary was introduced.

Male weanling rats were fed these liquid diets as the sole diet and allowed water ad libitum for 8 weeks, as shown in table VII. The weight gain on three of the products was quite satisfactory, but growth was not good on the other five products.

More striking than the differences in weight gains were those in hemoglobin levels. Animals fed formula diets 3, 5, 6, 7, and 8 had low hemoglobin levels, from 11.8 to 14.4 grams per 100 milliliters, even though adequate iron was present. The anemia was shown to be due to a deficiency of copper, as also seen in table VII. Pigmentation of the fur was also noted in the rats on the copper-deficient diets. These data serve to show that *all major and minor nutrients required by man and animals must be included in formula diets* in order to insure good nutritional value when used as the sole diet.

TABLE VI.—*Composition of Dietary for Weight Control*

	Dietary for weight control (Metrecal), per day
Fluid volume, fluid oz (4×8 fluid oz)	32
Calories	900
Protein, g	70
Fat, g	20
Carbohydrate, g	110
Minerals	Complete
Vitamins	Complete

TABLE VII.—*Growth of Weanling Rats on Various Diets for Weight Control*

Diet	Dietary copper, mg/900 cal	Gain in weight, g		Caloric efficiency, g gain/1000 cal (8 weeks)	Hemoglobin, g/100 ml (8 weeks)
		4 weeks	8 weeks		
1	1.5	126	216	68	16.6
2	2.4	124	229	73	17.0
3	.3	96	158	66	13.1
4	1.8	106	214	72	16.8
5	.1	88	133	56	11.8
6	.1	100	176	59	13.0
7	.4	110	171	65	14.4
8	.3	114	163	61	13.7

Protein efficiency values for some of these products are shown in table VIII. Values range from 2.10 to 2.87 grams gained per gram protein, as compared with a value of 2.50 for the casein standard. This study suggests that methods of handling and processing formula diets may significantly affect their protein value.

Coming back to nutritional studies in the development of the dietary for weight control, good protein quality and adequacy for good growth were assured in initial tests as just described. (Similar studies were applied in the later development of the wafer form of this dietary.) To provide a more severe test of nutritional adequacy of this diet, long-term reproduction studies were performed. Rats of our stock colony were fed this formula diet as the sole food for several weeks before mating and

TABLE VIII.—*Protein Efficiency Values of Diets for Weight Control*

Diet	Protein efficiency, g gain/g protein
Casein control	2.50
Product	
1	2.64
2	2.87
3	2.26
4	2.70
5	2.56
6	2.10

during pregnancy and lactation. The young of these animals were then continued on this formula diet to maturity, mated, and the second generation young raised on this formula. As controls, similar groups of rats were studied, while being fed the stock Purina Chow diet used for the rat colony.

The data on reproductive and lactation performance of the animals on these diets are summarized in tables IX(a) and IX(b). Animals receiving the formula dietary as the sole diet gave birth to normal young of good average weight, and these grew well during lactation and following weaning. Weight gains after weaning were higher with the Purina Chow diet than on the formula diet, but the formula diet contains a high level of lactose, a sugar which is not well tolerated by the young rat. These studies show that the formula dietary is not only of good nutritional value in short-term studies, but can be relied on for long-term nutrition through two generations. Other studies in obese rats showed that weight loss during caloric restriction was essentially all fat tissue and not lean body mass.

Clinical studies with this dietary showed that it was nutritionally adequate and effective in short- and long-term studies in weight reduction and control (refs. 9 to 11). Its low sodium content also made it useful in weight reduction in patients with cardiovascular disease (ref. 12). In a study at Purdue University (ref. 13), it was shown by whole body counting of K^{40} that obese subjects who lost from 12 to 36 pounds in 8 weeks on this dietary did not lose any lean body tissue. The total weight loss was excess body fat.

TABLE IX.—*Reproduction Study—Dietary for Weight Control*

(a) Part I. Mother and young

Diet	Generation	Number mated	Number pregnant	Mothers: Preparturition weight, g	Mothers: Wt. at weaning, g	Young: Number per litter	Young: Birth weight, g	Young: 21 day weight, g: Male	Young: 21 day weight, g: Female	Survival, percent
Dietary for weight control	Stock									
	F_0	24	18	291	243	9. 0	5. 8	36	32	47
	F_1	26	23	260	214	8. 7	6. 1	28	27	64
Purina Chow	Stock									
	F_0	24	17	308	272	9. 1	5. 8	36	36	61
	F_1	31	24	292	251	9. 5	5. 6	36	34	58

(b) Part II. Growth of young, 6 weeks

Diet	Sex and generation	No. of rats	Weaning weight, g	Weight gain, g	Caloric efficiency, g gain/1000 cal
Dietary for weight control	Males: F_1	27	41	147	86
	F_2	50	38	170	88
	Females: F_1	26	35	108	73
	F_2	50	36	116	72
Purina Chow	Males: F_1	22	43	184	80
	F_2	66	45	205	76
	Females: F_1	32	39	116	61
	F_2	51	42	124	59

FORMULA DIETS—WATER REQUIREMENT

The composition of a formula diet which supplies 400 calories in 12½ fluid ounces for use as a readily digestible meal, for occasional meal replacement, or for a survival ration is described in table X. Nutritional studies in animals have shown that it supports good growth in short- and long-term experiments. Another important attribute of this diet is that it provides adequate water as well as other nutrients. Studies in the rat, summarized in table XI, show that rats fed this dietary alone—with no supplemental water—gained weight as well as animals given a complete casein diet with water ad libitum, or the formula diet with extra water allowed. At the end of the 8-week period there was no evidence of hemoconcentration in the animals, as shown by levels of protein, sodium, and potassium in plasma, and by hemoglobin and hematocrit values.

TABLE X.—*Composition of Complete Liquid Meal*

	Complete liquid meal (Nutrament), per meal
Fluid volume, fluid oz	12.5
Calories	400
Protein, g	20
Fat, g	13.3
Carbohydrate, g	50
Minerals	Complete
Vitamins	Complete

TABLE XI.—*Complete Liquid Meal—Water Requirement of Weanling Rats During 8-Week Growth Study*

Diet	Initial weight, g	Food intake		Added water intake, g	Weight gain, g	Hemoglobin, g/100 ml	Hematocrit, percent	Plasma		
		g	cal					Protein, g/100 ml	Na, meq/liter	K, meq/liter
Casein [a] + water	50	774	3251	932	236	17.3	55	6.0	147	9.8
Complete liquid meal	50	[b] 3396	3491	----	260	17.2	54	6.3	150	8.4
Complete liquid meal + water	50	[c] 3680	3783	140	275	17.9	54	5.9	145	8.0

[a] Casein diet: 22 percent protein, 10 percent fat.
[b] Supplied 2500 ml water.
[c] Supplied 2700 ml water.

Similar studies have also been carried out with this formula diet in man. Chow et al. (ref. 14) maintained men on this diet (1600 calories per day) without any additional water for 2 weeks in rooms kept at 23±2° C with relative humidity of 60 to 70 percent. The formula diet provided 1200 milliliters of water per day. Other groups were allowed an additional 240 milliliters of water or water ad libitum. There was no evidence of dehydration or hemoconcentration in the group receiving the formula diet alone, as shown by hemoglobin and hematocrit values (table XII).

CONCLUDING REMARKS

These studies show that formula diets may be devised for many special nutritional purposes: for infant feeding, for tube feeding and other hospital uses, for weight loss and control, for the peptic ulcer patient, for use as survival rations, and for providing water as well as other nutrients. Liquid diets may conveniently provide from 20 to 40 calories per fluid ounce, depending on the formulation. It should be noted that the change to a formula diet requires a few days of orientation or adaptation, as does any other marked change in diet form or ingredients.

There are many technical factors in formulating these products and in devising optimal processing conditions which will provide good taste acceptability and good keeping quality of

TABLE XII.—*Hemoglobin and Hematocrit Values in Subjects Receiving Complete Liquid Meal Diet*

[Data from reference 14]

Diet	Hemoglobin, g/100 ml		Hematocrit, percent	
	Before study	After 2 weeks	Before study	After 2 weeks
Complete diet alone	15. 0	15. 0	45. 3	45. 9
Complete diet plus 8 oz water/day	15. 1	15. 1	45. 0	45. 9
Complete diet plus water ad lib	14. 8	15. 0	44. 9	45. 3

the formula diets. These do not fall within the scope of this presentation.

The studies show that careful attention must be paid to the levels of *all* nutrients in a diet if it is to be used as the sole diet for an extended period of time. Short- and long-term nutritional studies on formula diets are essential to assure complete nutritional adequacy. The formulas should also be evaluated after extended storage to make sure that they still contain the nutrients desired as well as good organoleptic properties.

The data presented in this paper briefly review some of the special nutritional conditions for which formula diets have been successfully prepared. Space travel poses other conditions which may alter requirements for various nutrients and for water. When these requirements are known, it appears that appropriate formula diets can be prepared.

Some of the major advantages of a formula diet in space travel are as follows:

- Can be tailor-made to supply the nutrients needed
- Assures adequate nutrition
- Permits monitoring of the amount of diet consumed
- Simplifies metabolic studies
- Provides sterile food, avoiding bacteriological contamination
- Can be fed simply, without time-consuming preparation in flight

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Multiple Uses for Foods

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Since the United States embarked upon an ambitious program of space exploration and exploitation using man, it has been recognized that food would play an important part in the success of this effort. Food technologists and nutritionists are faced with a variety of problems, involving physiology, psychology, and engineering, in an environment where data are, as yet, inadequate.

One facet of these problems that is of primary concern to the engineer is the maintenance of spacecraft weight to within tolerable limits. For multimanned missions of 3 months and longer, the consumables, including food, become a significant weight factor. It is estimated that when vehicles are developed it would cost about a million dollars to soft-land 200 pounds on the lunar surface.

The problem before us, then, is by what means we can reduce the weight penalty of this food requirement. There are several avenues:

(1) Provide semistarvation diets
(2) Regenerate food (photosynthesis)
(3) Synthesize food chemically
(4) Use food for several purposes

This paper is concerned with the fourth way of saving weight by distributing the weight cost among several engineering and physiological requirements.

Man's manipulation of foods has existed almost as long as man himself. He has experimented to obtain certain desired effects such as taste, digestibility, appearance, and lasting qualities under changing humidity and temperature or in the environment of contaminating living organisms (fungus, bacteria, molds). The molecular variety possible in carbohydrates and proteins is almost infinite, and man has taken full advantage of this in synthesizing materials for foods, fibers, leather, paper, and so forth. Foods can be fabricated by molding, casting, rolling, and extruding into almost any desired shape. Heating, hydration, dehydration, and lypholization are other processes used in the production of food. In effect, then, food may be processed by many of the techniques that are also used to fabricate structures and shapes from plastics.

Let us explore the existing possibilities for using food as a basic material that may perform several functions of an engineering nature in addition to its primary physiological role.

UTILIZING FOOD AS RADIATION SHIELDING

The amount of shielding required to protect the space crew on a trip to Mars and return is known only approximately. Since some shielding will be required to protect the crew from energetic particles in trapped belts and from solar flares, the merits of using food for this purpose should be explored. Food with its high hydrocarbon content should provide on a weight basis a more efficient shield than either steel or lead. Figure 1, taken from a report prepared by Convair Division, General Dynamics Corporation (No. TSM-1908) for NASA, shows the range of protons (300 Mev) and electrons (1 Mev) in materials of varying atomic num-

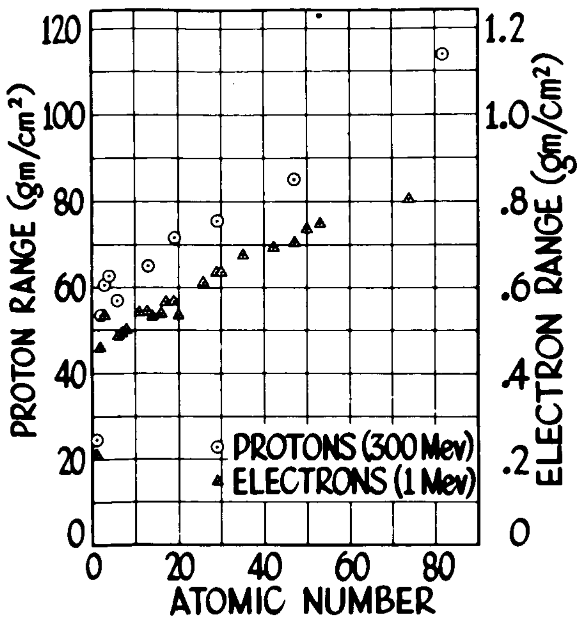

FIGURE 1.—Proton and electron range versus atomic number.

bers. The penetration range in hydrogen is about one-third that for lead on an equal weight basis. Carbon and oxygen are also among the most efficient elements in attenuating these energetic particles.

In figure 2 (also taken from Convair Report No. TSM–1908) the range of protons and electrons in carbon is given for varying energies. The use of low-atomic-number elements such as those found in food has another important advantage over the use of dense materials such as lead because of a significantly lower production of secondary Bremsstrahlung radiation produced by nuclear interactions. Little or no special processing or fabricating will be required to make an effective shield. Incidentally, the quality of food (taste, acceptability, purity) will not be perceptibly altered by using it as a radiation shield.

UTILIZING FOOD AS A HEAT SHIELD

Use of food for a heat shield or ablator is promising because of its high carbon content. Since there are a number of possible ways of designing heat shields, this possibility for a Mars or Venus mission would merit investigation by specialists in the field.

UTILIZING FOOD FOR STRUCTURES

The factors that cause food to spoil on Earth, such as oxygen, moisture, and microbial action, are absent in space so we have the advantage of a favorable environment for food preservation. It is conceivable that certain expended structures that have been relegated to the level of "space garbage" could, if made from food, provide literally a depot of potential food stores. Applications where edible structures could be used to an advantage would be:

- Lunar and space supply craft
- Expended fuel tanks
- Containers—food packaging and instrument casings
- Rocket motors
- Lunar rocket launch facilities

Structures made from food could be placed in space, on a lunar or planetary surface, for years and remain unchanged except for minor effects from ultraviolet radiation and high temperatures. Such structures could use sandwiched materials with a hard impervious

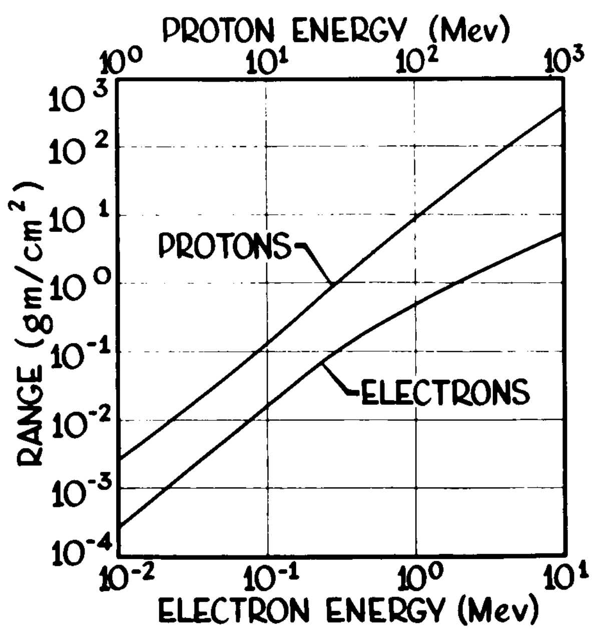

FIGURE 2.—Range in carbon versus proton and electron energy.

surface having a softer, pliable, shock-resistant interior. Variety and palatability could be designed into these edible plastic laminates.

UTILIZING FOOD AS CONTAINERS

The use of conventional plastic, metal, and glass containers for food, fuel, and so forth, is a luxury that cannot be afforded. If space food must be carried in containers, the containers, too, must be edible, because it is estimated that each pound of food landed on the Moon will require about 1000 pounds of fuel and vehicle weight to get it there.

UTILIZING FOOD IN THE FORM OF FIBERS AND CLOTHING

A space crew of four men will, for a 90-day flight regime, dispose of approximately 120 pounds of clothing if laundry facilities are not available. An approach to this problem is to spin fibers from a known nutritious food. Several firms already have underway extensive programs for making clothing textiles from soy beans. One has produced a textile containing 90 percent protein. Fibers have also been produced commercially from casein and zein, both edible proteins. The Department of Agriculture has prepared fibers from egg whites and chicken feathers that would be highly acceptable as food under the controlled environment of a spacecraft. During World War II the Japanese used hydrolyzed chicken feathers as a substitute for soy beans in producing soy sauce.

Another approach to the problem would be to convert clothing fibers to edible proteins. Such keratin protein fibers as wool and silk could be converted to food by partial hydrolysis of the disulfide linkages with ascorbic acid and partial breakdown with enzymes.

UTILIZING FOOD AS A DEAD-WEIGHT BALLAST IN TEST VEHICLES

Normal practice of NASA and the Department of Defense prior to major engineering advance in propulsion or in manned spacecraft design is to use several test vehicles often filled with a ballast of sand, concrete, water, or instruments. The possibility that some of this payload may be used for food, oxygen, or water has interesting aspects. This would necessitate a rendezvous with a source of supply by manned spacecraft.

Is it possible that biologists could justify reasons that this ballast or dead weight should contain a supply of food and water for a probable manned space venture? What is being suggested is that we select points in space and on the lunar planetary surfaces where we would want to carry out future manned space operations. Test vehicles containing supplies of food, oxygen, and water would rendezvous with this point as would scientific satellites and probes. Eventually, an operating base would be built up that would be a supply depot of food, water, oxygen, and so forth.

UTILIZING FOOD IN OTHER WAYS

If the imagination is allowed to wander, a number of other uses may be suggested for foods such as:

Transparent sugar castings as a substitute for optical glass (windows)

Glue and adhesives from fish, animal, protein, or starch

Paper from soy bean, egg albumin, or starch

Ink from vegetables

CONCLUDING REMARKS

The message here is the significance of a parametric approach to the food and nutrition problems of manned space flight. The best designed spacecraft cannot be described by separate contributions from scientific and engineering areas. The parameter biology should be factored into the design equations and concepts with the result that the spacecraft will be a blending of knowledge and ideas.

In summary, I have attempted to describe means for handling food as a material that will provide a substitute for plastics and other basic structural materials to satisfy several engineering functions in addition to its primary physiological role—food.

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Panel Discussion

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Massachusetts Institute of Technology
ROBERT E. JOHNSON
Professor, Department of Physiology and Biophysics
University of Illinois
CHARLES S. DAVIDSON
Department of Medicine, Harvard Medical School
Boston City Hospital

DR. SCRIMSHAW: There is a strong tendency for people to look at formula diets on the basis of what is acceptable for the feeding of institutional or military groups, in which food is an important element of morale, source of discontent, and relief from boredom. Such groups bitterly resent monotonous diets of any kind and would certainly rebel against liquid ones. There is abundant experience, however, to show that properly motivated individuals can thrive on formula diets for long periods of time without undue complaint, without resentment, and with good morale. Over the past 2 years at M.I.T., more than 75 students have consumed formula diets, half of them for over 20 days and 14 for more than 60 days. We now have experience with over 2000 man-days on formula diets at M.I.T., and over 1000 child-days on formula diets at the Institute of Nutrition of Central America and Panama (INCAP) in Guatemala.

Some M.I.T. students find the formula regimen convenient because it is less time consuming. Many of the commercial low-calorie formulas are being consumed, not to lose weight, but simply for convenience. Persons with other worthwhile and challenging things to fill their time do not necessarily require bits to hold in their mouth and to chew or a variety of foods in order to be productive and to have high morale.

The misconception that food variety is always essential is reinforced by the nature of our own culture. We do relish good steaks, salads, rich desserts, and a variety of other foods. Millions of people, however, see nothing unusual in consuming day after day a diet almost entirely of rice or some type of corn preparation. In Guatemala there is no difficulty in feeding a 100-percent corn diet such as tortillas for as long as needed to almost anyone in the lower social and economic groups. As a contrast, Dr. Grace Goldsmith, in her successful efforts to produce experimental pellagra, could not persuade her New Orleans' subjects to consume diets with more than 40 percent corn.

People do not psychologically need variety rather than a bland diet unless they are conditioned to depend on it and to associate many other desirable things with it. For college students, $5.00 per day, a chance to contribute to science, the opportunity of receiving extra attention and belonging to a group, or a combination of several of these motives are sufficient to obtain any number of volunteers. We have given them their formulas cold, direct from the refrigerator, or as hot as comfortable with no difference in N retention or acceptability beyond minor variations in personal preference.

I am sure that the astronauts are no less readily motivated than M.I.T. students and would willingly accept formula diets if there is a good reason for them to do so just as they accept the many other inconveniences and changes in habit required of them. It should be clear at this point in the conference that formula diets are needed to obtain accurate and useful balance data. The formula need not be liquid; it may be liquid, solid, or a combination of both but it must be the same throughout the mission, except for possible flavor variations if desired. With this background, I would like to add to Dr. Sarett's paper on formula diets.

First, the diet should be bland. The oily-sweet diets frequently used in metabolic experiments soon become sickening. One should take a clue from the acceptability of bland corn, rice, or cassava diets. Dr. Sarett indicated that vanilla Metrecal is preferred to chocolate or orange flavored. Ahrens et al. also finally abandoned chocolate or coffee flavor for a bland formula.[1] It is worth noting that synthetic amino acid diets have a strong taste which is impossible to mask entirely.

Secondly, the initial experience of an individual with a formula diet should be discounted. We recognize a regular "first day syndrome" in a large proportion of inexperienced subjects. The complaints include headache, bloated full feeling, sleepiness, inability to concentrate, and occasionally flatulence. These are generally minor and disappear by the second or third day. There is a tendency to consume the liquid diet more hastily than solid food and associated swallowing of air is thought to be a factor in the flatulence when it occurs.

The subjects usually miss solid food and have vivid dreams of eating food. Nearly all subjects look forward with great anticipation to their first meal following the diet. Most of the experienced subjects, however, are pleased to return to the diet, not because of its taste, but because of the sociability involved, the money earned, and sometimes scientific interest or desire to make a contribution as well. Interestingly enough, we have had good results with random samples drawn from the freshman class as well as with volunteers.

Dietetic chewing gum and dental peridontal stimulations are helpful for oral hygiene and chewing seems to reduce craving for solid food. The principal difficulty encountered with long-term feeding has not been the attitude of the subject but the need for special cleansing of the gums to avoid peridontal disease.

In summary,

(1) Prolonged use of formula diets is readily achieved with well motivated individuals.

(2) Formula diets will be required in order to obtain reliable balance data from the astronauts during early space missions.

(3) Prior experience of the astronauts with the formula diet is required before they begin the balance study of the mission.

(4) Formula diets need not necessarily be entirely liquid. They can, in fact, be a combination of a diet in liquid form and in moderately chewy freeze-dried cubes.

(5) Formula diets are so much more acceptable than most persons believe who have not worked with them that they are likely to have usefulness beyond balance studies. They could well be the standard food supply even for missions in the 30- to 90-day range.

(6) There is no disagreement with those who believe that a variety of solid foods will be needed for Moon bases or wherever boredom becomes a serious problem.

Dr. Combs: It might be of interest just to indicate the primary ingredients in the diet.

Dr. Scrimshaw: We have used a variety of diets; one which has been particularly acceptable consists of 5.59 percent soy protein, 7.4 percent skimmed milk, 1.86 dextrose maltose, a small amount of salt, vitamin A, 6.85 percent corn oil, and 1 percent lemon juice, with 48.4 percent water. This formula was made up for maximum palatability, and not specifically for space flight. The experience is applicable, however, since no ill effects have been encountered.

[1] *See* Ahrens, E. H., Jr.; Dole, V. P.; and Blankenhorn, D. H.: The Use of Orally Fed Liquid Formula in Metabolic Studies. Am. J. Clin. Nutr., vol. 2, 1954, pp. 336–342.

Dr. Combs: It seems to me one might improve the present menu-type diet that is being used merely by attempting to make certain that the diets were reasonably well balanced in terms of overall nutrition following the idea of a formula diet by using different menu items.

Dr. Johnson: The experience we have had with these formula diets is very similar to that of other people, I think. In metabolic studies the diets are exceedingly useful, and subjects can be found to use them. There are other areas of research which, I believe, need attention. In spite of all the careful studies on thirst and water balance in relation to thirst, enough work has not been done on two very important aspects of water balance. With some of these diets, not only the formula diets but the bite-size diets, something happens in the mouth, so that the apparent water requirement is off balance; generally speaking, there isn't an abolition of thirst but an increase in thirst. This could happen even on a liquid diet with certain combinations. I don't believe this is related to osmotic. It probably goes back to the old dry mouth or osmotic controversy which has gone on for so many years about what causes thirst.

The second very important piece of research that I don't think has been done properly, and certainly, in my opinion, Gemini needs to have some research done on this point, is the negative water balance which often occurs when people are forced to drink tepid water. I don't know of a single really good study which correlates the temperature of the water which is taken in with the actual water balance. If the Gemini astronauts are to be fed 80° F water, I think research should be done on this point. I would mistrust a diet in which all the water intake was an incremental part of the ration. I don't think any one diet is going to be the solution because there will be places where you want formula diets and places where you want ham sandwiches. A lot more about in-flight feeding will be learned in the prolonged SAC missions.

Dr. Combs: The use of formula diets should not be confused with the need for providing additional water supply at all times.

Dr. Davidson: It would seem that a thorough study should be made of the gastrointestinal tract bacteria and what their function is for good or evil. It might be determined, for example, whether modification of gastrointestinal tract bacteria or flora would make for improved efficiency.

Dr. DuBois has made studies with clean animals, in which the food is clean, sterilized but not necessarily bacteria-free, and in which the animals are raised in a clean environment, not germ free but simply a clean environment. These animals rapidly change their gastrointestinal flora from the usual ones to lactobacilli. The animals have larger litters, they grow at a better rate, they are less susceptible to endotoxin or shock, and they are much less susceptible to steroids and stressful situations. I think this is an area which might very well be further investigated.

One of the functions of the liver is to remove a good many toxins, among them ammonium in a normal individual; in patients with liver disease, ammonium and other noxious materials produced by gastrointestinal bacteria bypass the liver; they reach the general circulation and produce a diseased state called hepatic coma or liver coma. Thus, such research would have practical applications in dealing with this diseased state and might possibly have importance from a nutritional standpoint.

Should we give careful study to changes of the gastrointestinal flora of "clean" men and, if improved efficiency or health results, perhaps consider this for space flight?

With regard to formula diets, I am impressed that food does mean a great deal to people. It means a lot more to some people than to others. Unless we change our concepts of what food does for us psychologically, beyond its taste, and so forth, it is going to be difficult not to, from time to time, feed astronauts in spacecrafts during long flights good food that tastes good and looks good and is enjoyable.

We need more metabolic studies. Certainly it is important to provide models on Earth in confined spaces and do careful metabolic studies of not only what people will eat and how long they will eat it when confined in a difficult environment, but also of what happens to their metabolism.

COMMENTS

QUESTION: Should a sample form of some kind of stimulant such as coffee be included in metabolic studies?

DR. DAVIDSON: Why not coffee? Why not furnish a two carbon compound that is generally consumed about 5 o'clock in the afternoon in small quantities?

DR. SCRIMSHAW: It might be expedient to allow subjects to have coffee; it does not seem to interfere with the experiments we are carrying on. I think this is a good suggestion.

DR. JOHNSON: The astronauts are probably going to insist on having some kind of beverage. However, there must be a constant intake of whatever it is, tea, coffee or whatever; if he can get into this habit it is all right.

DR. HESSBERG: If we ask the astronauts to do an experiment and convince them of the need, they will eat anything within reason that we give them. Actually, we are hoping, in the Gemini program, to go to some type of formula diet for one of the flights. We will use it during preflight, during the flight, and for a 2-week period postflight.

Obviously, when we don't have to use the formula diet, we can offer the astronauts a seminormal type of diet. Is there any reason to depart from this as long as the water is there in the fuel cell, and space is available for the food? Why should we go to the Spartan approach? Another question?

QUESTION: One practical point in regard to attempting to do a metabolic study in flight might be made. Metabolic studies in the ward of a hospital are monitored by individuals 24 hours around the clock and the subjects are watched carefully to be sure that they do not take anything else or do any "cheating". It has been mentioned that a formula diet can be in various forms, liquid or solid.

A real practical question arises: When a subject does not consume, on a given day, a certain amount of his diet for one reason or another—because he's too busy or he doesn't feel like it—how can what is left over in a solid type pack be measured as opposed to an unused liquid formula?

DR. SCRIMSHAW: One of the reasons that there is a certain amount of variation of opinion regarding formula diets is that, in general, they have been used in situations where the individuals are under constant observation and confinement. The difference in our M.I.T. experience is that the subjects are going about their normal activities; the basis of the experiment is explained to them, they know about the mathematics, and so on, so that the compliance is voluntary.

Under these circumstances the degree of satisfactory voluntary compliance, without constant monitoring or supervision, has been quite extraordinary as revealed by the constancy of the urinary excretion and the creatinine excretion and by the constancy of the data on baseline periods.

Now, as to how, if you are going to use part formula and part solid diet, for example, you are going to control this, I think the answer is to be sure that the quantities of the solid diet are less than they are going to consume. There should be no variation in the first place, but, if there is any, let it be in the liquid portion, or have your solid in small sizes so that what is unused can be measured without the small bite-size container ever being opened.

SESSION VIII

Space Vehicle Energy Management

Chairman: *A. Layton Ingelfinger*
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It is essential that optimal nutritional support be given to the astronaut to assure peak performance, both physical and mental. At the same time, excessive supply of any one constituent of the diet is not acceptable due to weight penalty. Thus, the effect of the stress of the space environment on man's metabolism must be determined as accurately as possible. All factors of this environment cannot be reproduced on Earth but the effects on man's metabolism of such stresses as confinement and continuous wearing of a space suit can be evaluated.

In addition to supplying energy to man in the form of food it must also be supplied in the form of thermal and mechanical energy. Such energy operates compressors, provides communications capability, and makes possible the reclamation of oxygen exhaled in the carbon dioxide from the breath of an astronaut. Energy is also used for food preparation and processing of body wastes. The reclamation of oxygen and purification of water from body wastes permits reuse of these constituents, thus greatly reducing the weight penalty for life support during space missions. The nature and amount of food and water consumed affect the reclamation processes which must be used and thus the efficiency of reclamation. The use of waste heat in these reclamation processes also permits reduction of the vehicle penalty. The importance of these considerations may be illustrated by the fact that it presently requires a power supply of 2.2 kilowatts for a life support system which will support four men for 90 days without resupply.

As the durations of the missions which man desires to achieve are increased, complete closure of the material loop will be necessary to achieve acceptable weight penalties. Because of the complexity of the problem it is not anticipated that food regeneration in a space vehicle will be achieved in the immediate future.

A. Layton Ingelfinger

Protein, Energy, and Water Requirements of Man Under Simulated Space Stresses[1]

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It is essential that optimal nutritional support be given to the astronaut to insure maximum physical performance and mental acuity. Although much is known about nutritional requirements of man living on Earth, we do not know if these same nutritional requirements will be optimal under the conditions of space environments. Recent studies have shown that changes in body metabolism do occur when healthy young men are confined to long periods of bed rest (ref. 1). It is logical to assume that an astronaut living in prolonged periods of weightlessness, wearing a full-pressure suit, breathing in an altered atmosphere, confined to a very small space, permitted very limited physical activity, and being exposed to periods of vibration, high temperature, and acceleration also will undergo changes in his metabolism.

Studies concerning individual nutritional requirements have shown that wide differences do exist in human requirements (refs. 2 and 3). The large quantity and wide variety of foods consumed by most people in the United States provides for a margin of safety in meeting everyday requirements. Such a luxury will not be possible for the astronaut because the limited space and payload aboard the spacecraft will demand a very conservative management of the food supply. It is necessary, therefore, that nutrition studies be performed to determine the precise nutritional requirements of men under simulated space conditions in order to best assure adequate nutrition for the astronaut during extraterrestrial habitation.

A series of experiments has been undertaken at the Aerospace Medical Research Laboratories to determine the precise nutritional requirements of man in simulated space conditions. To date, three experiments have been completed. The first experiment was a preliminary study designed to evaluate procedures and a basic metabolic diet. Since no stresses were placed on the subjects during that experiment, the data obtained will not be reported at this time.

EXPERIMENTAL PROCEDURE

Two experiments, using carefully selected young men, were performed to determine the metabolic effects of prolonged wearing of unpressurized space suits. Prospective subjects were given a flight physical examination, psychiatric interview, food preference test, and a claustrophobia test before they were selected for the experiments. The subjects were confined in the experimental activity facility at the Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio, during each experiment. Each subject was required to perform according to an activity schedule which

[1] This research was partially supported by the National Aeronautics and Space Administration under Defense Purchase Request R-85.

was designed to provide work, exercise, relaxation, and adequate sleep. Work consisted of monitoring display panels, performing mathematical calculations, and estimating time. The exercise consisted of either two 10-minute periods of calisthenics or two 10-minute periods of walking on a treadmill at 3 miles per hour on a 10° incline. For relaxation, the subjects were permitted to work on handicrafts or watch television. Subjects were closely monitored 24 hours per day and were examined daily by a physician.

Each subject in experiment II wore continuously the torso and boots of an MA–10 pressure suit for a period of 14 days. The gloves and helmet were worn by the subjects approximately 4 hours each day. The ventilation rate of the suit was from 7 to 10 cubic feet of air per minute. The MA–10 suits were furnished specifically for these experiments by the Manned Spacecraft Center, NASA, Houston, Texas. Personal hygiene consisted of brushing teeth, shaving, and washing the hands and face. Each subject spent an additional 2 weeks on a control period wearing long underwear and hospital pajamas and was limited to the same personal hygiene procedures that were permitted while wearing the pressure suit. These subjects were maintained on a freshly prepared metabolic diet having a 2-day cycle menu. This diet was composed of three meals and three snacks per day. Distilled water was consumed ad libitum and daily individual intake was recorded. The experimental design is outlined in table I.

Each subject in experiment III wore the torso and boots of the pressure suit for 16 days and spent 16 days on a control period wearing long underwear. Personal hygiene was limited to chewing gum, using a gingival stimulator, shaving, and washing the hands and face. These subjects were maintained on a diet composed of freeze-dried foods for 20 days and a matching diet composed of freshly prepared foods for an additional 20 days. The diet consisting of freeze-dried foods and the matching fresh diet were composed of a 4-day cycle menu of four meals per day. All meals in this experiment were served at room temperature. Distilled water was consumed ad libitum and daily individual intake was recorded. All food was accu-

TABLE I.—*Design of Experiments II and III*

(a) Experiment II

Subject	1st week	2d and 3d weeks	4th and 5th weeks	6th week
5	Adjustment	Control	Suit	Recovery
6	Adjustment	Suit	Control	Control
7	Adjustment	Control	Suit	Recovery
8	Adjustment	Suit	Control	Control

(b) Experiment III

Subject	4 days	16 days	4 days	16 days	2 days
9	Fresh diet No suit	Fresh diet Suit	Dehydrated diet No suit	Dehydrated diet No suit	Recovery
10	Fresh diet No suit	Fresh diet No suit	Dehydrated diet No suit	Dehydrated diet Suit	Recovery
11	Dehydrated diet No suit	Dehydrated diet Suit	Fresh diet No suit	Fresh diet No suit	Recovery
12	Dehydrated diet No suit	Dehydrated diet No suit	Fresh diet No suit	Fresh diet Suit	Recovery

rately weighed, and the subjects were required to consume all food given to them. At regular intervals, each daily menu was homogenized; aliquots of the homogenate were freeze-dried in a 10-cubic foot sublimator and saved for analyses.

Fecal samples were pooled into four-day collections for each subject. Every fourth day of the experiment, ½ gram of carmine was administered to each subject to mark the limits of the collections. The fecal collections were weighed, homogenized, and freeze-dried; and aliquots were saved for analyses. Urine was pooled into 48-hour collections, and the volumes were recorded for each subject. Aliquots of the 48-hour collections were saved for analyses and frozen. All samples of food, urine, and feces were analyzed for nitrogen, water, energy, calcium, sodium, potassium, and phosphorus content.

Fasting blood samples were taken from each subject twice a week. The following determinations were performed on each blood sample: differential cell count, white cell count, red cell count, hemoglobin, hematocrit, glucose, calcium, sodium, potassium, and creatinine.

Body temperature, body weight, and blood pressure measurements were recorded each day for all subjects. Continuous metabolic rate measurements were performed during one full day's activity on each subject during experiment II. In experiment III, continuous metabolic rate measurements for a period of 16 hours were accomplished on each subject while wearing a pressure suit and again during the control period. During experiment III, careful measurements of weight losses during periods of exercise were made with a balance capable of detecting weight change with a precision of ±2 grams.

RESULTS

Each of eight subjects completed the continuous wearing of the torso and boots of an MA-10 pressure suit for a period of 14 or 16 days. During this time the helmet and gloves were worn from 4 to 8 hours per day. The subjects found the first 24 hours the most difficult period for wearing the suit, but, after this initial period, working, exercising, and sleeping, for the most part, returned to normal. All biochemical determinations of blood were normal.

Average nutrient analyses of the diets are shown in table II. The metabolic diet contained more carbohydrate and less fat than either the diet containing freeze-dried foods or the matching fresh diet. These data show that the diet containing freeze-dried foods and the matching fresh diet were very similar in nutrient content.

TABLE II.—*Analyses of Daily Diets*

Analysis	Experiment II; metabolic diet	Experiment III, g	
		Freeze-dried [a] diet	Fresh diet
Dry weight, g	616	560	549
Moisture, g	2829	[b]1350	1516
Crude protein, g	117.8	107.0	113.0
Gross energy, kcal	2891	2780	2770
Total fat, g	57.6	95.0	96.1
Carbohydrate, g	408	318	316
Calcium, g	1.12	0.65	0.73

[a] Average of 4 menus.
[b] Water used for rehydration.

The coefficients of apparent digestibility of the diets used in experiments II and III are recorded in table III. In experiment II, the overall averages were 92.2 percent for protein, 95.5 percent for fat, and 94.5 percent for energy. These data indicate there were no differences found due to treatment. The average coefficients of apparent digestibility for experiment III are 91.4 percent for protein, 97.2 percent for fat and 95.6 percent for energy. These data indicate there were no significant differences in digestibility of protein, energy or fat in respect to treatment or diet.

Nitrogen balance data are shown in table IV. A positive average nitrogen balance was obtained for all experimental periods in experiment II, and there were no significant differences found between treatments. In experiment III, slight negative nitrogen balances were indicated for both the control period and suit pe-

TABLE III.—*Coefficient of Apparent Digestibility*

Period	Protein, percent	Fat, percent	Energy, percent
Experiment II			
Adjustment	91.8	95.0	94.4
Control	90.9	94.7	94.5
Suit	93.5	96.0	95.0
Recovery	92.5	96.2	94.1
Experiment III			
Control	90.8	----	95.3
Suit	91.9	----	96.0
Fresh diet	91.1	97.6	96.2
Dehydrated diet	91.6	97.8	95.0

riods. A comparison of the nitrogen balance for the two diets used in experiment III indicates that the subjects were in positive balance while consuming the freeze-dried diet and in negative nitrogen balance while consuming the matching fresh diet. These data indicate that the protein requirements of the subjects were greater than 102.0 grams per day, and 113.0 grams per day was adequate. Consideration must also be given to losses of nitrogen through perspiration which was not measured in these experiments.

Data on water balance are shown in table V. In experiment II, average water consumption was 3788 milliliters per day; of this amount 2028 milliliters were excreted in the urine and feces and 1760 milliliters were available for

TABLE IV.—*Average Daily Nitrogen Balance for Four Subjects*

Period	Average nitrogen balance, g
Experiment II	
Adjustment	1.8
Control	2.8
Suit	2.2
Recovery	4.2
Experiment III	
Control	−0.5
Suit	−0.7
Control diet	−1.9
Freeze-dried diet	0.7

TABLE V.—*Average Daily Water Balance*

Period	Consumption, g				Excretion, g (urine and feces)	Available for evaporation, g
	Dietary	Drinking	Metabolic	Total		
Experiment II						
Adjustment	2830	747	341	3918	1849	2069
Control	2830	634	340	3804	2076	1728
Suit	2830	713	343	3886	2210	1676
Readjustment	2829	376	338	3543	1977	1566
Experiment III						
Control	1434	1741	285	3460	1747	1713
Suit	1432	1199	286	2917	1442	1475
Control diet	1516	1377	287	3180	1623	1557
Freeze-dried diet	1350	1562	283	3195	1566	1629

evaporation through respiration and perspiration. In experiment III, average water consumption was 3188 milliliters per day of which 1594 milliliters were excreted in the urine and feces and 1594 milliliters were available for evaporation. A greater water consumption and excretion was found during experiment II than during experiment III. This difference may be due to the high protein level in the diet used for experiment II.

These data also indicate that a slightly lower quantity of water was lost through evaporation during the wearing of the pressure suit as compared to the control periods when a suit was not worn. On the other hand, limited data obtained with the use of a very sensitive balance indicated that during exercise the loss of water of suited subjects was over twice as great as that loss of water for nonsuited subjects. These data are recorded in table VI. These differences indicate that insufficient air flow was available to keep the temperature inside the suit at a comfortable level during periods of exercise.

TABLE VI.—*Weight Loss for 10 Minutes of Exercise on Treadmill*

[Losses were calculated from measurements taken at beginning of exercise and 20 minutes after completion of exercise]

Subject	Experimental treatment	Weight loss, g	Body weight, kg
9	Control	75	62. 0
10	Suited	289	85. 0
11	Suited	220	68. 5
12	Control	120	78. 0

Individual weight changes during both experiment II and experiment III were found to be a function of initial body weight. In figure 1, body weight changes were plotted against initial body weight. The regression indices obtained from these data indicate that subjects which initially weighed 66 kilograms maintained their weight while subjects weighing less than 66 kilograms gained weight and subjects weighing greater than 66 kilograms tended to

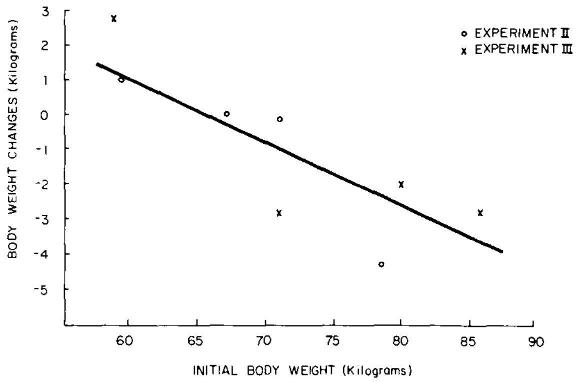

FIGURE 1.—Weight changes in 6 weeks plotted against initial body weight.

lose weight. The average body weight changes during the experiment are recorded in table VII. Data showing the average weight changes by experimental periods are recorded in table VIII. No significant differences are found between treatments in either experiments or between diets in experiment III.

Data obtained from continuous measurement of metabolic rate indicate no detectable differences in caloric expenditure for suited and nonsuited subjects during rest; however, some dif-

TABLE VII.—*Average Body Weight Changes of Four Subjects*

Period	Duration, days	Average weight change, kg
Experiment II		
Adjustment	6	−0. 04
Control	14	+0. 05
Suit	14	−0. 39
Recovery	6	−0. 34
Experiment III		
Adjustment	4	+0. 47
Control	16	−0. 82
Suit	16	−1. 06
Recovery	2	+0. 18
Fresh diet	21	−0. 66
Dehydrated diet	21	−0. 43

TABLE VIII.—*Caloric Expenditure During Exercise*

[Walking on treadmill at 3 miles/hour at a 10° incline]

Subject	Expenditure, kcal/min		Body weight, kg
	Wearing pressure suit	Control	
9	4.75	2.81	62.0
10	4.94	4.72	85.0
11	4.22	4.10	68.5
12	5.49	3.38	78.5
Average	4.85	3.75	

ferences were found during exercise. Subjects walking on a treadmill at 3 miles per hour with a 10-degree incline expended 4.85 kilocalories per minute while wearing an unpressurized MA–10 suit as compared to 3.75 kilocalories expended per minute during the control period.

CONCLUDING REMARKS

Two studies, each 6 weeks long, were performed to measure the nutritional requirements of healthy young men while continuously wearing an MA–10 pressure suit. It was found that a freshly prepared diet or a diet composed of precooked freeze-dried foods is equally efficient in supplying the nutrient requirements of the experimental subjects. The subjects in experiment II had a slightly positive nitrogen balance and the subjects in experiment III had a slightly negative nitrogen balance; neither condition was found to be significant. Energy requirements for the subjects engaged in limited activity were shown to be a function of body weight. Subjects weighing approximately 66 kilograms required approximately 2800 kilocalories per day.

Results also indicated that the daily water requirements for the subjects were approximately 3200 to 3800 milliliters per day. The results of this experiment demonstrated that young men are capable of continuously wearing the torso and boots of an MA–10 pressure suit for a period of 16 days. During periods of inactivity, no increase of nutritional requirements was observed for the suited subjects. An increase in both water and energy requirements was demonstrated for suited subjects during periods of exercise.

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Overall Energy Management as Related to Nutrition and Waste

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Energy management, as considered herein, refers to the spacecraft as a whole, excluding propulsion, and the significant forms are primarily electrical and thermal. In food and waste systems these energy forms may be used in heating and cooling—or to operate pumps, blowers, or compressors—and a small amount is used for instrumentation and control. The purpose of this paper is to present some fundamentals of overall spacecraft energy management and to portray briefly the relationship to food and waste systems. Some of this information is based on space station studies at General Dynamics/Astronautics, and much is drawn from work on development of an advanced prototype life support system. This latter work is under contract with the NASA and is monitored by the Langley Research Center.

Considering electrical energy first, it is fairly obvious that a spacecraft will have some sort of central electrical power system, since it is not economical to provide a separate source for each component which needs power. Also, since we are considering a manned spacecraft and a mission long enough to have nutrition and waste problems (20 days to 3 years), we should consider only the types of power systems appropriate for such a mission. The particular characteristics of interest are the capacity, such as a certain number of kilowatts, and the weight penalty for this power in pounds per kilowatt or pounds per kilowatt-hour.

Figure 1 shows some typical weight penalties for power which are based on conditions of a spacecraft in a 150 nautical mile orbit at 30° inclination and for flight late in this decade. The isotope dynamic power system is the type with a radioisotope heat source, a gaseous working fluid, and rotating machinery to generate electrical power. The solar dynamic is similar except that the working fluid is heated at the focus of a solar energy collector and uses thermal storage for the shaded side of the orbit. Both are relatively independent of mission duration in their weight penalties except that radiation shielding weight increases with longer missions

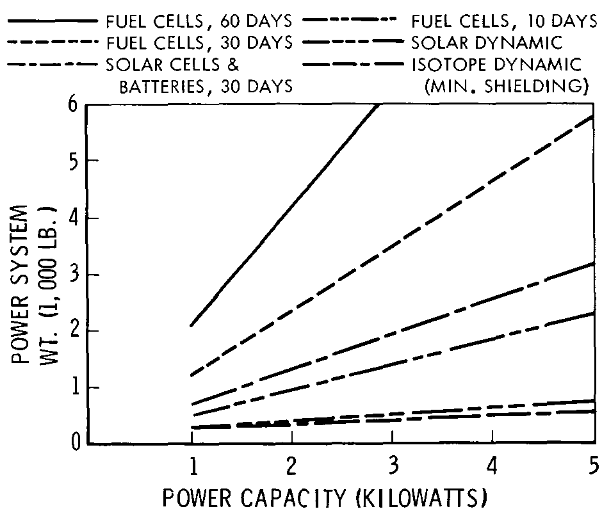

FIGURE 1.—Weight penalties for electric power.

due to longer crew exposure. The solar cell system has photovoltaic cells with rechargeable batteries for the shaded side of the orbit. The weight penalty is somewhat time-dependent because of limited battery cycle life and the degradation of photovoltaic cells in the space radiation environment. The fuel cell systems have expendable reactants, hydrogen and oxygen, of about 1 pound per kilowatt-hour plus tank weights of about 0.5 lb/kw-hr. It is apparent that fuel cells will not be competitive except for relatively low power levels and short durations.

The significance of all this is that when techniques are selected in food or waste management, any weight optimization must include a penalty for electric power; and the penalty for a few watts could be relatively important or unimportant depending on the type of power system. The trend seems likely to be toward power systems of the isotope dynamic or solar dynamic types for the longer missions. Then the penalty is small and electric power may be used more freely than in present spacecraft.

As an example, there is the familiar case of evaluating a freezer for storing solid wastes of a spacecraft crew. Power requirements were determined for a thermoelectric freezer sized for a 4-man crew and 90 days storage, and operating at a storage temperature of −10° F. If heat rejection is to a 70° F cabin atmosphere, the refrigeration coefficient of performance is about 0.333 and power required is about 300 watts. If heat is rejected to a coolant fluid at 45° F, the coefficient of performance is about 0.8 and the power required is 125 watts. The weight penalty evaluation for the power requirement is as follows:

Case 1: Isotope—Dynamic, 290 lb/kw
Load 300 watts
0.3 (290) = 87 lb

Case 2: Fuel Cells, 125 lb/kw + 1.5 lb/kw-hr
Penalty: 37.5 lb + 10.8 lb/day

Case 3: Solar Cells, 600 lb/kw
Maximum Power = 1.5 kw
300 watts is an excessive demand on a power system of capacity.

Thermal energy management refers to the control of temperatures and heat transfer. It is fundamental that thermal energy is useful at high temperatures and must be disposed of at low temperatures; and that over a period of time the quantity to be rejected equals the quantity received, taking into account the conversions to and from other energy forms. There are weight penalties to a spacecraft for both the heat source and the heat rejection.

The use of heat for food preparation and for waste processing has been mentioned. Considering the available heat sources, electrical heat is certainly the most convenient. High temperatures are available, the efficiency is high, and electrical heaters can be made in sizes and geometries to meet almost any need. The weight penalty for the heating element is unusually small, but the weight for the electrical power source must also be charged to the using process. If the load is low or infrequent, electrical heat may be the best solution. Otherwise, a trade-off is likely to show that some other heat source will provide better weight economy.

Another potential heat source is solar energy. With good concentrators and precise orientation some high temperatures can be attained, but the area of the collector still has to be consistent with the solar energy density. Also, thermal storage is required for the shaded portion of the orbit, unless cyclic operation is feasible for the process involved.

"Waste" heat is frequently mentioned as being almost "free", that is, the weight and volume penalties are small. "Waste" heat is heat that must be rejected from the spacecraft. One example would be heat from cabin air which originates as crew metabolic heat or electrical equipment heat. Although the quantity may be significant, this heat is generally at too low a temperature for efficient use.

When electrical and electronic equipment is cooled by a liquid circuit, this liquid temperature may be at about 150° F. This is high enough for some distillation processes to recover water from liquid wastes. It is also adequate for vacuum drying of solid wastes. Of course, the temperature drops as heat is extracted from the fluid circuit.

Dynamic power systems offer the best source of waste heat. They reject a quantity of waste heat about three to five times their electrical output, and the fluid temperature is several hundred degrees Fahrenheit. As an example, the power system to accompany the life support system mentioned previously is assumed to be an isotope dynamic type. Its characteristics include an electrical output of 5 kw, and heat rejection of over 15 kw from the working fluid. This heat rejection involved cooling a fluid from about 400° F to about 60° F; thus, several kilowatts of heat can be extracted from the fluid without lowering the temperature below 300° F.

The use of waste heat in a water recovery process is illustrated in figure 2.

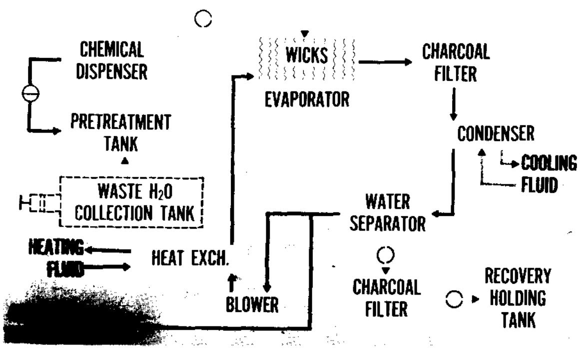

FIGURE 2.—Water recovery subsystem. Air evaporation system pressure approximately equal to ambient.

Whatever heat is used, there is a requirement to reject a like amount and at a lower temperature. Radiation exchange with the environment is the only feasible method for the mission durations we are considering. Since the rate varies directly with the difference between absolute temperature to the fourth power, if we reduce the temperature of heat rejection we pay a penalty in larger radiator area. Thus, even the use of "waste" heat is not free. We have degraded the temperature and must compensate with large radiator area.

Figure 3 shows a representative radiator configuration for a life support system. In this case there are circumferential tubes about 8 inches apart which provide for conduction from a heat transport fluid to an outer skin of the spacecraft. The outer skin then radiates to the environment. Weight of the radiator is almost directly proportional to area.

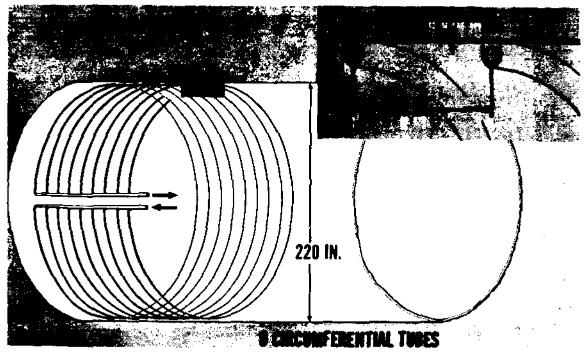

FIGURE 3.—Radiator configuration.

Figure 4 shows the relationship between coolant flow and radiator area for a given heat rejection load and with control to a constant outlet temperature. The increased area for increased flow arises from the inverse relationship between flow and the temperature drop from radiator inlet to outlet. That is, inlet temperature and average heat rejection temperature are lower, so that radiator area must be larger.

Figure 5 is a diagram of a representative coolant circuit including a radiator for an advanced life support system. The components pertaining to waste and nutrition are a water chiller, to provide 40° F drinking water, and the condensers of the water recovery apparatus. In this case water is being recovered from urine in one of the units, and from mixed humidity condensate and used wash water in the other unit.

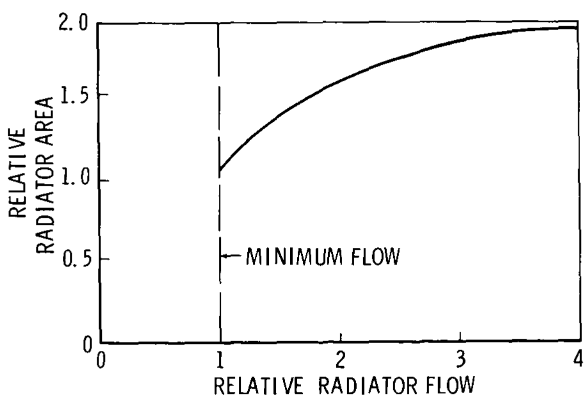

FIGURE 4.—Coolant flow in radiator circuit.

Figure 6 illustrates use of waste heat from an isotope-dynamic power system. A silicone fluid is circulated by a pump in a "process heat" circuit. Nutrition and waste components include two water recovery evaporators; a water heater for hot beverages and to reconstitute dry foods; and a waste dryer, in which moisture is vented to vacuum and the latent heat is provided from the process heat fluid.

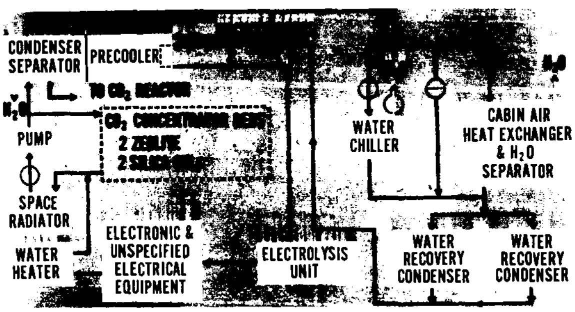

FIGURE 5.—Coolant circuit.

The coolant circuit (fig. 5) and the process heat circuit (fig. 6) are two types of heat transport circuit by which thermal energy management is executed in an advanced life support system. Circulation of the cabin air provides a third heat transport circuit.

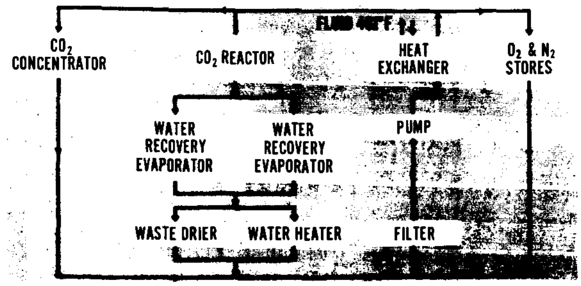

FIGURE 6.—Process heat circuit.

As a final point for emphasis, energy management always includes a large task in thermal integration. The components cannot be considered only in the light of individual characteristics. Some of the nutrition and waste components are included in each of the three heat transport circuits. It is a task of the engineer to determine an optimum arrangement which is compatible with characteristics of all components in each circuit.

Discussion: Overall Energy Management as Related to Nutrition and Waste

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INTRODUCTION

The preceding paper discusses some of the engineering considerations in designing advanced life support systems for extended-duration space missions. As space missions extend in duration beyond the 2-week class now in development, there will be an increasing incentive for conservation of expendables at the cost of increased fixed weight and power consumption. In advanced life support systems for long-duration missions, emphasis will be placed on processing of waste products to conserve essential materials such as oxygen and water. For the 90-day to 1-year class of space mission, closure of the oxygen and water loops will be essential to avoid excessive weight penalties. Complete closure of the material loop by food production from human wastes appears to be in the distant future because of the complexity of the problem and the many research areas remaining with such systems.

Present knowledge is adequate to permit the design of a life support system providing oxygen regeneration and water reclamation, although there are many problem areas that require resolution. Much of the previous research work concerning advanced life support system concepts has involved laboratory investigations on a process basis. Because of the complex nature of the interrelationships between the life support system and other spacecraft systems, process evaluation and selection must be performed on a system basis, considering the many system interfaces, if the final system is to have any validity.

Mr. King's paper is concerned with the important problem of thermal integration of the life support system with the power system, to use waste heat from the power system for some of the life support processes. In this way, the electrical power consumption of the life support system can be reduced. Of course, the thermal energy extracted from the power system is not obtained without thermodynamic cost, since the heat obtained from the power system must be ultimately dissipated at a lower temperature by the environmental control system. Therefore, it will still be necessary to design systems for high thermal efficiency, although the requirements in this regard may not be as stringent using waste heat as with electrical power.

INCENTIVES FOR USE OF WASTE HEAT

Extraction of waste heat from the power system will result in a decrease in the heat sink radiator area required for the power system. For example, if the waste heat is obtained at a source temperature of 400° F, the power system radiator area will be reduced by approximately 5.1 ft^2/thermal kw (assuming an external thermal environment providing an effective sink temperature of 350° F). If this waste heat is ultimately rejected at a temperature of 100° F by the spacecraft environmental control system, the environmental control system heat sink radiator area will be increased by approximately 33 ft²/thermal kw. Therefore, for this typical case, illustrated in figure 1, a net increase in radiator surface area of approximately 28 ft²/thermal kw is obtained for the assumed conditions.

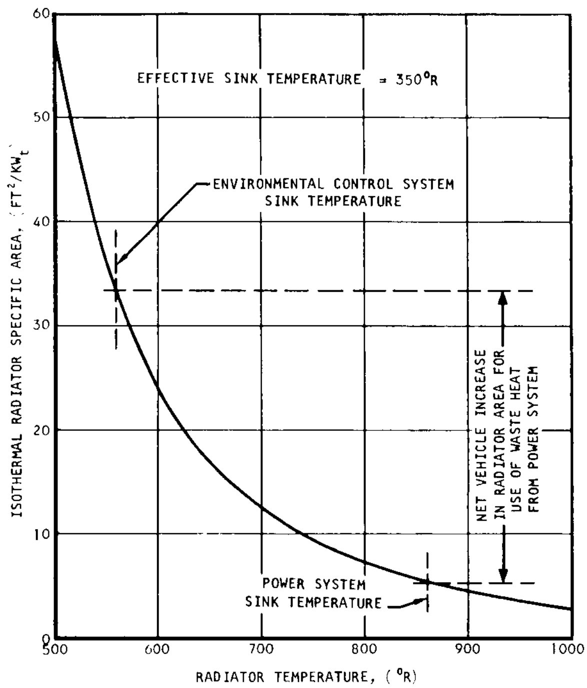

FIGURE 1.—Vehicle radiator area penalty for use of waste heat from power system.

Radiator specific weight will vary, depending upon type of surface, installation, and so forth, but will usually weigh around 1.0 lb/ft². On this basis, the cost of thermal energy obtained from the power system is only 28 lb/thermal kw (not including the thermal transport loop required to convey the waste heat from the power system, where it is generated, to the life support system, where it is used). This penalty can be compared with the usual 200 to 600 lb/electrical kw power penalties characteristic of many spacecraft power systems. If waste heat is used to replace electrical power as the source of a given thermal energy requirement, the environmental control system radiator area will not be changed. The net change in vehicle radiator area is then a 5.1 ft²/thermal kw decrease in power system radiator area.

It is evident that there is ample incentive for use of thermal energy derived as waste heat from the power system, instead of electrical power. However, it will be seen that in many cases for life support system processes either the thermal energy requirements are low or else can be provided by waste heat at a relatively low temperature level. As a consequence, the weight savings may not be spectacular for thermal integration of some processes.

CO_2 REMOVAL

The life support system is required to handle and dispose of the various gaseous, liquid, and solid waste products produced by man while maintaining him in a suitable environment for his proper functioning. One of the most important problems in this area involves CO_2 removal from the cabin atmosphere at suitably low partial pressure levels. Expendable chemical absorbents (lithium hydroxide) are used for CO_2 removal for the Mercury, Gemini, and Apollo spacecraft. For longer duration missions, use of CO_2 removal methods not requiring expendables will be required. At the present time, molecular sieve absorbents are the leading contenders for regenerable CO_2 removal systems.

Molecular sieve systems can be designed for operation in a variety of different cycles, using thermal energy at various temperature levels. System design will be largely dependent upon the requirement for material recovery (e.g., regeneration processes that involve venting H_2O and/or CO_2 overboard as compared with regeneration processes that provide material recovery). Where regenerable CO_2 removal is to be accomplished with subsequent processing of the CO_2 for oxygen recovery, the molecular sieve system will require approximately 100 thermal watts per man at a temperature level of the order of 400° F. Clearly it is thermodynamically possible to provide this thermal energy requirement for the regenerable CO_2 removal system with waste heat from many types of power systems.

O_2 RECOVERY

In advanced life support systems provided with oxygen regeneration, water electrolysis will be a principal consumer of energy, requiring from 250 to 300 watts of d.c. electrical power per man for the production of oxygen. Since only 130 watts of this electrical energy input is actually used to dissociate water, waste heat ranging from 120 to 170 watts per man is generated by the electrolysis cell. This waste heat, in addition to the 20 to 44 watts per man in waste heat generated by carbon dioxide processing, could be used for some of the life support processes requiring thermal energy input. This involves a type of thermal integration different from that discussed in the preceding paper.

EXTERNAL VERSUS INTERNAL INTEGRATION

The type of thermal integration discussed by Mr. King can be described as "external" since it involves two different systems. The other type can be called "internal" since waste heat generated within the system for one process is used to effect another. Depending upon the particular requirements, it may be expedient to use one or the other, or both, types of thermal integration.

Internal thermal integration can be used to make a process or a subsystem thermally sufficient. Take, for example, the vapor compression distillation process for water reclamation (shown in fig. 2) where the heat of condensation is used for vaporization of water from the wastes. The temperature lift necessary for operation of the cycle is obtained by compressing the water vapor to a higher pressure prior to condensation. Thermally sufficient systems are relatively independent of the performance of other systems, although, characteristically, they have limited flexibility with regard to part-load operation.

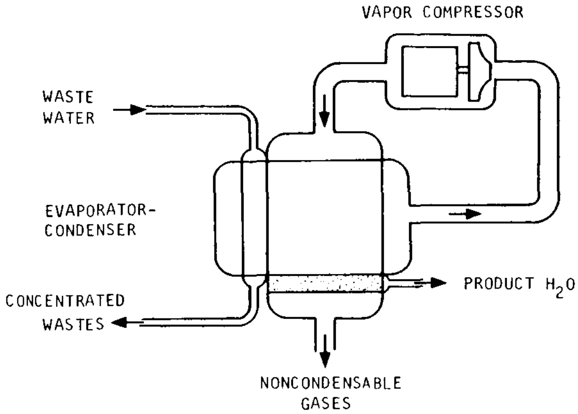

FIGURE 2.—Thermally sufficient water reclamation system.

WATER RECLAMATION

A number of different evaporation and distillation cycles can be used for water reclamation where the process is thermally integrated in the heat transport loop or with another process. Figure 3, for example, shows thermally integrated air-evaporation water recovery cycles. The energy required for evaporation is obtained on the hot side of the heat transport loop; condensation is performed on the cold side of the heat transport loop. Systems of this type will operate at different temperature levels, depending upon available heat source and sink temperatures.

Figure 4 shows the performance dependence of thermally integrated air-evaporation cycle systems on condensing temperature for an evaporating temperature level consistent with electronic cooling. The power requirement for the adiabatic air evaporation cycle shows a marked decrease with reduced condensing temperature. The power requirement for the isothermal air evaporation cycle is not only lower but is also less dependent upon condensing temperature.

Obviously, process selection will not be made on the basis of weight and power consumption alone. For example, the adiabatic air evaporation process may be preferable to the isothermal air evaporation process because of its superior ability to provide zero-gravity evaporation without buildup of deposits on the heat exchanger surface.

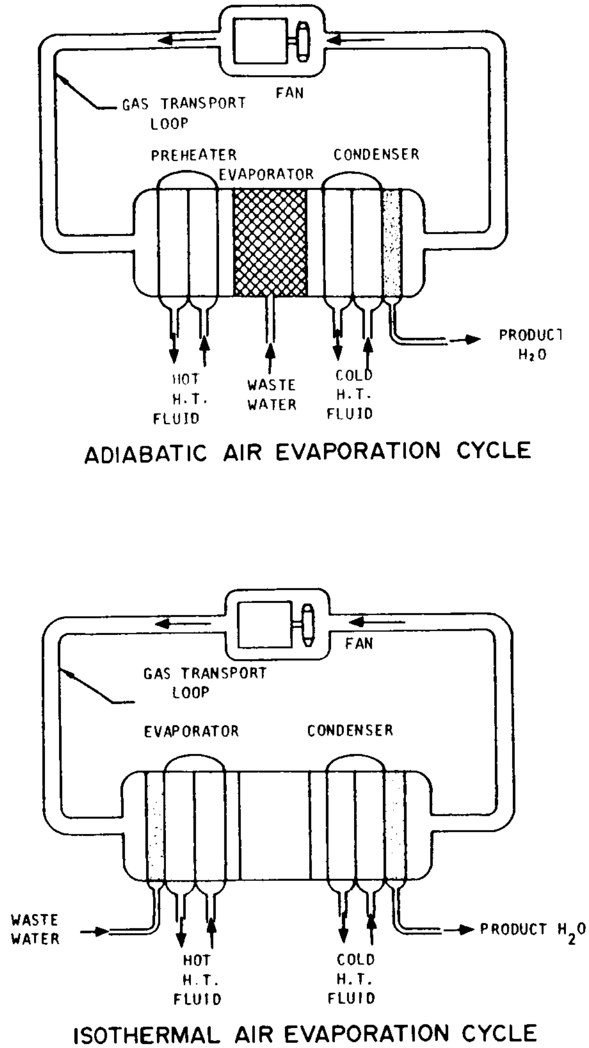

FIGURE 3.—Thermally integrated water reclamation systems.

OTHER USES OF THERMAL ENERGY

Other possible uses of thermal energy in spacecraft life support are listed in table I. For the most part, the energy requirements for these processes are low. For the processes shown, a potential saving in electrical power consumption of 178 watts per man can be effected through thermal intergration. Some of the processes, such as water recovery, can be accomplished with low-temperature waste heat, permitting thermal integration with heat sources other than the power systems.

TABLE I.—*Typical Thermal Energy Requirements for Life Support Subsystems*

	Average thermal energy, watts/man	Temperature level, °F
Thermal desorption of CO_2 absorbents (for O_2 recovery)	100	400
Urine distillation or evaporation	45	120
Food preparation (water heating)	5	200
Personal hygiene (water heating)	3	120
Trace contaminant burner	20	400
Solid waste dehydration	5	300

CONCLUDING REMARKS

It appears that thermal integration of the life support system with the power system to use waste heat offers a potential saving in system equivalent weight of from 50 to 100 pounds per man. This is a worthwhile objective. Mr. King correctly emphasizes the system aspect of life support and the relationship of system design to constraints established by the mission,

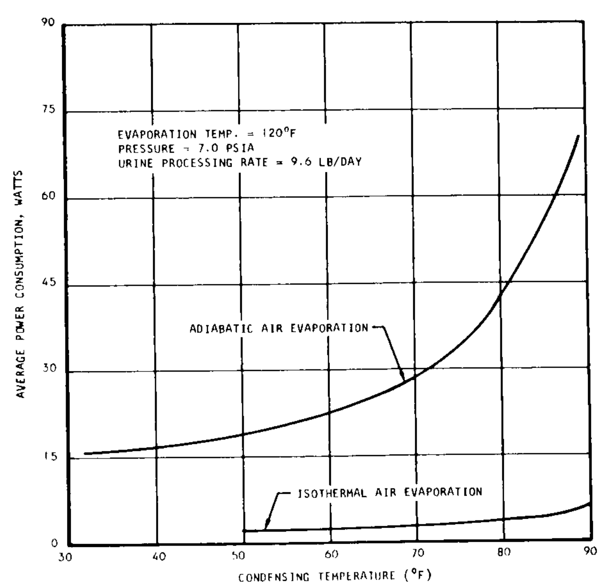

FIGURE 4.—Performance of typical thermally integrated water reclamation systems.

vehicle design, and other subsystems. This has certainly been verified by experience on Mercury, Gemini, and Apollo which have also shown that systems that are conceptually simple require a formidable engineering effort before they can be flight-rated.

The system concept described by Mr. King is predicated upon the availability of waste heat from the power system at a temperature level of the order of 400° F, which presumably involves use of a nuclear reactor, radioisotope, or solar collector heat source with a closed-cycle heat engine, such as the Brayton cycle. Several of the early space station concepts now under study involve use of solar cells or fuel cells with 90-day resupply periods. With solar cells, high temperature waste heat will not be available as a byproduct of power generation. With fuel cells, there is no incentive for oxygen recovery or water reclamation. However, it is clear that ultimately power systems of the type required with thermal integration will be available.

Many of the previous life support system studies have had the requirement for low energy consumption, based upon high weight penalties for power consumption. The availability of thermal energy at low penalties through use of thermal integration concepts will permit consideration of processes that would otherwise be noncompetitive. Therefore, to a greater extent, process selection can be based on factors such as reliability, maintainability, and recovery efficiency, which will be important considerations in the design of advanced life support systems.

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Conference Conclusion

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Chairman's Closing Remarks

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Space Science Board

The one point that has been stressed over and over again during this conference is the water problem. Water problems and the electrolyte balance appear to be critical even in short term flights into space and become extremely critical in longer flights. The observation has been made a number of times that unintentional dehydration may occur and that perhaps some thought should be given to enforcing water intake.

Another item that has been discussed at rather great length is the formula diet; perhaps there is a question of semantics here. The formula diet is not, I think, necessarily typified by a liquid meal. It is quite acceptable to produce a formula diet in almost any form and it need not be monotonous or possess extremely low acceptability. It also can possess tactile qualities.

Perhaps another point which should be stressed is that at the moment it appears we have no clear-cut idea of how we are going to feed people for long space flights. As the flights become longer provision will have to be made; many methods have been suggested for solving the problem and thus we have a multiple pathway of investigation. The consensus of opinion seems to be that these methods must be investigated in a parallel fashion since we do not have the criteria nor do we have the knowledge at the present time to make any choice.

There are a number of questions the biologist needs to have answered, or investigated, as fully as possible and as quickly as possible. For example, what is the estimate of the life of the fuel cells in flight; that is, how long can a fuel cell be used and be able to supply water. Without this knowledge it is very difficult to worry a great deal about the regenerative systems if they are not to be used in the near future.

Another important consideration is the individuality problem. This is the problem of applying general data to individuals. An example, certainly, is the recommended allowances of the water specifications. These were set up and existed for a particular situation and generally for large population. They do not necessarily apply to the individual, or certainly to the individual who is to travel in space. There has been talk of characterizing the individual metabolically and, perhaps, in some cases to select individuals for space flight on a nutritional basis.

These are a few of the problem areas which were discussed at length during the conference. There are many, many others, all of which need solutions.

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APPENDIX

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