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SESSION L

Bioastronautics

Chairman, G. DALE SMITH

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33. Environmental Biology

By George B. Smith, Jr.

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INTRODUCTION

Space is a hostile, uninhabitable environment for man. It is necessary for man to take his environment with him into space. As space flights become longer and longer in duration, the task of providing the artificial environment for space crew pyramids in complexity. This is the subject of a later presentation in this series, and this paper is confined to the effects on the man of the many possible variations in his environment in space.

In our philosophy of space flight, man maintains a function of command in the man-machine complex. This means that decisions concerning environmental conditions are based on promoting and maintaining the man's efficiency for prolonged flight durations. Not only must man survive journeys into space but he must be an active participant in many phases of the trip.

When we consider the effects of environmental stresses on man, the concept of "tolerances" should be made clear. Unlike most material structures, man does not usually proceed undisturbed to the point of chaotic collapse as increasing stresses are applied to him. The more common reaction is a progressive decrement of function. Rather than a single numerical value analogous to the compression strength of concrete, human tolerances can be better stated as a curve, relating applied stress to some measurable performance or function. Then tolerance, as points along this curve, can be awareness that the stress is present, discomfort, transient or temporary injury, permanent injury, or death. Unfortunately, our present knowledge does not allow us to construct such curves for most physiological stresses.

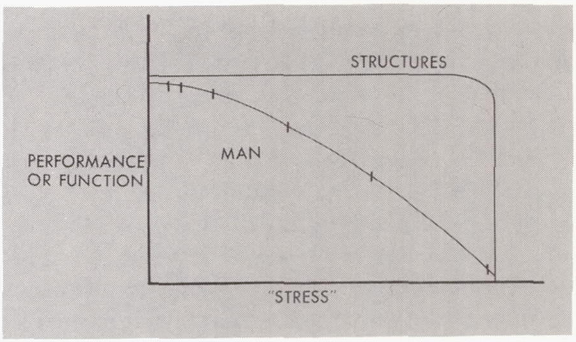

FIGURE 33–1.—Human tolerances.

DISCUSSION

Biodynamics

This area of environmental physiology is concerned with a study of certain environmental physical factors imposed on the man making a journey into space. In this category are included noise and vibration, sustained accelerations and impacts, and the effects of weightlessness. With the exception of weightlessness, these problems are not new and have long concerned the specialist in aviation medicine.

Investigations of noise and vibration as they pertain to manned space flight study subjective comfort and ability of man to perform, physiological changes, and acute and chronic damage caused by vibration of the man or those vibrations impinging on the man. These vibrations may vary in frequency, intensity, direction, and duration. From previous studies with animals and humans we have learned something of the natural frequencies of certain body organs under these conditions. This resonance is largely responsible for lethal effects in animals and for subjective discomfort in man. Man's tolerance to vibration up to 20 cycles per second is quite low. The effects of subaudible noise have not been explored very deeply. Because vibration frequencies in advance boosters, such as Titan and Saturn, are anticipated to be from a few to 2,000 cycles per second, it is important that we know the effects of these forces on man, establish levels of tolerance, and develop attenuation methods when these are required.

Studies of acceleration forces, both sustained and impact, are intended to establishing tolerance levels in terms of magnitude, direction and duration of these forces, and to define protection requirements for space crews. Tolerance to impact accelerations (with durations up to 0.2 second) is known to be much greater than tolerance to sustained accelerations, primarily because there is too little time for fluid and tissue shifts to occur. Our knowledge of tolerance levels and effects of accelerations along the major orthogonal axes of the body is meager. When we consider combined forces or rapidly changing forces, tolerance limits are almost nonexistent. The method of estimating these limits in the past has usually been to extrapolate or interpolate data along the major axes to other axes. The validity of such interpolations is open to question, and it is becoming increasingly important that factual information be obtained.

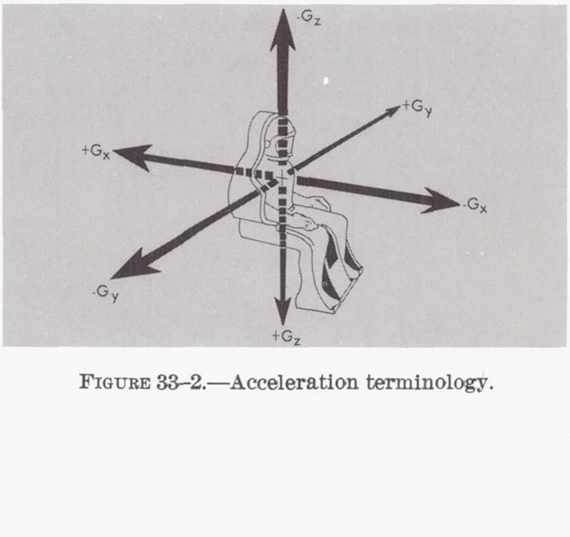

FIGURE 33–2.—Acceleration terminology.

Very little is known about the effects of prolonged weightlessness or prolonged exposure to hypogravic states. There has been considerable conjecture and speculation in the past about the effects of prolonged absence of normal gravity on the vestibular system, on the cardiovascular system, on the musculoskeletal system ,and on diurnal rhythms and sleep patterns. At present, there is no method by which prolonged weightlessness can be simulated on or near the earth's surface; and it is unlikely that such a method will soon be developed. Orbital flight has therefore served as a method of exposing man to progressively longer periods of weightlessness. Despite the most careful observation, our experience to date has shown no demonstrable ill effect of weightlessness. This cautious, stepwise, and observant approach will be continued to better define what, if any, are the detrimental effects of prolonged weightlessness. There are certain very definite beneficial effects of weightlessness in terms of comfort, and the energy expenditure necessary to do certain types of work. It is important that we continue to investigate means of turning this unfamiliar environment to our advantage.

Rotation of spacecraft has been proposed as a method of producing an "artificial gravity" by centrifugal force. As indicated above, it is not yet demonstrated that an artificial gravity is necessary for man's well being, though it might "make life easier" for the space traveler if he could function in a rather constant gravitational field. Rotation of the spacecraft, however, may produce some very undesirable physiological effects, sometimes referred to as "space sickness." Very little has yet been learned about the etiology or prevention of this syndrome, or man's adaptation to constant rotation.

Radiation

Man in space may encounter radiation from several sources—the sun, the stars, the Van Allen belts, and from nuclear-reactor propulsion or power systems. It is necessary to ensure that space crews are adequately protected from acute and chronic harmful effects of such radiation. In Project Mercury, ambient space radiation does not present a significant danger. The apogee, or highest point in the orbit, is well below the Van Allen belt, and the earth's magnetic field affords protection against solar flare radiation. In Project Apollo, when three men travel around the moon and land on it, it will be necessary to traverse the Van Allen belt. In addition, much of the protective effect of the earth's magnetic field will have been left behind. The radiation spectrum as it exists in the space, the shielding required for protection from it, and the biological effect of both primary and secondary radiation on the astronauts must be known. Lack of such knowledge could result in paying a great weight penalty in unnecessary shielding, or risking injurious or lethal exposure. Much information has already been collected about the radiation environment in space. Within the weight limitation of the Apollo spacecraft, allowable shield weights are expected, with 99-percent reliability, to reduce radiation exposure to less than 50 rad—25 rad being the expected mission exposure, and an additional 25 rad being allowable emergency exposure. The feasibility of chemical and biological means of affording protection against or counteracting the effects of radiation exposure is being investigated.

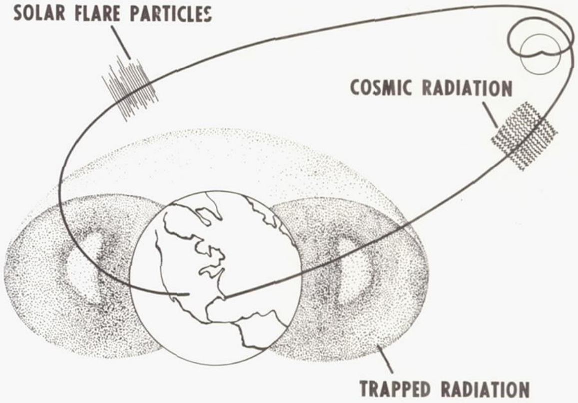

FIGURE 33-3.—Radiation considerations.

Life Support

The normal gaseous environment of man consists of about 20-percent oxygen and 80-percent nitrogen, at a total pressure of 14.7 pounds per square inch at sea level. Although the Russians have indicated that their Vostok spacecraft provide their cosmonauts with such an atmosphere, American spacecraft have not been designed to do so. A two-gas system increases the complexity of the environmental control system (and thus decreases its reliability), additional pressure increases cabin leakage rates, this amount of gas imposes an additional weight penalty, and the presence of nitrogen could have detrimental effects if the astronaut were suddenly exposed to a lower pressure because of an emergency. In Project Mercury, an atmosphere of 5 pounds per square inch consisting almost entirely of oxygen was selected. Oxygen at less than this pressure is sufficient to prevent hypoxia, but the additional pressure provided significant added protection against dysbarism and assisted the ventilation of electronic equipment within the spacecraft. The spacecraft was constructed so that leakage rates were acceptable. Although entirely satisfactory for flights of relatively short duration, there is no reason to believe that this atmosphere is optimum for longer flights. We are just now expanding our experience with exposures of days, weeks, and months to this and other artificial atmospheres. We know that there are certain nuisance effects of breathing pure oxygen atmospheres for extended periods—for example, the reabsorption of oxygen from the middle ear while sleeping—but no other significant detrimental effects have been demonstrated at the reduced pressures contemplated for spacecraft. Our investigations in this direction will continue in an effort to establish a truly "optimum" gaseous environment for the space traveler, from all points of view.

The sustenance of astronauts during flights of short duration has been relatively simple. The provision of food, water, and oxygen has not necessitated any particular scientific advances. As the duration of flights becomes longer, however, this will loom as a larger problem. The question of whether man's metabolic demands during space flight are the same as under comparable situations on earth has not been answered. These demands must be forecast with accuracy and precision to insure that man's capabilities are not compromised by hunger, malnutrition, thirst, dehydration, or hypoxia. At the same time, all unnecessary stores must be left behind and replaced by useable items. Development and testing are currently under way in methods of preparation and storage of food, and Project Mercury has been used as a test bed for some of these new ideas. On flights of long duration, tasty and attractive food will doubtless be of great psychological benefit during hazardous or boring periods of flight.

Man's metabolic wastes in space flight to date have presented no serious problems. Carbon dioxide is absorbed by lithium hydroxide, evaporated perspiration and respiratory moisture are condensed in a heat exchanger and evaporated to space, urine is collected in a plastic bag within the suit, and the astronaut is fed a low-residue diet prior to flight so he should not have to defecate. However, simple as they are, collection, accumulation and storage of these wastes will become unsatisfactory on longer flights. Overboard disposal is almost equally unsatisfactory for a number of reasons—it is wasteful of potentially useful materials, and it represents a source of contamination of space by microorganisms. Investigations are in progress to perfect techniques of recovery, utilization, and synthesis of water, oxygen, and even nutritional elements from metabolic wastes. These techniques may someday lead to a truly "closed ecological system" of a size that can be launched into space.

Medical Selection and Maintenance

It would be an omission to discuss environmental factors in space flight and their effects on man without some consideration of the man himself and the way in which he is selected and maintained. It is hardly necessary to point out that we are not dealing with average responses, but the very particular responses of specific individuals. The men who have been selected to participate in manned space flight programs have been chosen for a variety of attributes, not the least of which are physical and mental health, high motivation and intelligence, and general resistance to stresses and danger. During their training, they are exposed to all of the in-flight stresses that can be simulated on the ground, singly and in combination, and their reactions and responses monitored and evaluated. In effect, an individual baseline is established, which allows more intelligent interpretation of the effects of space-flight environmental conditions.

CONCLUSION

The intent of this brief resumé of the known environmental factors present in space flight has been to indicate, in a general way, the framework of the medical support aspects of the total NASA research effort. Medical research efforts in the manned space flight program are concerned, in many cases, with establishing the environmental conditions that can be expected to exist; in most cases, with establishing or better defining man's tolerance levels to these conditions; and, in some cases, with influencing hardware design so man is provided with more than a survivable environment in space. In these endeavors, NASA has adhered to the concept that the entire national capability should be regarded as the laboratory for its program. Accordingly, we have utilized the skills and facilities of the Atomic Energy Commission, the Department of Defense, other federal agencies, the academic world, and industry, as well as our own centers. This utilization must be continued and expanded, in view of the magnitude of the problems confronting us in attaining the national goal in space.

N63-11117

34. Physiological and Behavioral Sciences

By Siegfried J. Gerathewohl and Bo E. Gernandt

Dr. SIEGFRIED J. GERATHEWOHL *is Chief of the Biotechnology Division of the NASA Ames Research Center. Interested in the integration of man and machine, in problems of aerospace physiology, and in space medical subjects, Dr. Gerathewohl has conducted experiments on the effects of weightlessness on animals and humans using high-performance aircraft in parabolic trajectories. He contributed to the development of the School of Aviation Medicine Space Cabin Simulator, and was instrumental in the transportation and recovery of two primates (Able and Baker) in a Jupiter IRBM. He is a member of the National Academy of Sciences-NRC Armed Forces Committee on Bioastronautics, Aerospace Medical Association, American Rocket Society, American Astronautical Society, German Rocket Society, Psychonomic Society, and the German Psychological Society. He received his Ph. D. degree from Saxony Institute of Technology in 1936, and Diploma Psychologist from Bavarian State University in 1944.*

Dr. BO E. GERNANDT *is staff scientist in the Environmental Biology Division of the NASA Ames Research Center.—Principally interested in the field of neuro-physiology, Dr. Gernandt has contributed to the knowledge of the neurophysiology of the spinal cord. He earned his Doctor of Medicine degree at the Karoliuska Institutes in Stockholm, Sweden, in 1946, teaching there and at the University of Sothenburg from 1948 to 1958. He was awarded the Alvarenga Prize in 1944 and 1952.*

INTRODUCTION

The bioastronautical program of the National Aeronautics and Space Administration is based on the classical disciplines of the life sciences as major areas of research. Since man is a terrestrial organism, he has been studied almost entirely under this aspect. However, with his entry into extraterrestrial space, new conditions arise which warrant intensive investigation. Generally, the physiologic research concerns the fundamental bases of human functions, the determination of man's tolerances, and his protection against stressful alterations of his biological homeostasis. The behavioral studies mainly deals with man's performance capabilities and limitations under normal and extreme conditions. In accordance with NASA's mission, the work in these areas is primarily applied and supporting in nature; but there is also a need for basic research. The scope of these investigations reaches from such academic problems as biologic pattern formation and localization at the cellular level to the practical application of cybernetic principles for the monitoring of the organism and complex systems, communication and information theory, and orientation and navigation processes in animals and man. Also included in this program is the blending of the disciplines of biology and physics in such fields as biotechnology and bionics, which are aimed at the development of improved techniques and instruments as well as of the acquisition of new information. The requirements of man in space necessitate those research efforts, which will result in design criteria for various types of equipment, protective devices, life support systems, communication channels, displays, and controls for space flight and planetary explorations. However, in many ways is the life scientist not yet in a position to inform the engineer, which conditions he must produce in order to accommodate the man or what systems must be made available for his protection (1). This paper will describe some of the NASA's efforts to answer this question. The bioastronautics program of the NASA will cover a much wider range of subjects in which the universities can play a major role.

STUDIES OF ACCELERATION STRESS

One of the major research areas associated with the gravity problem concerns acceleration effects. The acceleration forces encountered by the crew of a spacecraft during lift-off depend mainly on the velocity to be attained and the booster characteristics, whereas the deceleration stresses during re-entry will vary widely with the lift-drag ratio of the vehicle. Numerous centrifuge studies have shown that healthy persons can remain conscious under sustained negative and positive accelerations in the main direction of motion—that is, in the so-called eyeball-in (EBI) and eyeball-out (EBO) direction—but the adequate performance of control tasks during these stresses requires more than the maintenance of consciousness. Therefore, the development and implementation of refined criteria of pilot tolerance to these accelerations are essential not only for the investigations of the physiologic effects of acceleration but also for the objective evaluation of personnel, protection devices and the level of performance that can be reasonably expected of men under acceleration stress (2, 3).

For several years experiments have been conducted by Smedal and cooperators in the human centrifuge using experienced pilots as test subjects. The studies concerned the three organ systems most acutely affected by acceleration stress, namely the circulatory, respiratory, and visual. The subjects under investigation are listed in table 34–I. Concommitant to the planning of these experiments was the development of adequate instrumentation for the measurement of physiologic functions. Such an instrument package used for the measurement of the electrical activity of the heart (ECG), blood pressure, and respiration, and the records obtained are shown in figures 34–1, 34–2, and 34–3. A suitable restraint system permitted the study of physiological functions in the aircraft and on the centrifuge under accelerations of varying magnitude and directions. This mobile support and restraint system is shown in figure 34–4.

TABLE 34–I.—*Physiological Measurements Under Acceleration*

Circulatory System

1. Electro- and vector-cardiograph.
2. Blood pressure, systolic and diastolic.
3. Arterial pulse wave at eye level (ear pulse).

Respiratory System

1. Tidal and minute volume.
2. Vital capacity.
3. Inspiratory pressure.
4. Oxygen uptake.
5. Carbon dioxide concentration in expired air.
6. Nitrogen concentration in expired air.
7. Functional residual capacity.

Eyes

1. Placedo disc reflection on cornea for distortion.
2. Accommodation ability of eye.
3. Visual fields (subjective).
4. Visual acuity (objective and subjective).

The results of these studies have been previously published (4, 5). Several interesting findings were reported. While it was previously assumed that the EBI orientation could be better tolerated by the pilot, there is now evidence of a distinct ventilatory advantage to the EBO direction (see figure 34–5). It was found that alveolar ventilation and arterial hemoglobin saturation are severely diminished during EBI forces, and that the latter decrement is progressive. The reduced venous return contributes essentially to the progressive hypoxia and hypercapnia. The dyspnea in the EBI direction is caused in part by the hypercapnia; but the deflation of the lungs is probably the main reason of this discomfort.

In contrast, alveolar ventilation and arterial hemoglobin saturation are essentially normal

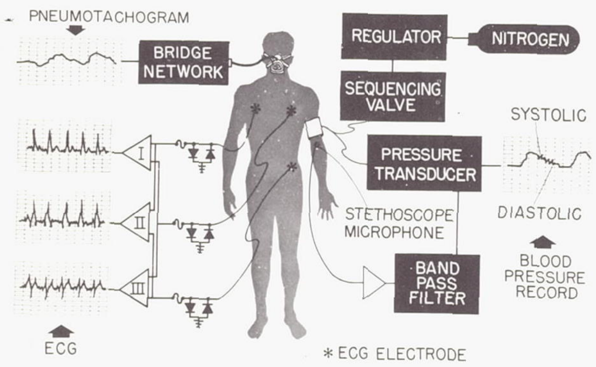

FIGURE 34–1.

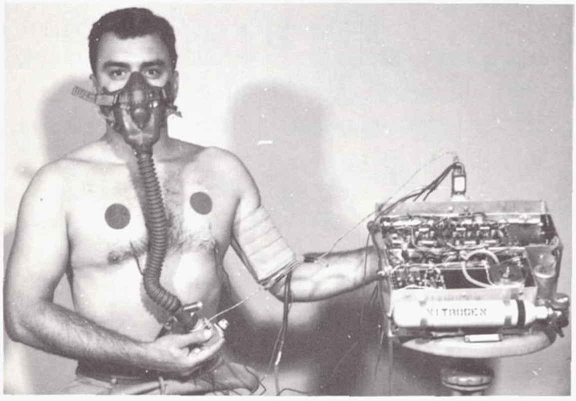

FIGURE 34–2.

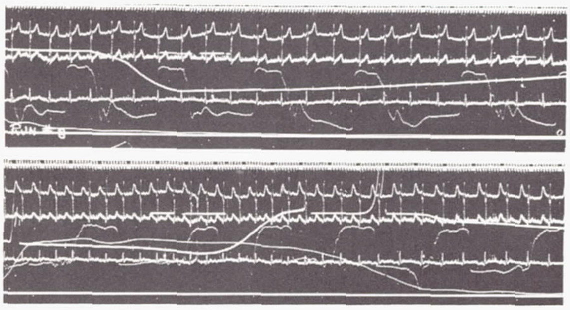

FIGURE 34–3.

under EBO forces (see figure 34–6). The ear pulse, blood pressure, and heart rate data suggest that the cephalic blood flow is certainly better than under EBI orientation. However, tracking performance did not show the superiority to be expected from the physiological benefits described above. Performance deteriorates in both acceleration vectors; and yet the physiological data suggest that only in EBI conditions there is that amount of cerebral hypoxia which should cause the deteriorations. It thus appears that other factors cause the decline in performance in the EBO force field. Despite the greater respiratory comfort, EBO force constitutes a strange experience even to the seasoned test pilot. While the main reason for the decrement of visual tracking seems to lie in the accumulation of tears on the cornea (see figure 34–7), it may also result from the subject's unfamiliar sensations and his concern about the safety of his restraint.

PHYSIOLOGY OF MEN UNDER CONFINED CONDITIONS

Several experiments were recently conducted on the physiology and psychology of men in confined spaces. They included one 2-man and two 3-man crews during 3-and-one-half and 7-day exposures to simulated space flights. The studies were made at the North American Avi-

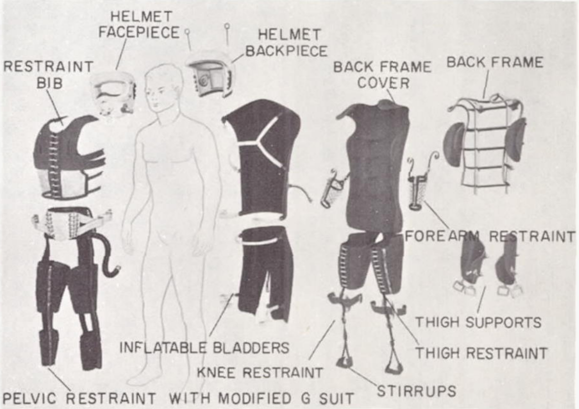

FIGURE 34–4.

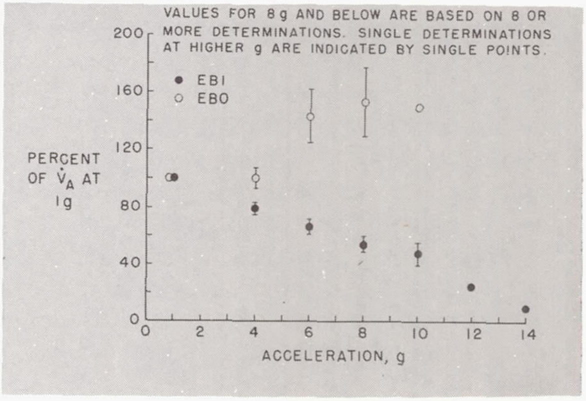

FIGURE 34–5.

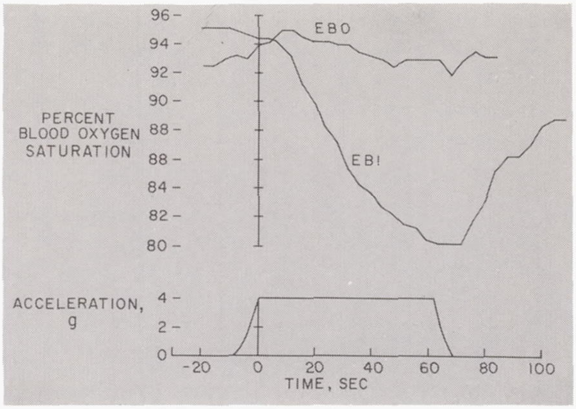

FIGURE 34–6.

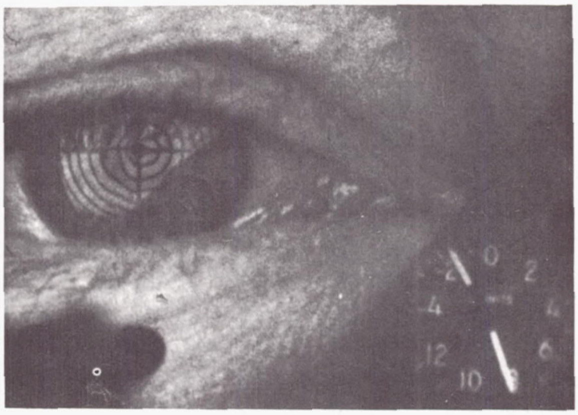

FIGURE 34–7.

ation, Inc., the Martin Marietta Corporation, and the NASA Ames Research Center (6–8). The duty cycles varied from a rigid 4-hours-on, 4-hours-off cycle (Ames) to a more flexible schedule which included 4 and 8 hours sleep, respectively, and a 2-hours-on, 1-hour-off duty program (Martin Marietta) per person. The following physiological indexes were generally controlled: (1) Vital signs (ECG, respiration, pulse, diet, food and water intake, BMR, blood pressure, body temperature, body wastes); (2) blood analysis (white and red blood cell counts, hemoglobin, sedimentation rate, total protein, albumen, globulin, glucose, total CO_2, electrolites, hematocrit); (3) urine analysis (specific gravity, pH, sodium, potassium, calcium, phosphorus, creatinine, epinephrine, nor-epinephrine, 17-ketosteriods, and 17-hydroxycorticosteroids). In addition, operational tasks and psychological tests were administered in all three studies. There were also periods of physical exercise either programmed at certain intervals or left at liberty to the test subjects. The Ames capsule is shown in figures 34–8a and 8b.

Although the three experiments varied considerably with regard to their objectives, mission profiles, and schedules, the results show some interesting general trends. By and large, food and water consumption was slightly reduced. The two subjects lost about 0.5 kg and 1.0 kg in the Ames study, where the diet was constant. Greater weight loss due to mild starvation and dehydration occurred in the NAA experiment. If a significant loss of weight occurs during a controlled study, the distribution of change due to tissue metabolized and water loss can be estimated. For actual space flight missions it seems necessary that food and water

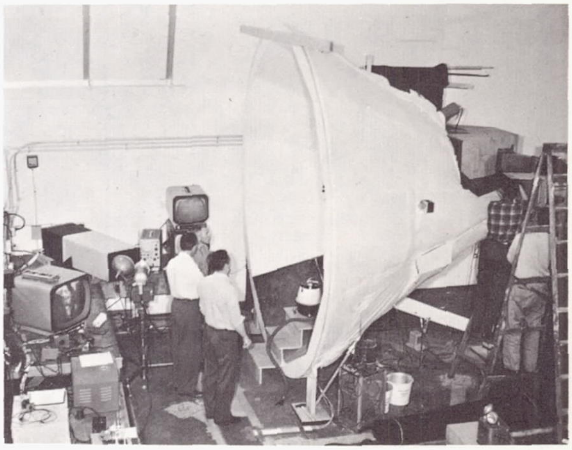

FIGURE 34–8a.

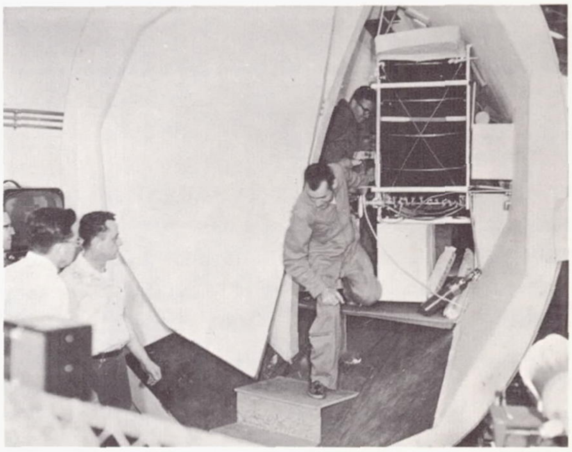

FIGURE 34–8b.

intake are programmed daily in accordance with the subject's baseline requirements.

One of the hazards encountered in forced encumbrance is a diminution of blood volume. The standard diet in the Ames study during the 4-day period prior to the experiment provided a near-steady state of sodium excretion. The fluctuations during the confinement thus indicated changes in extracellular fluid volume; and an increased excretion of sodium, calcium and phosphorus were found during the experiment. The calcium mobilization may prove to be a hazard in space flights of long duration because of demineralization and the high concentration of urinary calcium salts in the renal tract. Therefore, an increased fluid intake seems necessary. If the space vehicle is equipped for the recovery of body fluids, a more rapid turnover of water will not present a serious problem.

The evidence of emotional stress was generally indicated by an increase in catecholamine and ketosteroid excretion. Results of the Ames study are given in figure 34–9. The excretion of all these compounds is particularly high in one subject during the prior control period, during which he was engaged in strenuous activities. Moreover, the overall mood changes as observed by psychological testing during the confinement period indicate a distinctly cyclic rhythm and is highly correlated with the catecholamine data.

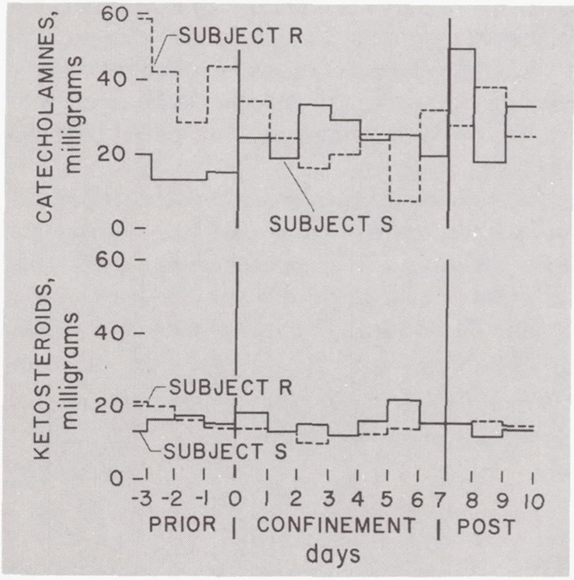

FIGURE 34–9.

In this experiment, the subjects wore lateral chest electrodes throughout the confinement period, permitting almost continuous tape recording of the ECG. Moreover, the subjects took blood pressure readings at 4-hour intervals. The only cardiovascular manifestation was a steadily declining heart rate and blood pressure of Subject R throughout the experiment. This is entirely consistent with his catecholamine excretion and the psychometric data. The most important result of all three studies is that the confinement in a small-volume cabin of 2 or 3 men, who are submitted to a simulated space flight program, poses no serious threat to well-being and performance. The physiologic deterioration observed was of the same kind as that to be expected from a week's confinement to bed. The only symptom of concern was the excretion of calcium in excess of intake reported in the Ames study. In the NAA experiment, where the subjects did not physically exercise, two of them showed 17=OHCS values above normal range. The peak of one subject on the 4th day of confinement, when he considered terminating the experiment, was 2 standard deviations above his mean. All subjects were fatigued and sleepy as the study progressed. They experienced rise in blood pressure and heart rate upon leaving the cabin. In contrast, no such symptons were observed in the other two studies, which included voluntary and programmed body exercises. Even under zero=G conditions, physical exercise can minimize demineralization of the skeleton as well as prevent muscular atrophy. Theoretical calculations made by King and Mans under NASA contract provide an indication of the differences in muscular work for simple movements of the extremities under 1 G and zero=G conditions (9). The differences range from an average of approximately 5% more to 10 and 15% less muscular work, depending on whether the gravitational force normally acts to aid or oppose the movement. The work of accelerating and decelerating masses of the extremities during zero=G is the same as under normal conditions, but differences certainly arise when movements are made in the formerly "vertical" plane. Since gravitational forces normally oppose physical work, the overall metabolic requirements will be reduced accordingly.

PROJECT MERCURY PHYSIOLOGICAL STUDIES

The Project Mercury provided an excellent opportunity to observe the physiological responses to space flight. Clinical evaluations of the astronauts were performed on the ground in order to (1) determine the fitness of the astronaut for flight, (2) provide baseline information for the aeromedical flight controllers, (3) measure any changes which might occur between preflight and postflight conditions.

The bioinstrumentation used in Mercury consists of two ECG leads, respiratory rate sensor, body temperature sensor, and a manually or semi-automatically operated blood-pressure measuring system. The instrumentation and the medical and physiological results of the flights have been described in several reports (10–13). The studies can be subdivided in the Project Mercury ballistic and orbital animal flights employing chimpanzees, the manned suborbital flights (MR–3 and MR–4), and the manned orbital flights (MA–6, MA–7 and MA–8). In all cases valuable data were obtained, but only those of the manned flights will be briefly discussed.

Preflight physical examinations were accomplished by flight surgeons prior to each mission. The aeromedical debriefing team, representing the specialities of internal medicine, neurology, ophthalmology, aviation medicine, psychiatry, radiology, and clinical laboratory conducted comprehensive medical examinations including labyrinthine studies (modified caloric tests and balance tests), ECG, EEG, and audiogram. The findings were always correlated with the physiological inflight information.

As to the suborbital flights, a number of changes were found in body weight, temperature, respiration, blood pressure, and pulse rate. Tachycardia and hyper-ventilation occurred during critical events, such as system checkout and booster engine cutoff at about 6 g. The pulse rate was sometimes erratic during the short weightless phase of about 4½ minutes in suborbital flight. The maximum occurred shortly after the 12 g peak re-entry acceleration. Respiration reached a high value at and preceding launch, was normal during weightlessness, and increased again upon re-entry. ECG traces showed no significant abnormalities throughout the countdown and flight; deep body temperature stayed about normal. By and large, the records of the suborbital Mercury flights showed exactly the physiological characteristics of man under the physical and emotional stress, which were known and predictable from human and animal data under comparable conditions.

The extension of time during the orbital flights permitted the inclusion of special tests and biochemical studies. By and large, the level of the blood chloride and alkali metals remained stable. In the MA–6 and MA–7 flights, xylose tolerance tests were performed to measure intestinal absorption while the men were weightless. In conjunction with these flights, a number of enzymes systems were studied to evaluate variations in muscle or liver activity resulting from acceleration followed by a weightless period or from the prolonged immobilization. Neither the MR–3, MR–4, nor the MR–6 pilot showed significant deviation from normal transaminase, aldolase or acetylcholine activity. The biochemical analysis included glutamic, alfa-ketoglutaric, isocitric, malic and lactic dehydrogenases, of which only the latter one showed a consistent and appreciable change. The lactic acid level was increased in one pilot. Increments were also found in leucylamino peptidase activity and in phosphohexose isomerase. Further studies concern the heat stability of the enzyme systems, the Michaelis-Menton constants for the enzyme reactions, and the tissues of origin.

In summary, it can be stated that all physiological responses during the Mercury orbital flights were in the acceptable ranges, and that the stresses of space flight were well tolerated. Although the episodes of high G force were brief, the extremes were considerable. In spite of this, the cardiovascular, respiratory and biochemical processes were fully maintained. Specifically, the heart response to physical exercise during weightlessness demonstrated reactive cardiovascular functions. Some aberrant ECG waveforms recorded during countdown and re-entry reflected the emotional and physi-

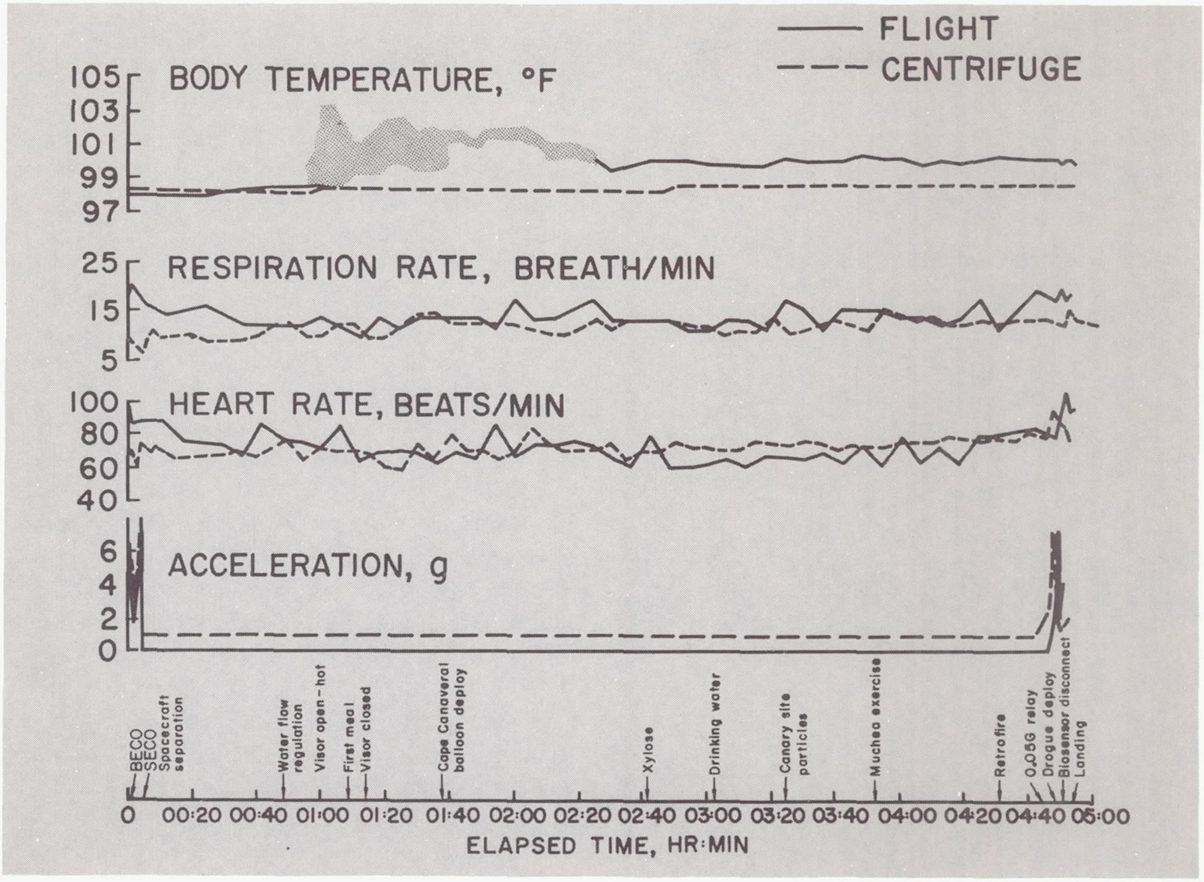

FIGURE 34–10.

cal stress during these procedures. Analysis of the inflight records revealed normal sinus rhythms with short periods of sinus bradycardia and arrhythmis (MR–6); and some premature atrial contractions, aberrant QRS complexes, and abnormal beats during the 7.5 g re-entry acceleration (MR–7). No disturbing symptoms or body sensations were reported during weightlessness. Liquid, semi-solid and solid foods were consumed and digested in flight. With the exception of the blood pressure meter, all biosensors provided useful data. The physiological flight records of MA–7 are plotted in figure 34–10.

LIFE SUPPORT

Experimental and theoretical investigations are underway to assure the ultimate life support for the protection of man under extraterrestrial conditions. This concerns the artificially engineered environment within all sorts of space vehicles and the human requirements; such as radiation protection; thermal, waste and humidity control; the various types of atmospheres to be used in spacecraft; and the preservation of health and the prevention of disease during planetary flights and stay on other celestial bodies. Attention will be paid to determining methods of enhancing the capability for physical and mental work through nutrition, drugs, exercise, and atmospheric and general environmental control. Studies of the logistics problem for spacecraft, space stations, and lunar and martian outposts will be conducted. The specification of requirements and design criteria for vehicles and shelters will be based on the results of measurements of the function of the CNS, endocrine activity, metabolism, psychomotor performance, and the general physiology and biochemistry of the body.

This part of the program will be accomplished by in-house work and by the monitoring of grants and contracts with military organizations, industry, and universities. Some environmental control systems already in use and in the planning stage will be described in another paper of this session.

NEUROPHYSIOLOGY

The neurophysiological studies concern the functions of the nervous system—in particular the central nervous system (CNS)—under normal, simulated and actual flight conditions. Of paramount importance is the maintenance of equilibrium and orientation in three-dimensional space. The ability of man and his close relatives among the vertebrates to maintain these functions depends on an integrated sensory input from the vestibular organ, the eyes, the interoceptors of the muscles, tendons, joints and viscera, and the exteroceptors of the skin.

Certain parameters of the environmental and space flight conditions drastically affect man's ability to maintain equilibrium and spatial orientation. Centrifugal forces modify or reverse the directional vector of gravity. Linear acceleration may increase enormously, as may angular stimulation. The sensory organs listed above are unreliable under such conditions. The very organ, which is designed specifically to furnish information on spatial orientation, may malfunction in man while he is in flight. Thus, with respect to sensory orientation, these labyrinthine organs are by no means precision instruments.

The use of classical histological methods and the observation of equilibrium disturbances resulting from operative interference with the internal ear have in the past been the two principal sources of knowledge concerning the structure and function of the labyrinth, but the answers given to various questions vary considerably in their value. The development of electrophysiological techniques and the refinement in recent years of the ultrastructural analysis by means of the electron microscope may allow more precise experimental studies of the correlation of function and structure.

Before considering vestibular impulses in their bulbar and descending spinal pathways, a recent study concerning the generation of impulses in the labyrinth must be mentioned. Von Bekesy's (14) finding of direct current potentials in the cochlea aroused speculation about the existence of similar labyrinthine potentials. Such DC potentials were also detected in the semicircular canal of the guinea pig by Trinker (15), who measured the potential changes in the endolymph, surface of the cupula, or side of the crista during cupular deflection. It seems likely, however, that the effects do not represent the physicochemical changes in the cupula but the electrical potentials in the nerve and nerve endings of the crista. Attempts at differentiating these effects have failed so far. Great expectations are brought by the advances of microchemistry, microphysiology, and physical chemistry with regard to the excitatory processes, the generation of the nerve impulse. Quite apart from a need to understand vestibular nerve discharges and patterns more adequately in such terms, the analysis of the vestibular system has in the past revealed general biological principles which were not readily discernible through the examination of other issues (16).

The neural connections of the vestibular organ consist of numerous chains of neurons, reciprocally linked in many ways and having their synapses in various anatomical nuclei. All the chains work in intimate collaboration, and the final pattern of reflex responses is attributable largely to the highly complex integrating activity of the center. The labyrinthine function is automatic, carried out in a reflex fashion; in other words, mostly below the level of consciousness. The brain centers through which the labyinth elicits the various appropriate muscular reactions of the head, body, limbs, and eyes—the righting, the postural and the ocular reflexes—represent an intricate mechanism. Before we can hope for a satisfactory understanding of their functional organization we will have to know their anatomy in more detail. Thus, we are confronted with a fruitful field for the exploration of basic mechanisms of neuronal activity. Major advances during the last years have provided us with new information about the neuroanatomy of the vestibular system (17–20).

Vestibular impulses invading the brainstem ascend and descend the neuraxis and cross the midline. It was previously implied that the vestibular apparatus had only subcortical projections. Recently, however, it has been established by means of electrophysiological methods that the organ is represented by a projection area in the cerebral cortex of some animals (21–24). The use of brief electrical stimulation of the vestibular nerve in order to elicit a cortical response has been of great value for the mapping of these areas.

Among a great variety of sensory receptors, the vestibular ones are capable of evoking the most widespread somatovisceral effects throughout the body. Moreover, vestibular effects seem to be relatively more imperious and less dependent upon the state of readiness of the nervous system. As a consequence of the extensive distribution of vestibular effects, there are many opportunities for central integration. From the intricate compensatory motor performance following activation of the vestibular system, it can be asserted that vestibular activity is influenced in a delicate and purposeful manner. Proprioceptive and vestibular systems are both known to be active in posture and locomotion; streams of impulses arising from the receptors in each of these systems must converge to influence the activity of the final common path. The state of the motor centers of the spinal cord, as affected by vestibular stimulation, has been tested by dorsal root and other sensory input interventions. These experiments have provided us with insight into the mechanisms concerned with the vestibular control of spinal reflexes (25–32).

It has long been known that the vestibular apparatus is essential for the development of motion sickness. Commonplace subjective experience of nausea relates to visceral changes mediated through autonomic efferent pathways and may ultimately involve rhythmic somatic nerve discharges to skeletal muscles responsible for retching and vomiting. However, very little is known about the central nervous mechanisms responsible for elaboration of the whole syndrome. Since the maintenance of vestibular bombardment for some length of time seems essential for the development of motion sickness, one would presume this to be an instance of slow temporal summation. Experimental findings demonstrate a powerful effect of temporal summation upon somatic motor outflow during vestibular stimulation (33), and not upon parasympathetic outflow (34).

The practical implication of these studies are closely related to physiological effects of weightlessness. Based on experimental evidence from short weightless periods obtained in aircraft it was concluded that "when the exposure becomes longer, there may develop minor physiologic disturbances which, if cumulative or irritating, may cause or enhance psychiatric symptoms" (34). Many of the early theories were repudiated or verified by controlled experiments and casual observations. Although the zero–G condition per se does not cause spatial disorientation if visual cues are provided, the astronauts reported a temporary loss of orientation during the orbital flight while they were engaged in activities which diverted their attention. However, no disturbing sensory inputs were observed during the weightless period. Violent head maneuvers within the limited mobility of the helmet were performed in every direction without symptoms of illusions or vertigo. The subjective sensations of "tumbling forward" after sustainer engine cutoff reported by the Mercury astronauts, and Titov's motion sickness attacks, which were particularly dismaying during head movements, were well within the entire range of psychosomatic experiences already obtained during aerodynamic trajectories (35). Interestingly enough it now appears that the otolithic output in mammals and man is the differential quotient of linear acceleration, but unaffected by zero–G. (30, 37).

Of pertinent interest in this connection are the problems which may be encountered during and following long-term exposure to weightlessness. Although there is no evidence of adverse effects on operative behavior, the possibility of biological disturbances on a cellular or sub-cellular level, which may cause a deterioration of the somatic basis, has been repeatedly stressed (38). Whether effects of this sort will occur or whether the organism will be able to adapt is still an open question. Since motion sensitivity based on vestibular stimulation is highly different among individuals, the selection of astronauts is not only necessary but may also solve the problem of agravic vestibular disturbance. Reports from the MA–8 and Vostok III and IV flights seem to support this assumption. Moreover, experiments are being made in the slow rotation room at the Naval School of Aviation Medicine to study the Coriolis effects which arise when "artificial gravity" is produced by angular acceleration. Since man can adapt to wave motion on shipboard within a few days, a similar process may be expected to occur in case of long-term weightlessness (39).

Another subject under study is the amount of sensory deprivation associated with space flight. In experiments on sensory deprivation, pain, and personality relationships conducted at the Republic Aviation Corporation under NASA contract, highly significant differences in sensory deprivation tolerance were found between subjects, who endured pain of various degrees. In addition, differences in response were apparent between different test populations. Unlike other reports, hallucinations were infrequent, which may be due to careful avoidance of suggestions by the experimenters. These experiments will be supplemented by a study—under another NASA sponsorship—of the psychophysiology of stress, motivation and conditioning by means of a sophisticated complex test battery. Up to 14 channels of physiologic, psychologic and environmental functions will be recorded simultaneously under normal and abnormal environmental conditions. Physiologic patterns of the basic deprivation states such as hunger, thirst, fatigue, and sleep deprivation and their relief will be studied in order to develop the means for objective description of motivation and learning inherent in these psychophysiological response patterns. This research is supplemented by electroencephalographic studies through grants and contracts; but in-house competence in this field will also be established.

BEHAVIORAL STUDIES

The behavorial studies within NASA concern man's ability to perform a wide variety of tasks required in space system operation. Figure 34–11 presents a concept of man's role in system operation. The viewpoint is that man is essentially a handler of information. First, he collects information concerning the vehicle and the environment, usually from sources within the vehicle itself, such as his instruments and the radio and occasionally directly from the environment, simply by looking out the window. Second, he processes this information in various ways, combining data from various sources, including his own memory, according to formulae which are typically complex and largely the products of his training and experience. Such judgments form the basis of various activities, overt and covert, such as exerting direct control over vehicle outputs, modifying automatic control system action where appropriate, reprogramming data processing equipment, or simply allowing the system to continue to function as before.

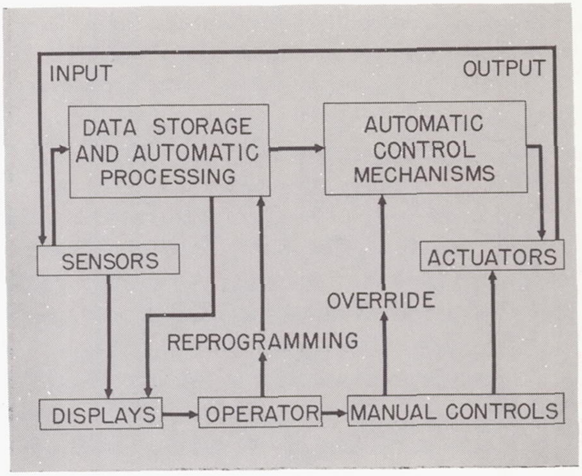

FIGURE 34–11.

There are numerous features related to the hardware design, the immediate physical environment, and events of the mission, which can influence the types of performance listed above. Examples of those which are of interest to mission performance are listed below. Individual psychological adjustment to mission conditions is of concern. For example, conditions which threaten performance in some aspect of the mission may produce anxiety. At the extreme, personal danger may evoke fear. Moreover, poor interpersonal relationships may develop among crew members, especially on trips of long duration. Confinement within a small crew compartment for long periods of time will be detrimental, in that movement is restricted and the variety of sensory inputs are reduced. Finally, overly difficult task performance may be demanded. As examples of this at a gross level, required on-duty periods may be excessive, or specific task performances may be required which are simply beyond man's capabilities. For instance, unreasonable requirements for sensory discriminations may be imposed, or specific task sequences may be such that the operator's information receiving, processing and control capabilities may be exceeded.

TABLE 34–II.—*Research Areas*

1. Visual perception.
2. Auditory perception.
3. Intellectual skills.
4. Skilled motor performance.
5. Personnel selection.
6. Personnel training.
7. Man-machine interaction in mission task performance.

To attack these problems, the research areas shown in Table 34–II have been recognized. The first 4 areas involve the development of basic information concerning man's capabilities in vision, audition, intellectual skills and skilled motor performance. We need to have more information concerning man's fundamental capabilities in these categories of activities, the laws governing his learning and retention of these skills under space flight conditions. This involves investigations of the compatibility of present and proposed assemblages of man and equipment within the particular environmental and operational conditions of the mission, the selection of personnel in accordance with mission requirements, and the development of appropriate training procedures.

PILOT CONTROL OF AEROSPACE CRAFT

The controlability of certain types of aircraft, which operate at the fringe of space, has been studied mainly by means of dynamic and fixed-base simulators. Representative of such studies are the X–15 and Project Mercury ground-based studies and the assessment of critical problem areas of the supersonic transport. Some of the simulators include the Mercury Procedures Trainer (figure 34–12) and the Johnsville centrifuge, which have been used to study attitude control problems during orbit, retrofire, and re-entry. In addition, the Air-Lubricated, Free-Attitude (ALFA) Simulator (figure 34–

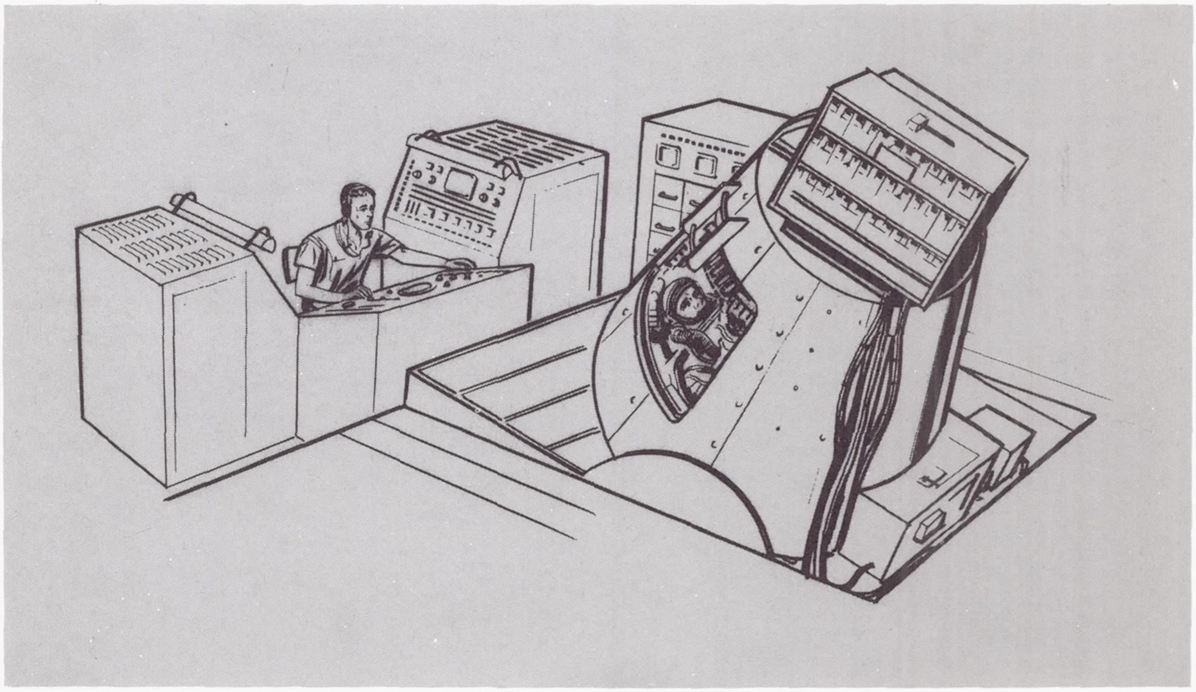

FIGURE 34–12.

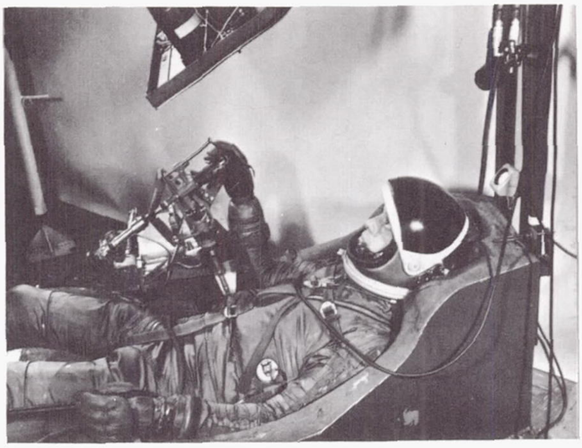

FIGURE 34–13.

13) has been used to investigate the ability of the pilot to control precisely during retrofire, and the Multiple-Axis Test Facility (MASTIF) has been employed to determine the ability of the astronaut to recover from tumbling.

In order to assess the capabilities and limitations of the human pilot or astronaut as a primary element in the control loop of advanced vehicles, NASA has conducted a number of research investigations (40–42) to obtain fundamental performance measures on pilot-vehicle systems. These measures have included:

1. Pilot physiological responses in various stress environments.
2. Pilot-vehicle performance in simulated control tasks.
3. Pilot opinion, reflecting a subjective measure of pilot-vehicle compatibility.
4. Pilot dynamic response, or transfer function.

The first item—physiological response—has been touched upon in previous sections of the discussion. The second measure—pilot-vehicle performance—is fairly straightforward and refers to quantitative measures of the ability of the pilots to perform simulated control tasks, e.g., atmosphere entries, orbital injections, etc. The third item—pilot opinion—is really a subjective measure of pilot-vehicle suitability and has been the primary measure used in so-called vehicle handling qualities studies. Ratings from 1 to 10 describe various degrees of acceptability of the vehicle, ranging from satisfactory to completely unacceptable or catastrophic. The last item—pilot transfer function measures—is probably the least known and understood measure, and I would like to spend a minute or two describing what a pilot transfer function is and some of the results we have obtained.

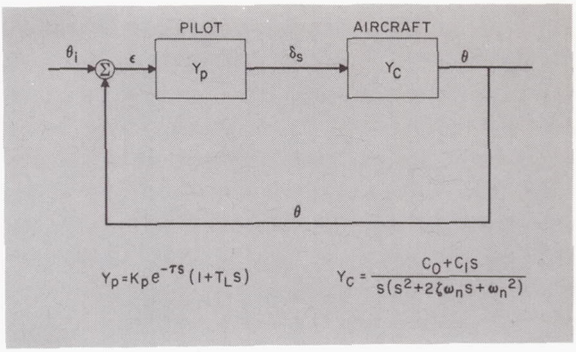

FIGURE 34–14.

Perhaps the best way to describe a pilot transfer function is to refer to the simplified block diagram of a closed-loop, pilot-vehicle system shown in figure 34–14. The control task pictured here is a simple one-dimensional tracking task where:

$\theta_i(t)$ is the command signal or forcing function,
$\epsilon(t)$ is the error signal or pilot stimulus displayed visually to the pilot,
$\delta(t)$ is the pilot control output,
$\theta(t)$ is the vehicle response.

The pilots' transfer function Y_p relates the pilots' control output $\delta(t)$ to his stimulus $\epsilon(t)$ by the equation shown,

$$Y_p = \frac{\delta}{\epsilon} = Kpe^{-\tau s}(1+T_L s), \text{ where}$$

Kp is the pilot static gain,
τ is the visual reaction time,
T_L is a first-order lead term which indicates the degree of error-rate information utilized by the pilot, and
s is the Laplace transform operator $\left(s=\frac{d(\;)}{dt}\right)$.

It should be noted that the linearized pilot transfer function shown here has been simplified for the present discussion.

Actually, the human pilot is a remarkably adaptive non-linear controller, who constantly changes his response characteristics to maintain good performance as the characteristics of the command signal or vehicle characteristics change. However, the linear model shown has provided useful results.

For example, in one study the human pilot transfer-function parameters Kp and T_L have been related quantitatively to pilot opinion of a wide range of vehicle characteristics ranging from satisfactory to unacceptable. These results have been applied in recent studies to predict pilot-vehicle control problems with considerable success.

In other studies directed toward human pilot control capabilities in various stress environments, e.g., high linear accelerations associated with atmospheric re-entries, we have measured the pilots' control task performance deterioration at high accelerations and related this to significant changes in the pilots' transfer-function characteristics.

These encouraging results have provided us with considerable incentive for follow-on studies in which we hope to obtain still more basic information on human pilot control characteristics. It is anticipated that these studies will lead to a more rational approach to the problem of optimizing advanced pilot-vehicle systems. The newest flight simulator employed for Apollo navigation studies is shown in figure 34–15.

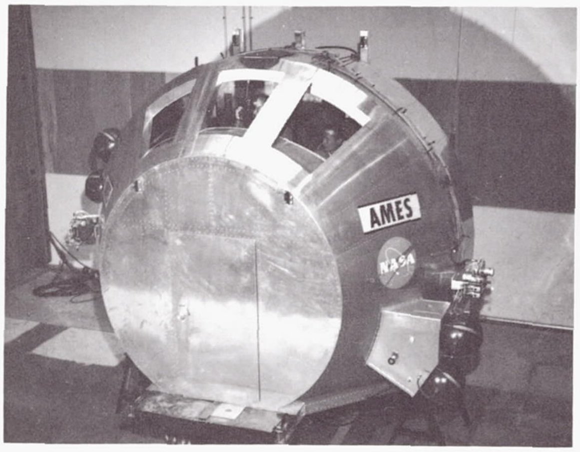

FIGURE 34–15.

ASTRONAUT PERFORMANCE

The philosophy described above has already paid off in the X–15 and Mercury program, where the pilot had to operate the spacecraft under various flight conditions. Main emphasis was placed toward maintaining the capability of the man to perform under high accelerations and weightlessness with about the same proficiency demonstrated under normal conditions. The validity of two major prerequisites has been established; namely, the test pilot criterion of the selection battery, and the extensive and elaborate conditioning process during the training period. The results of the flights indicate that the astronauts were able to perform the space-flight functions not only within the performance levels demonstrated on the centrifuge, in the aircraft, and the fixed-base trainers on the ground, but also within the tolerances required for the successful completion of the mission. The centrifuge training provided valuable experience for the launch and re-entry periods. The weightless flights in the aircraft were valuable as a confidence-building maneuver. The fixed-base procedure training provided an accurate simulation of the vehicle dynamics and flight program. By giving the pilot a major role in system operation, the most rapid and effective attainment of advanced missions is possible. His capability of corrective measures beyond those practiced in the training process can be extrapolated to the design and operational philosophy for highly complex multistage missions of the future. Furthermore, the pilots have demonstrated their ability to operate scientific instruments and to obtain useful data, which lends credence to the scientific mission assignment of Gemini, the Earth-Orbiting Manned Laboratory, and Apollo.

Finally, it is worthwhile stating that none of the original seven astronauts has failed or was eliminated from the program for psychological reasons. Their performance seems to justify the selection of highly experienced, mature professionals and the rigorous training program employed so far (10–13, 43). It should also be mentioned in this connection that the selection and training procedure of the Russian cosmonauts is basically very similar to that of Project Mercury.

In conclusion, it must be stated that the role of basic theory will become increasingly important as the NASA man-in-space program develops. In the design of advanced vehicles it is essential to provide for optimization and reliability. The quantitative aspects of the *machine* system are usually well-known on the basis of existing engineering knowledge. In order to optimize the performance of the entire system, it is necessary to succeed in the quantification of *operator proficiency*. Systematic analysis of this problem can only proceed on the basis of a mathematical theory of the human operator. This will allow not only the deduction of human transfer functions for the control of spacecraft, but also the accurate description of the whole man-machine-system complex.

REFERENCES

1. Gerathewohl, S. J. Chap. 26.1 Handbook of Astronautical Engineering (ed. H. Koelle), McGraw-Hill, 1961.
2. Holden, G. R., J. R. Smith, Jr., and H. A. Smedal. Aerospace Medicine 33:420–427, 1962.
3. Smedal, H. A., H. C. Vykukal, R. P. Gallant, and G. W. Stinnett. ARS Journal 31: 1544–1548, 1961.
4. Rogers, T. A., and H. A. Smedal. Aerospace Medicine 32:737–740, 1961.
5. Smedal, H. A., T. A. Rogers, T. D. Duane, G. R. Holden, and J. R. Smith, Jr. 33rd Annual Meeting of the Aerospace Medical Association, Atlantic City, N.J., April 9–12, 1962.
6. Celantano, J. T., D. G. Copping, H. F. Falbaum, and B. G. Martin. IAS National Summer Meeting, Los Angeles, California, June 19–22, 1962.
7. Algranti, J. S., D. L. Mallick, and H. G. Hatch, Jr. NASA Conference on Space Stations, NASA Langley Research Center, July 31–Aug. 1, 1962.
8. Rathert, G. A., Jr., N. M. McFadden, T. A. Rogers, R. M. Patton, R. F. Weick, and G. W. Stinnett. 17th Annual Meeting ARS, Los Angeles, California, Nov. 13–18, 1962.
9. King, B. G. and M. C. Mans. Operations Research Incorporated, Tech. Rept. No. 170, Feb. 28, 1962.
10. Proc. Conf. on Results of the First U.S. Manned Suborbital Space Flight, NASA, Nat. Inst. Health, and Nat. Acad. Sci., June 6, 1961, pp. 53–60.
11. Results of the Second U.S. Manned Suborbital Space Flight, NASA Manned Spacecraft Center, July 21, 1961.
12. Results of the First U.S. Manned Orbital Space Flight, NASA Manned Spacecraft Center, Project Mercury, Feb. 20, 1962.
13. Results of the Second U.S. Manned Orbital Space Flight, NASA Manned Spacecraft Center, Project Mercury, May 24, 1962.
14. von Bekesy, G. J. Acoust. Soc. Am. 23:576, 1951.
15. Trincker, D. Pflügers Arch. 264:351, 1957.
16. Livingston, R. B. Chapter 25 in: Rasmussen, G. L. and Windle, W. F., eds. Neural mechanisms of the auditory and vestibular systems. Springfield, Ill., Charles C. Thomas. 1960.
17. Brodal, A. Chapter 17 in: Rasmussen, G. L. and Windle, W. F., eds. Neural mechanisms of the auditory and vestibular systems. Springfield, Ill., Charles C. Thomas. 1960.
18. Brodal, A., Pompeiano, O. and F. Walberg. The vestibular nuclei and their connections, anatomy and functional correlations. Springfield, Ill., Charles C. Thomas. 1960.
19. Carpenter, M. B. Chapter 22 in: Rasmussen, G. L. and Windle, W. F., eds. Neural mechanisms of the auditory and vestibular systems. Springfield, Ill., Charles C. Thomas. 1960.
20. Dow, R. S. and G. Moruzzi, The physiology and pathology of the cerebellum. Univ. Minnesota Press, Minneapolis. 1958.
21. Kempinsky, W. H. J. Neurophysiol. 14:203, 1951.
22. Mickle, W. A. and H. W. Ades, Am. J. Physiol. 170:682, 1952.

23. Walzl, E. M. and V. Mountcastle. Am. J. Physiol. 159:595, 1949.
24. Andersson, S. and B. E. Gernandt. Acta oto-larying. Suppl. 116:10, 1954.
25. Gernandt, B. E., Y. Katsuki and R. B. Livingston. J. Neurophysiol. 20:453, 1957.
26. Gernandt, B. E. and S. Gilman. J. Neurophysiol. 23:516, 1960.
27. Gernandt, B. E. and S. Gilman. J. Neurophysiol. 23:269, 1960.
28. Gernandt, B. E. and C. A. Terzuolo. Am. J. Physiol. 1831, 1, 1955.
29. Gernandt, B. E. and C. A. Thulin, Am. J. Physiol. 172:653, 1953.
30. Gernandt, B. E. Chapter 23 in: Rasmussen, G. L. and Windle, W. F., eds. Neural mechanisms of the auditory and vestibular systems. Springfield, Ill., Charles C. Thomas. 1960.
31. Gernandt, B. E. Handbook of physiology. Baltimore, Waverly Press, 1960. Sec. 1, Vol. II.
32. Erulkar, S. D. Proc. Int. Union of Physiol. Sciences. Vol. I, Part 2, 500, 1962.
33. Akert, K. and B. E. Gernandt. Electroenceph. clin. Neurophysiol. 14:383, 1962.
34. Gernandt, B. E. (In preparation).
35. Gerathewohl, S. J. and J. E. Ward. Chapter 26 in: The physics and medicine of the upper atmosphere and space. John Wiley and Sons, 1960.
36. Gerathewohl, S. J. Astronautica Acta 2:303–317, 1956.
37. Gerathewohl, S. J. and H. D. Stallings, Jr. J. Aviat. Med. 28:345–355, 1957.
38. Tobias, C. A. and J. V. Slater. ARS Meeting, Gatlinburg, Tenn. May 3, 1961.
39. Henry, J. P., W. S. Augerson, R. E. Belleville, W. K. Douglas, M. K. Grunzke, R. S. Johnston, P. C. Laughlin, J. D. Mosely, F. H. Rohles, R. B. Voas and S. C. White. Aerospace Medicine 33:1056–1068, 1962.
40. Sadoff, M. and C. W. Harper. IAS National Spec. Meeting, Seattle, Wash., 10–11 August 1962.
41. Rathert, G. A., Jr., B. Y. Creer, and M. Sadoff. Fluid Dynamics and Flight Mech. Panel, Advisory Group f. Aeronaut. Res. and Developm. Brussels, Belgium, 10–14 April 1961.
42. White, M. D., M. Sadoff, R. S. Bray, and G. E. Cooper. 30th Annual Meeting IAS, New York, N.Y., 22–24 January 1962.
43. Voas, R. B. Astronautics, March 1962.

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35. Bioengineering

By Richard S. Johnston

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INTRODUCTION

Bioengineering is a relatively new field that has emerged as a major area of importance with the era of manned space flight. Basically, the bioengineering deals with the application of engineering principles to provide life-support and crew systems to meet the physiological requirements of aerospace flight. During World War II, with the advent of aircraft flights at altitudes above 20,000 feet, bioengineering was given birth. The development and use of breathing-oxygen systems was one of the major contributions during this period. As aircraft performance increased during the late and postwar era, additional protective systems were developed that required the combined talents of the biologist and engineer. Examples of this are: anti-"G" protective systems required by high-speed aircraft maneuvers, ejection seats for escape from jet aircraft, and full pressure suits to provide decompression for flight at altitudes above 40,000 feet. As we proceed into the manned space flight projects, the bioengineer is faced with an ever increasing, more complex challenge to provide space crewmen with systems and equipment that will meet the complete life-support requirement. The purpose of this paper is to better describe the role of the bioengineer in our manned space flight programs, to trace the evolution of current and future life-support requirements, and to define some of our research goals for the next 5 years.

FUNCTIONS OF THE BIOENGINEER

The discussion of the functions of the bioengineer begins with a review of the factors relating to manned space flight. Figure 35-1 shows these various factors. The life-support requirements of manned space flight include an atmosphere at a satisfactory pressure and composition to maintain blood-oxygen levels, adequate breathing oxygen supplies, and food and water. The metabolic products of carbon dioxide, heat, and water must be controlled to maintain a livable environment. Systems must

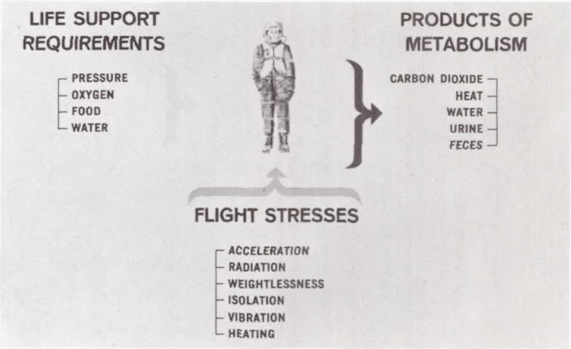


FIGURE 35-1.—Bioengineering factors in manned space flight.

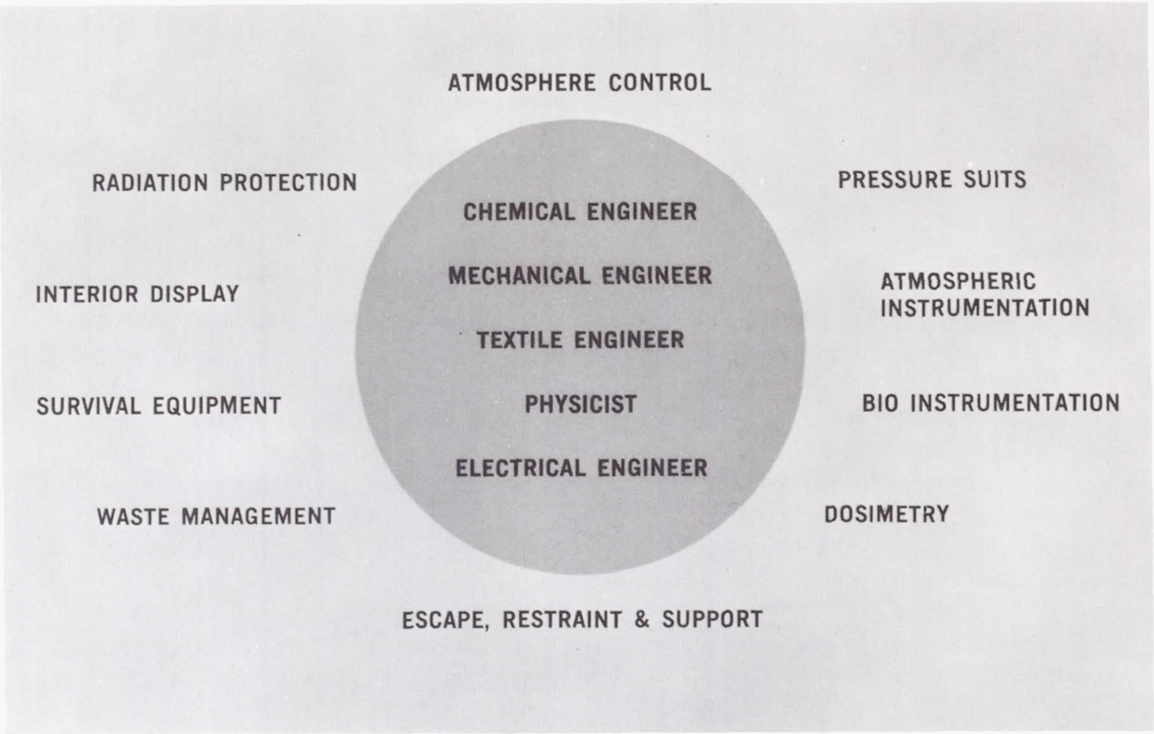


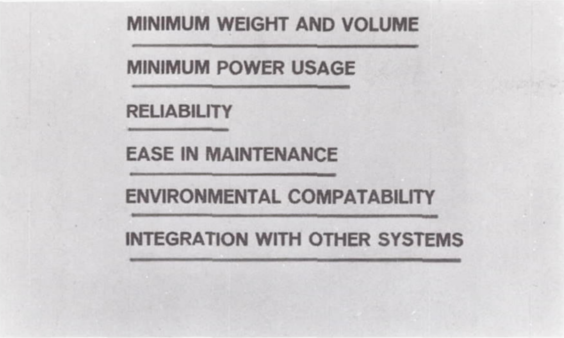
FIGURE 35–2.—Fields of bioengineering.

be provided for collecting, storing, and treating human body wastes. The flight stresses further complicate the maintenance of the life-support cycle. Adequate protective systems for these factors must be devised. These flight stresses span straightforward developmental problems, complex emergency problems, and rather unpredictable situations and areas of the unknown or undefined.

With this definition of the bioengineering requirement, what disciplines are needed and how are they used? Figure 35–2 gives a simplified breakdown of the utilization of physical and biological specialists, engineers, and scientific talents in the bioengineering field. It should be stressed that a clear line between engineer and biologist does not exist. The engineer must have an understanding of physiology, and the biologist must have some knowledge of engineering. From this figure, it can be seen that the mechanical engineer works with the design of many life-support systems; the electrical engineer works in atmospheric instrumentation, bioinstrumentation, and dosimetry. The chemist or chemical engineer is involved in the development of environmental control systems since these systems can be thought of as chemical treatment plants. Physicists and mathematicians work in the areas of radiation protection and, with the engineer, are involved in conducting parametric studies for various life-support systems. The physician, physiologist, psychologist, and bacteriologist provide the system requirements and assist in the validation of system designs.

SYSTEMS DEVELOPMENT

The efforts of the bioengineer can best be shown by a review of the development of several life-support systems. The design requirements that exist for these systems are shown in figure 35–3. The prime design requirement for all spacecraft systems is to provide the necessary equipment in the minimum volume with the minimum weight. System reliability must be provided. As the mission time increases, systems must be devised to allow the crewmen to trouble-shoot malfunctions and to make inflight system repairs. The systems must have the capability of withstanding both the natur-



MINIMUM WEIGHT AND VOLUME
MINIMUM POWER USAGE
RELIABILITY
EASE IN MAINTENANCE
ENVIRONMENTAL COMPATABILITY
INTEGRATION WITH OTHER SYSTEMS

FIGURE 35-3.—Life support design requirements.

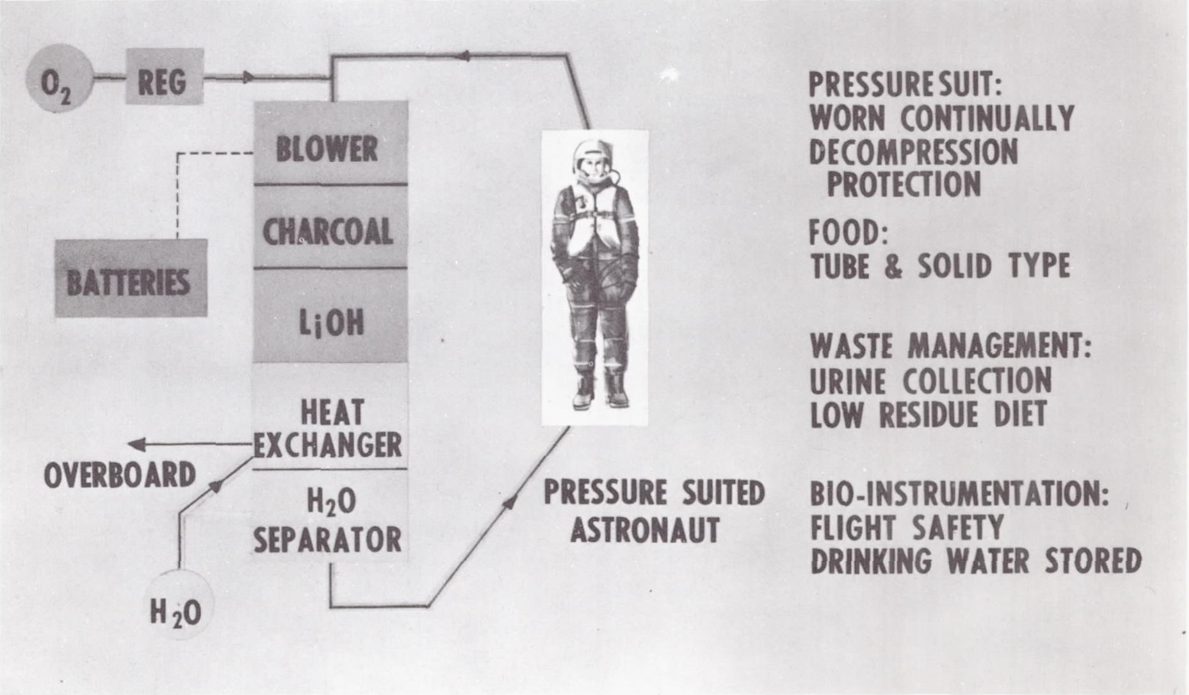
ally occurring or induced environmental conditions of space flight, that is, vacuum, acceleration, heat, vibration, etc. And last, the systems must be devised to integrate with other spacecraft systems to allow usage of common supplies and to serve dual purposes.

ENVIRONMENTAL CONTROL SYSTEMS

Three types of environmental control systems are described to show the evolution of design and the integration of various components as mission durations increase.

Mercury

The Mercury environmental control system is shown in figure 35-4. A closed-type environmental system was selected in Mercury to conserve oxygen and thus reduce the oxygen-supply weight and volume required by the open-type aircraft system. The astronaut wears a full pressure suit at all times for emergency decompression protection. Both the cabin and suit pressures are maintained at 5 psia with oxygen. Oxygen is forced into the pressure suit at a torso connection by a battery-powered electric blower. In the suit, body cooling takes place, oxygen is consumed, and a gas mixture of carbon dioxide, water vapor, and oxygen is produced. This mixture leaves the suit by a helmet connection and enters a physiochemical treatment cycle. Odors are removed by activated charcoal; carbon dioxide is removed by chemical absorption with lithium hydroxide (LiOH), and heat is removed by a water-evaporative heat exchanger. The water vapor condensed in the heat exchanger is removed by mechanical water separation. Oxygen pressure is maintained in the pressure suit by a demand regulator that meters oxygen from a 7,500-psi oxygen supply.



PRESSURE SUIT:
WORN CONTINUALLY
DECOMPRESSION PROTECTION

FOOD:
TUBE & SOLID TYPE

WASTE MANAGEMENT:
URINE COLLECTION
LOW RESIDUE DIET

BIO-INSTRUMENTATION:
FLIGHT SAFETY
DRINKING WATER STORED

FIGURE 35-4.—Mercury life support system.

The operating time for this system is dependent upon the system consumables: oxygen, coolant water, LiOH absorbent, and electrical power. Food is provided in Project Mercury mainly as a research experiment to study eating in weightless flight. Waste management is accomplished by a urine collection device worn in the pressure suit. Fecal waste production is controlled by the use of a special low-residue diet prior to flight. Bioinstrumentation is provided for flight-safety monitoring. The biosensors are worn under the suit continuously. Drinking water is provided from a stored supply.

Apollo

The Apollo-type system shown in figure 35–5 can be considered as the next generation of environmental control systems. It is basically a closed system which provides a normal "shirt-sleeve" cabin environment with provisions for pressure suit operation during critical flight periods where the decompression hazard is most serious. The 14-day mission requirements allow usage of a modified Mercury environmental control system cycle. Major design changes are made for storing and using the system consumables. System weight trade-off studies showed that more complex regenerative-type systems were not justified for Apollo. Oxygen is stored in the super-critical state to supply both the environmental control system and the electrical power producing fuel cell. Heat is removed from the system by a coolant loop connected to a space radiator. Water condensed in the system cycle is collected and stored to provide additional cooling during high-heating periods in the flight. This water is fed into an evaporative heat exchanger system to provide increased cooling capacity. A catalytic burner has been added to the system to control the build up of trace contaminate gases. Drinking water is produced in the fuel cell. Pressure suits are provided for use in the spacecraft and to permit manned exploration of the lunar surface. Food is stored in the freeze dried condition to eliminate the need for refrigeration. The food is reconstituted by adding a measured quantity of water to the food packets. This water also is provided by the fuel cell. Body wastes are collected and stored. System trade-off studies indicated that reclamation of urine and fecal material is not justified from a weight-power consideration for this mission.

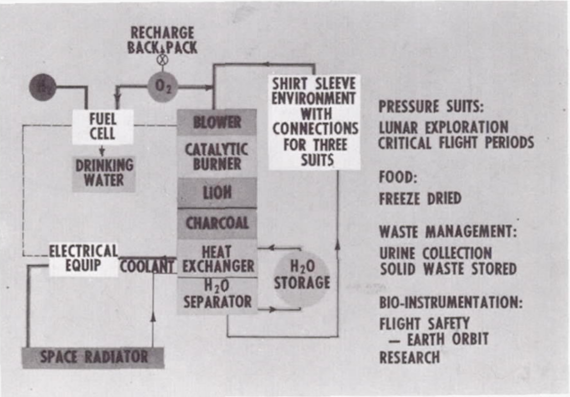


FIGURE 35–5.—Apollo type life support system.

Bioinstrumentation is provided for flight-safety monitoring, primarily in the early earth-orbiting Apollo flights. As crew validation for 14-day weightless flight is accomplished, this bioinstrumentation requirement will be reduced. In later flights, monitoring will be accomplished by the crew with simple clinical devices.

In addition to this life-support equipment for the Apollo spacecraft, a system similar to the Mercury system is being developed as a back-pack to support extra-vehicular space suit operation. This system is extremely light, completely self-contained, and provides several hours of lunar operation.

Space Station

The next system, shown in figure 35–6, is proposed for a multiman space station currently being studied by the Manned Spacecraft Center. The basic Mercury-Apollo cycle is still utilized in the system design. Space radiators would be used for cooling the space-station cabin and equipment. The duration of space-station operation now makes it feasible from a weight-volume consideration to utilize a method of regenerating oxygen from carbon dioxide. In the system shown, carbon dioxide would be removed by a molecular sieve and transferred to a CO_2 reclamation unit. In this unit, the CO_2 would be reduced by H_2 to form carbon and water. The carbon would be dumped over-

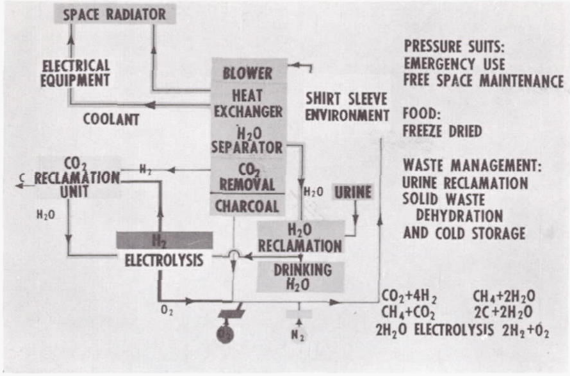


FIGURE 35–6.—Proposed space station life support system.

board. The water would be fed into an electrolysis unit where hydrogen and oxygen are formed. The oxygen would be fed back into the cabin, and the hydrogen would be reused to reduce more of the CO_2. Water collected from sweat and urine would be reclaimed and used as drinking water and the excess would be fed into the electrolysis unit to produce additional oxygen. Stored supplies of oxygen and nitrogen would be carried to maintain a satisfactory cabin pressure and mixture. For flights of several months, it is currently felt that a two-gas system will be required. Food would still be carried in the freeze-dried form or in other similar packages. Solid waste would be collected, dehydrated, and stored. Bioinstrumentation as we know it today for flight safety monitoring would be eliminated. Clinical-type measurements would be made by the crewmen and transmitted by voice to earth. Studies are currently under way to develop system components for evaluating this type system by the end of 1964.

From the description of these three systems, the evolution of design leading to a completely closed ecological system becomes apparent. The Mercury and Apollo systems are being developed with current state-of-the-art components. The space-station system requires extensive developmental efforts and a dynamic evaluation program.

CREW SYSTEMS

One other major area in bioengineering that should be considered is the development of crew systems. This includes pressure suits, restraint and support systems, survival equipment, escape systems and the integration of this hardware into the crew stations. The development of crew systems requires many talents, that is, mechanical engineering, textile technology, physiology, and human engineering. The two most difficult design tasks other than meeting the performance requirements are satisfying the crew with personal equipment and integrating this equipment into the spacecraft. Pressure suits are the prime example of these problems. The suits first must be designed to provide a comfortable garment which will be easy to don and which will provide mobility when pressurized. The suit must be compatible with the environmental control system, contain a minimum of connectors for communications, bioinstrumentation, and other services. Integrating the suit with the spacecraft is complicated by the need for simple ingress, adjustments for comfort and mobility, and rapid egress during emergencies following earth landing. The Mercury pressure suit has been described in reference 1. This is a continuous-wear suit which requires only arm and shoulder mobility.

The development of the Gemini pressure suit presents a new spectrum of design problems. The mission time in Gemini may extend to 14 days. The cabin volume does not allow sufficient room for the astronaut to remove or don the complete pressure suit and, therefore, the suit must be worn at all times. To provide a measure of crew comfort, a partial-wear suit shown in figure 35–7 is being evaluated for possible use in Gemini. The suit is designed so that for comfort the arm, leg, and helmet sections can be removed during normal flight periods. During critical flight periods, these components would be attached to the suit to provide decompression protection. Provision for waste collection are provided in these suits.

So far the Apollo suit has been the most difficult to develop. This suit must be compatible with the Apollo command module and the lunar excursion module and also provide sufficient mobility, thermal protection, and durability for manned lunar exploration. The suit shown in figure 35–8 affords excellent mobility and, from preliminary studies, appears prom-

FIGURE 35–7.—Partial wear concept suit.

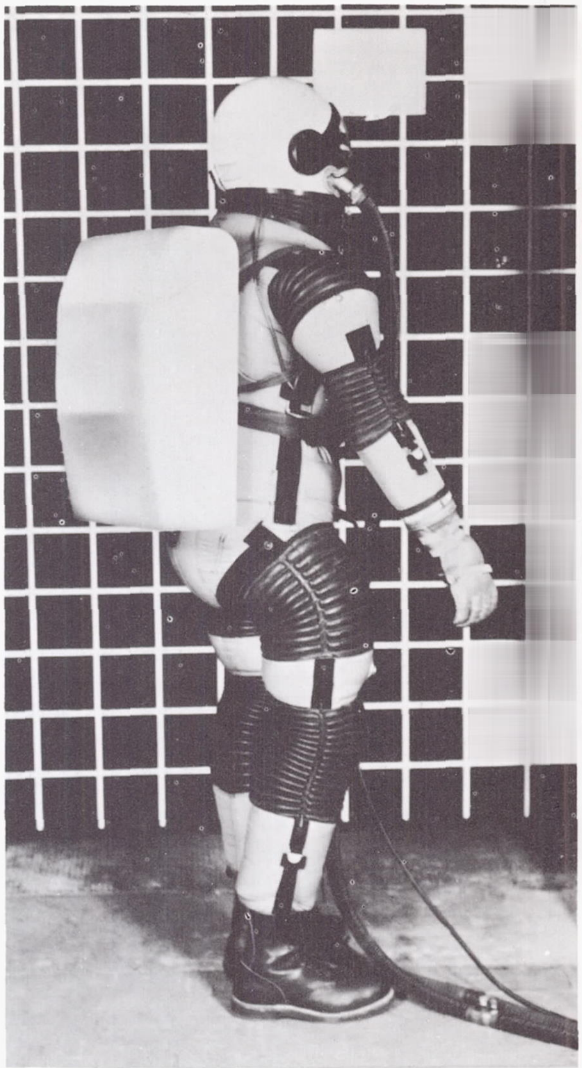


FIGURE 35–8.—Bellows design suit.

ising. The astronaut can convert this vehicular-type space suit for extra-vehicular lunar operations by donning a super insulation coverall and connecting a self-contained environmental control system. Other concepts with integral insulations are being developed for evaluation.

The Project Mercury support and restraint system has also been described in reference 1. The support- and restraint-system requirement for Gemini differs from that for the Mercury system in that it must also provide support and restraint during ejection-seat operation, that is, provide adequate body positioning during catapult thrust and preclude flailing of arms and legs when the seated man is exposed to tumbling and wind blast after ejection. The Apollo support- and restraint-system requirement is identical to that of Mercury. The solid couch performs its function well; however, "in-house" development of net couches capable of being stowed is going on at a rapid pace (fig. 35–9). Successful completion of this work will relieve the volumetric constraints within the spacecraft. A continuous and basic complication in this area of crew-system design is the factors of integration. There must be complete and simple compatibility between the space suit, the support and restraint system, the various disconnects between the spacecraft

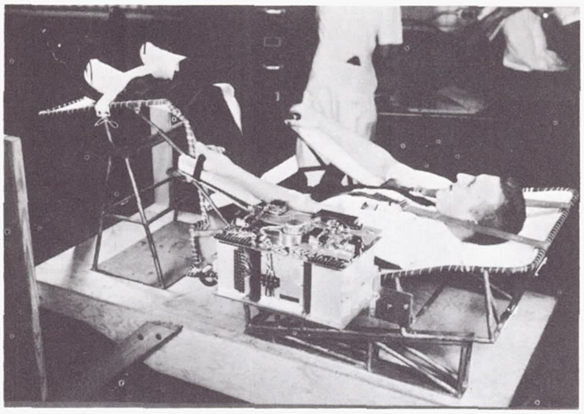


FIGURE 35–9.—Net couch-restraint system developed for human centrifuge tests.

environmental control systems and the portable life-support system, the water and waste management system, the drinking water and food systems, and any other on-board system that requires the attention of the astronaut. These compatibilities must be available when the suit is unpressurized or pressurized. Careful attention to detailed design and development of desired components and a similar order of care in the over-all integration problems is the only successful method of providing the astronaut with a work station within which he can perform his important and vital job.

RESEARCH AND DEVELOPMENT REQUIREMENTS

A summary of research and development requirements is presented in figure 35–10. This summary does not reflect official NASA schedules or projects but is included to give perspective to the future bioengineering research and development requirements for manned space flight.

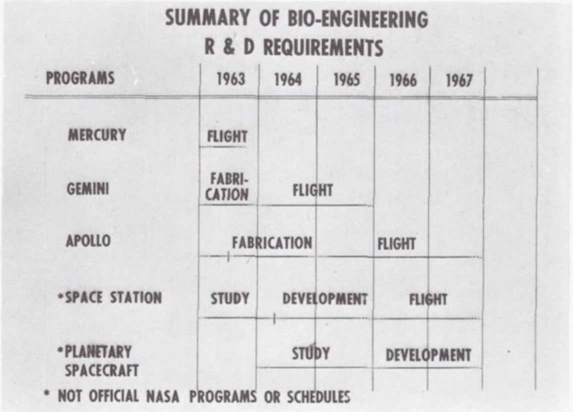


FIGURE 35–10.—Summary of bioengineering research and development requirements (Three parts). Part a.

In the next 5 years, research is needed to develop methods for removing carbon dioxide and processes for recovering oxygen from CO_2. This research effort should be directed toward developing with reliable, low weight components requiring minimum power. This work should encompass basic research into new conceptual methods as well as applied research for current state-of-the-art concepts. Lightweight low-power blowers are needed with operating lives of a year or more. New methods are needed for testing the reliability since current

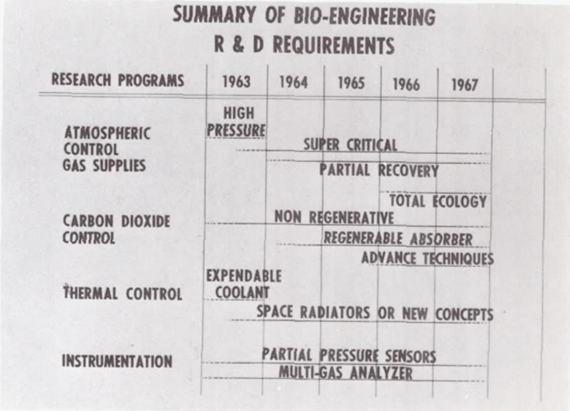


FIGURE 35–10.—Part b.

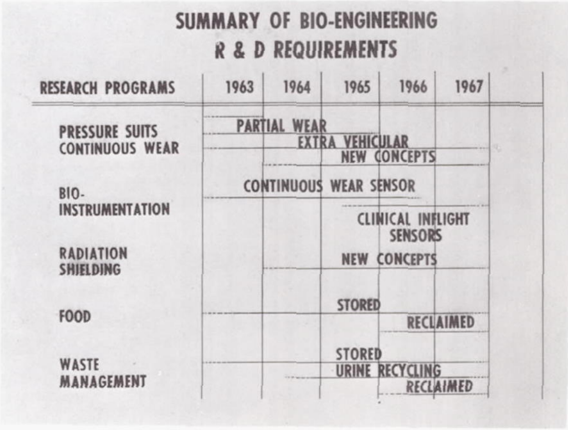


FIGURE 35–10.—Part c.

methods become impractical, economically, with the flight duration involved. New approaches to improving a thermal control system are required. For example, the problems of thermal control on the lunar surface need better resolution. Atmospheric instrumentation is an area which also requires additional research and development. Satisfactory methods of measuring partial pressures of nitrogen, oxygen, and carbon dioxide for extended flights are currently not available. In addition, similar instrumentation is required for monitoring trace gas and particulate contamination of on-board atmospheres.

Pressure suit research is receiving a major share of our current research funds. All current suit development utilizes soft suit concepts and studies are required to determine whether other types are required. All suit development projects are based on the required tasks to be performed; therefore, research and evaluation of crew tasks in free space and in planetary exploration are needed to bring suit development into proper focus.

Research is required in food and waste management systems to provide methods of control and synthesis of food products.

These problems, as presented, are not new or unique as stated in this paper. They have been put forth to establish a logic in life-support systems development.

CONCLUDING REMARKS

This paper has presented a definition of bioengineering and has attempted to define the functions of the bioengineer in our manned space flight programs. The complexity in the evolution of life support systems was presented and a limited research requirement was outlined.

In conclusion, bioengineering is emerging as one of the major fields of effort in the space era. To meet this challenge and to provide the skills required, some thought should be given in planning curriculum to establish a course of instruction in bioengineering. The course could combine basic engineering with some training in physiology. Graduates with such a background are needed and required by our space programs.

REFERENCE

1. Staff of the Manned Spacecraft Center: Results of the First United States Manned Orbital Space Flight, Feb. 20, 1962. Government Printing Office.

36. Exobiology

By Richard S. Young

Dr. Richard S. Young *is currently Acting Chief, Exobiology Division of the NASA Ames Research Center. Concerned with the effects of space environment on living systems, Dr. Young was scientific director of the BIOS I flight program in 1961. His fields of interest include astrobiology, and detection and study of extraterrestrial life. He received his B.A. degree from Gettysburg College in 1948, and his Ph. D. degree in Zoology from Florida State University in 1955. Dr. Young is a member of Phi Sigma, Sigma Xi, American Association for the Advancement of Science, and Society for Experimental Biology and Medicine.*

The question of where, how, and when did life arise is as fundamental a question as man can ask. An examination of the large number of extraterrestrial bodies in the universe, whose physical relationship to their respective suns should provide them with environments in which life could have arisen, certainly must lead us to question the uniqueness of life on Earth. According to Oparin (Ref. 1)

> . . . Consequently, the origin of life is not a "fortunate," extremely improbable event, but quite a regular phenomenon subject to a deep scientific analysis and all-round study. It is obvious that there must be numerous inhabited planets in the Universe and, in particular, in our Galaxy. This quite indisputable assertion, however, is based on considerations of a general nature and must be confirmed in each concrete case by an examination of the actual conditions which prevail on the cosmic bodies accessible to investigation by the methods of modern science.

A broad definition of exobiology could be the detection and study of extraterrestrial life, and its impact on the origin and evolution of life on Earth and elsewhere in the universe. Life, of course, is an extremely difficult thing to define, but perhaps a working definition for our purposes could be any self-replicating, metabolizing system capable of mutation.

Life on Earth (the only life we know at present) has certain unifying characteristics, particularly in its chemistry. For example, compounds, such as the nucleic acids (the hereditary material), and the proteins are found in all living things. With the advent of space vehicles capable of reaching the planets of our solar system with instrumented payloads designed to detect the presence of life, we now are nearing the capability of determining whether or not life as we know it is unique, or whether the remarkable sequence of events (chemical evolution) leading up to the first living system has occurred elsewhere. We will know whether or not the nucleic acids and proteins or the carbon-based chemistry common to all life on Earth is a universal factor or not. It is conceivable (although unlikely) that some extraterrestrial life is based on a system of chemistry we have never experienced and may even have difficulty identifying. If this should prove to be the case, we have the exciting prospect of a totally new science of biology and biochemistry.

Biology, unlike most of the physical sciences, is lacking in universal principles, because of its restriction to the planet Earth. Perhaps the nearest thing to a universal biological principle is that of Darwin's theory of evolution through the natural selection of random hereditary fluctuations. A discovery of extraterrestrial life would determine the universality of this and perhaps other concepts.

Since life on extraterrestrial bodies should be randomly distributed with respect to its placement in evolutionary history, we may contemplate its ultimate detection in all stages of development. The possibilities are as follows: (1) We may find a "protolife" in which chemical evolution has proceeded to a point where the necessary precursor molecules (e.g., amino acids, fatty acids, etc.) are present in detectable amounts, under environmental conditions (proper inorganic constituents, simple hydrocarbons, reducing atmosphere and energy sources) conducive to the continuing production of these and more complex molecules. (2) We may find primitive life—where the above molecules have been organized within the confines of a selectively permeable membrane in such a way that they now constitute a self-replicating, mutating system. (3) We may find diversified life—where various metabolic pathways have evolved in multi-cellular organisms of different degrees of complexity. (4) We may find intelligent life. (5) We may find evidence of a once-living culture, now extinct. (6) We may find evidence of life or "protolife" in which the characteristic compounds are only slightly (but significantly) different from our own, or in which alternate metabolic pathways and energy-converting systems have evolved. (7) We may find evidence of life which is chemically completely different from our own. (8) We may find no indications of life at all.

Of immediate concern to us, of course, is the detection and study of extraterrestrial life in our own solar system, since our space vehicle program will give us the capability of exploring our own planets long before those of other solar systems. Within our own solar system, the planet Mars apparently has the only environment at all suitable for the evolution of life as we know it, and as a result, Mars will probably be the first to be explored in this context. Even Mars, however, has an environment which will be extremely hostile to any terrestrial life. The diurnal temperature extremes (as much as −100° C to +30° C) and the apparent very low moisture content on Mars (ref. 2) present the most formidable difficulties. It is likely that living organisms from Earth (bacterial spores for example) can survive this environment, but it is difficult to see how they could multiply and grow. If life does exist on Mars and if it has evolved in a fashion similar to that on Earth, it must be very different (at least morphologically and biochemically) from life on Earth. It must have evolved with great water-conserving capabilities or with greatly reduced water requirements, since it is impossible for carbon-based life to have arisen without water. It must have evolved the capability of utilizing the short periods of warmth for metabolism, then quickly converting to a freezing situation at night. It may have evolved radiation protection mechanisms since the ultraviolet flux on Mars is probably quite high due to the absence of oxygen, and an atmospheric ozone layer as a shield. Therefore, in order to hope to study life on Mars and elsewhere, we must be prepared to look for something quite unfamiliar to us, and under conditions of great difficulty, at least at first.

The NASA exobiology program then may be considered in several different ways.

The first consists of laboratory studies on the chemistry of formation of biologically significant molecules under conditions that may have prevailed on the primitive Earth or some other likely planet. Conditions on the primitive Earth were undoubtedly quite different from now, and at some time in history must have been suitable for the bio-organic synthesis which ultimately led to the first living system. In the laboratory we can simulate these and many other theoretically primitive conditions and apply a suitable form of energy (ultraviolet light, electrical discharge, microwave, ultrasonic, heat, etc.) to various mixtures of gases (ammonia, water, methane, carbon dioxide, hydrogen, etc.) in the absence of oxygen, and determine what sorts of compounds will be formed under these conditions. Many different combinations of gases and energies have been used (refs. 3–8) with always the same remarkable result. No matter what form of energy is used in a mixture of primitive gases in a reducing atmosphere, biologically important organic molecules are always formed in significant amounts, particularly the amino acid building blocks of proteins. Recent unpublished data indicate that other compounds (purines, pyrimidines, fatty acids, etc.) of great biological significance are also formed under these conditions, although in smaller amounts. It seems that very early in the history (perhaps even during the formation) of any planet physically similar to the Earth, it would be inevitable that these compounds and subsequent chemical evolution would occur. It has also been demonstrated (ref. 9) in the laboratory that once such compounds as amino acids are present in sufficient quantity, and energy is applied (in the form of heat) under the proper conditions, polymerization takes place with the formation of larger molecules including "proteinoids" (protein-like compounds). Here again there is evidence (unpublished data) of other highly significant molecules being formed at the same time, including some of the components (purines and pyrimidines) of the DNA molecule which is our hereditary unit. Interestingly enough, this same synthetic protein, upon further treatment (ref. 10), will condense and become structured in the form of microspheres with many of the characteristics of cells.

The above sequence of events is not necessarily what happened on Earth or anywhere else in the universe—the picture is, of course, much more complex than indicated here; however, this type of research is gradually filling in gaps in our knowledge of chemical evolution and suggests pathways along which life could have arisen somewhere in the universe. The ultimate answer and complete story may be very near or quite far in the future. Discovery of a extraterrestrial life at an earlier stage of evolution than appears on Earth could do much to answer some of the questions associated with the origin of life on Earth, where it is already too late to determine by any but indirect means how life arose and evolved. The pathways of chemical evolution are probably almost entirely obliterated by subsequent life, since the very materials which give rise to life become "food" for life and thus a disappearing substrate. This is true also because physical conditions on the present Earth are such that the syntheses possible on a primitive body are no longer possible (because of the presence of oxygen) except perhaps in very special locations (such as areas of volcanic activity where reducing conditions persist).

The second phase of the NASA program is thus the detection and study of extraterrestrial life, with the first object of study probably being the planet Mars, although the Moon, Venus, and Jupiter are not without possible biological significance. Preliminary investigations of the Moon, Venus, and Jupiter will be confined to physical determinations which have special biological significance. For example, although we probably do not expect to find life per se on the Moon, the lack of an oxidizing atmopshere may be conducive to the long-term preservation of any material impacting the Moon from space (ref. 11). Therefore, an organic as well as inorganic analysis of the lunar surface to some depth is contemplated, probably by gas chromatography. As far as we now know, the surface temperatures of Venus are too high (300° C, ref. 2) for the presence of organic compounds and certainly for life. The present and subsequent Venus probes should confirm or deny these measurements and allow a more accurate evaluation of the possibility of life on Venus. The remaining planets are even more unlikely candidates for life because of the proximity to or distance from the Sun and resulting temperatures; attention therefore presently centers on Mars. As previously mentioned, the planet Mars seems to be an extremely hostile environment for the existence of life as we know it on Earth. Liquid water apparently does not exist on the surface of Mars (except perhaps in certain microenvironments, ref. 12), oxygen has not been identified, the atmospheric pressure is about 0.1 of an Earth atmosphere, the temperature ranges from about −100° C to +30° C with a diurnal freeze-thaw situation even in the summer. There does seem to be CO_2 in the atmosphere and polar ice caps (probably only a few millimeters thick) which wax and wane with the seasons. Other atmospheric components are still unknown, although nitrogen and argon are likely. The surface composition is unknown, although C–H compounds have tentatively been identified. There are seasonal changes in coloring on the surface of Mars which have been attributed by some to life (ref.

2). There has been much theorizing for many years on Martian life and its characteristics. The space program has now brought us to the point of being able to settle the question within the next few years (1) by flying instruments beyond the Earth's atmosphere to perhaps within a few thousand miles of Mars, enabling us to improve our present knowledge of the physical conditions and composition of the planet, (2) by landing a series of life-detection devices on the surface of Mars, which will be various means determine the presence of life and telemeter such information back to Earth in the form of a simple yes or no, plus whatever other detailed information can be obtained, (3) by landing a sampling device on the surface of Mars which will obtain and then return samples of Mars to Earth for study, and (4) by landing man or men on the surface of Mars with all of the above capabilities.

Several different life-detection systems are currently under development for NASA as shown in table 36–I. All of these are based on characteristics of life as we know it on Earth, which as mentioned previously may be completely wrong for Mars. However, at the present time we must assume that life on Mars is based on a carbon chemistry (because we know of no substitute) with a metabolism that will be similar to ours. We assume that the biologically critical molecules will be the same or nearly so, and that we will be able to recognize this life by essentially the same ground rules we use on Earth.

As previously indicated, certain molecules (such as protein and DNA) are to the best of our knowledge found only in living systems (with the possible exception of the virus). Therefore, several life-detection devices are intent mainly on the chemical identification of these molecules or their component parts. There are many ways in which these compounds can be identified, such as (1) infrared spectroscopy (2) mass spectrometry (3) special staining (4) optical rotary dispersion (ultraviolet), etc., and each of these techniques is being considered in a detection instrument. Another characteristic of life is its utilization of energy sources (e.g., organic and inorganic substrates, or light for photosynthesis) to maintain itself in its environment. Many metabolic activities are widespread among living things on Earth, such as the production of carbon dioxide as a cellular waste product. One device (fig. 36–1) is based primarily on this principle, in that it samples an extraterrestrial surface by throwing out a sticky string which is reeled back into the device. As it is reeled in, the collected material is combed into a nutrient medium in which the substrate contains isotopic carbon. If there are viable organisms present they will metabolize the substrate with the subsequent release of $C^{14}O_2$ which will be detected by a solid-state counter past which the evolved gas must flow. If there are no viable organisms there will be essentially no $C^{14}O_2$ evolved. In this device, a variety of tagged substrates could be used to broaden the detection capability. Another device (fig. 36–2) utilizes the fact that growing organisms will increase in size and number under the proper conditions causing changes in turbidity and pH of the medium. These changes can be measured and telemetered. With a device such as this, several different kinds of media can be used and monitored. Another device will have a multiple capability, and will be able to perform a number of chemical analyses and molecular identifications, detect certain enzyme systems, gas production, turbidity and pH changes, etc., all in one instrument. This, of course, is a complex device and will probably require a later generation of vehicle to achieve its mission. Also under development is a microscope which will perform

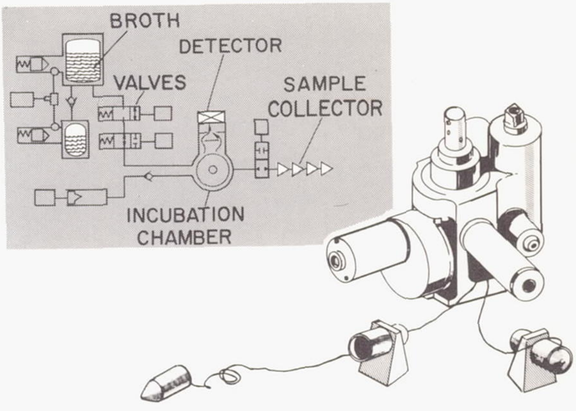


Figure 36–1.—Gulliver.

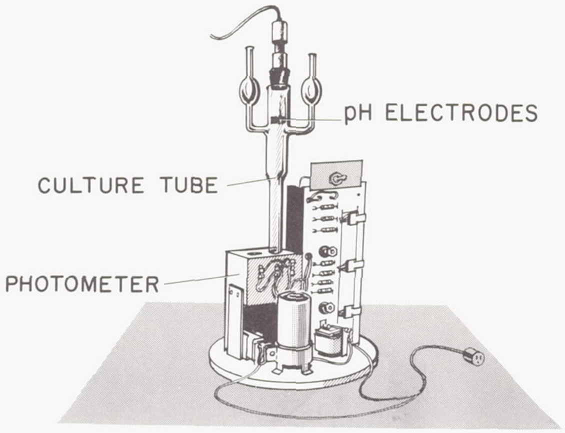


FIGURE 36-2.—Wolf trap.

remote controlled observations of extraterrestrial samples in both visible and ultraviolet light.

TABLE 36-I.—*Techniques of Life Detection*

Turbidity and pH
Microchemical and microbiological
Metabolic C^{14}
Optical rotation
"J" Band formation
Optical-particle detection
Mass spectrometry

Ultimately, it may be left to manned expeditions or at least manned observations of returned samples to settle the question.

Interestingly enough, extraterrestrial material is presently being analyzed for bioorganic content by scientists in several laboratories with rather controversial results. Meterorites are extraterrestrial samples, and carbonaceous chondrites (meteorites with a relatively high carbon content) from several museum collections have been analyzed with very provocative results. There appear to be biologically significant compounds (refs. 13, 14) in these samples, with some investigators reporting the identification of fossilized organisms (ref. 15) similar to algae in certain chondrites One investigator (unpublished) even reports the recovery of living bacteria from meteorites. Obviously, these reports must be verified or settled in some way. Since all meteorites currently under investigation have been on Earth for years, these results are subject to the question of contamination. It would be very exciting to have uncontaminated meteoritic material for these analyses, and NASA is looking into a program of meteorite collection in which "fresh" meteorites will be collected on a nationwide scale as soon as possible after atmospheric entry. Ultimately, we hope to have meteorites collected in space or from the Moon.

The third area of interest consists of laboratory studies on Earth in which extraterrestrial and primitive environments are simulated so that as much as possible can be learned about the adaptation and evolution of organisms in such environments. We might consider as part of this program the problem of decontamination of spacecraft. One of the primary reasons for sending vehicles to the Moon and planets is to search for life, and we must be certain the life we detect is not from Earth, carried along by the vehicle itself. Also, we must consider this opportunity to study the biology and biochemistry of a planet as a unique event in that once a planet is contaminated with a species of bacteria which can grow successfully in this new environment, its biology will no longer be the same. In other words, an irreversible process may have begun which will mask or perhaps destroy the existing ecology through biological interaction and competition. Therefore, great precaution must be taken to avoid the introduction of Earth organisms to extraterrestrial bodies, at least until they have been studied adequately. This problem of vehicle decontamination is of course, immense, and NASA has several studies under way to determine the most effective means to solve it. Combinations of sterilization techniques (ref. 16) are being used, such as dry heat for sufficient periods of time, combined with gas treatment (ethyleneoxide), with special vehicle components actually being manufactured under sterile conditions. A great deal of work must be done to find components which will not deteriorate under the conditions of sterilization since the reliability of the vehicle must not be impaired. Assurance must be given that the sterilization of space vehicles which are likely to impact extraterrestrial bodies is an internationally recognized necessity. These requirements bring new problems to the engineer and also to the biologist who now must study the effects of the space environment and extraterrestrial environments on living organisms such as bacteria and molds. If, for example, it could be shown that bacterial spores cannot survive the rigors of space or that the surface of Mars is such that all organisms are killed, our decontamination problem would be much simpler. However, our laboratory studies indicate that this is not the case. Some bacteria and molds will not only survive Martian freeze-thaw cycles but will adapt and grow under these conditions. Also under way are studies on the morphological and biochemical adaptations required for growth of organisms in extraterrestrial environments, which will perhaps yield information that will aid in the development of better life-detection systems. As previously mentioned, we cannot expect Martian organisms to be exactly like Earth organisms. They must have evolved both morphologically and biochemically along different pathways. We should not expect these organisms (if they exist) to behave optimally when presented with a device containing an environment that is best suited for Earth forms. For example, we know that free water is not available on the surface of Mars (except perhaps in very special locations, such as salt deposits, hot springs, or subsurface permafrost layers) and is probably rare anywhere on Mars. It is not necessarily true that an organism which has evolved essentially in the absence of quantities of free water and oxygen will grow best when suddenly placed in a watery medium in a life-detection device, We may need detection devices which provide for detecting Martian life under optimum conditions for Martian life. We would hope, through planetary simulation, to learn more about the characteristics of Martian organisms, by studying the adaptations undergone by Earth forms in this environment. It is obvious, however, that extrapolations of this nature are risky.

When we have the capability of returning materials from planetary surfaces to Earth for study, we have the additional problem of insuring against back contamination by extraterrestrial organisms which could conceivably present a hazard. Also, it will be necessary for NASA to prepare a laboratory to treat such samples analytically and without contamination in either direction.

It would thus appear that the study of exobiology imposes upon NASA the need for highly specialized laboratory facilities and personnel, particularly in biology, biochemistry, and organic chemistry. Some of this work is being done in NASA laboratories (particularly at the Ames Research Center)—some of the work must be done in industry, but much of this very basic research is being done in universities throughout the country, and this desire for university research support is expanding.

REFERENCES

1. Oparin, A., and Fesenkov, V.: Life in the Universe. Twayne Publishers, New York, N.Y., 1961.
2. Kellogg, W. W., and Sagan, Carl: The Atmospheres of Mars and Venus. Nat. Acad. Sci., 1961, p. 944.
3. Garrison, W. M., Morrison, D. C., Hamilton, J. C., Benson, A. A., and Calvin, M.: Reduction of Carbon Dioxide in Aqueous Solutions by Ionizing Radiation. Science, vol. 114, 1951, p. 416.
4. Miller, Stanley: Production of Some Organic Compounds under Possible Primitive Earth Conditions. J. Am. Chem. Soc., vol. 77, 1955, p. 2351.
5. Berger, Rainer: The Proton Irradiation of Methane, Ammonia, and Water at 77° K. Proc. Nat. Acad. Sci., vol. 47, 1961, p. 1434.
6. Groth, W. E., and Weyssenhoff, H. V.: Photochemical Formation of Organic Compounds from Mixtures of Simple Gases. Planetary Space Science, vol. 2, 1960, p. 79.
7. Oró, J., and Kimball, A. P.: Synthesis of Purines under Possible Primitive Earth Conditions. I. Adenine from Hydrogen Cyanide. Arch. Biochem. Biophys., vol. 94, 1961, p. 217.
8. Walker, P. L.: Microwaves Induce Hydrocarbon Formation. Chem. and Eng. News, July 1962.
9. Fox, Sidney W.: Evolution of Protein Molecules and Thermal Synthesis of Biochemical Substances. Am. Scientist, vol. 44, 1956, p. 347.

10. Fox, Sidney W., Harada, Kaoru, and Kendrick, Jean: Production of Spherules from Synthetic Proteinoid and Hot Water. Science, vol. 129, 1959, p. 1221.
11. Sagan, Carl: Indigenous Organic Matter on the Moon. Proc. Nat. Acad. Sci., vol. 46, 1960, p. 393.
12. Lederberg, J., and Sagan, C.: Microenvironments for Life on Mars. Proceedings of the Nat. Acad. of Sci., vol. 48, 1962, p. 1473.
13. Calvin, M., and Vaughn (Himes), S. K.: Extraterrestrial Life. Some Organic Constituents of Meteorites and their Significance for Possible Extraterrestrial Biological Evolution. Space Research, edited by H. Kallman, North-Holland Publishing Co., Amsterdam, 1960, pp. 1171–1191.
14. Nagy, B., Meinschein, W. G., and Hennessy, D. J.: Mass Spectroscopic Analysis of the Orgueil Meteorite. Ann. N.Y., Acad. Sci., vol. 93, 1961, p. 25.
15. Clause, G., and Nagy, B.: A Microbiological Examination of Some Carbonaceous Chondrites. Nature, vol. 192, 1961, p. 594.
16. Phillips, C. R., and Hoffman, Robert K.: Sterilization of Interplanetary Vehicles. Science, vol. 132, 1960, p. 991.

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