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GEORGE C. MARSHALL SPACE FLIGHT CENTER
HUNTSVILLE, ALABAMA

THE HUMAN PARAMETER IN SPACE FLIGHT
(A State-of-the-art Review)

By

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National Aeronautics and Space Administration

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SCIENCE AND TECHNOLOGY SECTION
SPACE SYSTEMS INFORMATION BRANCH

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SUMMARY

The role of man as an integral part of a spacecraft is discussed from the viewpoint of his physiology and the ambient space environment. The deleterious effects of this environment upon him and the measures necessary to keep him alive in it are also reviewed. The known as well as the unknown hazards are treated briefly. An appendix summarizes the cyborg concept, which is often proposed as an alternative to human space travel.

INTRODUCTION

The one component of a man-rated spacecraft that cannot be redesigned or modified* is the astronaut. With the exception of minor evolutionary changes, he is essentially unchanged after 100,000 years. Thus all spacecraft designed to place him in orbit about the Earth or to allow him to escape Earth's gravitational field must take into account his tolerances to the psychophysiological stresses of space flight and the effects of the space environment on him. The task of defining these stresses and calculating the tolerances is the function of space medicine.

1. <u>What is Space Medicine</u>? Dr. Fred A. Hitchcock, founder of the Laboratory of Aviation Physiology at Ohio State University, states, "Space medicine may be said to have attained respectability on October 4, 1957, the day the Russians successfully launched Sputnik 1. Before this date, anyone working seriously in this field was likely to be considered by sober-minded medical men as a bit eccentric at the best and downright crazy at the worst." (Ref. 1)

Within a decade or so following World War II, aviation medicine had solved, by and large, most of the problems of flight within the Earth's atmosphere. But investigations did not cease. It soon became apparent that man's flight to the stars was closer than even science fiction

*For an interesting theoretical exception, see Appendix.

writers predicted. The rapid development of rocket propulsion helped to expand the scope of aviation medicine to include physiological and, later, psychological research into areas that would determine whether man could withstand the forces associated with rocket launching and the rigors of the space environment.

Dr. Ursula T. Slager defines the subject and its scope by saying that "space medicine...is related to ecology, the study of the relation between living organisms and their environment, and is thus a part of environmental medicine. As such, it is interested both in the physical factors of the space environment and the physiological effects such factors have on man. Space medicine is also preventive medicine. As such it aims at the ultimate goal of all medical practice--the recognition and prevention of abnormal response patterns to stress before they become rigidly fixed into classically recognizable disease patterns manifested by permanent structural and functional disturbances." (Ref. 2)

2. The Functional Borders of Space. As far as man as a living organism is concerned, space begins at that point above Earth's surface at which he cannot exist without duplicating to some degree the environment that exists on its surface. Above this altitude the air lacks sufficient oxygen to sustain him. This point is at 12,000 ft (3640 m). Thus space for man begins less than 3 mi (4.2 km) above Earth. Since he is unable to exist naturally in the space environment, the concept of the functional borders of space or of space equivalent conditions has evolved for studying the problems of keeping him alive and operable in space. The functional borders of space are those altitudes at which certain vital, human functions cease because of some constituent of the ambient environment. (Ref. 3)

This useful concept was formulated by Dr. Hubertus Strughold (Ref. 4) and is discussed below.

THE SPACE ENVIRONMENT

Dr. Strughold differentiates between the environmental aspects of space and Earth's atmosphere in qualitative terms: "Space as a physical environment is essentially a radiation environment with thinly dispersed matter. In contrast, the atmosphere is essentially a material environment with attenuated radiation. Emptiness permeated by radiations of a broad intensity range and temporal fluctuations and spiced with meteoritic pepper is the environment with which an astronaut is faced unless he is protected." (Ref. 5)

Basically man's ecological relationship to the environment of space can best be studied in terms of vacuum, temperature, light, and radiation.

1. Vacuum. Once above 80,000 ft (24.4 km) man will have to be completely sealed in a cabin that approximates in gaseous composition and pressure the atmosphere of Earth. At this altitude the ambient atmospheric pressure is only 3-1/2 per cent that of sea level. Any attempt to utilize this tenuous atmosphere would require enormously large compressors that consume tremendous amounts of power.

Assuming the astronaut is sealed within his protective cabin, what happens if it is punctured by a meteorite? If the hole is small enough, the cabin will slowly lose pressure, giving the crew time to repair the leak. However, if the hole is large enough, the cabin may undergo explosive decompression, in which case the crew members will have a very limited amount of time in which to react. This period is called the time of useful consciousness or time reserve. It is shown graphically in Fig. 1.

The functional borders of space or space equivalent conditions, mentioned above, vividly point up the physiological effects of the vacuum associated with space.

The first border is reached at approximately 3 mi (4.2 km). At this altitude the unprotected human being suffers from hypoxia or oxygen deficiency in the blood. It occurs because the partial pressure of oxygen in the atmosphere is so low that the body cannot absorb it. At a distance of some 4.5 mi (6.3 km) above Earth, man meets another functional border. It is here that he experiences dysbarism or the formation of bubbles in the tissues of the body. This condition is known also as the bends. On Earth's surface the atmospheric pressure of 760 mm Hg is sufficient to keep the nitrogen within the body in solution, but at an ambient pressure of 300 mm Hg, found at an altitude of about 4.5 mi (6.3 km), this gas comes out of solution and forms bubbles in the body tissues--causing the excruciating pain associated with the bends.

The next functional border is at approximately 10 mi (14 km). At this altitude the body suffers from anoxia or a complete lack of oxygen. The deficiency is biological rather than technical, for oxygen in some form is found at altitudes up to 70 mi (98 km). The reason for this condition is that at all times (regardless of altitude) the alveoli or air sacs of the lungs contain a combined partial pressure of 87 mm Hg of water vapor and carbon dioxide. These gases are constantly supplied to the alveoli by the excretory processes. Once the body reaches an altitude at which the ambient pressure is equal to 87 mm Hg, no oxygen can be taken up by the alveoli, even though the ambient atmosphere were pure oxygen.

An an altitude of 12 mi (17 km) the ambient pressure drops to 47 mm Hg. This pressure is the same as that of the water vapor of the body tissue at normal body temperature. This altitude presents another functional border of space. Ebullism or the boiling of body fluid occurs as a result of this low pressure.

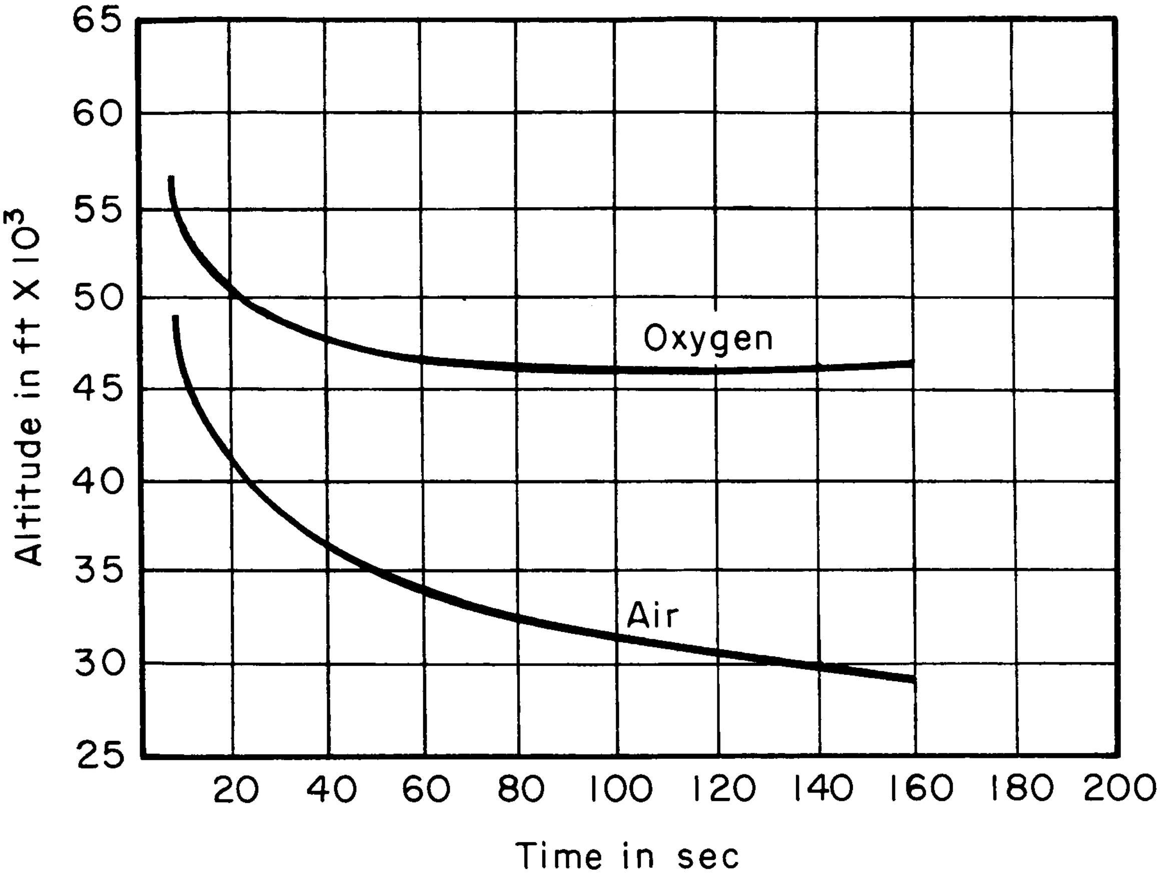

FIGURE 1. TIME OF USEFUL CONSCIOUSNESS AFTER EXPLOSIVE DECOMPRESSION OF SPACE CABIN

These functional borders of space illustrate the need for the elaborate protective devices and complex artificial environment for the astronaut to survive even that portion of the space journey within the Earth's atmosphere.

2. Temperature. While man can tolerate some change in his pressure environment, the temperature limits between which he can live and function are very narrow. Even though 98.6°F (37°C) is considered as norm for body temperature, man has withstood, for varying periods of time and under varying conditions, a temperature range of -90°F (-68°C) to 500°F (260°C). However, the span in which he can function efficiently is very much narrower. Below 50°F (10°C) physical efficiency is reduced by stiffness of the limbs. Above 85°F (29°C) mental activity becomes sluggish. Thus a realistic temperature variance so far as the astronaut is concerned is some 35°.

This range of temperature places exacting demands on the design of the environmental control systems for the space cabin. For long-term efficiency, it is obvious that the astronaut will have to function in a temperature environment that approaches the optimum on Earth. Once in space the temperature of his spaceship will be largely dependent on its surface texture and color.

3. Light. The problem of light in space resolves itself into two areas. How much light is needed within the vehicle and what are the possible visual hazards from light outside the vehicle? If we assume that the primary task of the space crew, in so far as piloting is concerned, will be the reading of meters and monitoring of instruments, then an illumination level of some 30 candles/ft^2 (322.8 candles/m^2) should suffice. (Ref. 6)

Since the space environment is essentially a radiation one, there is very little matter to diffuse the light of the Sun. The most obvious hazard to the astronaut is that of retinal burns. Even a quick glance at the Sun may a leave a permanent burn on the retina if the eye is unprotected.

A problem of some magnitude associated with the darkness of space is one familiar to crews of high-altitude aircraft. In the absolute darkness of space (with no visual stimulation), the eye cannot relax its accommodation or ability to adjust for varying distances. Thus the astronaut peering into empty space would have no idea of whether his eyes were focused at infinity or only a few feet beyond his ship. Under this condition, known as space myopia, an object must be twice as large to be seen as when visual stimulants appear at "infinity." (Ref.2)

An interesting situation could arise at a later date in space travel if man should ever succeed in reaching the velocity of light. Perception is not instantaneous. The process takes some 100 msec, which means that for the most part we live as much as 0.1 sec in the past at all times. Traveling at the velocity of light, the ship will have displaced 18,600 mi (29,760 km) during the astronaut's act of perception and many more before he can react.

4. Radiation. The environment of space consists of both ionizing and nonionizing radiations, which are either electromagnetic or corpuscular. Since the intensity of electromagnetic radiation follows the inverse square law, the radiation of this type will vary with distance from the source. In interplanetary space within the Solar System the Sun is the primary source of such radiations. Other sources include the planets of the Solar System and extra-galactic sources. Of most interest to space travel in the near future are the giant radiation belts circling Earth, Jupiter, and possibly other planets. Consisting of electrons and protons trapped in the magnetic field of the planet, they present formidable hazards to the astronaut and equally formidable problems to the spaceship designer.

Cosmic rays consist of very high-energy particles (usually completely ionized atoms) traveling at velocities approximating that of light. Their energies range above 1 bev. For the most part they consist of protons and alpha particles, but 1 per cent are elements with atomic weights greater than 4. In general, it is believed that the elements comprising cosmic rays occur in approximately the same numbers as found in the universe.

Solar components of the cosmic radiation consist of protons and electrons with energy ranges up to 1 Mev. The components of cosmic radiation from other sources are much higher, of the order of 0.1 bev to 1000 bev. But some 90 per cent of the cosmic rays have energies of below 10 bev. During solar flares, cosmic radiation increases by several orders of magnitude, chiefly with protons ranging between 20 Mev and 100 Mev.

The Van Allen radiation belt consists of two zones of intense radiation and is comprised of electrons and protons trapped in the Earth's magnetic field. The inner zone is found between 500 mi (800 km) and 2000 mi (3200 km); and the outer zone, which fluctuates with solar activity, lies between 9000 mi (14,400 km) and 12,000 mi (19,200 km). The inner zone has an electron density of some 10^{-4} particles/cm^3 and a proton density of about 10^{-6} particles/cm^3. The majority of the electrons have energies ranging between 20 kev and 600 kev, although some have been measured with energies up to 1 Mev. The protons generally range between 10 Mev and 40 Mev but may be found with energies up to 700 Mev.

a. Ionizing radiation. Any discussion of the effects of ionizing radiation on man must include a brief summary of the units of measurements involved. The most familiar unit, the roentgen, is that amount of x-radiation or gamma radiation that produces in 1 cm^3 of air (at 0°C and 760 mm Hg) 2.08×10^9 ion pairs. But the roentgen is not too adaptable for space medicine use. The roentgen equivalent physical or rep is that amount of ionizing radiation other than x-rays that produces an energy absorption of 93 ergs/cm^3 (sometimes defined on a weight basis as 93 ergs/g) in wet tissue. The roentgen equivalent man or rem is the absorbed dosage of any ionizing radiation that has the same relative biological efficiency as 1 roentgen of x-rays. Another useful unit is the radiation absorbed dosage or rad. It is simply the amount of ionizing radiation that results in an energy absorption 100 erg/g in any material.

Ionizing radiation produces its deleterious effects in human tissue by excitation, ionization, or nuclear disruption of atoms. The means by which damage occurs to the chromosomes of cells is not fully understood. It may be that the rupture of the molecular structure is purely mechanical, being caused by an ionized particle; or the damage may be caused by chemical means. Thus ionizing particles passing through a cell could create free radicals of hydrogen or the hydroxyl group that could recombine into a chemical such as hydrogen perioxide. In either event, the damage to the chromosomes becomes especially critical when the density along the track of an ion reaches a value of 1 x 10^6 ion pairs/cm.

Radiation of gamma rays, nuclei of low Z numbers, protons and electrons produce a spray of ionization within the tissue. On the other hand, cosmic rays of nuclei of heavier atoms produce a gradual thin down, with ionization concentrated along the track. Its effect has been compared to the damage done by a rifle shot, whereas the damage done by other forms of radiation is like the damage from birdshot. These analogies, suggested by Dr. Davis G. Simon of the US Air Force School of Aerospace Medicine, are shown in Fig. 2.

Much discussion revolves about the effect of cosmic radiation on heredity. It is often pointed out that an astronaut returning from a space trip, and having been irradiated for a considerable period of time, would pose a threat in the form of mutations to his progeny. However, it is also pointed out that a primary cosmic ray hitting a testicle would damage only six sperm cells and that only 200 to 300 such cells would be hit in a 24-hr period. The probability that these particular cells would be used in the fertilization process is about one in one million. (Ref. 7) Another view of the problem is, "All in all the risk to the astronaut's descendants seems remote. The genetic danger to posterity is much more problematic in the case of fallout from atomic warfare, where large numbers of people are exposed to relatively small overdoses of radiation, than in the case of one astronaut's receiving a large dose." (Ref. 8)

While any amount of radiation from any source is damaging to the human organism, some guides have been drawn up. Whether they will be valid in the long run for space travel remains to be seen. Maximum total dosages in rem recommended by the National Committee on Radiation Protection and Measurements are:

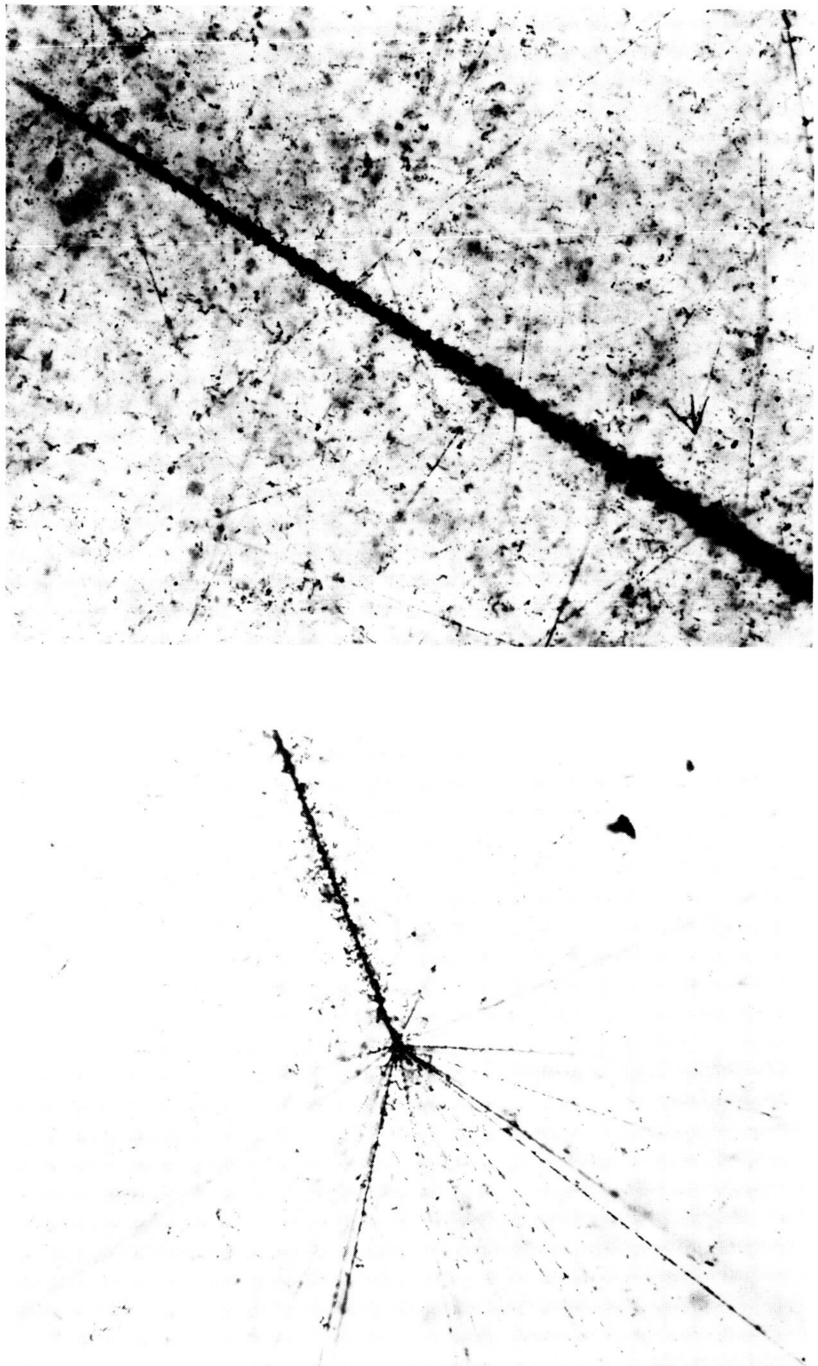

FIGURE 2. TOP, "RIFLESHOT" IONIZATION PRODUCED BY COSMIC RAY OF HIGH Z NUMBER. BOTTOM, "BIRDSHOT" IONIZATION PRODUCED BY RADIATION OF LOW Z COSMIC RAY

Week	0.3
Year	5.0
Emergency	25.0
Lifetime	225.0

The effects of whole-body irradiation as a function of dosage is listed in Table 1.

A theoretical radiation problem may face the future interstellar space traveler who manages to attain velocities approaching the speed of light. James Van Allen speculates on the possibilities of relativistic radiation produced by a vehicle traveling at a velocity of 201,333,600 mph (90,000 km/sec) colliding with interstellar matter. Assuming that the space density (remote from planets) is one hydrogen atom per cubic centimeter of space and that a vehicle is traveling at 0.3c (three-tenths the speed of light), the spacecraft will be bombarded on its frontal area by 9×10^9 electrons/cm^{2}sec and 9×10^9 protons/cm^{2}sec. With respect to the vehicle and because of its velocity, these particles have kinetic energies of 25 kev and 45 Mev respectively. If there were no shielding on the spaceship, the dose rate would be 20×10^6 r/hr! The assumptions are made by Van Allen to illustrate the magnitude of the problem of radiation and shielding as velocities approach the speed of light. (Ref. 9)

b. Nonionizing radiation. The nonionizing radiation environment of the spaceship will consist of the same electromagnetic frequencies as that on Earth. Basically they will be light, radio waves of varying frequencies, microwave frequencies, with ultraviolet and infrared radiations. With the possible exception of the infrared, discussed in the section on light above, and microwave energy, there are apparently no new hazards in space that cannot be countered by known means. The full effects of microwave energy are not yet known, but safety standards are being developed to prevent injury to personnel from this type of electromagnetic radiation. The photochemical reactions produced by ultraviolet radiation, i.e., the decomposition of trichlorethylene into phosgene, a poison gas, are sometimes seen as a possible hazard.

5. Magnetic fields. Man evolved on Earth in a magnetic field of less than one gauss. The extent to which Earth's magnetic field shaped his development or the part it plays in his physiology is largely unknown. Industrial workers report no ill effects after being exposed to momentary fields as great as 5000 gauss (0.5 Weber/m^2). But experiments with mice raised in a field of 5000 gauss showed amazing results: cancer disappeared, sexual ardor lessened, and youthful looks remained. (Ref. 10)

Table 1. Effects of Whole-body Radiation on Human Beings (Ref. 3)

Acute Dose (r)	Probable Effects on Persons Exposed
0 to 50	Some change in white blood count.
80 to 120	Vomiting and nausea in one day to 5 to 10 per cent of those exposed.
130 to 170	Vomiting, nausea, some diarrhea for one day, followed by loss of appetite, sore throat in some 25 per cent of those exposed. No deaths attributable to radiation.
180 to 240	Radiation sickness symptoms, as listed above, for one day in about 50 per cent of those exposed. No deaths attributable to radiation.
260 to 330	Radiation sickness symptoms in all persons exposed. Some 20 per cent deaths can be expected within two to six weeks.
400 to 500	Radiation sickness symptoms in all exposed. Approximately 50 per cent will die within one month.
550 to 750	All persons exposed will exhibit radiation sickness symptoms within 4 hr. Probably all will die, although a few may live.
1000	All persons exposed will vomit and become nauseated within 1 to 2 hr. No survivors expected.
5000	Immediate incapacitation and death within one week to all exposed.

The only observable effect on man is known as magnetic phosphene. When the head is held in a collapsing or building field, a colorless, flickering light is often observed, especially if the eyes are moved. The phosphene occurs whether the eyes are open or closed. Soviet scientists suggest that a strong magnetic field can affect the nerve processes of the cerebral cortex. After hypnotizing a man and implanting a very strong scene in his mind, unknown to him, they placed a powerful magnet near his head and the picture immediately faded.

THE BIODYNAMICS OF SPACE FLIGHT

The human anatomy is a wonderfully adaptable organism, but it has limits of elasticity and tensile strength that cannot be exceeded. Space flight, with its requirements for high accelerations, places stresses on the body that it never is called upon to sustain in other modes of transportation. Also, the human body and its individual organs respond in a complex way to vibrations within the range of frequencies to be expected in space flight.

In addition to these mechanical effects of space flight upon the human body, another condition results that produces no mechanical stresses at all: weightlessness. Collectively these problems can be considered under the general heading of the biodynamics of space flight.

1. Acceleration. In examining the effects of acceleration, it is important to consider a novel concept of weight. Dr. Heinz Haber (Ref. 11) considers weight as "a subjective experience that is best defined as the resultant external force exerted on a body by a restraining agent in response to the forces of gravity and inertia." While this concept is of academic interest only to the engineer and physicist, it is a matter of some import to the physiologist and physician concerned with astronauts. (Ref. 12) An increase in weight caused by acceleration severely incapacitates and limits the astronaut: beyond certain limits it results in a variety of physiological reactions and biological damage. Since human beings vary in their skeletal and muscular makeup, their tolerances to acceleration vary accordingly and limits are hard to define.

In general, acceleration associated with rocket launching produces two immediate effects:

a. Mechanical interference with voluntary muscular activity

b. Interrupting of normal blood circulation with loss of vision and consciousness.

Unlike other physiological stresses of space flight, the forces of acceleration cannot be attenuated or filtered. The degree to which they interfere with the muscular activity of the astronaut is indicated in Fig. 3 which shows the range of movement possible under certain accelerations.

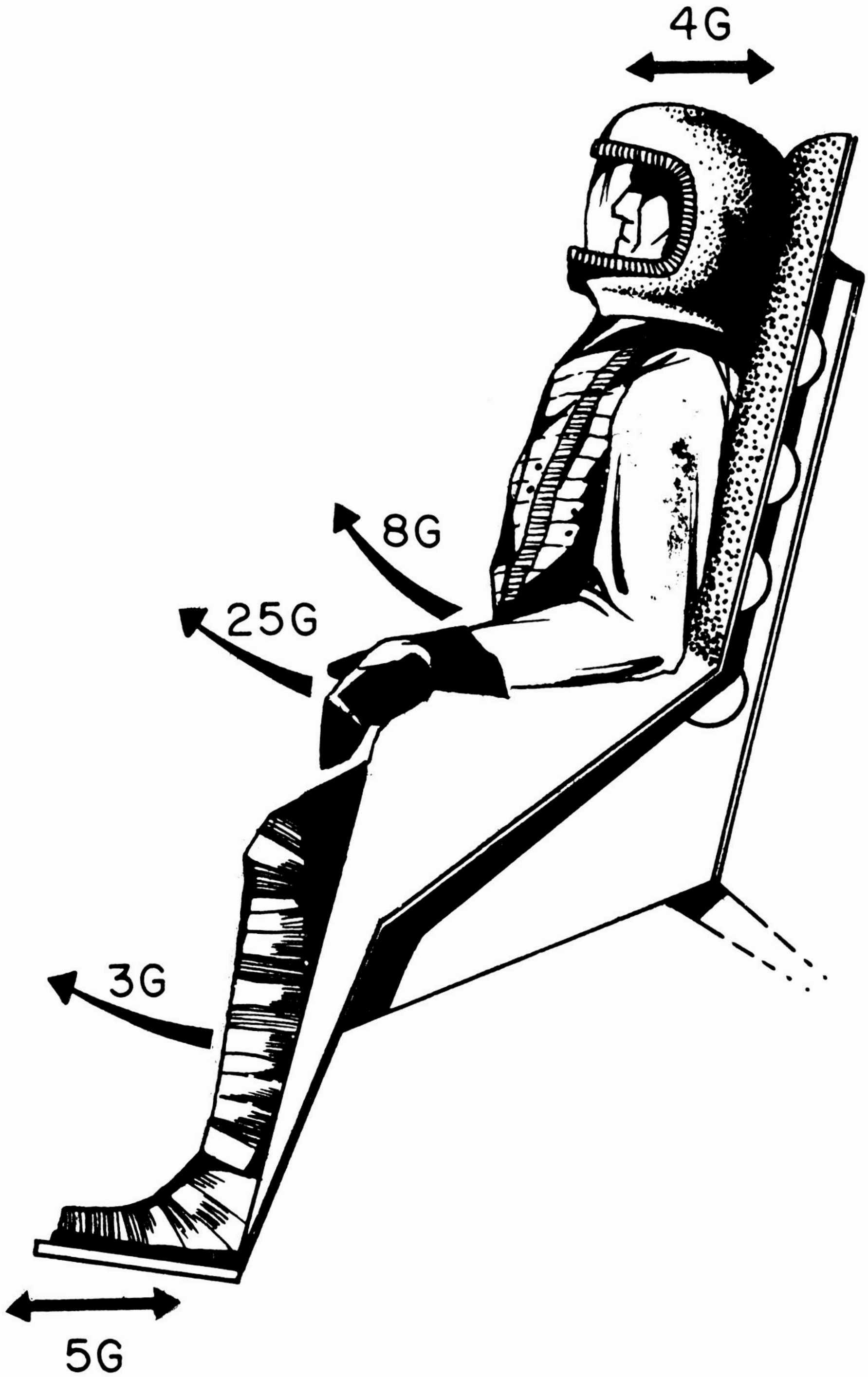

FIGURE 3. EFFECTS OF ACCELERATION ON MOVEMENT OF BODY

Essentially what happens during high acceleration is that the blood becomes so heavy (at 14 G's the blood weighs as much as mercury) that the heart can no longer pump it to the head. Coupled with this is the fact that the blood vessels and organs of the body are elastic; thus the blood tends to pool in the abdomen and legs, assuming the accelerative force is acting from foot to head. When this occurs, at an acceleration of about 3.5 G's, the astronaut blacks out because the retina of the eyes can no longer be supplied with blood. If the force acts in the opposite direction, the dynamics are the same except that the blood tends to pool in the head, and "red out" occurs.

Another visual effect is caused by acceleration and was noted by the Project Mercury astronauts. They experienced changes in vision that cannot be explained by the alterations in blood dynamics described above.

Acceleration is best tolerated by placing the astronaut supine on a specially contoured couch (as shown in Fig. 4) or by a special protective suit (Fig. 5), which allows him to sit in a more conventional seat from which he can detach himself and move about. The astronauts of Project Mercury as well as their Soviet counterparts used the former means. The astronauts of Project Apollo, on the other hand, will use the latter type of protection. A purely experimental device to protect man against high accelerations is shown in Fig. 6. Developed by the US Navy, this "Iron Maiden" is filled with water on which the occupant floats. So protected and mounted on a centrifuge, a naval research scientist withstood 31 G's for a period of 5 sec.

It appears that tolerance to acceleration can be increased by training on such devices as centrifuges and high-performance aircraft. Both the American astronauts and Soviet cosmonauts found that such training helped them to withstand the forces created during the boost phase of flight. But other things also determine tolerance (Ref. 13) to acceleration:

a. The direction in which the force is applied to the body

b. The magnitude of the force

c. The length of time the force is applied

d. The rate of onset of the force

e. The manner in which the body is supported

f. The ambient temperature

g. The oxygen level of the surrounding atmosphere

h. Length of time spent in zero gravity prior to accelerating.

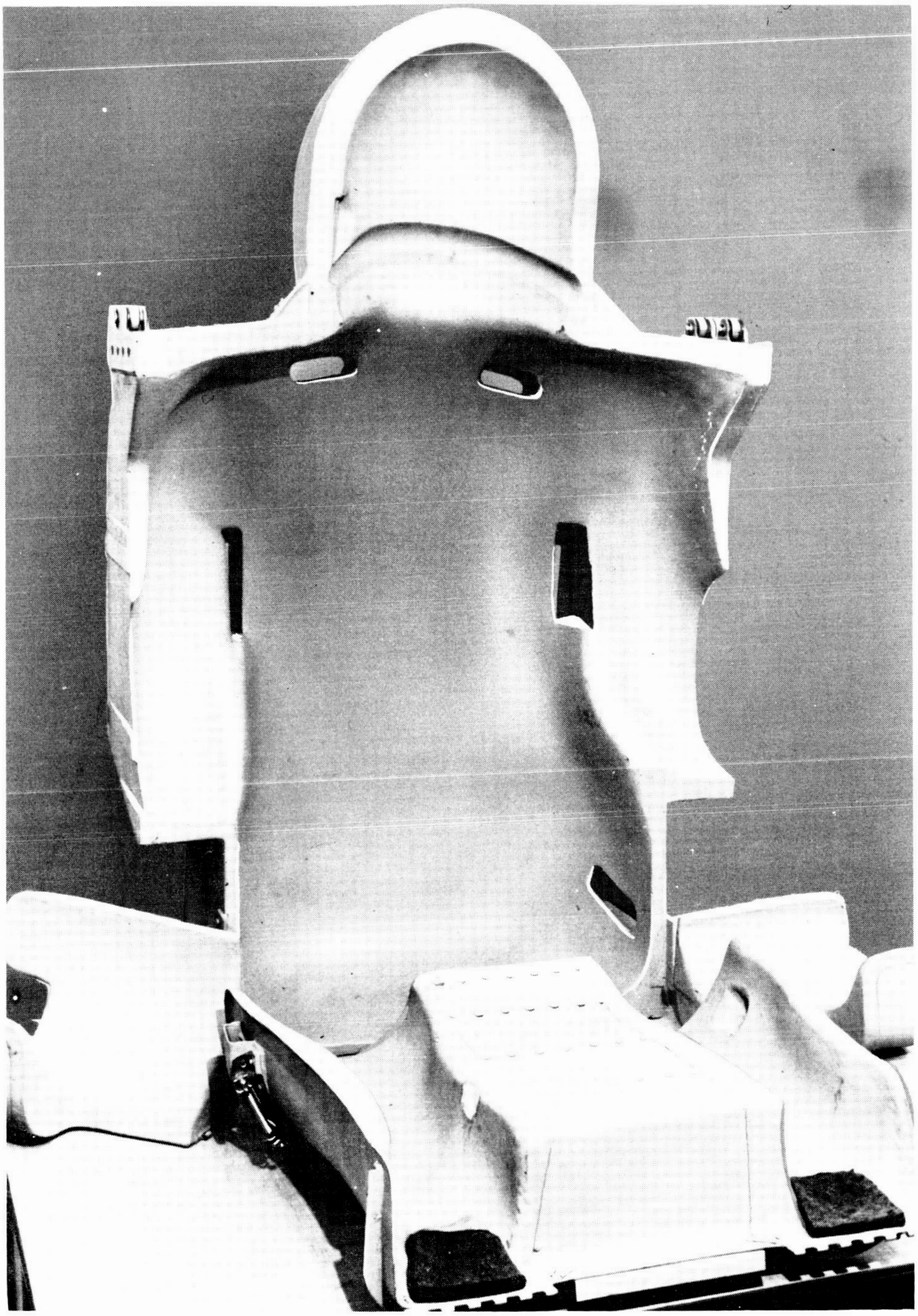

FIGURE 4. CONTOURED COUCH FOR MERCURY ASTRONAUTS

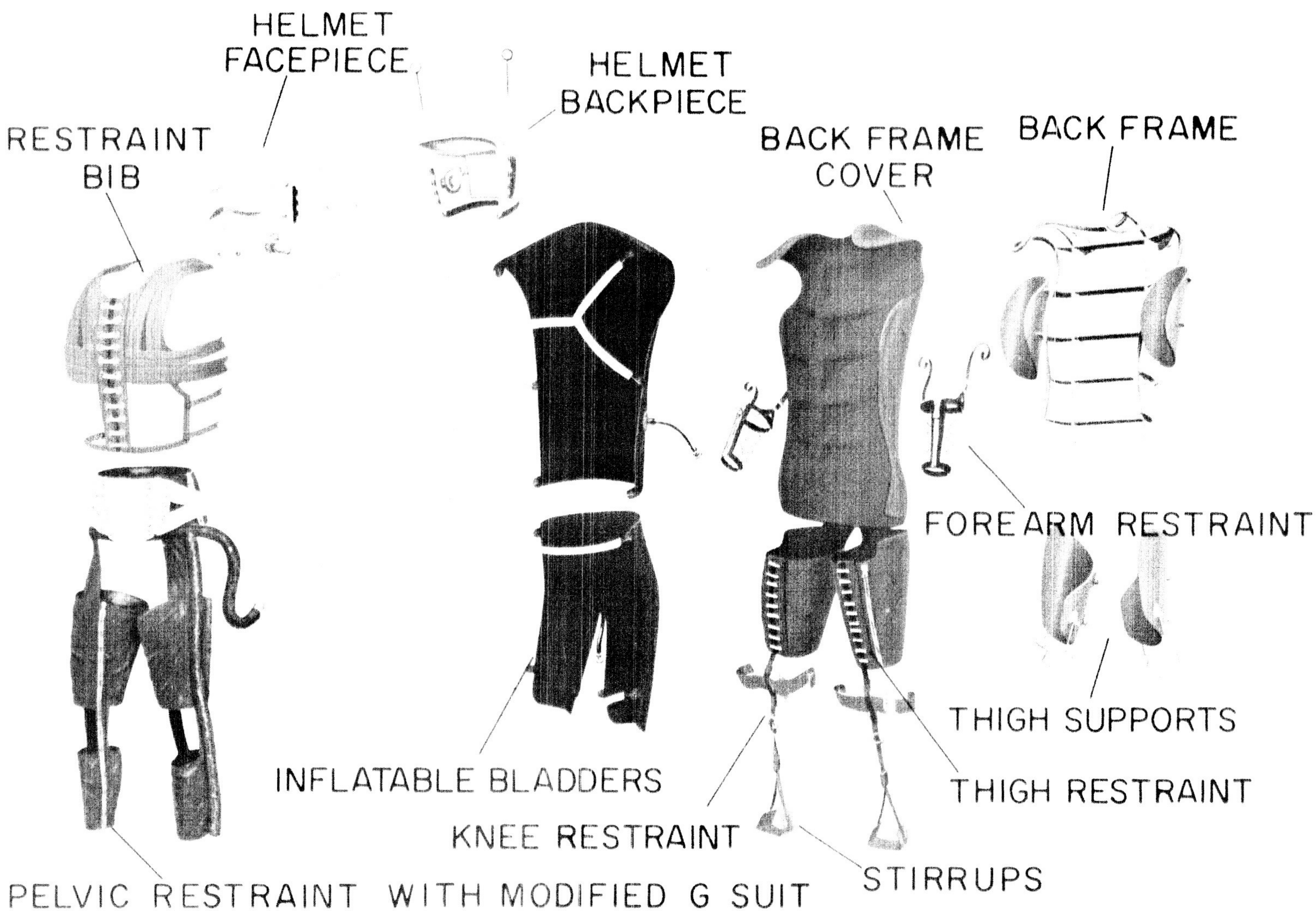

FIGURE 5. SPECIAL RESTRAINT SUIT FOR HIGH-G PROTECTION

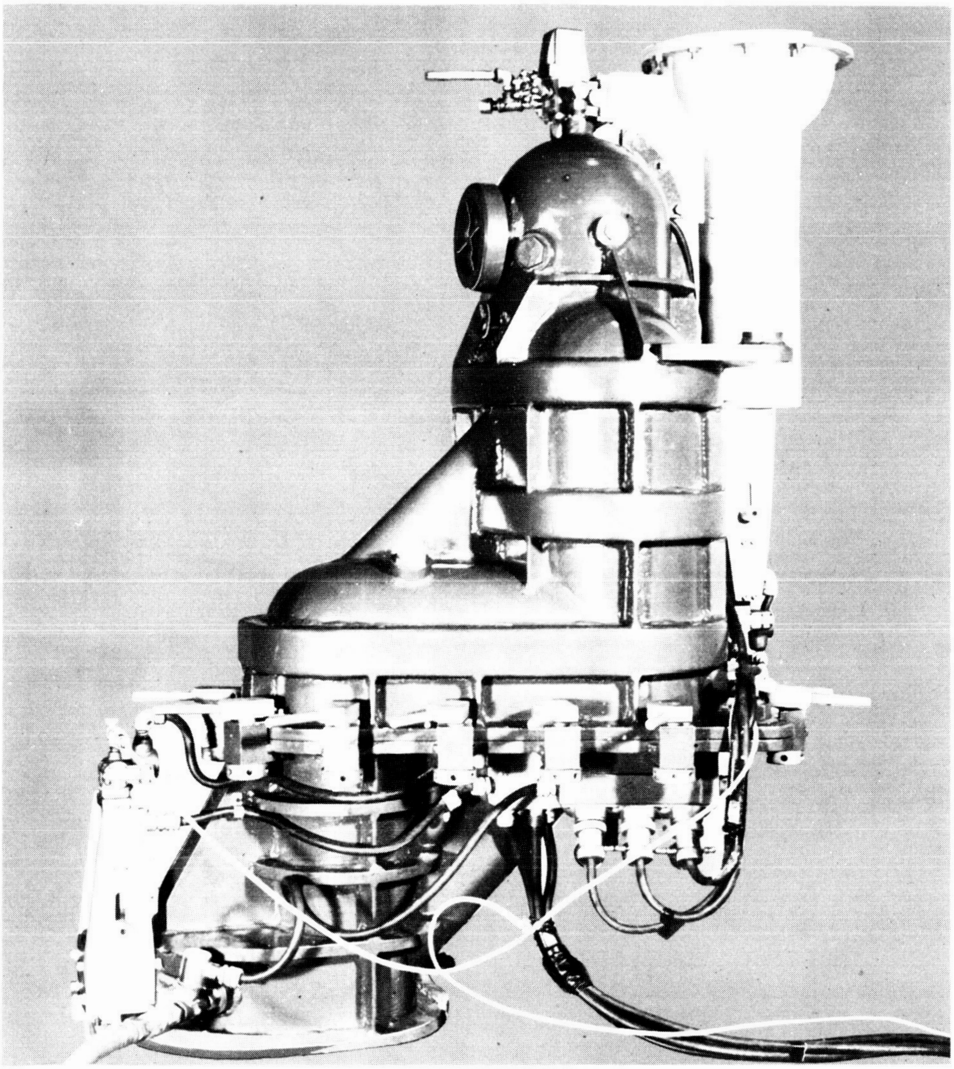

FIGURE 6. EXPERIMENTAL, WATER-FILLED, "IRON MAIDEN" DEVELOPED BY US NAVY IN ACCELERATION STUDIES

To illustrate the interrelationship of these factors, Fig. 7 shows a US Air Force captain sustaining a deceleration (which can be considered negative acceleration) of 83 G's. But the time it is applied is only 0.1 sec at a rate of 5000 G/sec. In general, the limits of tolerance to acceleration (Ref. 14) are illustrated by the curve in Fig. 8.

2. Noise and Vibration. The psychophysiological effects, either singly or combined, of noise and vibration on the human being have not been fully investigated. However, some consequences of repeated exposure to each is known. The consequences of high intensity noise are generally two: auditory, which produces deafness, and extra-auditory, which produces psychological effects. These are usually temporary unless damage occurs to the bond structure of the middle ear. Drivers of heavy trucks, tractors, and army tanks often report traces of blood in the urine, pain in the lower back and abdomen--all of which are attributed to the vibration they encounter occupationally. Similarly workers who use impact or vibrating tools often suffer from Reynaud's phenomenon or "dead hand," a loss of feeling and stiffness in the fingers.

To illustrate the effects of high intensity sound on human beings, helicopter crews were exposed to a noise environment of 114 db (1 db = 10^{-13} W/m^2). Those crew members wearing no ear protection suffered an average hearing loss of 22 db after a 2-hr flight. Those who wore combat helmets had a 19-db loss, while those who used cotton ear plugs had only a 6-db loss. Members who wore special ear defenders had only a 3-db loss. Those with no ear protection required 32 hr to regain normal hearing, while those who wore ear defenders needed only 4.5 hr.

The sound power level of noise to be expected with the launching of large space carrier vehicles is shown in Table 2. The structure of the manned cabin can attenuate noise levels outside it by about 10 db, but well-planned soundproofing can reduce the level by 25 db, and the Mercury-type space suit helmet reduces noise by about 20 db. However, as the orbital flights of both the American and Soviet astronauts proved, noise during the boost phase of flight is no particular problem. The interior noise level of manned spacecraft on extended orbital or interplanetary flight is not expected to be great enough to present insoluble problems, although the monotony occasioned by an unvarying sound intensity level may be unpleasant. In addition, noise at various levels can produce annoyance, inattention, fatigue, and other behavioral responses that are undesirable in a closely designed man-machine unit. (Ref. 15)

The problems of vibration so far as the astronaut is concerned are greatest during the boost and powered phases of flight. The effects of vibration are aggravated because the frequency range at which the human body is resonant falls within the high-amplitude, low frequencies generated in the space vehicle by the engine. Generally these range between 0.5 and 20 cps. Within this bandwidth the body may respond as a whole at a frequency below 3 cps, or various organs or portions of the anatomy may find

FIGURE 7. US AIR FORCE EXPERIMENT IN WHICH SUBJECT WITHSTANDS FORCE OF DECELERATION OF 83 G

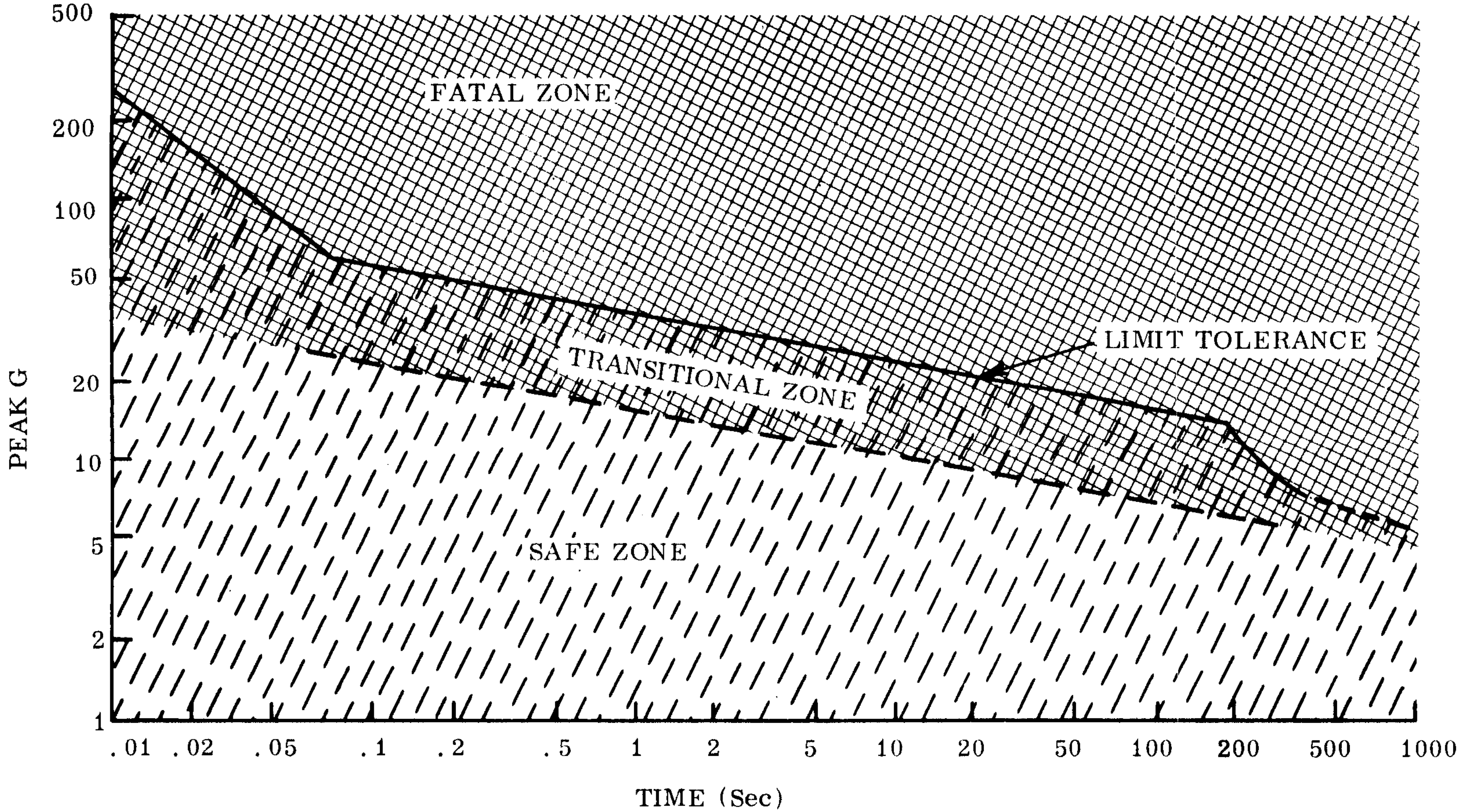

FIGURE 8. REGION OF HUMAN TOLERANCE TO ACCELERATION

Table 2. Maximum Acoustic Power Generated by Space Carrier Vehicles (Ref. 3)

Carrier Vehicle Thrust lb (Newtons)	Power and Frequency Band[a] db and cps
150,000 (6.7×10^5)	192; 37.5 to 150
600,000 (26.6×10^5)	200; 18.75 to 75
1,300,000 (57.8×10^5)	205; 18.75 to 75
3,000,000 (136×10^5)	208; 20 to 60
6,000,000 (266×10^5)	211; 20 to 60
7,500,000 (333×10^5)	212
12,000,000 (532×10^5)	214
22,000,000 (975×10^5)	220

[a]1 db re: 10^{-13} W/m^2

a resonance. Experiments show that the natural frequency of the head and neck is approximately 20 cps; the upper torso, 5 cps; the thoracic-abdomenal region, 3 cps; the pelvis, 5 and 9 cps. (Ref. 16) Vibrations generally within these frequency ranges can be expected at intermittent intervals during extended orbital or interplanetary space flight as attitude control or course corrections are made by reaction jets. Some vibration is experienced in reentry.

The physical damage done to the body by vibration is occasioned mainly by the displacement, straining, or detachment of tissue and organs. However, continued exposure to higher frequencies may produce basically psychological effects that result in changes in attitude, lack of enthusiasm, and degraded work performance and efficiency. Such effects could be produced during extended orbital flight or free fall by vibrations resulting from machines with rotating parts transmitting them through the spacecraft structure. But careful design of fittings to damp vibrations within the critical ranges can alleviate this should it prove to be a real problem. (Ref. 17)

3. Weightlessness. The dynamic weightlessness produced in orbital flight or free fall seems to be more of a nuisance than a hazard to the astronaut if the results of limited Soviet and American space flight can serve as a guide. Early orbital flight established that man can function while weightless. The anticipated disorientation resulting from the effects of zero gravity on the vestibular apparatus failed to appear, except in the case of Soviet cosmonaut Gherman Titov, who experienced some nausea and disorientation. However, the long-term effects of continued weightlessness are unknown and may present serious problems to personnel in extended space travel.

In fact, the list of possible disorders predicted by doctors and physiologists includes such various disorders as ulcers, osteoporosis (or softening of the bones), orthostatic collapse, kidney stones, asthenia (or loss of muscle tone), and sinus trouble. In addition, mucus may accumulate in areas of the body that depend on gravitational drainage. However, the heart's task will be easier since it will not be pumping the blood against the force of gravity. This may cause complications when the astronaut enters a gravitational field or experiences weight after longer periods of weightlessness.

In a weightless environment normal means of walking is impossible. As a remedy, it is suggested that the astronaut be fitted with magnetic shoes and walk on steel plates, but experimentation shows that the shuffling, skating gait required is very unnatural and inefficient. An alternate means often mentioned is the use of a compressed air jet, the reaction of which would propel the astronaut in the opposite direction.

While perfectly feasible, such devices would be clumsy to use, especially in close quarters. In order to halt at the desired point, an opposite and equal thrust would have to be applied. A body colliding with a hard object or surface would be hurt or damaged even though weightless, since it still has mass. Any use of a jet propulsion system would also require that the force be directed through the center of mass of the astronaut; otherwise the body would tumble and spin. (The incautious astronaut who sneezes will also find himself tumbling at a spin rate of 0.2 rpm for the same reason.)

Artificial gravity induced by centrifugal force is also suggested as a means of circumventing the inconveniences of weightlessness. Generally this is mentioned in conjunction with a torus-shaped space station (Ref. 18) rather than cylindrical configurations. In theory this solution seems to be both practical and desirable. The various parameters involved in selecting the optimum degree of artificial gravity in a rotating space station are shown in Fig. 9. Point A in this illustration represents a typical circus carousel, while point B is that suggested by Dr. Wernher von Braun for a torus-shaped station.

However, artificial gravity so produced has a limitation in the appearance of Coriolis forces that always appear on a body due to simultaneous rotation in two different planes with two different radii of rotation. The effect of the Coriolis force acting on the astronaut can become restrictive. A convenient equation for computing the magnitude of this force with respect to the astronaut's weight is

$$F_{cor} = 2\,V \left(\frac{W^2\,n}{gr}\right)^{\frac{1}{2}}$$

where V = velocity of man walking
W = weight of man with respect to Earth
n = centrifugal acceleration in $\underline{G}$
g = gravitational constant
r = radius of rotating vehicle

The Coriolis force will also introduce effects that are more annoying than dangerous until the astronaut learns to compensate for them, as shown by Table 3.

As an alternate means of producing a feeling of weight, it is suggested that the spacecraft have a magnetic field and that the astronaut wear a snugly fitting suit made of a fabric with steel wires. (Refs. 20, 21) But this would produce a feeling of weight only on the surface of the skin and the skeletal muscles; the inner organs would be weightless and unaffected by the magnetic field.

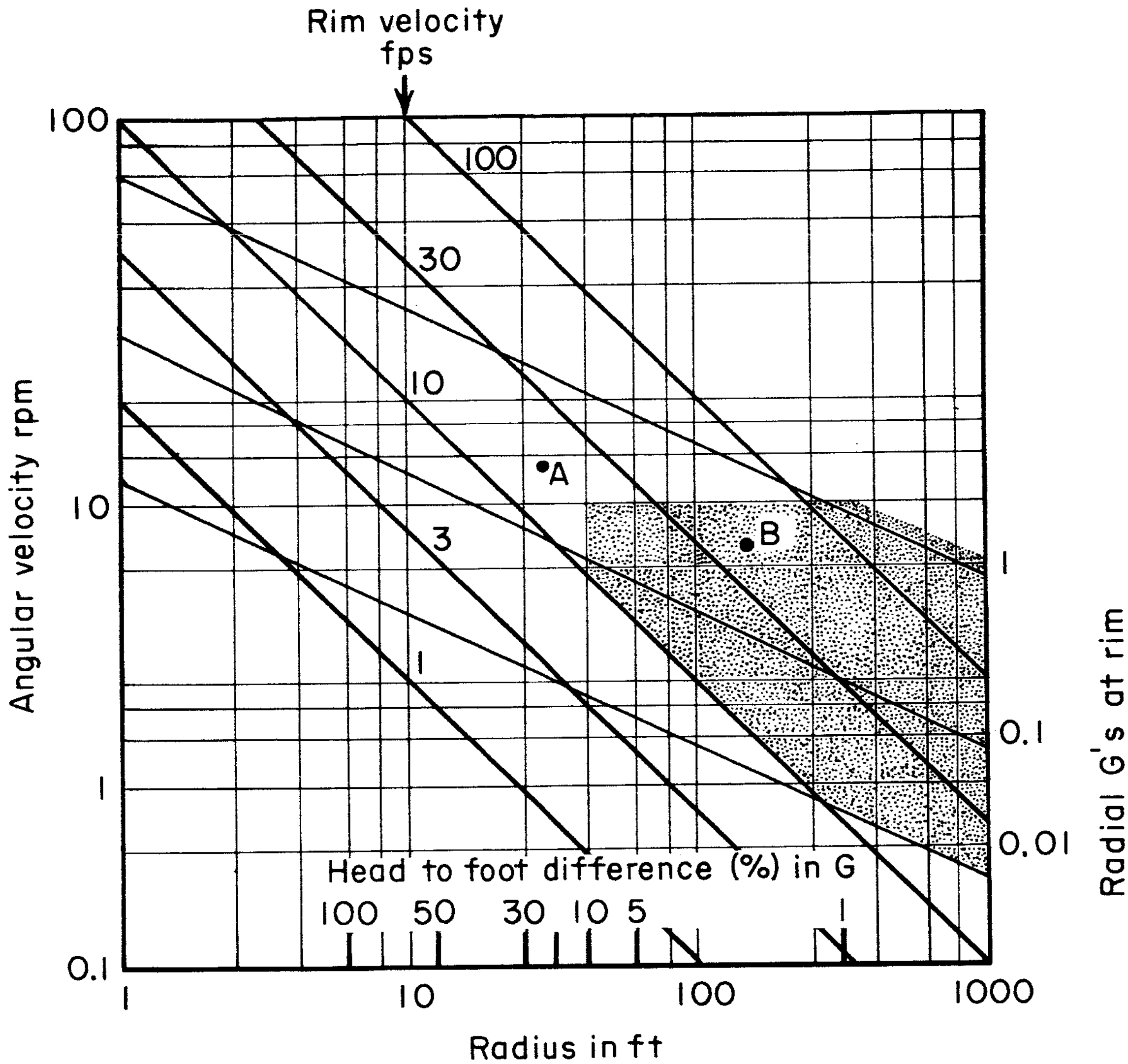

FIGURE 9. FACTORS INFLUENCING THE OPTIMUM FORCE OF ARTIFICIAL GRAVITY IN A ROTATING SPACE STRUCTURE (REF. 19)

Table 3. Direction of Coriolis Force upon Reaching Motions within a Rotating Satellite[a]

Orientation of Body	Direction of Reaching Movement					
	Up	Down	Left	Right	Forward Extension	Retraction
Facing forward[b]	forward	rearward	none	none	down	up
Facing rearward	rearward	forward	none	none	up	down
Left side forward	left	right	down	up	none	none
Right side forward	right	left	up	down	none	none

[a]Table supplied by courtesy Dr. Charles P. Greening, Autonetics Inc., Downey, California.

[b]Direction of motion due to satellite rotation or "into the wind."

In summary, the resultant effects of exposure to long-term weightlessness are unknown and will be described only after long-term space travel, since extended periods of weightlessness cannot be produced on Earth. It seems reasonable to assume that some biological or physiological effects must accrue.

THE SPACE CABIN

Once man leaves the gaseous envelope surrounding Earth for travel in space, he must take along a micro-model of it if he is to remain alive (unless he is modified as suggested in Appendix 1). This is true whether he is circling the Earth at an altitude of a few hundred miles or is in a spacecraft en route to Mars.

His space cabin will have to employ one of three forms of life support systems: open, semiclosed, or closed. Generally speaking, the open system is of no practical value to manned space flight and has been used only in biological experiments involving small animals. The semiclosed system is economical and efficient only for flights of a few weeks. For longer periods, the closed system is mandatory.

A. LIFE SUPPORT SYSTEMS

1. Open System. In the open life support system all breathing gases must be stored onboard, generally in the compressed state, and exhaled gases are vented overboard. Solid wastes from animal passengers are stored for disposal after the flight. Food and water, if necessary during the short flight, are of a kind not requiring refrigeration or preparation. This type of system has been used extensively by the US and USSR as well as other countries performing biological experiments with small animals in rockets or balloon-borne containers. Generally it has an operational life of 1 to 8 hr.

2. Semiclosed Systems. This type of life support system is most often employed in manned artificial Earth satellites where the planned flight is from one day to three weeks. In the semiclosed life support system breathing gas is usually stored in the liquid state (or under very high pressure*) and boiled off to supply the cabin and space suits of astronauts. In addition, the atmospheric pressure established by this gas may be either one atmosphere, as it is in the Vostok manned spacecraft of the USSR, or a lower value, as it is in the Mercury (Fig. 10) and Gemini capsules. Liquid and solid wastes of the astronauts are collected and stored for the duration of the flight, and exhaled gases are passed through filters to remove the carbon dioxide, odors, and water vapor.

*The Soviets report that the oxygen for Vostok was stored "in highly active chemical compounds from which it is easily extracted without additional power" (Ref. 22).

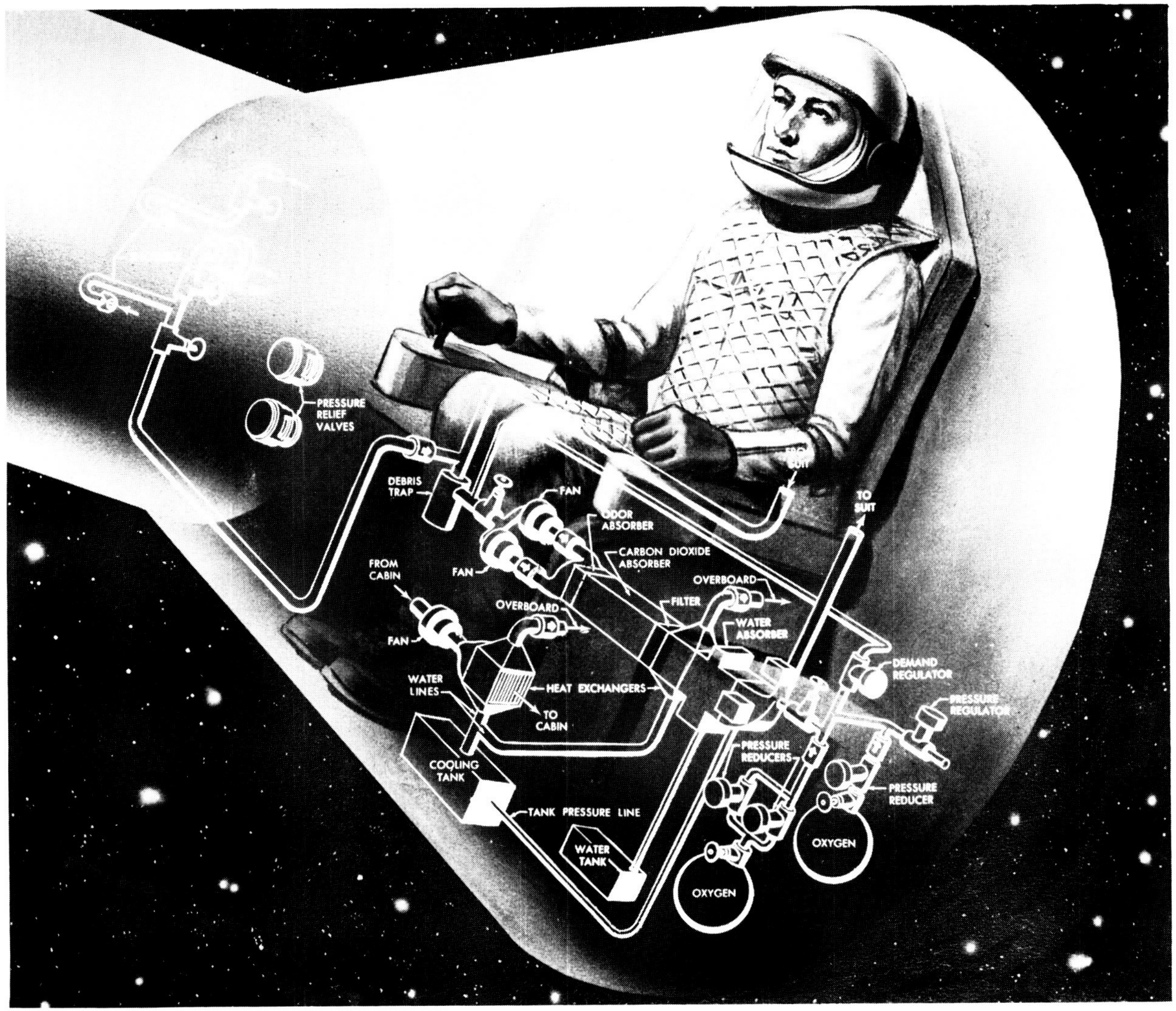

FIGURE 10. MERCURY CAPSULE LIFE SUPPORT SYSTEM

The carbon dioxide must be removed by physical or chemical means so that its partial pressure within the ambient atmosphere remains at an acceptable level. The two most commonly used means are mechanical filters containing an adsorbent such as activated charcoal silica gel, activated alumina, and chemical filters. These latter units consist of canisters containing a chemical such as lithium oxide or calcium oxide with which carbon dioxide reacts. The carbon dioxide so trapped is driven off as a gas and vented overboard or simply stored, depending upon the design of the system. Another means of removing carbon dioxide mentioned is dissolving it in a solution of monoethanol amine. (Ref. 23)

For flights longer than three or four weeks, the only practical form of life support system is the closed ecological system. In it the ecological cycle of Earth is reproduced on a minor scale. Graphically this cycle is shown in Fig. 11. Essentially the cycle within the space cabin is a simplified form of that shown here.

The closed cycle life support system (Fig. 12) in theory at least, accounts for every atom. Basically man inhales oxygen and exhales carbon dioxide. His urine is reprocessed to supply water for the system. Plants of some form take up the carbon dioxide and by photosynthesis convert it to oxygen and carbohydrates. The plant most often mentioned for this function is an alga or a lichen. Detailed descriptions of such systems are numerous. Ref. 24, 25, and 26 are typical. In addition man is pictured as eating the algae, which in turn subsist on his metabolic wastes. In theory such a cycle seems disarmingly simple, but in practice it is very difficult to accomplish. For one thing the power requirements are enormous (estimated between 2200 W/man and 9600 W/man) especially when it is realized that they are in addition to other power requirements for communications, propulsion, etc. Since the system requires that the algae in a water suspension be circulated constantly, a pumping system is called for that will operate in zero gravity (assuming no artificial gravity). There is also the danger that bacteria will infect the algal colony and destroy enough of it to upset the system seriously. Also, if man attempts to live exclusively off the algae, he may develop an allergy to it. In order to maintain the delicate balance between the algae needed to support a crew, (estimated at 1 lb/man or 2.2 kg/man) new algae have to be harvested constantly. It remains to be seen whether it can be stored or eaten fast enough to keep the cycle intact. Perhaps the greatest drawback to such a system is that algae are very unpalatable. No matter how they are processed they can never be made to taste good. The prospects of mustering a space crew would seem dim once prospective members learned they would be required to subsist off of reprocessed urine and algae.

On extended flights, another problem may arise to complicate the life support system. In view of the various electrical components aboard the spacecraft, there may be a significant amount of ionized air produced

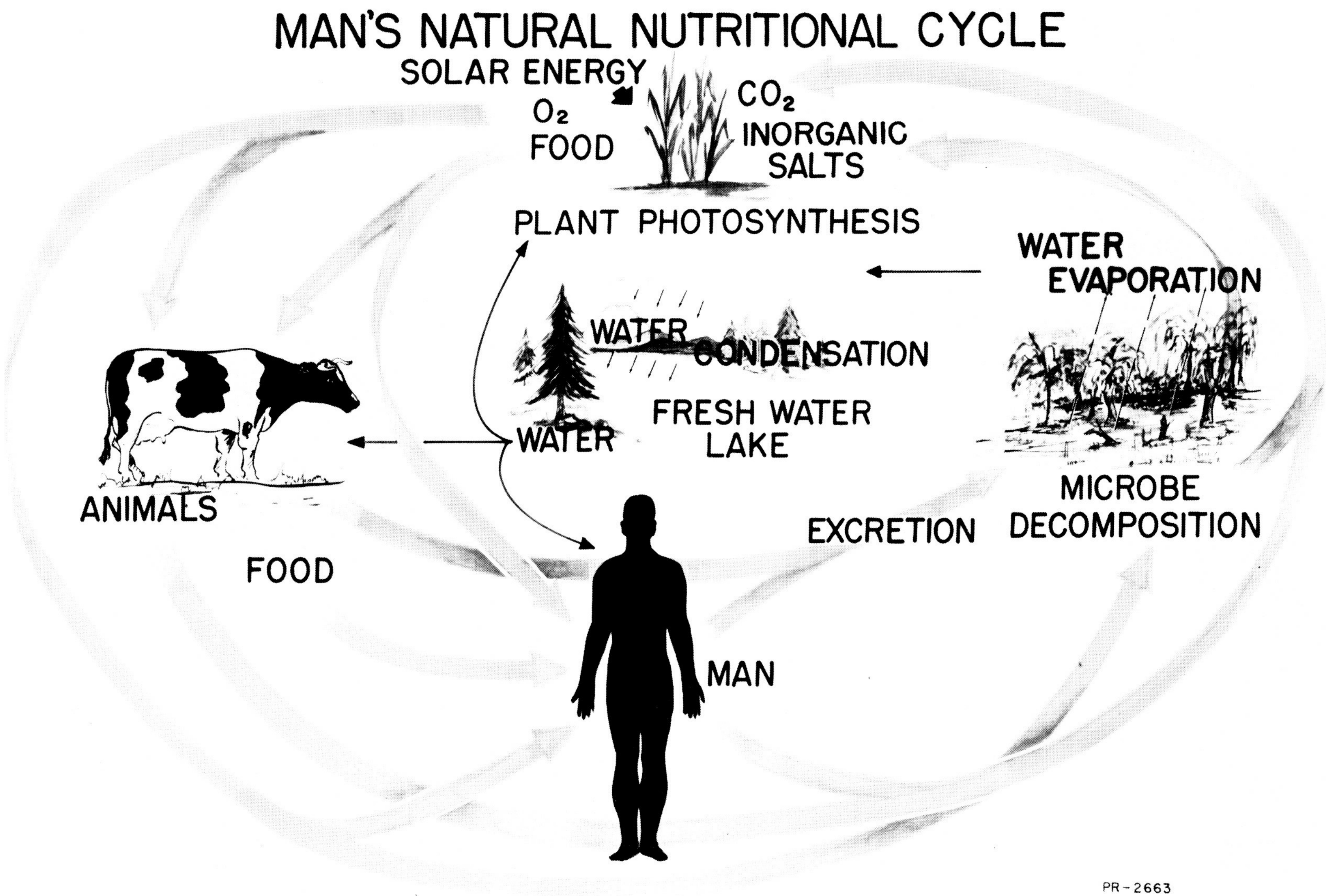

FIGURE 11. MAN'S NATURAL ECOLOGICAL CYCLE

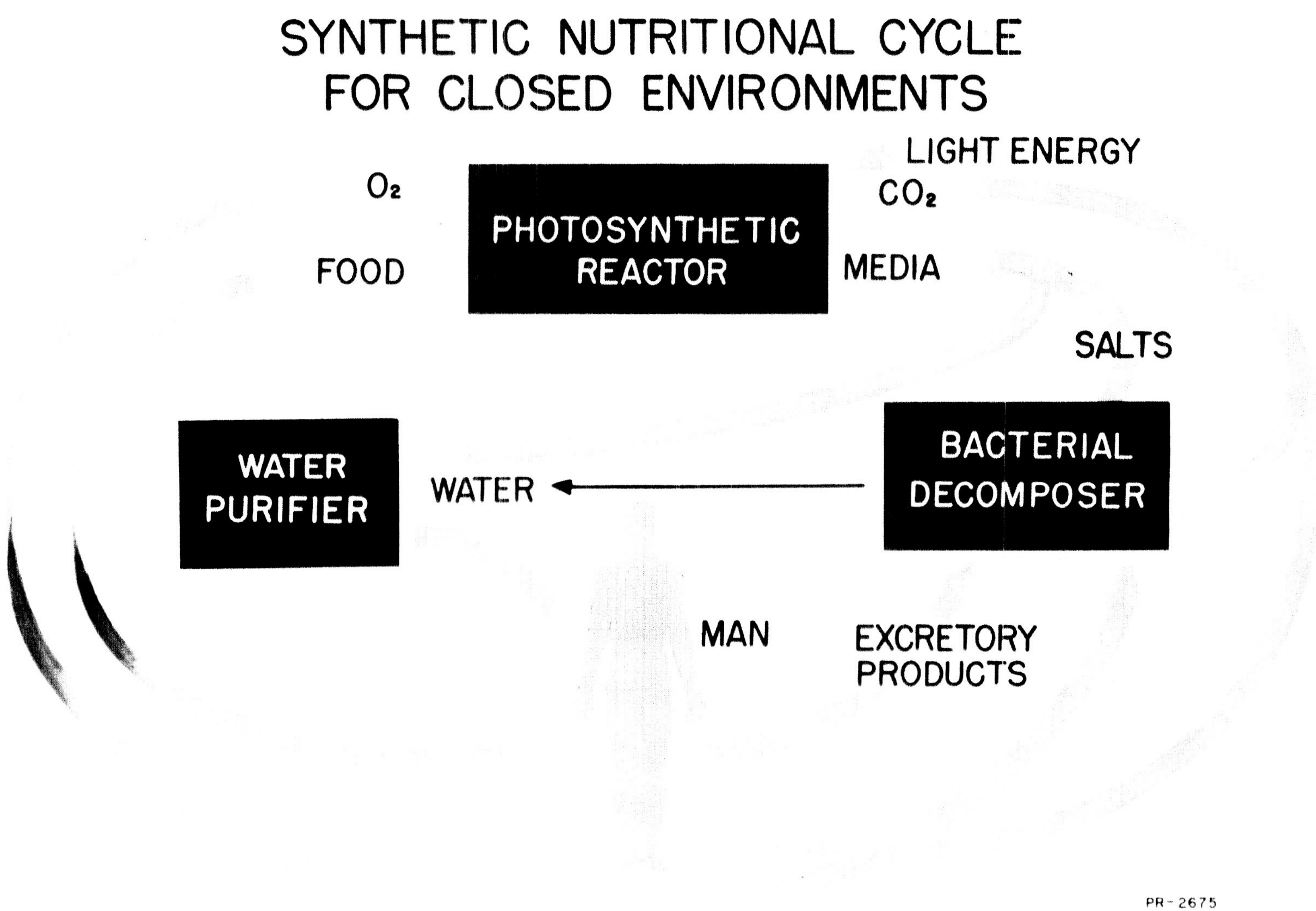

FIGURE 12. CLOSED ECOLOGICAL LIFE SUPPORT SYSTEM

by high-voltage and high-frequency discharges. The effect of ionized air on human beings is an area that has not been fully investigated, but findings to date indicate that it may be important enough to merit detailed experimentation and study. (Ref. 27) Experiments in Germany indicate that the oral breathing of positive ions artificially generated have a statistically significant effect on respiration rate, pulse rate, and alpha rhythm frequency (brain activity). Soviet scientists claim that athletes who breathed negative ions for 15 min a day over a period of 25 days were able to maintain a standard grip on a dynamometer 46 per cent longer than control subjects. (Ref. 28) The general effects seem to be that negative ions produce a feeling of relaxation and mild euphoria, while positive ions produce or contribute to nausea, headaches, irritability, dizziness, and sore throat.

Another integral part of the space cabin life support system will be concerned with foods and feeding. Relatively simple foods and feeding implements (Fig. 13) were developed and proven during the Mercury and Vostok space flights. But for longer voyages a more sophisticated system and better diet must be provided.

Recent advances in food processing indicate that it may be possible to take along fresh foods with a minimum of waste. Thus it is suggested that some foods can be irradiated with gamma rays and wrapped in papers made of edible fibers. Since there will probably be sufficient water, some dehydrated and freeze-dried foods can be stocked. Frozen foods, in edible wrappers, are also a possibility. The only processed foods definitely ruled out are tinned goods. Their initial weight and empty containers make them uneconomical.

A kitchen especially developed for use in a spacecraft is shown in Fig. 13. This unit is capable of feeding three men for a period of two weeks, and it will operate in zero gravity.

It is also suggested that for interplanetary voyages the closed life support system be modified to include animals in the man-alga ecological cycle. If fish or other aquatic life were placed into the cycle, fresh protein could be introduced into the food supply. Other animals suggested include yeast, shrimp, slugs, snails, and goats. (Ref. 29) However, such a menagerie seems unlikely, at least on the first interplanetary spaceships.

B. SPACE SUITS

The purpose of the space suit is to provide protection to the astronaut against the environment of space. It seeks to do exactly what the deep sea diving suit does--protect the wearer from a lethal environment. In its basic form it compensates for the vacuum and supplies him with a breathing gas. In its more complex forms it may provide protection against

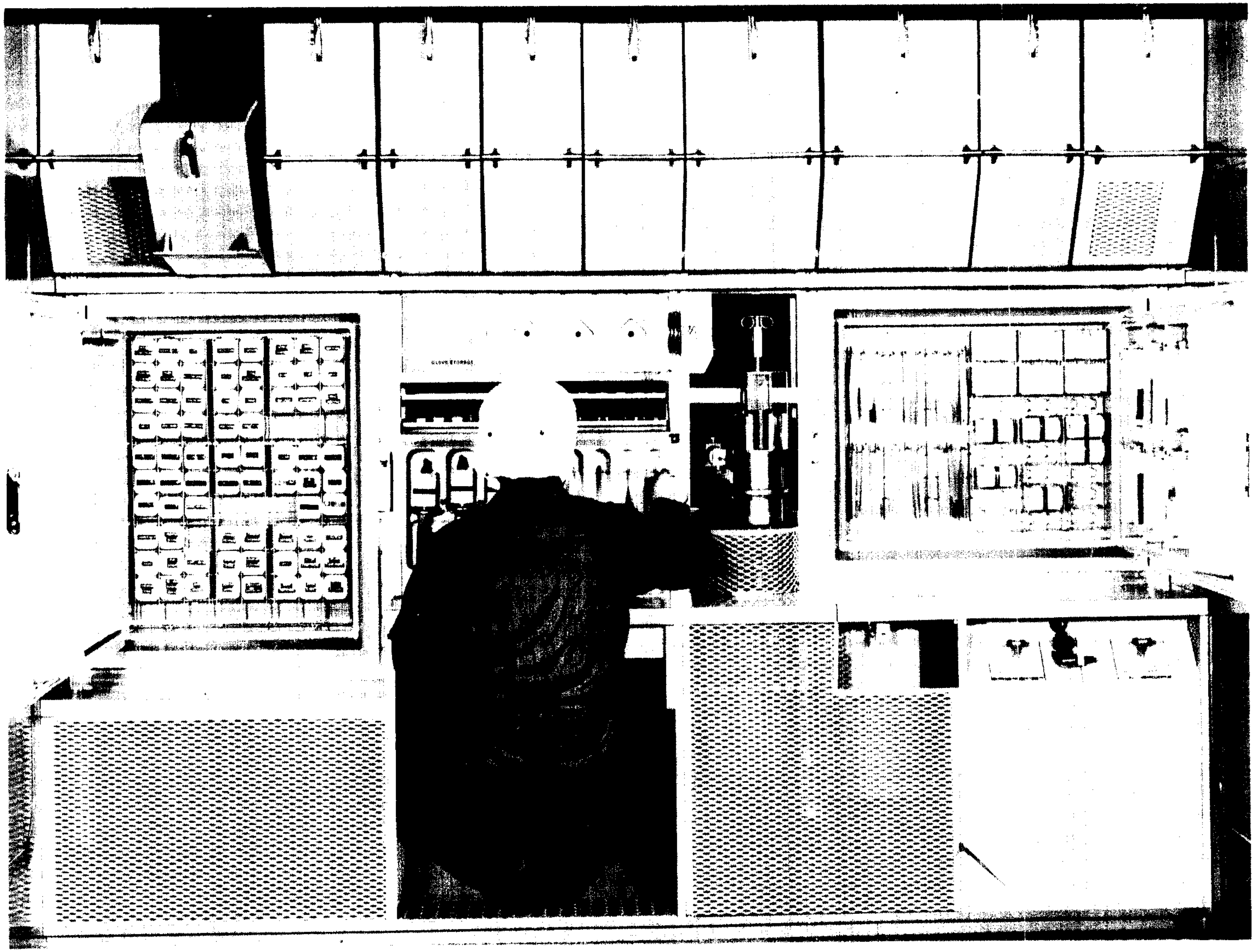

FIGURE 13. SPACESHIP KITCHEN AND FEEDING IMPLEMENTS

radiation and fire. The ideal space suit has been described as one that would "satisfy a chorus girl for lightning changes and an acrobat for mobility." (Ref. 30) This degree of flexibility is not likely to be realized soon if extrapolations can be made from present models.

Typical space suits are shown in Figs. 14.1 through 14.4. While these all offer some degree of flexibility and mobility, they are designed for the Mercury (Fig. 14.1), Gemini, and Vostok (Fig. 14.2) spacecraft, in which the astronaut is relatively immobile and not required to leave his seat and move about. As closed life support systems become more reliable, the need for this type of suit within the cabin will lessen. Its use will be reserved for emergencies and excursions outside the spacecraft. The life support system for the Apollo spacecraft calls for a shirt sleeves environment, wherein the astronauts will wear a partial space suit.

The ideal space suit would accomplish the following:

1. Provide protection against the vacuum of space, and to some degree, the temperature and radiation.

2. Contain a self-regenerating oxygen supply capable of extended operation.

3. Provide a means of external communications for the wearer.

4. Have provisions for feeding and drinking without breaking the sealed atmosphere of the suit.

5. Permit the collection and temporary storage of metabolic wastes from the wearer.

6. Be light and flexible enough to be worn for long periods of time. (Ref. 31)

The advanced space suit shown in Fig. 14.3 is pressurized to 3.5 psi (3516 kg/m^2); yet its construction permits a high degree of mobility, and it weighs only 21 lb (10 kg). It can be donned by the wearer in about 5 min. Made of nylon cloth with neoprene corrugated joints, it also has a special aluminized coverall, as in Fig. 14.4, that offers additional protection from heat and flash fires. Provisions exist for filling the void between the suit and coverall with water or a saturated hydrocarbon solution for additional protection against radiation. The helmet can be adapted to accept a self-contained radio unit. The breathing gas for the suit is supplied from an external storage tank in the life support system of the spacecraft.

FIGURE 14.1. PROJECT MERCURY

FIGURE 14.2. VOSTOK COSMONAUT

FIGURE 14.3. ADVANCED US DESIGN

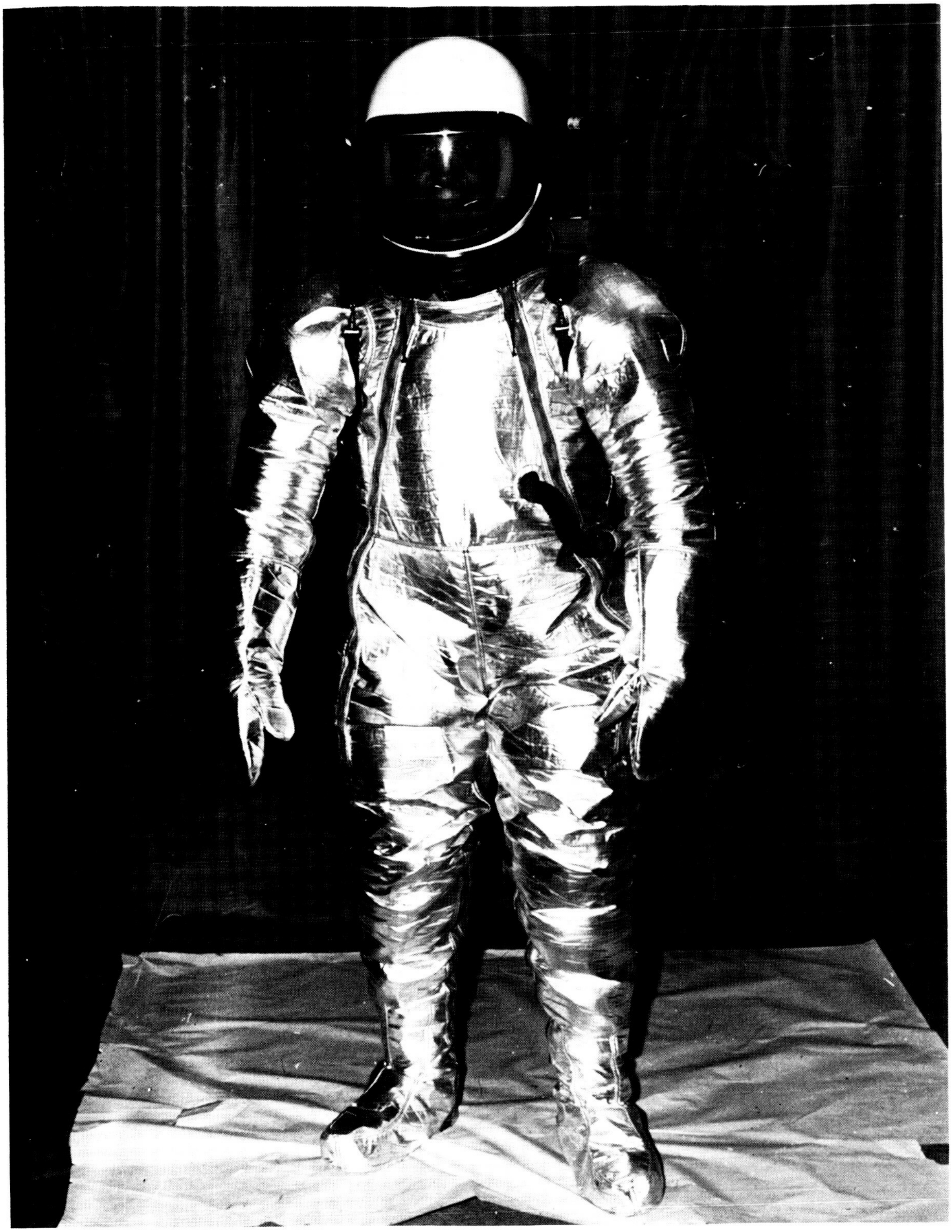

FIGURE 14.4. ALUMINIZED COVERALL THAT OFFERS FIRE AND RADIATION PROTECTION WHEN WORN OVER (3)

A unique feature of this suit is the special biopack that fits on the back (Fig. 15). With this unit the wearer has an independent air supply and regeneration system that will function for 6 hr. The unit weighs only 50 lb (22.67 kg) (on Earth) and requires no electric power.

A different type of space suit is shown in Fig. 16. It was developed especially for use on the Moon. Consisting of two pieces, it has a tripod support that permits the occupant to withdraw his legs for resting or sleeping. The unit contains a two-way radio system, water tank, food storage facilities, and a lighting system. Special monitoring systems inside the suit transmit danger signals in case of an emergency.

The problem of locomotion in a weightless environment is discussed above. However, a special propulsion pack and biopack have been developed and tested during brief periods of zero gravity produced in cargo aircraft flying ballistic trajectories. This device is shown in Fig. 17. It has a gyro-stabilized guidance system and utilizes hydrogen peroxide as a monopropellant for its jet nozzles. The pack also contains an integral oxygen supply of 4 hr. Another interesting but not very practical experiment in propulsion of a weightless individual is shown in Fig. 18. Here the experimenter has a compressed air tank strapped to his back and attempts to propel himself with an air pistol attached to the tank. Since it is difficult to judge the center of mass, the reaction to the jet pistol produces tumbling and spinning. A belt-type device of the same principle is also shown in Fig. 18, being tested in a cargo aircraft.

For operations outside the space cabin, some authorities believe that the environment will preclude the development of reliable space suits with biopack and locomotion adapters of the type described above. The only alternative seems to be a "bottle suit." Again there is the analogy of protecting deep sea divers. Conventional diving suits are limited to certain depths beneath which the pressure is too great to be counteracted by pressure within the suits. The bottle suit concept has the astronaut incapsulated in a rigid, pressurized structure. The suit is maneuvered by small thrusters and is stabilized gyroscopically. As shown in Fig. 19, work can be performed by mechanical arms manipulated from controls within the suit.

Thus man's survival of space flight is the ultimate goal for any space venture, and all designs and configurations must be planned toward this end. The vulnerability of man with his structural limitations greatly complicates space exploration vehicles; yet man is an integral part of the space vehicle system, and in the entire complex the most critical element of space flight success.

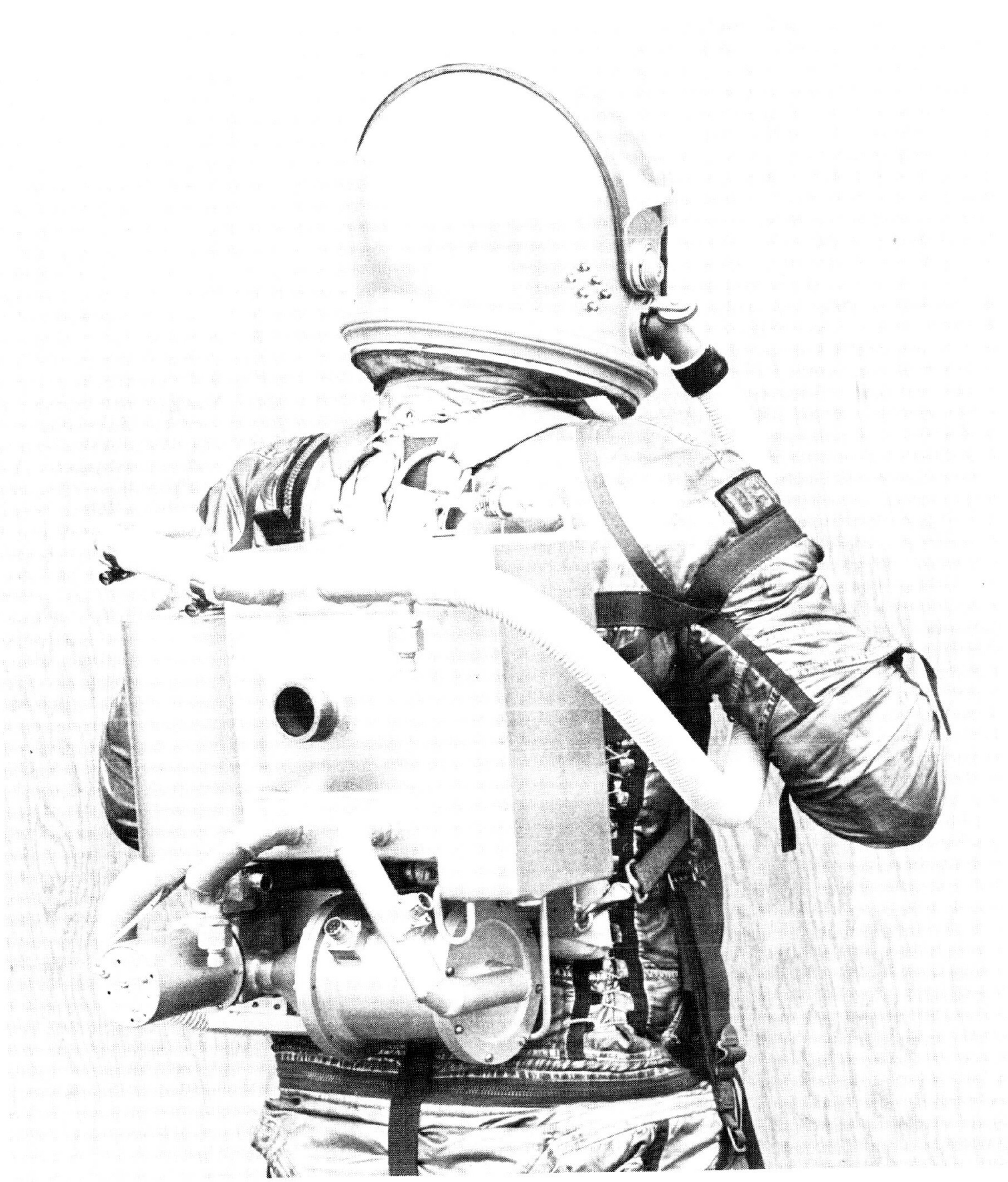

FIGURE 15. BIOPACK FOR SPACE SUIT

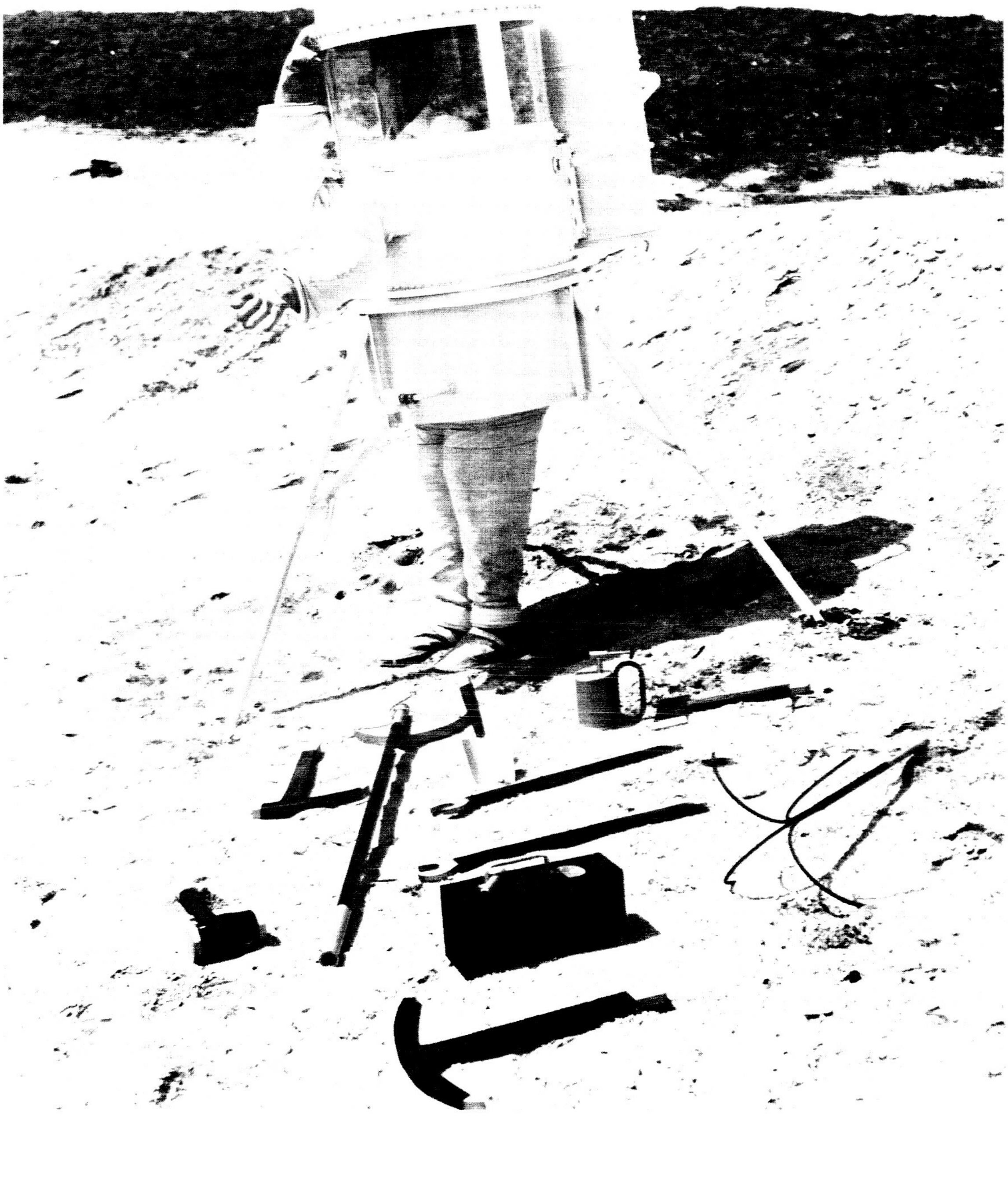

FIGURE 16. SPACE SUIT DEVELOPED FOR USE ON MOON

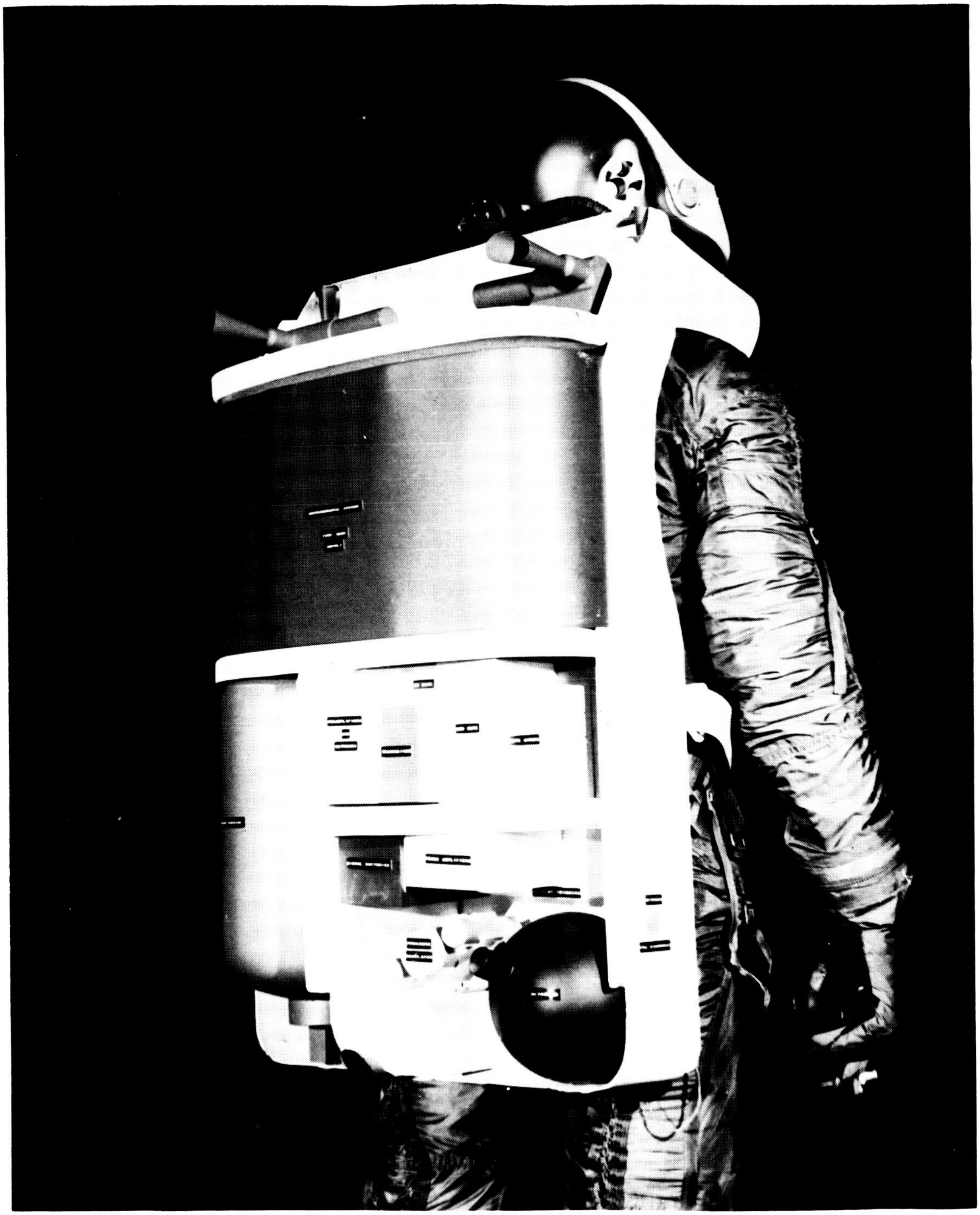

FIGURE 17. COMBINATION LOCOMOTION AND BIOPACK FOR SPACE SUITS

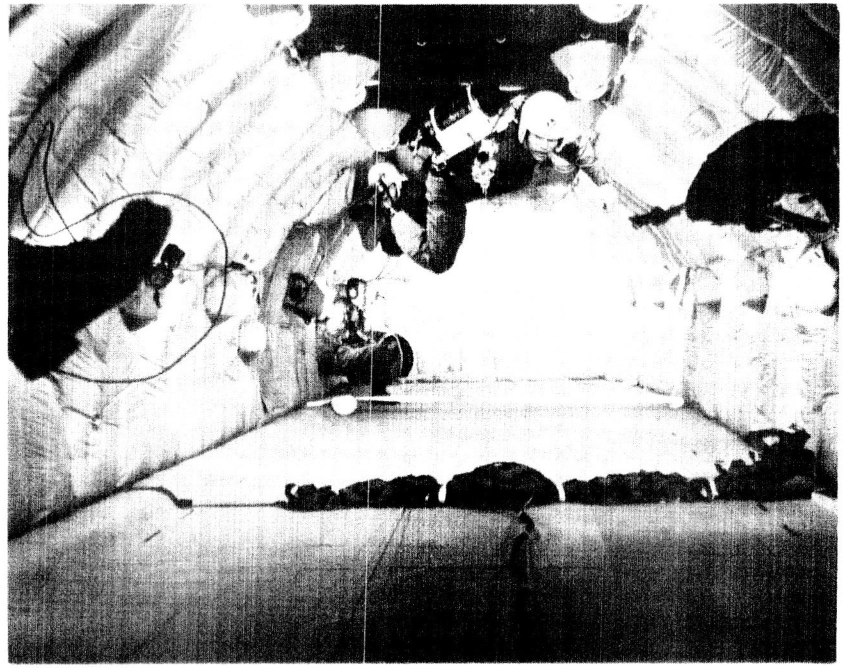

FIGURE 18. TOP, ATTEMPTED LOCOMOTION DURING WEIGHTLESSNESS USING COMPRESSED AIR. BOTTOM, COMPRESSED AIR BELT USED FOR LOCOMOTION DURING WEIGHTLESSNESS

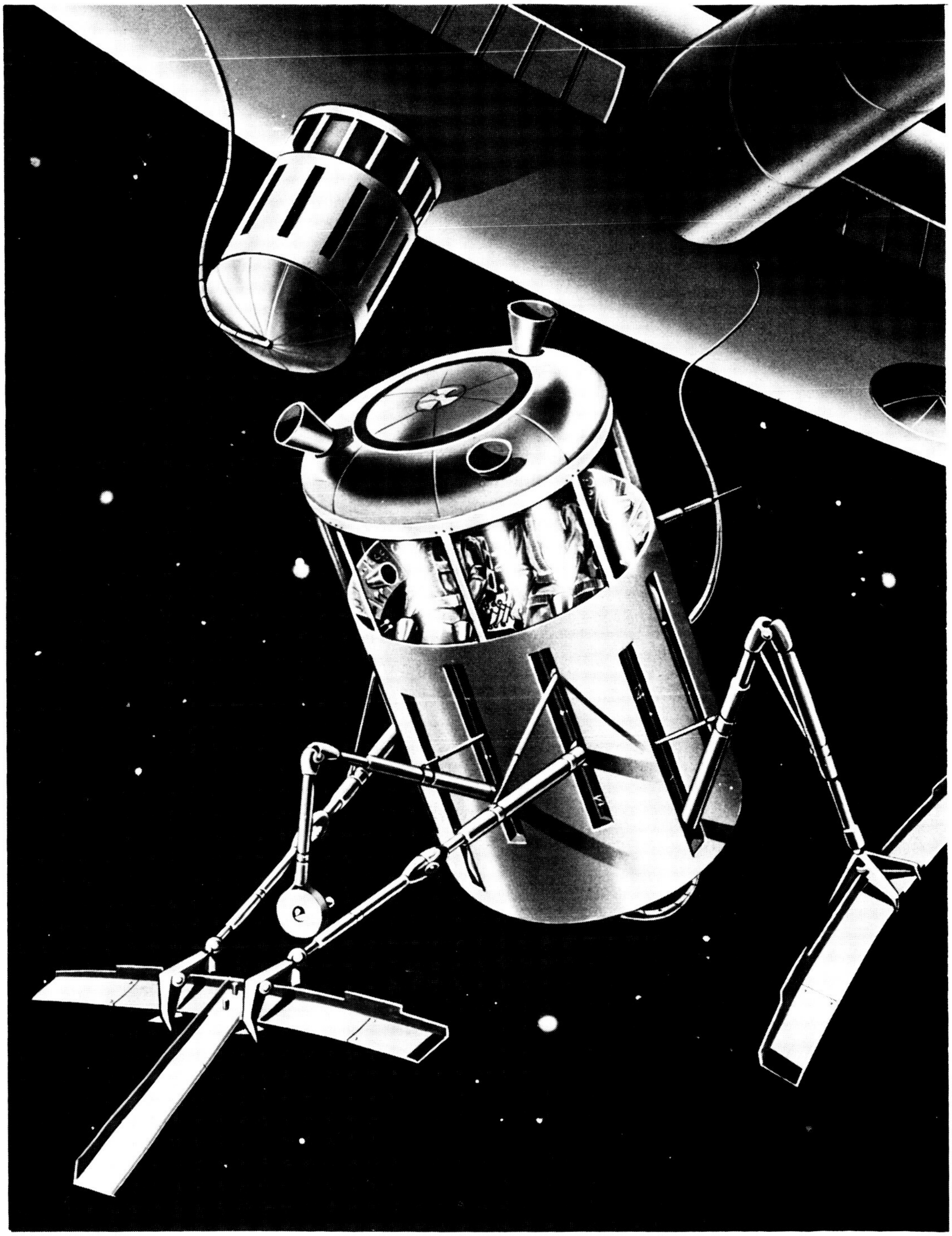

FIGURE 19. CONCEPT OF A "BOTTLE SUIT" FOR USE IN SPACE

APPENDIX

THE CYBORG CONCEPT

Dr. Nathan S. Kline and a coworker, Manfred Clynes, of the Rockland State Hospital, Orangeburg, New York, believe that it may ultimately be necessary to biologically adapt man to the alien environment of space rather than to try to construct a reliable microenvironment of Earth for him to take into space. The concept that they have evolved is that of the cyborg, a being that "deliberately incorporates exogenous components extending the self-regulatory control function of the organism in order to adapt to new environments." (Refs. 32, 33) Kline and Clynes feel that the present approach of creating a microenvironment of Earth for man to take into space is a "dangerous temporizing" in a solution to the problem. In the long run it is no more satisfactory than it would be for a fish wanting to live on land to attempt to do so by carrying a small quantity of water around with it. Basically these two scientists feel that the proper approach is one that permits man to adapt himself to an alien environment (in this case space) without tampering with his heredity. Obviously man could never adapt by evolution to life in space or on another planet.

The idea is to adapt man by biochemical, physiological, and electronic modifications to a new environment. In so doing, the modifications must be tied into the body's homeostatic control system so that no conscious effort is needed by man to control them. Put more simply, the psychophysiological problems of space travel can be solved pragmatically. Thus if breathing in a vacuum is a major problem, which it obviously is, then the best solution is to do away with the process of breathing. An artificial organ could be developed to replace the lungs. In this unit the blood could be shunted from the pulmonary artery through a device that would chemically reduce the carbon dioxide, returning the right amount of oxygen to the blood. Perhaps some form of an inverse fuel cell could be used.

Similarly the problem of the disposal of metabolic wastes can be best solved by processing urine directly from the ureter through a shunt that could convert the urea to carbon dioxide and ammonia. The first gas could be processed by the inverse fuel cell mentioned already, and the ammonia could be otherwise disposed of. Feces, likewise, could be treated in a miniature septic tank stocked with appropriate pathogens. Other problems involving the body's endocrine system, glands, and muscular system might be solved if some automatic means were available for slowly introducing chemicals into the body.

Such a device does exist--the Rose osmotic pressure pump, seen emplaced on a rat in Fig. 20. The pump shown in this picture has since been reduced in size. It consists of a Congo red solution in a rubber

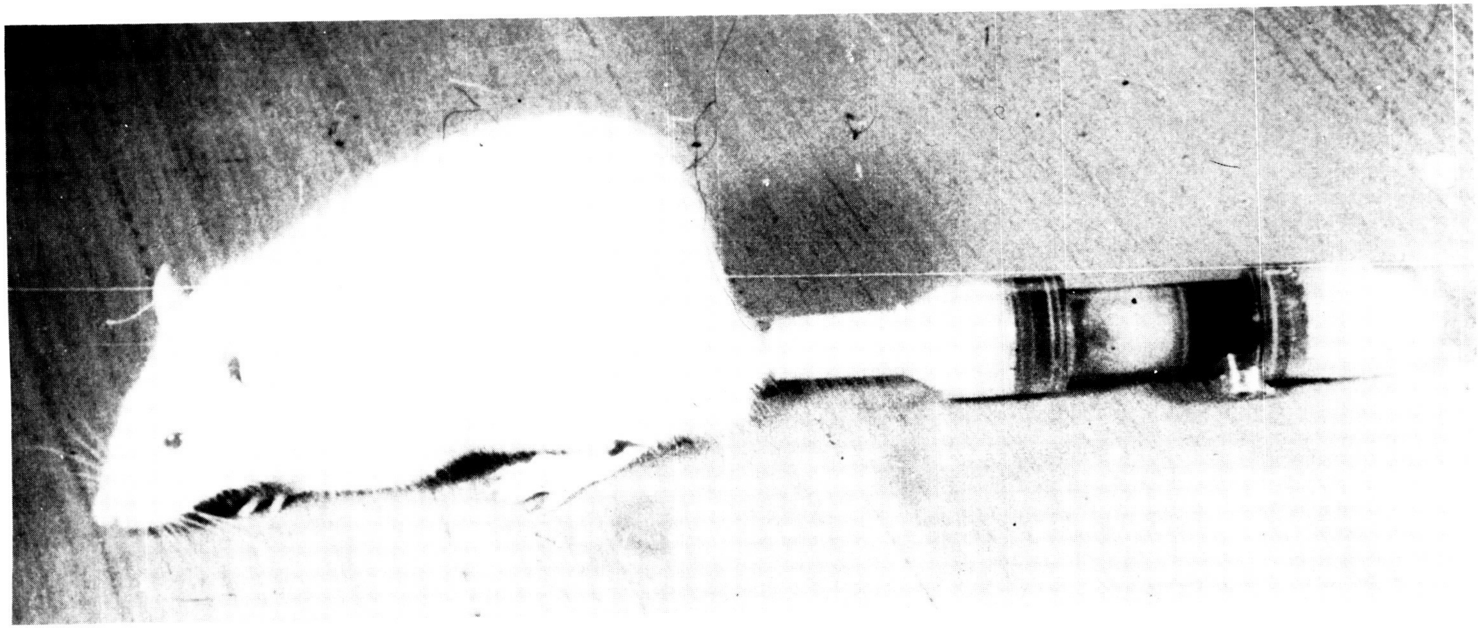

FIGURE 20. CYBORG MOUSE WITH A ROSE OSMOTIC PRESSURE PUMP IN SITU

bag within one compartment containing the chemical to be injected. Separated by a cellophane barrier is a compartment containing water. The water, by osmotic pressure, moves into the Congo red compartment and expands it (Fig. 21). This action produces the mechanical force needed for the pumping action. The rate of flow can be adjusted by varying either the thickness of the cellophane or its area. Through the use of such a pump containing a biochemical and an appropriate sensing device, a closed loop can be formed that requires no conscious effort on the part of the body.

The realization of the cyborg may be closer than is at first apparent. (Refs. 34, 35, and 36) Artificial organs are in an advanced state of development--two models of an artificial heart constructed and tested in dogs are shown in Fig. 22. Similar devices have been built in Russia, England, and Sweden. It is known that Soviet medical scientists are pursuing studies along lines that could be applied to the cyborg concept. They have, for example, succeeded in using fine platinum and tantalum wires to replace the sciatic and vagus nerves in dogs and are experimenting with the replacement of optic nerves. In addition, they have also succeeded in using the biopotential of the muscles to operate prosthetic appliances. In one case a patient wrote his name on a blackboard using an artificial hand controlled by biocurrents.

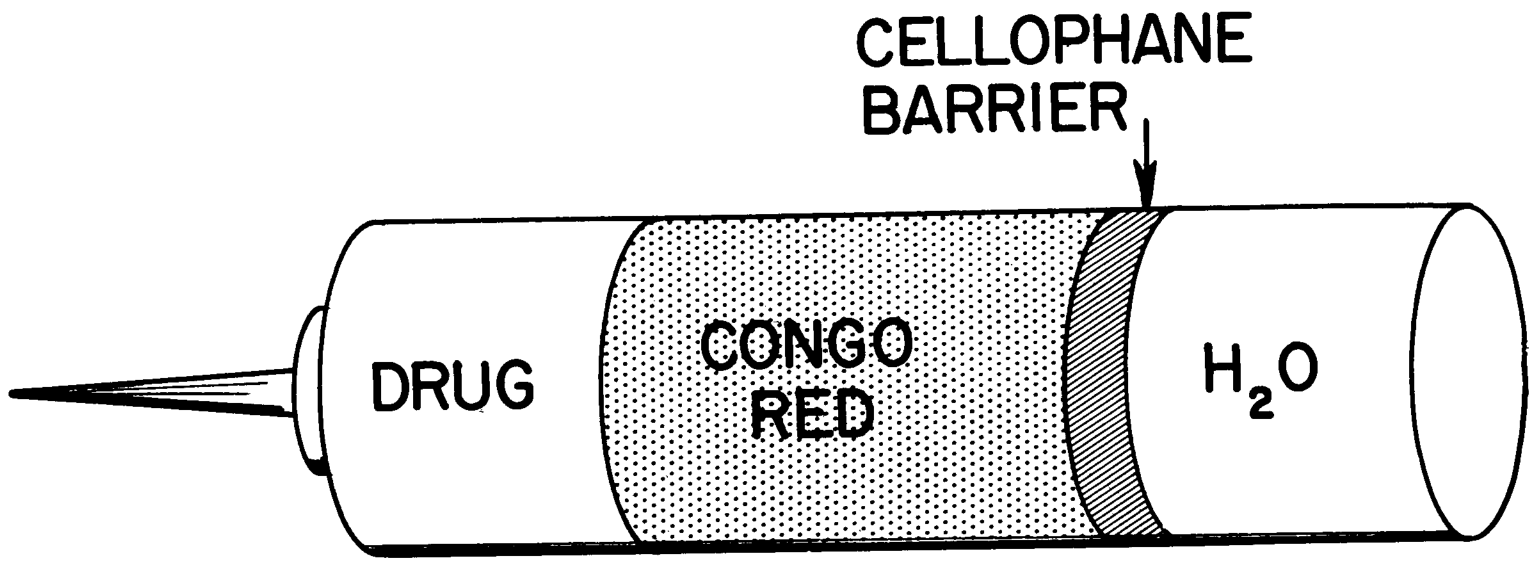

FIGURE 21. SCHEMATIC VIEW OF ROSE OSMOTIC PRESSURE PUMP

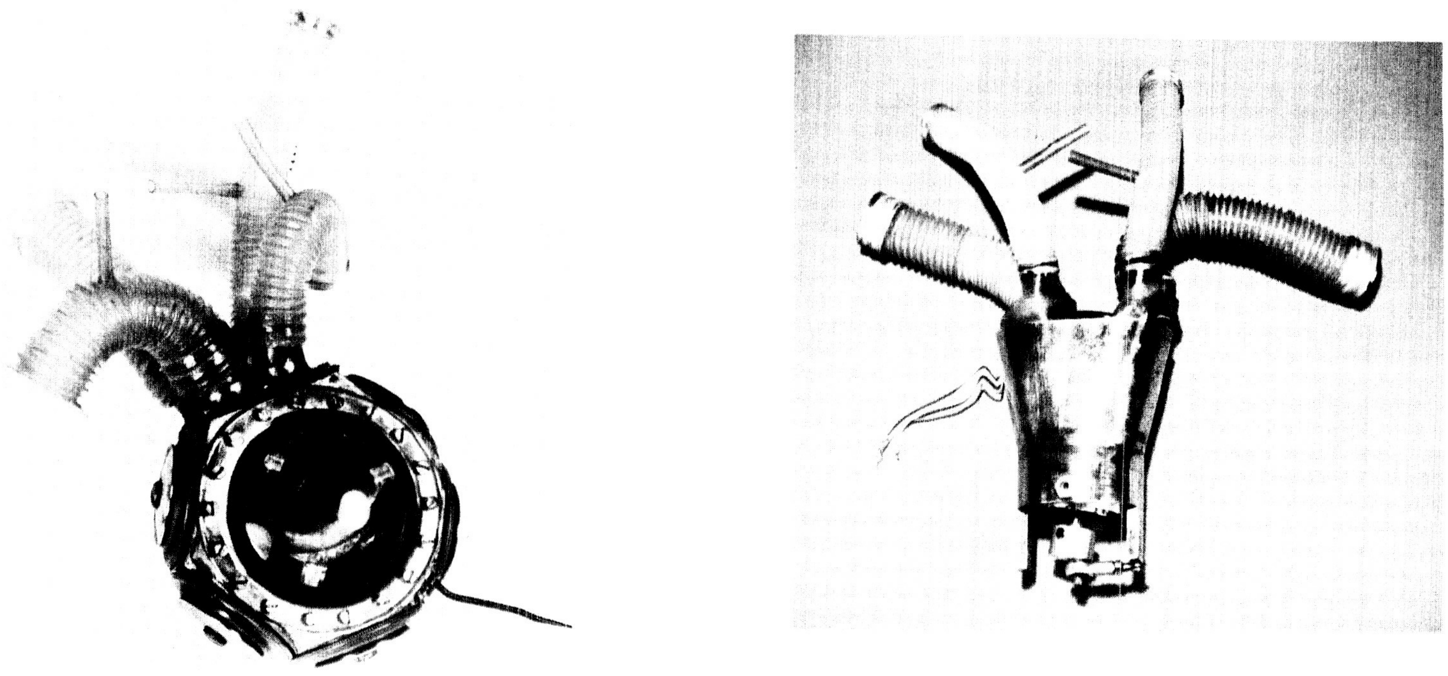

FIGURE 22. ARTIFICIAL HEARTS DEVELOPED BY THE CLEVELAND CLINIC, CLEVELAND, OHIO

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