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POTENTIAL PROBLEMS RELATED TO WEIGHTLESSNESS AND ARTIFICIAL GRAVITY

by Ralph W. Stone, Jr., and William M. Piland

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Langley Station, Hampton, Va.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1969

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SUMMARY

A study has been made of many publications to provide planners of future space missions with a summary of the pertinent problems associated with the weightless environment of space. Based on this study, a review is presented of the possible adverse effects of weightlessness on the astronaut's physiological processes and his performance in space. Techniques and devices which are potentially capable of counteracting the adverse effects of weightlessness are discussed. These counteractive measures include lower-body negative pressure devices, pressure cuffs, anti-g suits, the cardiovascular conditioning suit, exercise apparatus, and artificial gravity. The impact of additional weight and crew involvement in the inclusion of these devices on a particular mission is also discussed. The effects of these devices range from minor increases in launch weight and crew activity to significant vehicle-configuration complexity and astronaut involvement.

Results are presented of research on the therapeutic value of the counteractive devices for weightlessness. Where an insufficient assessment of these devices exists, further research is recommended which could influence a decision on their use. Primarily, it is important to determine whether the effects of simulated weightlessness are progressive beyond that which has been experienced to date or whether the effects plateau at a specific level of physiological adaptation. Further examination should be made of the counteractive devices, at least through the time period thus determined. Such studies could provide greater insight into the character of physiological deconditioning and the extent of application required for each device.

The questions concerning artificial gravity as a therapeutic and/or convenience technique appear to be as numerous as those associated with weightlessness. The effects of Coriolis acceleration, gravity gradient, and angular acceleration make artificial gravity an extremely complex environment. The adverse effects of rotation are discussed in detail and certain design criteria for large rotating space vehicles are identified. It appears that acceptable design criteria will include a vehicle rotational rate of about 6 rpm and a minimum vehicle radius of 55 ft (16.8 m). The gravity level required for convenience should fall between $\frac{1}{6}$g and 1g (1g = 32.2 ft/sec^2 or 9.81 m/sec^2). Further study is

identified and recommended which will provide more adequate data on the gravity level required for physiological conditioning and adequate performance of the astronauts.

INTRODUCTION

Gravity is so strongly associated with the normal human psychophysiological activities that the total effects of its removal are difficult to determine. Since the inception of the United States and Soviet manned space programs, considerable concern has been expressed that weightlessness during extended space missions might have a significant effect on man's physiological processes and thereby limit his effectiveness in performing such missions and returning safely. Recent Gemini and Voskhod flights have extended the knowledge of the effects of weightlessness until it is believed that lunar missions and earth-orbital missions up to 30 days can be performed without the aid of artificial gravity or elaborate physiological conditioning devices (ref. 1). But the question arises, What of planetary and extended earth-orbital missions in which the flight time could exceed the Gemini flights by a factor of 50? Man has not to date been exposed to the weightless environment for a sufficient period of time to allow an adequate assessment of the related problems. However, planners of future space missions require some basis on which to make preliminary decisions concerning the gravity problem. The purpose of this report is to provide planners and other interested parties with a document in which are discussed the pros and cons relative to the factors of the zero-gravity environment and methods or techniques for counteracting the possible adverse effects thereof.

Prolonged weightlessness may have certain adverse effects on the cardiovascular, skeletal, and other physiological systems due primarily to the adaptation of the human body to its environment. These effects, which may be considered physiological deconditioning, could result in subsequent reductions in tolerance to the rapidly applied overstresses of reentry and the stresses of readapting to the gravitational environment of the earth (ref. 2). Thus, the longer missions may not be possible without some method of counteracting the potential degrading effects of weightlessness.

Other factors of zero gravity must also be considered. For example, there are many comfort and convenience aspects of gravity, and man may find that it is difficult to adapt to weightlessness to perform even everyday tasks. In performing certain maintenance and repair tasks, it would appear advantageous for objects, such as tools, to remain where they are placed and not "float" away. Consequently, the performance of these tasks may also be improved by artificial gravity.

Since man may need artificial gravity for long-duration missions as a therapeutic and/or convenience device, considerable study has been expended to devise the most effective method of providing this near-natural environment in the unfamiliar environment of space. Results of studies to date imply that artificial gravity should be provided by a

centrifuge, by a spinning room, or by spinning the entire space vehicle either about one of its axes or by rotation with a connected mass separated from the vehicle. (See refs. 3, 4, and 5.) With the information now available, a position either for or against weightlessness or the need for artificial gravity may be reasonably argued. The literature includes various experimental results and opinions which give some insight into the problems of weightlessness. Reference 6 identifies over 2400 documents available on the subject of weightlessness and its effects. The material of the present report is a compilation of thoughts, opinions, and results of studies and experiments taken from some of those documents.

SYMBOLS

$\left.\begin{matrix} C_1, C_2, C_3, C_4 \\ C_5, C_6, C_7, C_8 \end{matrix}\right\}$	values representing criteria for design of rotating space vehicles
$\overline{F}_c$	Coriolis force vector, pounds (newtons)
$\overline{F}_g$	centrifugal force vector, pounds (newtons)
r	radius of rotation, feet (meters)
$\overline{v}$	relative velocity vector, feet/second (meters/second)
ω	rate of rotation, radians/second or revolutions/minute

ADVERSE EFFECTS OF WEIGHTLESSNESS

Much concern has been expressed regarding man's ability to survive the weightless environment of space. The potential adverse effects of weightlessness range from physiological deconditioning to the simple ability of man to feel comfortable in this environment. The physiological effects involved are considered to be primarily those which may be directly caused by the removal of the influences of gravity and secondarily those which may affect the nervous system by the removal or alteration of sensory inputs. Also there are psychological effects of weightlessness caused by this abnormal environment, such as emotion and stresses.

Physiological Effects

Cardiovascular deconditioning will most probably be the significant problem of extended weightless space flight (ref. 2). In a gravity environment, such as that which

exists on earth, there is a pressure gradient along man's body (except when lying down) which induces the cardiovascular responses responsible for maintaining a proper distribution of blood volume within the body. This pressure gradient, the hydrostatic pressure, results because the pressure at any point in a column of body fluid depends on the weight of overlying fluid. This hydrostatic pressure causes a pooling of blood in the legs and man has adapted to this condition in the earth environment. Without the gravity force, hydrostatic pressure in the cardiovascular system decreases to zero and most of the body blood will locate itself in the upper part of the body. Also, there is a tendency toward lower total blood volume. In the weightless environment in addition to the absence of the hydrostatic pressure, the astronaut will expend little energy in performing some of his activities and, as a result of this decrease in physiological stress, the demands on the cardiovascular system will be subsequently lessened. The heart, and generally the total cardiovascular system, will adapt to this condition. Upon reentering the earth's atmosphere, the astronaut will experience high deceleration forces and rapid reinstatement of hydrostatic pressure within the cardiovascular system. After having spent extended periods of time in the weightless environment, the astronaut may have difficulty in retaining his performance capabilities during reentry and while readapting to the earth environment (ref. 2). Experience to date indicates that the effects of weightlessness on the cardiovascular system may not be progressive and that the system tends to reach a new steady state in the new environment. Whether or not a new steady-state condition occurred in the 14-day Gemini flight is not known.

Accompanying this cardiovascular deconditioning might be decreases in muscle strength, alterations in mineral balance and cellular functioning, and an increase in urinary calcium excretion. (See refs. 1, 7, and 8.) The rate and degree of these physiological changes may be different and may be primarily caused by disuse and confinement and only in part caused by the weightless state. For example, clinical studies have shown that with an adequate calcium intake there is a direct correlation between the amount of calcium excretion from the bone and the amount of stress imposed on the bone structure through body activity. On the average, body weight loads impose only 3 percent of the stress on the bone, whereas muscle loads impose 97 percent (ref. 9). On the basis of this relationship, bone decalcification in the space environment may not be related significantly to the weightless state but may be related to the inactivity of the astronaut and the lack of mechanical stress in the body structure. In other words, the astronaut does not have to work as hard to move from one place to another, to move other objects, or to perform tasks normally requiring muscle stress in a gravity environment. The astronaut's muscle tone will decrease in a manner similar to that of inactive individuals on earth (such as bedridden patients).

Another area of potential trouble is the effect of prolonged weightlessness on human alertness and attention. The absence of weight sensing stimuli to the brain may produce

such an attenuation of hypothalamic and thalamic activity as to endanger the alertness needed in the astronaut (ref. 10). In addition, weightlessness may seriously affect draining of the sinus cavities (ref. 11).

The decreases in cardiovascular system efficiencies have been experienced on Russian and American space flights and in numerous simulation studies. At a symposium on space science in Florence, Italy, in May 1964, representatives of the Soviet Academy of Medical Sciences discussed some of the biomedical results of the Soviet manned space flights (ref. 12). They implied that certain decreases in the elasticity of the vascular system have been noted in cosmonauts even 2 days after returning from their flights. They also noted that postflight disturbances were largely related to the central nervous system, the cardiovascular system, and metabolism. At the same meeting, an American physiologist noted that there was some degree of orthostatic intolerance in American astronauts. Orthostatic intolerance was observed and measured during postflight examinations when the astronauts did not exhibit the same degree of tilt-table tolerance as during preflight examinations.

The effective simulations of the physiological effects of weightless flight are the bed-rest and water-immersion techniques. Data from the simulated-weightlessness studies using the bed-rest technique (refs. 13 to 17) demonstrate physiological changes similar to those produced by space flight. These changes include decreases in tilt-table tolerance, blood volume, exercise tolerance, and muscle strength. In addition, changes have been noted in the calcium contents of the bone and urine (ref. 18).

In the water-immersion technique, the man's body is immersed to a depth where he is almost neutrally buoyant. The hydrostatic pressure of the fluid balances, at every point, the hydrostatic pressures of the body fluids and thus this condition apparently reduces the workload of the cardiovascular system (ref. 19). Also, since the body weight is largely supported by the water, many of the gravity cues normally available to the man are diminished.

By maintaining the body (cardiovascular system) in the horizontal position during bed-rest studies, the cardiovascular system adjusts to the reduced workload due to the reduced hydrostatic pressure which exists along the longitudinal axis of the man's body. Therefore, if the body is maintained in this position for an extended period of time, the cardiovascular system functions in a manner similar to the function of the system in the weightless environment. Water-immersion tests and bed-rest studies have lasted up to 41 days. It is reasonable to assume that the adverse physiological effects noted in these studies may be similar to those which would occur under actual space conditions.

Another problem arising from extended weightlessness is the possibility of serious disturbances of vestibular function (ref. 20). The vestibular function has evolved in a gravity environment. Nominally, it is thought that the otoliths react to gravitational force

and linear acceleration and that the semicircular canals react to angular acceleration. The actual influence of the gravitational force, or of interrelations of the two organs, on the functions of the organs is not clearly understood. Actually, the absence of gravity directly affects the otoliths and, if interactions exist, would also influence the semicircular canals.

Experience to date in U.S. space flights has not indicated any serious weightlessness effects on the function of the vestibular system (ref. 20). Concern remains, however, that the absence of gravity and its effects on the vestibular system for longer periods of time may ultimately cause disturbances leading to reduced performance. Other sensory inputs of a proprioceptive nature will also be significantly reduced in weightless flight, and as with the loss of vestibular senses, their reduction may become a major factor during extended periods of weightlessness.

It has been reasoned that in a weightless or reduced-gravity environment man's energy expenditure in the performance of specific tasks should be less than that in earth's gravity. This reasoning is based on the fact that weightless or effectively lighter objects and bodily elements should be easier to manipulate than the same elements under normal gravity. However, the muscle system is exceedingly complex and is capable of expending energy without performing any useful work. The performance of a task becomes difficult because of the lack of facility for applying force. In addition, because such tasks tend to be frustrating, additional energy can be expended which has no direct influence on the intended work. The experience of U.S. astronauts in extravehicular activity has indicated the expenditure of more energy than expected (ref. 1).

Ground-based simulations have shown a greater expenditure of energy in the simulated reduced gravity than in earth gravity for work performed by the arms and upper body (ref. 21). However, simulations of mobility at $\frac{1}{6}$g show the expenditure of less energy than in earth gravity (ref. 22). These tests of walking and running were performed in a manner nearly identical or at least akin to the manner of performance in 1g. Therefore, it may be concluded that when a task is performed in a normal manner in reduced or zero gravity, the energy expended will be less than normal, but that when a task is performed in an abnormal or unfamiliar manner, more energy will be expended than in earth gravity. There is expected to be, therefore, a considerable influence of proper restraint design and use, and of adequate training and familiarization on the metabolic cost of astronaut activity. Clearly, man's energy requirements can have a strong impact on the work accomplished and the life-support system for extended missions.

Performance and Convenience

In addition to the effects on the physiological processes of the human body, other effects of weightlessness must be considered. For example, there are the comfort and

convenience aspects of gravity and man may have difficulty in adapting to the performance of everyday tasks without the aid of gravity. "Since it is clear that only when performance is preserved, is it possible to speak of man's mastery of space" (ref. 23), then every effort must be made to insure that the astronaut will be able to carry out routine and experimental tasks with as much ease as possible.

Man has learned to function within the earth's gravitational field. Although he has withstood moderate changes in this environment, it seems reasonable to assume that extended periods of weightlessness could prove to be disquieting. Adverse psychological effects could result from the astronaut's movements within the spacecraft and from his performance of various functions with "free" objects. Under the condition of a balance of forces, which exists in the weightless environment, the locomotion of the astronaut from one point to another could require excessive efforts for coordinated motion. Further, there is evidence that the astronaut, because of reduced or altered sensory stimulation, may experience sensory disturbances (sense of inversion, for example) which are accompanied by uneasiness, discomfort, and loss of spatial orientation (refs. 23 and 24). These experiences could be compared to motion sickness with reactions of mental anxiety, reduced coordination, nausea, vomiting, or all four.

Because of the confinement of the spacecraft which have flown to date, it has been difficult to evaluate the effects of weightlessness on man's performance. However, certain conclusions have been drawn which were based on astronaut extravehicular activities and ground tests using underwater neutral buoyancy simulation techniques (refs. 21 and 25).

Some of the Soviet cosmonauts experienced illusions of unusual body position in space. At the onset of weightlessness, some only sensed the feeling of lightness, whereas others did seem upside down or face or head down and retained the feeling when the eyes were opened or closed. Although this sensation was uncomfortable rather than acutely unpleasant or intolerable, it affected the ability of the cosmonaut to perform in a satisfactory manner because he was unable to determine adequately his body position and establish a degree of coordination. However, adaptation was soon obtained as demonstrated by the improvement in handwriting with increasing flight. In addition, by previously selecting visual orienting points within the spacecraft, spatial disorientation could be eliminated at the onset of weightlessness by setting in order information from the sense organs and thereby the man is able to determine the position of his body (ref. 24). It was found that highly trained pilots are the least affected by weightlessness and rapidly overcome most of the adverse sensations (ref. 23). The U.S. astronauts, who are all highly trained pilots, have not experienced illusions and have not been disquieted by the experience of space flight (ref. 1).

Outside the spacecraft, both the American and Russian astronauts have had difficulty in performing relatively simple tasks. The problems experienced were attributed

to the lack of positive resistive forces in the weightless environment rather than to the lack of coordination or orientation. However, since astronaut experience in this form of weightless freedom has been short termed, the possible complexity of the orientation problem for man in space for extended periods of time is yet undetermined. In addition, little is known about the influence of such variables as training, individual differences, and previously formed associations on orientation. There is, however, indication that vision itself, rather than the other gravireceptors (muscles, vestibular organs, etc.), will give adequate orientation information after an undetermined adapting period (ref. 25). As is discussed subsequently, after this adapting period in the weightless environment, satisfactory performance may be maintained with the aid of adequate measures such as restraining devices.

In performing certain routine operations, it would be advantageous for objects, such as tools, to remain where they are placed and not "float" away. In fact, some delicate repair and maintenance functions may be more difficult if not impossible to perform in the weightless environment. Furthermore, without the aid of gravitational acceleration or very sophisticated complex apparatus, simple hygienic functions may be difficult. These functions include washing, shaving, and haircutting. Human waste collection presents a significant problem in the weightless environment where equipment such as elaborate airflow devices would be required (ref. 11).

METHODS FOR COUNTERACTING THE ADVERSE EFFECTS OF WEIGHTLESSNESS

Numerous techniques have been proposed to insure the safety and performance of the astronaut during his extended stay in the weightless environment of space and his return to earth. To cope with the effects of weightlessness on the astronaut's physiological system, methods have been proposed and devised either to continuously maintain the astronaut in the space environment, to recondition the astronaut in space, or to protect the deconditioned astronaut during and subsequent to entry into the atmosphere of the earth or into that of another planet. In addition, through various experimental studies and extrapolations based on flight experience, techniques for retaining adequate levels of astronaut performance have been suggested. The most significant and promising methods for counteracting the adverse effects of weightlessness are discussed in this section. Some of these methods have been proved effective, whereas data on the value of others are lacking.

Astronaut Physiological System Protection and Maintenance

Suppose the astronaut's cardiovascular system is allowed to reach and remain at the condition it tends to seek in the weightless environment. Experiments show that simple elastic leotards on the legs will prevent the rapid redistribution of blood from the head and

chest areas to the legs when returning from the weightless flight and, thereby, any reduction in performance which would otherwise be experienced during and subsequent to reentry would be eliminated (ref. 26). However, the leotards are only a temporary protective measure, and further readaptation for the earth's gravitational environment would be required. If it is desirable to continuously maintain or to recondition the cardiovascular system while weightless, methods have been proposed for these purposes. One such method is the application of periodic negative pressure to the lower part of the body (fig. 1). This lower-body negative pressure causes a redistribution of blood to the lower extremities and the cardiovascular system is thereby stimulated in a manner similar to upright tilting in the earth environment. Stevens and Lamb (ref. 27) have experimented with lower-body negative pressures between 25 and 80 mm Hg on bed-rest subjects. They found that negative pressure counteracted the adverse effects of bed rest and that there was a redistribution of blood volume with pooling in the pelvis and legs.

Another device for cardiovascular system maintenance is a gravity or "g" suit which would provide the cardiovascular system with "gravitylike" stimulation while it is worn in the weightless environment (ref. 28). An illustration of this suit is shown in figure 2. The suit consists of a nonelastic outer garment within which are attached a series of elastic inner tubes. The pressure in these tubes and in the helmet area is adjusted by a control device so that the externally applied pressure on the body decreases from head to toe inversely to that of an equal column of blood in a gravity field. This pressure gradient on the body could adequately simulate the conditions obtained while standing in a gravitational field and could maintain the cardiovascular system at peak efficiency during prolonged weightlessness. The suit is presently being developed for the Langley Research Center, and preliminary results of initial tests indicate that the suit is effective (ref. 29).

Pressure cuffs applied to the limbs have also been proposed to stimulate the vascular system by periodically occluding venous return from the extremities throughout the space flight (ref. 26). Tests of such devices during water immersion have been encouraging; however, results from their use in orbital flight have been inconclusive (ref. 1).

For the purpose of exercising the cardiovascular system in the weightless environment, a double-end trampoline has been considered (ref. 30). This device would be used to apply cyclic acceleration levels to the body by bouncing from head to foot between the two ends of the double trampoline. Limited knowledge of the therapeutic value of the trampoline exists, but it remains a possible method of cardiovascular conditioning. In addition to these specific devices conceived to counter the deconditioning effects of weightlessness, there are also some self-induced stresses, such as the Valsalva (ref. 15) and Meuller maneuvers and the Flack test, that stimulate the cardiovascular system and may be beneficial in allaying degradation. Positive pressure breathing also stimulates the cardiovascular system and may have some value for this purpose. Inasmuch as such

maneuvers and tests, except for positive pressure breathing, require minimal or no equipment, their use in extended space missions must be considered.

Effects of bone and muscle adaptation to the weightless environment could obviously be quite serious, but these can be minimized by proper exercise and loading of the bones. Equipment for the prevention of these effects includes isotonic and isometric exercise apparatus (fig. 3) and the pedal ergometer (fig. 4) for exercise requiring a great deal of body motion. Other proposed methods for maintaining muscle tone include vibration and hand massage. In addition to cardiovascular conditioning, the previously discussed trampoline could also be used to maintain muscular tone and skeletal structure. The adequateness of these techniques during space flight has not been thoroughly verified experimentally, but all do offer potential for maintaining physical fitness and endurance by bone and muscle conditioning and, to some degree, help to preserve the cardiovascular system by stimulation.

The last technique to be discussed would preclude the adverse physiological effects of weightlessness by providing the astronaut with an environment similar to earth's – that is, by providing artificial gravity. Ground-based studies have shown that the short-radius centrifuge, for example, has the capability for generating a valid physiological stress (ref. 31). The centrifuge provides artificial gravity to keep the astronaut's physiological system functioning normally by stimulating it in a manner to which he has become adapted in the earth environment. Periodic use of the centrifuge should prevent physiological deconditioning of important reflexes which are vital for proper functioning, apply mechanical stress to maintain the normal metabolism of bone, prevent diuresis and deconditioning of the cardiovascular system, and give the individual a familiar orientation. The centrifuge should also be useful for conditioning a crewman for mission reentry acceleration. In short, the centrifuge has potential as a deconditioning countermeasure for the cardiovascular system, the musculoskeletal structure, and other parts of the physiological system adversely affected by weightlessness (ref. 11).

Many investigations have been performed to verify the therapeutic value of the short-radius centrifuge for providing intermittent gravity exposure for the crew of extended space missions. One of these studies (ref. 31) using a ground-based simulation explored the therapeutic value of centrifugation in counteracting the physiological degradation of five healthy men exposed to 41 days of bed rest. The 41 days were broken into 20 days of bed rest, 16 days of bed rest with periodic rides on a 4.5-ft-radius (1.37 m) centrifuge, 5 days of bed rest with centrifugation and physical exercise. A 10-day recovery period followed the 41 days of bed rest. During the 21st through the 41st days, the subjects made four 7.5-min centrifuge rides each day during a 6-hr period. The level of acceleration at the subjects' feet was 1g for one group (two subjects) and 4g for the other group (three subjects). The following significant conclusions were obtained from this simulation study:

1. Twenty days of recumbency brought about a deterioration in the mechanisms essential for adequate circulation in the erect position as indicated by (1) a tendency to faint during tilt-table tests, (2) venous engorgement, increased extravascular fluid, and capillary fragility observed during the first days of riding the centrifuge, and (3) declines in plasma and blood volumes.

2. The deterioration produced by recumbency in the ability of the subjects to tolerate 90° head-up tilt-table tests for 20 min was largely prevented by periodic centrifugation. The subjects receiving a 4g centrifuge ride four times a day showed less lability in blood pressure and heart rate during the tilt-table tests than the subjects exposed to a 1g ride.

3. Motion sickness is not a problem for the well-trained individual exposed to high rates of rotation with restricted body movements.

Another method for providing artificial gravity would be by rotation of the entire vehicle over long periods of time. This method would have the same type of therapeutic value for the physiological system as the short-radius centrifuge. The primary difference would be the time interval in which the gravity forces are applied and the level of gravity exposure. The rotating vehicle would provide continuous physiological maintenance instead of periodic conditioning.

Astronaut Performance

Many investigations concerning the preservation of astronaut performance in weightlessness have provided a number of proposed methods for both maintaining performance and providing a comfortable working environment without the aid of artificial gravity.

The experimental data from the tasks performed during Keplerian trajectories (ref. 10) and on air-bearing devices (ref. 32) have given evidence that, in general, a man can perform tasks as accurately and as quickly during a zero-gravity condition as during the normal 1g condition if the man and equipment are restrained appropriately. In addition, results of an experiment performed in an immersion tank, using the neutral buoyancy technique, to determine the relationship between task performance and weightlessness (ref. 25) indicate that most of the tasks required of a crewman can be adequately performed with some restraining device between the workman and the console where he is working. The type and amount of restraint depend upon the specific task which is to be performed. For some maintenance, assembly, and experimental tasks where both hands are needed, a rigid restraint device, such as a waist belt, has proved to be quite satisfactory (fig. 5). Where less firm restraints are needed, Velcro has provided an excellent restraint. For the performance of various routine tasks with small objects, Velcro, magnets, air currents, and electrostatic attraction devices have been proposed to force the objects being used to remain in place and not drift from the working area.

Washing, bathing, and oral hygiene could be accomplished in a manner similar to that on earth except the toothpaste and water would be swallowed. Electric razors with vacuum attachments for catching cut hairs could be used for shaving and haircutting. Human waste collection could be performed with the aid of airflow toilets. These techniques for personal maintenance and convenience appear feasible, but generally their practical use has not been verified and offer engineering problems that need to be solved.

To provide the astronaut with a means of locomotion in the weightless environment, magnetic boots and suction-cup or Velcro shoes have been proposed to allow the astronaut to walk within the spacecraft (refs.33 and 34).

Also from these studies, it has been shown not only that man can perform adequately with sufficient restraint but that no characteristics of stress, aversion, or discomfort existed during the performance of the tasks under restraint. It was concluded that vision itself could be the only sensing component giving accurate orientation information, and with proper designs of space vehicle interiors the crewman can be well oriented by vision alone (ref. 25). Finally, from the results of the flight of Gemini XII it appears that the effects of weightlessness on crew efficiency can be largely controlled by training, planning, and adequately designing restraints.

There remains the possibility that conditions can exist where the effectiveness of crew operations can only be improved by a gravity force field. Loose objects could be considered more hazardous in nonrotating vehicles than in a gravity field since their movements are not automatically controlled or directed. In addition, a continuous gravity field could conceivably make the living and working environment of the crew more acceptable than the weightless environment. In discussions of the term "convenience g" in the literature, it was pointed out that it would be advantageous to provide the crew with an environment in space similar to the environment on earth. Simple tasks which otherwise would be difficult (without restraining devices, etc.) may become much easier to perform with some level of artificial gravity. Certainly, if the individual failed to "adapt" to working in a weightless environment, he could become extremely frustrated and disturbed. Therefore, there could be a significant requirement for artificial gravity for maintenance of the crew psychological processes, in addition to their physiological processes, and to enhance performance.

Besides possibly enhancing the performance level of the crew, artificial gravity could also augment the operation of the vehicle subsystems. For example, eating, drinking, and hygienic techniques are considerably more complex without the gravity force than they are with it. In addition, the collection processes of liquid and solid products of the body are much cleaner and simpler in a gravity environment, without the need for extremely complex equipment.

IMPACT OF COUNTERACTIVE METHODS ON VEHICLE DESIGN

The methods for counteracting the adverse effects of weightlessness, discussed previously, will have both moderate and major impacts on the designs of future space vehicles. The negative pressure boot, the cardiovascular conditioning suit, and the exercise apparatus for physiological conditioning in the weightless spacecraft will offer little or no impact on the overall vehicle design. Their inclusion in the vehicle presents engineering considerations which are only related to the design and use of the particular apparatus itself. This is also essentially true of the techniques, such as the use of Velcro, magnets, and airflow devices, for preserving performance and providing conveniences within the spacecraft. However, if a centrifuge is included in the zero-gravity vehicle or if the vehicle is designed to rotate for artificial gravity, significant penalties become prevalent in the design of the particular space vehicle. In this section, typical designs for a centrifuge and rotating space vehicles are presented, and the corresponding penalties for providing artificial gravity are discussed.

Centrifuge

Perhaps one of the best defined examples of a short-radius-centrifuge design is that shown in figure 6. This centrifuge, designed for the zero-gravity configuration of the 260-in-diameter (6.6 m) Manned Orbital Research Laboratory (MORL), is capable of accommodating one or two men (ref. 3). It has two completely enclosed one-man cabs which can be positioned to provide a range of gravity vectors and which are attached to a 108-in-diameter (2.7 m) drive ring. The centrifuge assembly is mounted on three sets of rollers, one of which is driven by a 1-horsepower dc motor operating through a V-belt drive. Two speed ranges are available if the belt pulleys are shifted. The centrifuge provides up to 1g (20 rpm) for therapeutic purposes and as high as 9g for reentry simulation (fig. 7).

The design penalties incurred by this particular centrifuge configuration in the six-man MORL system are as follows:

(1) A weight penalty of 300 lb (136 kg) for centrifuge structure and drive system

(2) Approximately 1600 ft^3 (45 m^3) of volume unavailable for other purposes

(3) Sixty watts of power required for 1.3 hr daily

(4) An additional 7 lb (3.2 kg) of attitude control propellant per day to null centrifuge torques

(5) Crew time of 3.9 man-hr per day spent attending the centrifuge (two men riding in gondolas and one man observing) and lost from overall work availability time

In relation to convenience gravity levels, it has been suggested that instead of the aforementioned centrifuge concept, a "spinning room" could be included in the basic zero-gravity spacecraft not only to provide the crew periodic centrifugation but also to allow the crew to perform certain tasks in which the presence of a gravity field is beneficial (ref. 4). This concept (fig. 8) of the spinning room contains the centrifuge to simulate reentry acceleration and a separate 60-in-wide (1.5 m) rotating room. A 24-in-wide (61 cm) walkway or hall alongside the spinning room is used for access to the individual radial bays and for walking or exercise. The bays include a maintenance console, an experiment console, a galley with a recreational table and chairs, a toilet compartment, two sleeping bunks, a spinning-room entry ladder, and limited storage volume. The spinning room operates independently of the centrifuge and rotates continuously. A full crew of six men could inhabit the room simultaneously if all stations were occupied.

This spinning room concept is certainly the most elaborate of the centrifuge configurations. Perhaps a good compromise would be the concept shown in figure 9. The basic gondola concept is the same as that shown in figure 6 but two additional console cabs are included on the spin structure for performing gravity-dependent tasks.

Rotating Space Vehicles

Artificial gravity by rotation of the entire space vehicle is a concept which has been studied frequently by many investigators. For therapeutic value, continuous artificial gravity by rotation has the potential of being as beneficial as the centrifuge in eliminating the adverse effects of weightlessness and could be more convenient and comfortable for the crew. Two of the more recently proposed configurations of rotating space vehicles are now discussed.

The first configuration is the MORL in its spinning mode (fig. 10). For this configuration, the basic laboratory is separated from the S-IVB launch stage by a system of cables, and with the S-IVB stage acting as a counterweight the entire vehicle is rotated to achieve the desired gravity field within the laboratory. As an example, for a radius of 70 ft (21 m) from the common center of mass of the spinning vehicle to the outer floor of the laboratory, a gravity level of 0.333g can be achieved by rotating the deployed system at 4 rpm.

The inclusion of this spin capability in the basic-zero-gravity MORL has a considerable effect on the laboratory design. The major impact is the increase in weight of the structure, reaction control, and flight electronic systems to accommodate this additional operating mode. The total changes in dry launch weight of the laboratory and S-IVB combination amount to 3400 lb (1540 kg) and required about 600 lb (272 kg) of additional propellant to transfer to a circular orbit from an initial elliptical orbit. Therefore, the impact of the spin capability on the initial launch of the laboratory involves a decrease in

discretionary payload capability of approximately 4000 lb (1814 kg). Fewer consumable goods, experiments, and so forth, can thus be carried on the initial launch, and more severe demands are placed on the subsequent logistics schedules.

In addition to the initial launch penalties, the inclusion of the spin capability involves major increases in reaction-control propellant consumption. These increases are caused by larger drag and moments of inertia and the deployment and spin-up requirements. For the MORL in the spinning mode, the orbit-keeping propellant needed per month is increased by about 200 lb and the attitude-control propellant needed per month is raised by almost 400 lb (181 kg). Thus, an increase in overall propellant consumption of approximately 80 percent over the consumption of the basic-zero-gravity configuration results.

Besides the impact on system design, other factors also must be considered as influencing a decision to use rotation as a means of providing artificial gravity. One such factor involves the impact of vehicle rotation for artificial gravity on the performance of experimental research in space. For example, during the MORL studies a preliminary selection of a typical experiment program for the mission was made. The experiment program formulated covered all the major scientific and technical disciplines. As illustrated in figure 11, 40 percent of the total 157 experiments would demand almost absolute zero gravity, 43 percent would require a significant increase in design complexity for performance in the presence of artificial gravity, 16 percent would be gravity independent, and only 1 percent would actually require some level of gravity. Since the primary purpose of most future space missions will be the performance of a meaningful experiment program, perhaps the experiment program itself will be the dominating factor in the decision of whether or not to use artificial gravity.

A possible method of providing a continuous gravity force for the crew as well as satisfying the experimental requirements is illustrated in the second rotating spacecraft concept. Three proposed configurations (ref. 5) of a large, rotating, manned orbital space station are shown in figures 12, 13, and 14. Each is basically a 24-man station, rotating to provide artificial gravity at the operational floor levels. Zero-gravity-dependent experiments could be provided for in the counterrotating hub where the gravity level goes to zero.

For these larger rotating vehicles, there are problems similar to but more complex than those associated with the MORL spinning mode. Besides a tremendous launch weight, the aerodynamic and gravity-gradient torques and the orbit-keeping requirements will necessitate a very large increase in propellant consumption although a lesser number of spin and despin operations will be involved since docking would be accomplished at the zero gravity hub. Even though these vehicles are highly complicated and require subsystems of increased complexity to support the mission, such vehicles may be needed in the future. However, the initiation of any space mission in which such an elaborate vehicle is

used is difficult to justify without thoroughly establishing and understanding the true requirements for artificial gravity.

PROBLEMS OF ROTATION AND DESIGN CRITERIA FOR ARTIFICIAL GRAVITY

The comfort, convenience, and physiological conditioning techniques which may be required for extended weightlessness offer engineering problems with relatively simple solutions. Proper design and integration efforts should facilitate the apparatus use and adequate biomedical monitoring should insure that the apparatus presents no potential hazards to the crew during the mission. The only recognizable disadvantage appears to be the crew time lost from other activities while some of the techniques are being employed. However, the questions surrounding the use of an artificial gravity field produced by slow rotation of a large space vehicle appear to be as numerous as those associated with weightlessness. As with zero gravity, there are a series of effects which present serious biomedical and human factors problems.

Adverse Effects of Rotation

A man moving in a rotating space vehicle will experience forces and moments the magnitude and direction of which depend on his velocity vector (either linear or angular), the vehicle rate of rotation, and the radius of rotation where he is located. These forces and moments, byproducts of the artificial gravity environment, influence a man's performance in proportion to their magnitude. In addition to the physical influence of these factors, the vestibular and kinesthetic systems are also stimulated in an unaccustomed fashion. Such stimulations, which are common to all rotating systems, can become disquieting and sometimes incapacitating. Thus, if the stimulations resulting from these forces and moments are large enough, they could bring on motion sickness and reduce man's ability to walk or perform other simple tasks. These stimulations arise from Coriolis and centrifugal acceleration components produced by rotation. Centrifugal acceleration sets up the gravity field for a stationary man, but Coriolis acceleration results when he moves within the vehicle. Disturbing moments occur when a man rotates about a body axis not parallel to the axis of rotation of the vehicle. The accelerations that cause the Coriolis forces and the disturbing moments (crosscoupled angular accelerations) are the stimuli that cause human difficulties in rotating environments.

The Coriolis force environment (ref. 35) can best be analyzed by considering the motion of a crew member in each of three orthogonal directions with respect to the spin axis of the vehicle: radial motion, tangential motion, and axial motion. For radial motion (fig. 15), the Coriolis force acts tangentially in the prospin direction for motion toward the spin axis and in the antispin direction for motion away from the spin axis. The crew

member moving radially with a constant velocity $\bar{v}$ would therefore experience a constant tangential force superimposed upon a varying gravity force (radius r changing). The resultant force which he would experience would continually change in both magnitude and direction. Such a condition is illustrated by the following example from reference 36: If it is assumed that a vehicle has a 20-ft (6.1 m) radius and is spun to simulate a 1g field (ω = 1.26 rad/sec), a 150-lb (68 kg) man climbing up a ladder from the periphery to the center of rotation at 3.5 ft/sec (1 m/sec) would experience a 41-lb (182 N) side force. Although this force acts at the man's center of mass, the problem becomes complicated because his limbs will be moving upward at different speeds from his gross climbing speed and will be subjected to different Coriolis forces.

When a crew member moves tangentially within the rotating vehicle, his local weight will either increase or decrease depending on the rate he moves and the direction he moves (with the spin or against it). These weight changes are due to the increases and decreases in centrifugal acceleration and the Coriolis force acting on the body in motion. For tangential motion (fig. 16), the Coriolis force acts radially along the same line as the effective gravity force; it increases the gravity force for motion in the direction of the spin and it decreases the gravity force for motion in the opposite direction. Thus, if the crew member remains stationary, he will experience a constant gravity level; if he walks with the spin he will feel "heavier," and if he walks against the spin he will feel "lighter."

For axial motion in either direction, the Coriolis force is nonexistent. Therefore, except for minor Coriolis forces induced by nonaxial movement of the limbs or bobbing of the head while walking, the crew member would experience only a constant gravity field during axial movement.

Coriolis accelerations on an astronaut in a rotating environment would have an appreciable effect on the coordination of the individual and could subsequently sacrifice performance levels required of the man if he could not adequately adapt to the peculiar gravity field. Actually, the factors related to human tolerance to the distorted gravity environment are relatively unknown. The functions of the vestibular organs are also of primary concern in the rotating environment. Man maintains his spatial orientation through integration of information concerning the environment which is transmitted to the brain through his sensory mechanism consisting of the eyes, the vestibular organs, and the mechanoreceptors located in the muscle tendons and joints. Consisting of the semicircular canals and the otolith organs, the inner ear as an orientation sensor acts on inertial principles. Any accelerations which are applied to these organs act as stimuli. In response to accelerations resulting from complex rotations and motions, these organs send messages to the brain which conflict with the messages of the eyes and mechanoreceptors which are not modified by inertial forces.

The angular accelerations and the stimulations that they impose on the semicircular canals may be explained by considering the angular motions of a man's head within the rotating environment. Equations for these effects are given in reference 37. If a man is standing with the long axis of his body alined with a radial axis of the vehicle and if he faces tangentially and nods his head, no nonanticipated stimulus is felt. If, however, he turns his head, he experiences a sensation of tilting sidewise. Further, if he rolls his head from side to side, he experiences a sensation of turning. These sensations are, of course, from a direct stimulation of the semicircular canals which, along with a stable visual environment within the vehicle, causes conflicting cues to be sent to the brain. Other orientations of a man within the vehicle will cause different stimuli for the same head motions from those just described (ref. 37). Thus, there is not a single set of stimuli from one type of head motion in a rotating environment. The results of the cue conflicts may be dizziness, loss of orientation and balance, visual illusions, nausea, and, in some instances, possible collapse. Not only man but also objects within the vehicle will be affected by Coriolis and cross-coupled angular accelerations. Thus, the linear and angular motion of tools and equipment will not occur as anticipated and may add to man's discomfort.

In an experimental investigation (ref. 37) with a 15-ft-radius (4.6 m) centrifuge (fig. 17), Stone and Letko found that motion sickness is mainly dependent on the cross-coupled angular accelerations in a rotating environment and not specifically on the rates of rotation that exist. They showed that man can tolerate and adapt to larger cross-coupled angular accelerations when performing turning head motions than when performing nodding motions. In addition, man had a higher motion sickness tolerance in the 3-hour rotating experiment than in the 1-hour experiment. These results indicate that the subject adapts and may successfully continue in a rotating environment over a long period of time.

Many other studies have been performed to determine the ability of man to adapt and perform satisfactorily in the unusual environment of artificial gravity. These studies have involved simulations of the gravity fields through the use of rotating rooms such as those reported in references 38, 39, and 40. Typical results are presented in reference 39 of experiments performed in a manned revolving space station simulator (fig. 18). Adjustments in rate of rotation were made to investigate the adaptability and performance levels attainable by four test subjects exposed to 5 days of rotation at rates up to 6 rpm in a 20-ft-radius (6.1 m) simulator. The subjects were not exposed to large radial movements, but the normal body and limb motions in the outer level were investigated through the performance of everyday tasks. By the end of 3.5 to 4 days of rotation, three of the four subjects felt as well as they would under conventional circumstances. They were able to make any movement without disorientation or stomach awareness resulting. The data illustrating these results are shown in figure 19. The fourth subject adapted less

rapidly but obtained over 95 percent of baseline well-being by the fifth day. All four subjects required little postspin readaptation. Other conclusions from this study are as follows:

(1) Preexposure to rotation facilitates adjustment.

(2) Performance habituation proceeds at a faster rate than physiological adjustment (biomedical data were incorporated in the experimental analysis).

There is still another consideration. If the body axis of a man standing erect in a rotating space vehicle is alined with the radius of rotation, the radial acceleration at his head will be smaller than that at his feet. It has been suggested, by several investigators, that a sizable head-to-foot gradient (difference in g levels) might be uncomfortable to live with. Although past research has not identified this gravity gradient to be as critical a problem as the effects of Coriolis accelerations, an arbitrary maximum gradient has been suggested as 15 percent (ref. 38).

Design Criteria For Artificial Gravity

As a result of the many experimental investigations that have been performed to determine the human tolerance limits of artificial gravity, certain preliminary criteria for the rotating environment have been developed. These criteria include upper and lower limits of gravity levels, maximum tolerable rate of rotation, rotational radius, percentage change in gravity gradient between the head and feet, and the degree of Coriolis acceleration tolerable.

The minimum amount of artificial gravity needed to maintain good physiological tone and to prevent or allay the deconditioning and debilitation previously discussed is not known. Of the other criteria, the maximum tolerable rate of rotation seems to be the most critical and restrictive. The next most significant criterion is the amount of Coriolis force that is tolerable. These two criteria generally will define the vehicle inasmuch as they will set both the rotational rate and radius since the amount of Coriolis acceleration to be experienced varies with spin rate and radius. From experimental observation, the other criteria would allow vehicles of smaller radii and higher rates of rotation than those just discussed.

The maximum tolerable rate of rotation has been the subject of extensive research. Generally, a rotation rate of about 4 rpm has been suggested as safe, although rates of 10 rpm have been tolerated during many tests. It is believed that a relatively conservative value would be about 6 or 7 rpm. Until more significant conclusions can be drawn through additional research and through flight experiments on this subject, a rate of 4 rpm may be recommended. However, a rate of 6 rpm, which appears to be acceptable, would nearly halve the radius required at 4 rpm.

The second criterion, that of the ratio of Coriolis force to centrifugal force generated while moving tangentially, is not as well supported by experimentation. However, a ratio of 0.25 would nearly halve the radius required for a ratio of 0.15. Figure 20 illustrates how the Coriolis force in percent of centrifugal force would vary with radius of rotation, rate of rotation, and gravity level.

Coriolis acceleration.- The tangential and radial motions within a rotating vehicle are significantly affected by Coriolis accelerations. Motions parallel to the spin axis experience little of the Coriolis acceleration effects. In a rotating space vehicle a man would normally be functioning on the floor in a plane essentially perpendicular to the radius of the vehicle. When the man moves tangentially within the vehicle, the Coriolis force increases or decreases the centrifugal force and causes the man to become "heavier" or "lighter," depending on the direction in which he is working. This condition would not seem difficult to adapt to unless he should become excessively heavy or too light for proper traction or the change from the normal artificial gravity was such as to be disturbing. If the rate of walking is arbitrarily selected to be 4 ft/sec (1.2 m/sec) (relatively brisk), difficulty in walking would not necessarily be experienced between gravity levels of $\frac{1}{6}$g and 1g and rotational rates up to 4 rpm. However, a gravity level within these limits may not be sufficient to allay all ataxia (lack of normal coordination) problems. The proportional change in gravity level as a man moves about or moves things about may be disturbing and difficult to accommodate to if it exceeds some proportion of the basic gravity level. A criteria selection in this respect would require experimentation to determine at what level of change difficulty may be encountered.

Motion perpendicular to the floor occurs when moving radially such as climbing toward or away from the center of rotation (fig. 15). This particular motion undoubtedly would only be performed occasionally by an individual, but the characteristic Coriolis forces involved may be frequently encountered when raising and lowering objects. The criterion to be considered for radial motion would be one where the Coriolis force would not exceed a certain percentage of the normal weight (at that gravity level) of the object or person. The resultant of the Coriolis force vector and the gravity force vector would make climbing seem as if it is being performed on a tilted ladder. Possibly the best solution would be to arrange the ladders such that the crew members are forced against the ladder by this acceleration. There would then be up and down sides of a ladder.

Another factor of the problem of Coriolis forces is the way in which objects fall when they are dropped. Actually, an object has a tangential velocity at the radius of its release and as such does not drop but moves tangentially and the floor moves under it. Therefore, an object would fall a certain distance from where it is expected to land. This phenomenon, of course, is influenced strongly by the height from which the object is released above its final resting place.

On the basis of the foregoing discussion, the physiological adaptation to walking on the floor seems relatively easy provided the gravity level stays between $\frac{1}{6}$g and 1g, and objects are easily moved about if the Coriolis force related to the movement of these objects does not exceed a certain percentage of the normal weight of the object.

Gravity gradient.- From the physiological standpoint, the implications of a gravity-gradient environment are vague and most difficult to establish. The fact that a person is heavier when he squats than when he is standing erect seems to be of little significance. However, the hydrostatic pressure distribution within the body may be significant. The gravity gradient in rotating vehicles causes a nonlinear hydrostatic pressure distribution in the body fluid systems and is thus different from that on earth. In the earth environment, that portion of the pressure distribution due to gravity in an erect man's cardiovascular system varies linearly with his height on earth. Actually, the nonlinear pressure distribution in the rotating environment is a function of the square of the radius involved. The ratio of the pressures at the heart and feet, for example, may be an appropriate criterion where such a ratio in the rotating environment should be a certain portion of that in earth gravity.

Cross-coupled angular accelerations.- One of the most significant physiological effects of rotation occurs from cross-coupled angular accelerations. These accelerations occur when an object is moved angularly while it is rotating with the vehicle. Thus, when an object experiences two angular velocities which are not parallel, an angular acceleration occurs which is about a third axis perpendicular to the plane of the two velocities. From the physical standpoint, an object rotated in the revolving vehicle will experience these accelerations which could be annoying to one handling the object, for example. Clearly then, these undesirable accelerations probably should be appreciably less than the acceleration that the individual could impose on the object. Herein lies a criterion for maximum vehicle rate of rotation. On the basis of conservative rates at which objects are rotated and heads are turned, experimental results indicate that adaptation to the cross-coupled acceleration environment can occur at vehicle rotation rates up to 10 rpm (ref. 41). However, as noted previously, this problem has not been resolved and a rate of 4 rpm is frequently quoted as the maximum that should be used.

Design envelope.- Certain criteria for the design of a manned rotating space vehicle have been identified. These criteria have been incorporated in figure 21 to form a design envelope illustrating limits that might be imposed on such a configuration design. The criteria values presented are not as completely supported by experimental evidence as would be desired. However, if conservative selections are made, an arbitrary rotating vehicle can be defined and an estimation of its practicality can be made.

In figure 21, the value of C_1 represents the tolerable percentage increase or decrease of man's artificial weight as he moves at 4 ft/sec (1.2 m/sec) within the vehicle.

The correct value of C_1 must be established by experiment, but in figure 21 a graphical representation of values of C_1 from 15 percent to 50 percent is shown.

The value of C_2, the percentage weight change in the object when moved, was selected to be 25 percent when the velocity of that object is 4 ft/sec (1.2 m/sec).

The distance from the local vertical at which a dropped object lands C_3 was selected to be 1 ft (0.30 m) for objects dropped from 3 ft (0.9 m) above the floor. This criterion indicates that at a radius greater than 44 ft (13.4 m), such an object will strike the floor not more than 1 ft (0.30 m) from where it was expected to land.

The ratio of the weight of an object on the shelf to its weight on the floor C_4 was chosen to be 0.5 for a height above the floor of 6 ft (1.8 m); this indicates that an object so positioned shall weigh not less than one-half its artificial weight on the floor. Figure 21 shows that this condition will be satisfied at radii of rotation greater than 12 ft (3.7 m).

For the purpose of figure 21, the gravity gradient limit which would be comfortable for man in the rotating environment C_5 was selected to be 0.15; this indicates that the centrifugal acceleration at the head shall not be less than 85 percent of the acceleration at the feet. This condition is satisfied at radii greater than 40 ft (12.2 m) for a 6-ft (1.8 m) individual.

The ratio of fluid pressure at the heart to fluid pressure at the feet C_6 was selected to be at least 90 percent of the same ratio when in the earth environment. It is further assumed that the heart is 4.5 ft (1.4 m) above the floor level. The ratio equals 90 percent at a vehicle radius of 26 ft (7.9 m) and becomes more like that in the earth environment at radii greater than 26 ft (7.9 m).

The cross-coupled angular acceleration experienced when a man rotates an object C_7 was selected to be 0.50. This value indicates that the cross-coupled acceleration shall not exceed 50 percent of the angular acceleration that the man can impose on the object. It was assumed that a man can impose a ratio of maximum angular acceleration to angular velocity of 16 per second. Eight rpm is the upper limit at which this condition is satisfied.

The maximum rate of steady rotation tolerable to man C_8 was taken to be 6 rpm. However, for figure 21, several values are shown.

The hatched area in figure 21 is bound by an assumed value of Coriolis ratio of 0.25 ($C_1 = 0.25$), a maximum rate of rotation of 6 rpm ($C_8 = 6$), and a gravity level not to exceed 1g when moving within the vehicle. This design envelope allows a minimum rotational radius of about 55 ft (16.8 m).

From the convenience standpoint, table I shows that if the artificial gravity level selected falls within the design envelope of figure 21, the environment produced will satisfy the requirements of walking and performance of everyday tasks and, in addition, will simplify some of the designs of mechanical systems needed aboard the space vehicle.

DISCUSSION AND RECOMMENDATIONS

The numerous problems of weightlessness, including the possible physiological degradations and inconveniences imposed on the space traveler, have been reviewed. The various techniques that have been considered applicable to the prevention of physiological degradation and to the preservation of performance and convenience in the weightless environment have been discussed. Decisions pertaining to future extended space missions must, of course, include considerations as to which of these techniques need to be incorporated into the mission vehicle. However, such decisions require certain compromises. These compromises are involved with such factors as mission objectives, the exposure time of the astronauts, and the penalties of weight and crew time imposed by the addition of these equipments for physiological maintenance and convenience. The purpose of the following discussion is to examine these factors so that the appropriate trade-offs may be more judiciously made and to suggest areas where further research is required to attain a clearer understanding of the problems involved.

Mission Objectives

Exclusive of considerations, such as national prestige, there are three fundamental objectives of space flight: space-oriented experiments, earth-oriented experiments, and transportation to and from the vicinity of other planetary or space-borne objects. In addition, auxiliary technological development experiments are incorporated in most missions, wherein the development of equipment or systems for the enhancement of future missions is involved. Such technological experiments are only warranted if other justification exists for the future mission being considered. In most instances, more than one of the three fundamental objectives may be combined in a given mission. In earth orbit both space-oriented (astronomy, for example) and earth-oriented (weather observation, for example) experiments can be accomplished on the same mission. During a mission to transport men to Mars, space-oriented experiments will be performed enroute.

Future space flight will offer to the scientific community certain resources which will justify its use as a laboratory environment. These resources include

(1) A weightless or reduced-gravity environment

(2) A clearer view of space and a broader view of earth

(3) The opportunity for man to explore other planets and travel beyond the confines of earth

As previously discussed, most of the space-flight experimental program will require either a weightless environment or will be more easily performed in a weightless environment (ref. 3). Since 83 percent of the proposed experimental program should have a weightless environment and since the performance of an experimental program is a primary objective of the mission, any compromise of the feature of weightlessness requires most critical consideration.

As has been noted in the literature, if a rotating vehicle is used and an area of weightlessness is required, a counterrotating hub section could be incorporated. Of course, the vehicle could be periodically stopped from rotating provided the experiments are amenable. In either case, an exceedingly complex and costly vehicle is involved. On the other hand, man's ability to perform the experiment program is also a critical consideration because, if the experiments cannot be adequately accomplished, the mission is compromised. Therefore, another fundamental point of consideration is the influence of the techniques and devices for alleviating the psychophysiological problems of weightlessness on the accomplishment of a particular mission. The devices which have been discussed range from one having little or no influence on the state of the vehicle (the lower body negative pressure system, for example) to one completely altering the vehicle configuration (artificial gravity).

For a planetary transportation vehicle, compensation for the weightlessness problems may have a somewhat different impact on the mission depending on the en route experiments planned. However, experiments similar to those of earth-orbital missions probably would require a weightless and stable vehicle. Therefore, the vehicle complexity would be the same as that required for earth orbit. If, on the other hand, the vehicle was fundamentally for transportation, rotation would have much less impact on the mission accomplishments.

This discussion assumes first priority for the mission experiment requirements and only secondarily those requirements of the man. If the astronauts require a protective system and if the devices that do not require vehicle rotation for physiological conditioning are not adequate, then artificial gravity will be required.

Astronaut Exposure Time

Thus far, man has experienced 2 weeks of space flight with weightlessness with no serious degradation in his physiology or performance (ref. 1). It has been estimated that astronauts probably can tolerate 30 days of weightlessness without difficulty. Future missions appear to be grouped into two categories: earth orbital, in which except for a study of man the exposure to the space environment will be about 90 to 120 days (ref. 11), and

planetary, in which the astronauts will be exposed to the space environment for about 500 days.

From the standpoint of physiological response to weightlessness, there are two principal considerations: (1) physiological adaptations to the environment, and (2) a readaptation process during reentry accelerations and the subsequent earth gravity. Regarding adaptation to weightlessness, results of flights thus far indicate a relatively rapid physiological adjustment to an apparently stable situation. Eating, drinking, and exercise appear to have had a profound physiological influence during the flights to date, and the separate influences of weightlessness have not clearly been defined from the flights. However, the apparent result of past flights is that with proper food and water intake and with proper exercise a plateau of physiological condition is reached and on return to earth about 2 days are required to readapt. The readaptation to the earth environment was probably more imposing than the weightless adaptation, although in no instance was it serious. Whether some additional adaptation beyond that experienced to date will occur for extended missions or whether a slow degradation was occurring in past flights that was not evident is not known. Apparently only experience will clarify this point. It can be further stated that if stable situations have been reached in Gemini flights and if no further degradation occurs with time, then the readaptation to earth gravity environment will not be difficult or extensive and no special devices are required from the physiological standpoint. However, extended investigations are required through the use of ground-based techniques to determine whether physiological degradation will progress beyond that so far experienced and to determine the time and degree at which the plateau of weightless adaptation occurs.

If some additional adaptation or slow degradation occurs during extended space flight, one of the sundry prophylactic or therapeutic methods discussed in this text probably will be required. Actually until experience indicates otherwise, it will be propitious to provide such devices for some of the crew members to use, while others will not. Thus, such devices are basically equipment for physiological experimentation until the need for them is proved or disproved. Inasmuch as the evidence that exists does not clearly identify any of the sundry techniques previously discussed as being superior, continued ground-based studies and, where possible, space-flight experiments (for example, ref. 42) with each seem to be desirable. Table II summarizes the results of experience with the various devices to date. Only the pressure cuffs have been used in a space experiment and inconclusive results were obtained.

Anti-g devices are not intended to prevent deconditioning but to counter the effects of deconditioning by mechanically encompassing the lower limbs during reentry and during readaptation to the earth environment. As a result of simulated weightless studies, they have appeared very adequate for this purpose and would probably have the least impact on system weight and astronaut time consumption of any of the devices listed. However, further ground-based tests of the anti-g devices are required. Related investigations

which have been performed have been limited in duration and if the devices are tested following very long periods of simulated weightlessness (at least until the plateau of adaptation occurs), it will be possible to identify potential troubles which may occur when the subject is returned to 1g.

Experimentation is also needed to determine the level of artificial gravity required to prevent, or adequately reduce, the expected deconditioning due to weightlessness so that reentry and earth gravity do not seriously affect performance. A method of study using a centrifuge has been proposed in reference 43. In this approach, the subject is oriented radially on a centrifuge (effectively in bed rest) except when the centrifuge is in operation. An exposure of this nature would indicate the influence of partial gravity levels on physiological deconditioning.

Another, and possibly simpler, experimental program involves a subject in bed rest and during the normally active portion of the day the bed would be tilted to an appropriate angle to give the desired gravity level along the long axis of the body, this force being supported on the feet. In other terms, this technique would impose a hydrostatic pressure in the body fluid system represented by that portion of 1g caused by the tilt. During such tests, limb motions should be restricted to those in the bed plane and should generally remain in contact with this plane. The bed plane should be balanced and free to move in its plane to retain the basic reaction force of the gravity component being simulated on the feet. During normal sleep periods, the bed plane would be made horizontal.

Another similar approach using the concept of tilting so that the appropriate partial gravity level is attained along the long axis of the body is one in which a sling support and inclined plane is used such as that currently being utilized to examine mobility at lunar gravity (ref. 22). In this approach, all body members are supported and only the component of gravity desired imposes stress on the body. The subjects could be normally active and could work on the inclined plane during daytime hours and would spend the rest of the time in bed. These methods would establish the debilitating effect of reduced gravity without the imposed influence of rotation sustained on a centrifuge. Several subjects at each of at least three partial gravity levels would be required.

Although adaptation will occur at each gravity level, the trend of degradation with gravity level should indicate the minimum level from which the changes in response to normal stresses of exposure are within the normal variability of the subjects investigated. With such data a minimum level of artificial gravity to prevent degradation will be available.

Exclusive of physiological degradation, there remains for consideration the general problem of convenience and performance; in weightless flight, the absence of gravity could impose complexities to the performance of certain everyday tasks. Table III lists several of the common factors that may affect the crew's performance during extended missions.

Solutions for some of these problems have been found, whereas for other problems there is promise of solution. Whether the crew is amenable to continued exposure to these methods of solution is not known. The real answer to this question will occur only after extended experience in weightlessness.

There are, of course, several inconveniences of artificial gravity, as has been propounded previously in this paper. Exposure to rotation for several days (refs. 40 and 42) has indicated a general adaptation to rotation and a recovery of performance levels to prerotation levels. However, the appropriate level of gravity for locomotion,as noted before, required further study. A program of research using a rotating space station simulator (fig. 22) or similar devices to establish appropriate levels of artificial gravity for locomotion is required. Problems of maintenance and repair and the gravity level required for these activities also may be established.

It is not clear, however, that artificial gravity is really needed either for preventing physiological degradation or for alleviating the inconveniences of weightlessness. Further aspects of the use of the various devices for coping with weightlessness are the weight penalties involved and the astronaut time consumed.

Weight of Equipment and Astronaut Time Required

The remaining factor of significance in the use of the sundry devices to allay the effects of weightlessness is their direct costs to the mission. Such costs are measured in terms of direct weight for the system and the time lost in using the system. The weight involved causes a reduction in the useful experimental payload that can be carried. The astronaut time involved causes a reduction in time available to perform experiments or operate the vehicle.

Table IV lists the various devices considered, approximate weights for each, and approximate time required by each astronaut while using the device. The most critical device in terms of weight is, of course, the mechanism for providing artificial gravity; for the MORL, as noted previously, it represents a significant reduction in payload that could otherwise be carried. Essentially, no astronaut time is involved with artificial gravity, although there is an initial period of adaptation (fig. 19). As pointed out previously, many experiments cannot be performed in the rotating environment; this imposes a further real penalty on the availability of astronaut time. Time for stopping the rotating vehicle or transferring to the weightless hub would be involved if these experiments are to be performed.

All other systems impose appreciably less weight penalty than does the mechanism for providing artificial gravity, and except for the centrifuge there is little concern for weight in the choice of other systems. It should be noted that except for antigravity-type devices, energy in the form of electric power, compressed gases, or propellant is required

for each system, but this information has not been included in table IV. As was previously discussed, this factor will impose a rather large additional penalty on artificial gravity, and appreciably fewer penalties will be involved with the use of the other therapeutic techniques.

Two to four hours of each astronaut's active hours per day are involved in the use of the lower-body negative-pressure device. This time is one-eighth to one-fourth of the available awake time and, therefore, additional crewmen are required to perform a given mission in the period of time it could be performed without the physiological conditioning device. The same situation exists for the use of an onboard centrifuge where approximately 4 manhours per day (for a six-man crew) are required for riding and monitoring the centrifuge and are lost from other activity. This penalty is not as stringent as that paid for the use of the lower-body negative-pressure device. The astronauts can actively pursue their normal activities with pressure cuffs and cardiovascular conditioning suits, although each device (particularly the cardiovascular suit) may be distracting and inhibiting and reduce proficiency in the performance of tasks.

Additional earth-based studies of the cardiovascular suit, which in its basic form covers the entire body, are required to determine whether application of the principle only to the limbs or just the lower limbs would be adequate. Studies should be performed to determine the minimum time of wearing the suit required to prevent degradation and, after extended simulated weightlessness, to determine the period of application required to recover normal physiological condition.

POTENTIAL RESEARCH

The actual characteristics of the degradation due to weightlessness need further identification to establish whether a stable level of adaptation occurs and to establish the degree of change due to this adaptation and the time period involved in reaching this level. The effect of this change in the state of an astronaut on his ability to perform in space and return safely to earth also needs to be established.

The adequacy of antigravity devices to be worn during reentry and during rehabilitation on earth needs further examination. In addition, examination should continue of prophylactic and therapeutic devices which would be worn or used in space to allay, prevent, or recover from possible degradation due to weightlessness.

Artificial gravity remains a possible, although costly, method of coping with the problems of weightlessness. However, the minimum artificial-gravity level required to

maintain physiological condition and proper performance needs to be established. Further studies to establish levels of artificial gravity for adequate locomotion and for the performance of required tasks are also required. Inasmuch as artificial gravity involves rotation, an effort should be made to determine acceptable levels of angular velocity and accelerations for performance and manipulations within the vehicles as well as a continuing examination of the psychophysiological aspects of rotation. These examinations require earth simulations of weightlessness. Such simulations need continuing verification by correlation with flight experience. Possibly more precisely tailored simulations than have existed are required.

CONCLUDING REMARKS

In extended missions in space, the potential problems that weightlessness may impose on man remain rather complex and intractable. The solutions though numerous are generally unproved. From the physiological standpoint, if degradation does not proceed beyond that which has been experienced in the 2 weeks of Gemini flight, there is essentially little or no problem since performance was not significantly affected and readaptation to the earth's environment was reasonable. If experience in future flights and extended simulation studies show a further progression in degradation beyond that of the Gemini flights, some prophylactic or therapeutic method must be used on extended missions. A therapeutic device, such as the anti-g suit, worn during and subsequent to reentry probably has the least impact on the design of any mission or system and may be quite adequate for the problem. If ground-based tests prove otherwise, other more complex techniques, such as lower-body negative pressure, applied either as a therapeutic or prophylactic device may be required and should be planned for. These devices should be treated as experiments unless real space experience proves their need. Because of the massive impact that artificial gravity by vehicle rotation has on mission objectives, its use as a prophylactic (or therapeutic) device should be considered as a last resort. Studies of partial-gravity levels, either by tilted bed rest or with horizontally oriented subjects in rotating simulators, are needed to establish the required artificial gravity to prevent or to adequately reduce the expected degradation of weightlessness.

From the aspect of convenience to the astronauts and the potential loss of proficiency, or even the ability to perform continuously for extended missions in weightlessness, consideration must be given, firstly, to spatial aids and restraints for use in the weightless environment and, secondly, to a centrifuge for certain critical functions and critical kinds of work. Again, artificial gravity by vehicle rotation must be considered as a last resort because of its massive influence on mission objectives and complexity of vehicular design.

Studies of spatial aids are required, primarily in water immersion simulations and possibly for extended periods of time, to establish the satisfaction of such aids. Studies of artificial gravity are also required to establish proper gravity levels for mobility and other working conditions.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., August 27, 1968,
127-51-08-04-23.

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TABLE I.- ARTIFICIAL GRAVITY FOR CONVENIENCE

Item	g level	Remarks
Walking	$>1/6$ <1	Simulator studies on a firm flat surface have indicated the adequacy of $\frac{1}{6}$g. Less than this level may be adequate but insufficient data exist. Other means of mobility, such as jumping, also may be desirable. Studies on a rotating space station simulator should examine these areas.
Placement of objects	>0	If linearity of frictional forces with weight is assumed, objects would have the same position stability at any g level, except objects on flat surfaces will move to the largest radius. An object's stability when placed improperly would be the same at any g level. Upsetting stability would vary linearly, however, with a decrease in g level. Wider bases on objects may be required.
Waste collection	>0	Natural expulsion processes with any amount of g level and proper systems design should transport the material and hold it in place. Proper collector design would be required to minimize such problems as splashing which would be affected by radius and rotational rate.
Gas-liquid separation systems	>0	Any amount of gravity will maintain separation once it is accomplished. Sloshing from perturbations, however, will vary with g level. During a separation process, the rate of separation will be a function of the g level; thus system size will be influenced by g level. If all systems are designed for zero-g, as they most likely will be, then with proper orientation any g level will augment the system process. A study of the influence of g level on systems seems to be desirable.
General convection of the settling of dust, and so forth	>0	Forced convection and filtering is common in 1g systems, as in aircraft, and will certainly be used in spacecraft, especially as they will undoubtedly be designed for zero-g. Thus, any amount of g will supplement the system if it is properly oriented.
Manual application of forces and moments	>0	The ability to push parallel to the floor varies linearly with g level, assuming linearity of frictional forces, and would become nil at zero-g. Lifting ability increases with reduced gravity. Torques applied by using one's weight will decrease with g level. Proper use of the floor and other accouterments should allow manned application of forces and moments relatively unaltered by g level provided sufficient gravity exits for him to conveniently arrange himself to apply the forces.

TABLE II.- A SUMMARY OF DEVICES INTENDED TO PREVENT PHYSIOLOGICAL DEGRADATION IN WEIGHTLESS FLIGHT

Device	Ground-based experiment	Space experiment
Pressure cuffs	Water immersion (ref. 18)	Gemini – inconclusive results (ref. 1)
Lower-body negative pressure	Bed rest – reduced apparent (ref. 27) cardiovascular deconditioning	Possible to be flown on MOL and/or AAP
Cardiovascular conditioning suit	Bed rest combined with water immersion – reduced apparent (ref. 29) cardiovascular deconditioning	
Anti-g suit and/or elastic leotards	Bed rest – prevented the exemplifications of (ref. 26) cardiovascular deconditioning	
Onboard centrifuge	Bed rest and immersion – reduced apparent (ref. 31) cardiovascular deconditioning	Apollo Applications Program experiment T-010 (ref. 42)
Artificial gravity		Possible Apollo Applications Program workshop experiment

TABLE III.- MAN-RELATED SPACE-VEHICLE PROBLEMS

Problem area		Approaches
General	Specific	
Work environment	Crew convenience	(1) Work aids and restraining systems in weightlessness (2) Centrifuge for certain kinds of work (3) Artificial gravity
Mobility	Locomotion	(1) Pushing, hand guides, and maneuvering units in weightlessness (2) Walking in artificial gravity
Cabin debris	Particle control	(1) Collection and filtering by forced convection (2) Artificial gravity
Nutrition	Eating and drinking	(1) Syringe bottles and tubes in weightlessness (2) Normal utensils, and so forth, in artificial gravity
Personal hygiene	Bathing and cleaning	(1) Sponge or chemical pads in weightlessness (2) Showers and sinks in artificial gravity (3) Hydrotherapeutic devices and clothes washing machines applicable with either weightlessness or artificial environment
Defecation and urination	Collection and stowage	(1) Air suction (2) Centrifuge (3) Artificial gravity

TABLE IV.- WEIGHT AND ASTRONAUT TIME REQUIRED FOR DEVICES INTENDED TO PREVENT PHYSIOLOGICAL DEGRADATION IN WEIGHTLESS FLIGHT

[Approximated weights exclusive of power and fuel requirements]

Device	Weight	Astronaut time consumed
Pressure cuffs	≈20 lb (9.1 kg) per crewman	The device may be worn continually and may not specifically require time or attention. It may, however, have a distractive influence on the astronaut.
Lower-body negative pressure	≈100 lb (45.4 kg)	Each astronaut must use this device 2 to 4 hr per day.
Cardiovascular conditioning suit	≈20 to 100 lb (9.1 to 45.4 kg) (depends on additional tests to determine extent of bodily coverage required)	The device must be worn 2 to 6 hr per day, but after donning other work can be pursued. It may, however, have a distractive influence on the astronaut. Donning and doffing time would involve 1/2 to 1 hr.
Anti-g suit and/or elastic leotards	≈5 to 15 lb (2.3 to 6.8 kg) per crewman	This device would be donned prior to reentry and otherwise would require no astronaut time.
Onboard centrifuge	≈300 lb (136 kg)	Approximately 4 man-hr per day (for a six-man crew) must be devoted exclusively to its use.
Artificial gravity	≈4000 lb (1810 kg) (depends on vehicle configuration)	Basically this device requires no astronaut time. However, experiments requiring weightlessness require time for despinning or transfer to weightless portions of the vehicle.

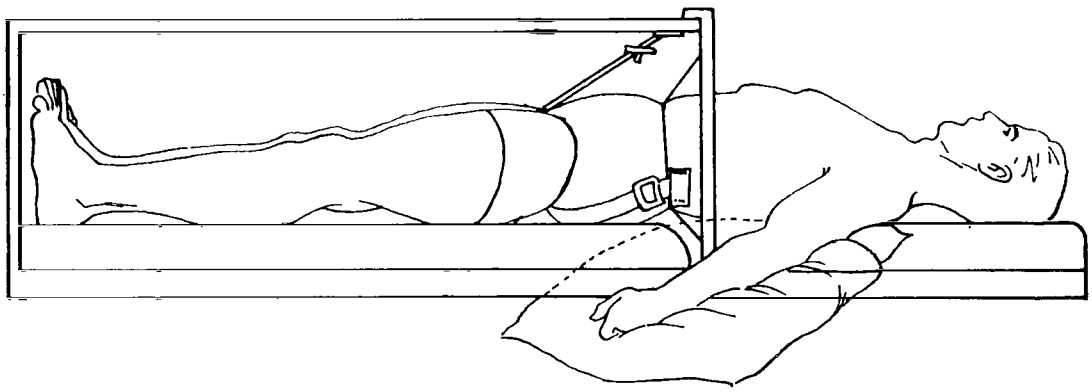


Figure 1.- Lower-body negative-pressure device.

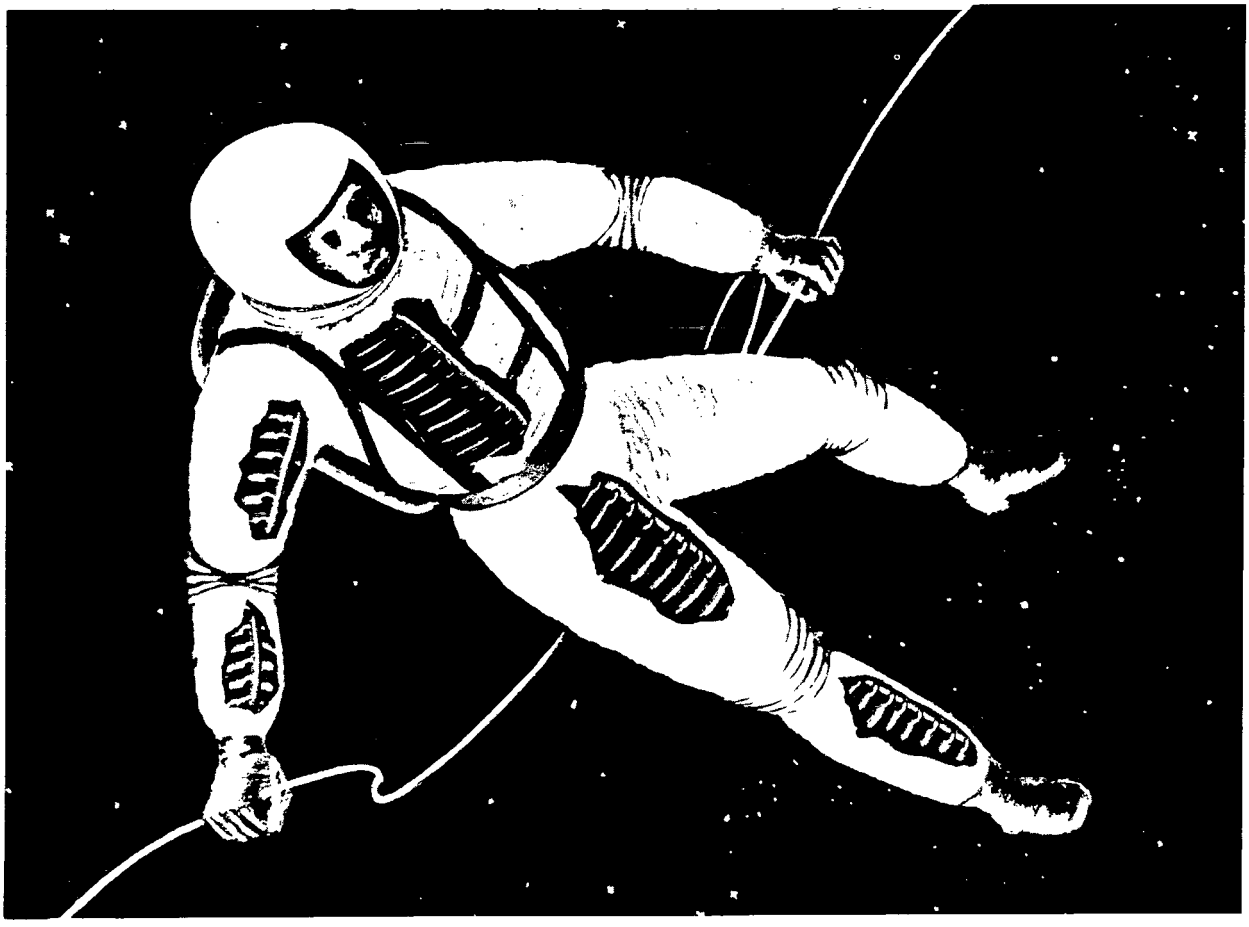


Figure 2.- Cardiovascular conditioning suit.

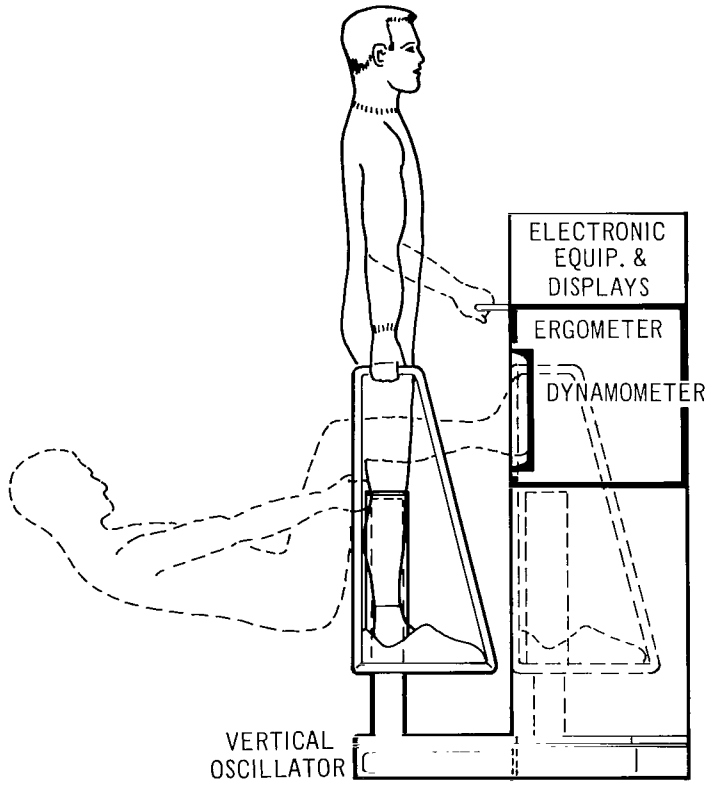


Figure 3.- Isometric exercise apparatus.

Figure 4.- Pedal ergometer.

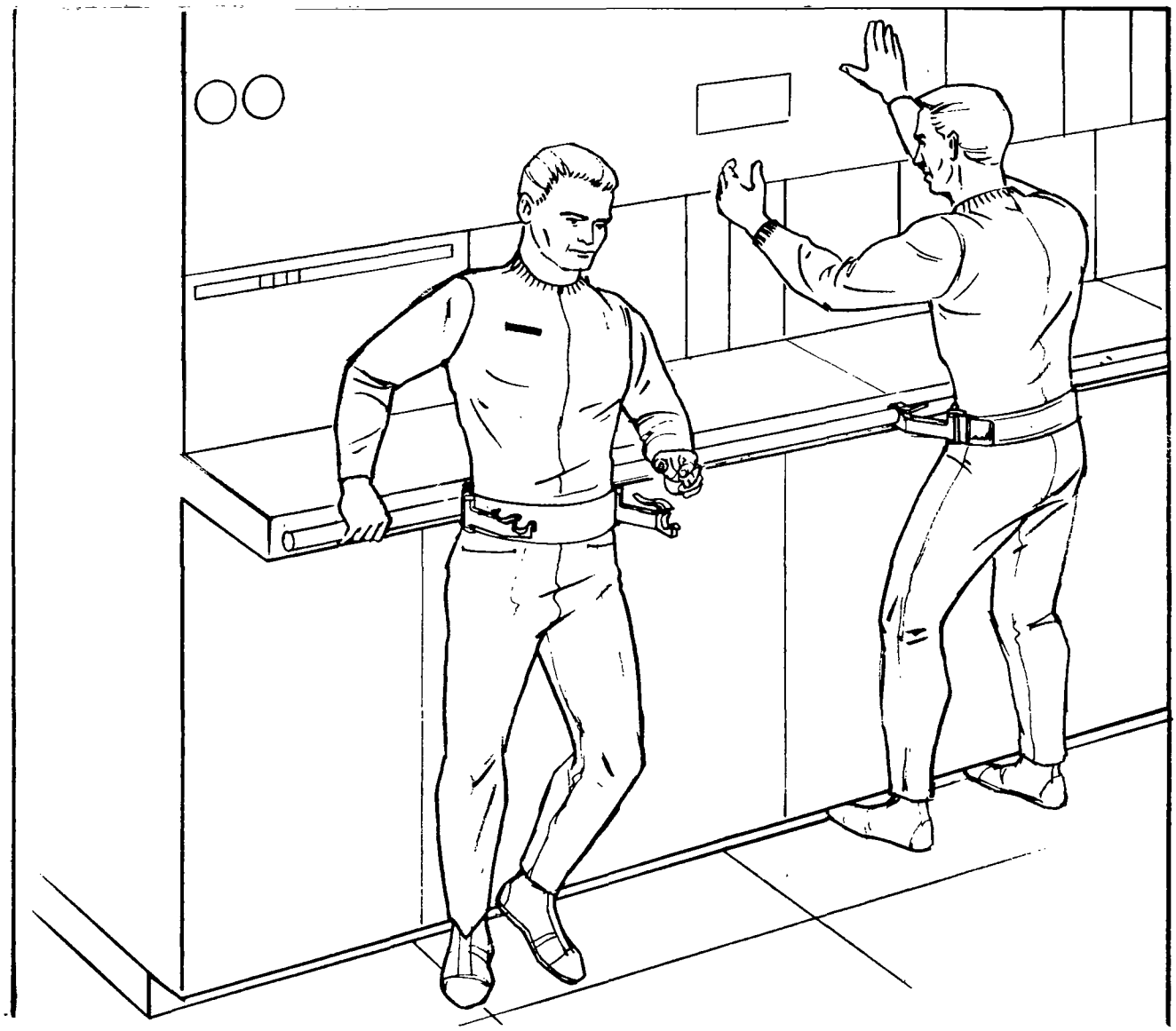


Figure 5.- Zero-gravity waist-belt restraint.

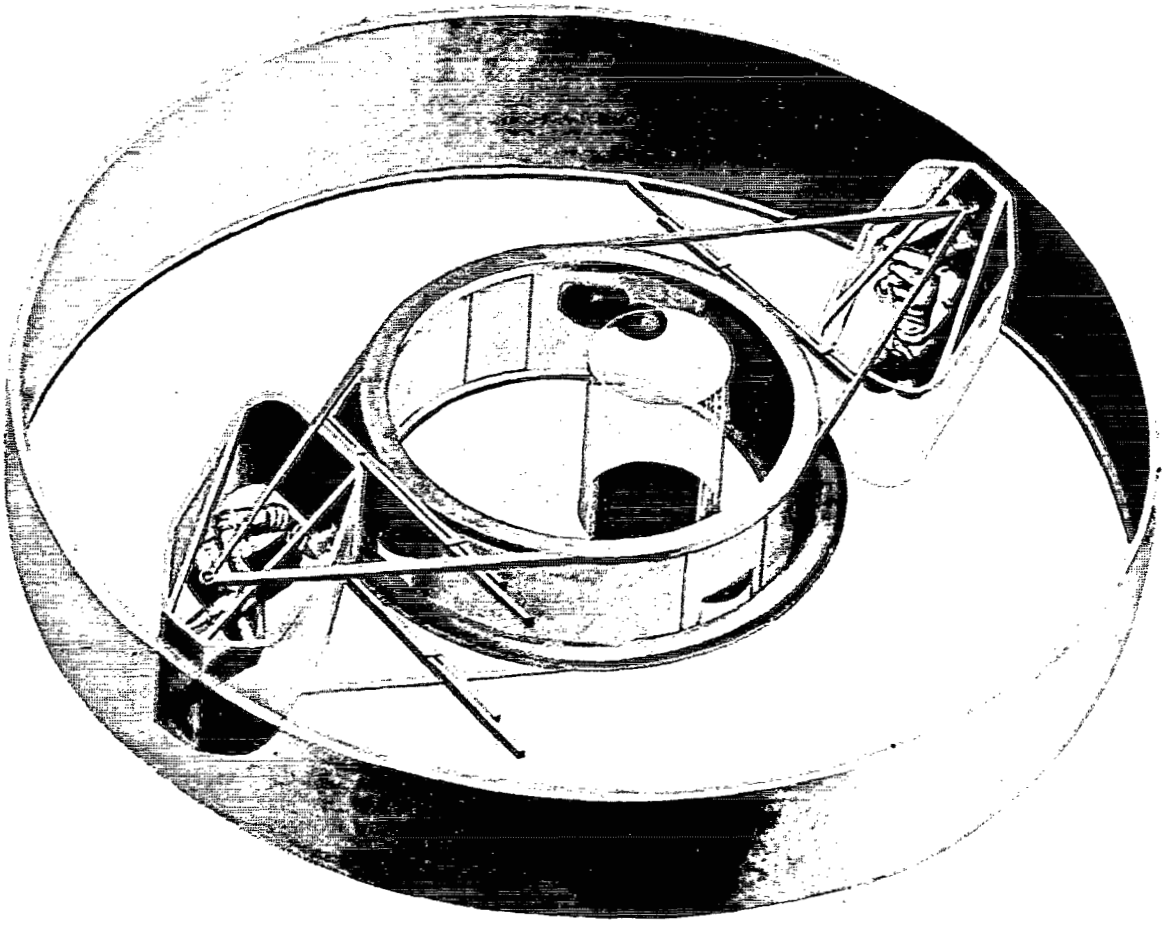


Figure 6.- Short-radius-centrifuge concept.

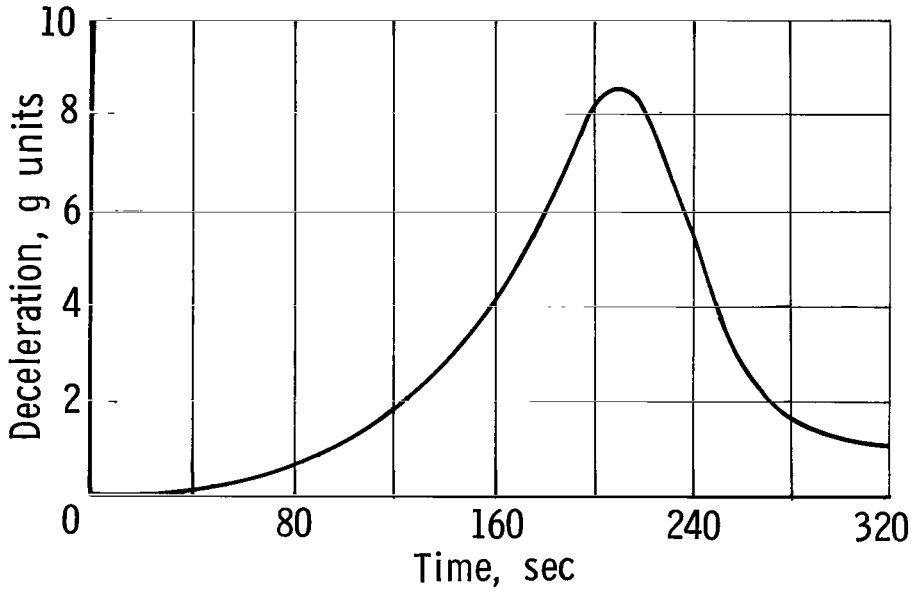


Figure 7.- Typical Apollo spacecraft reentry deceleration profile.

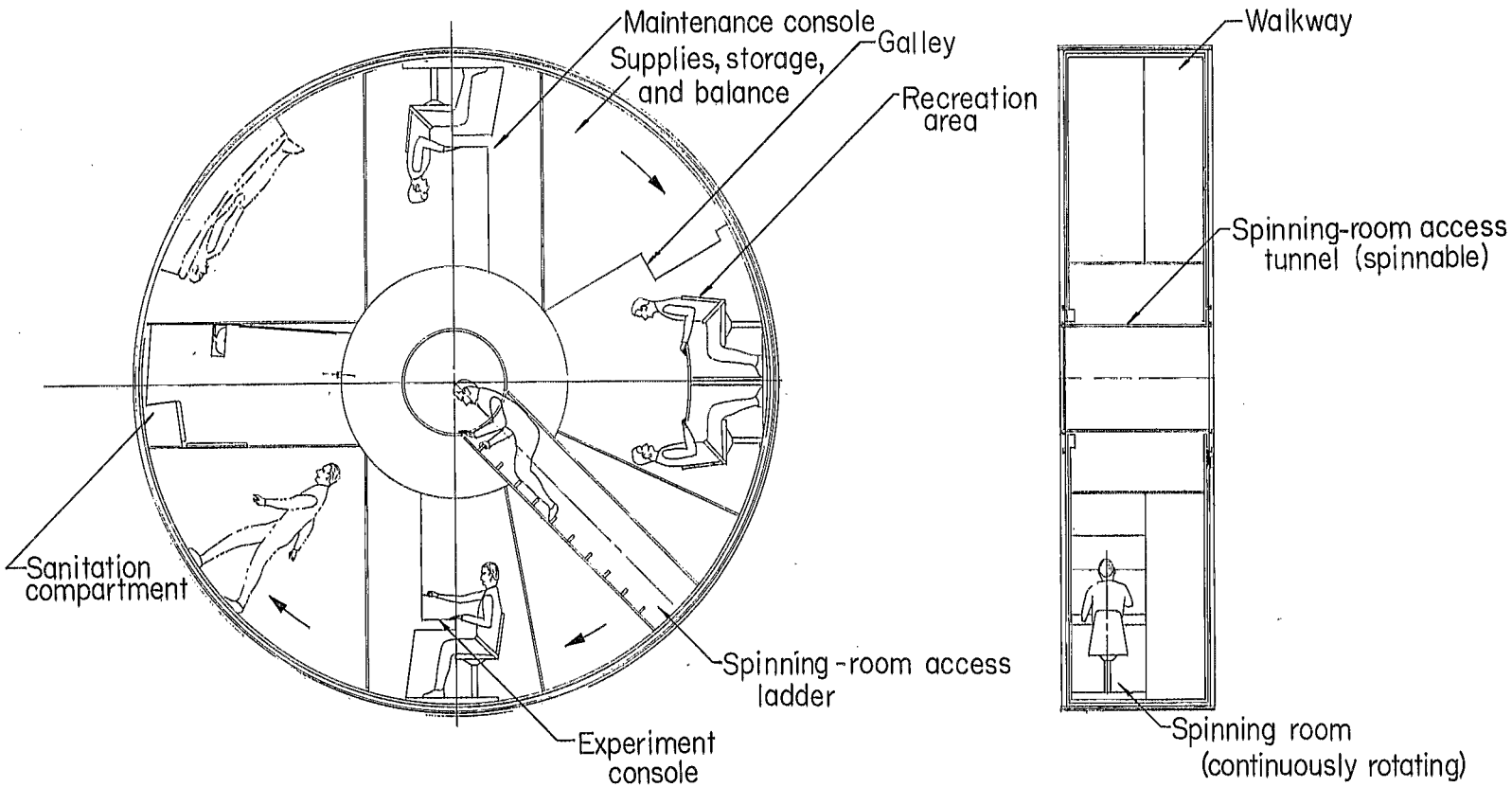


Figure 8.- MORL spinning-room concept.

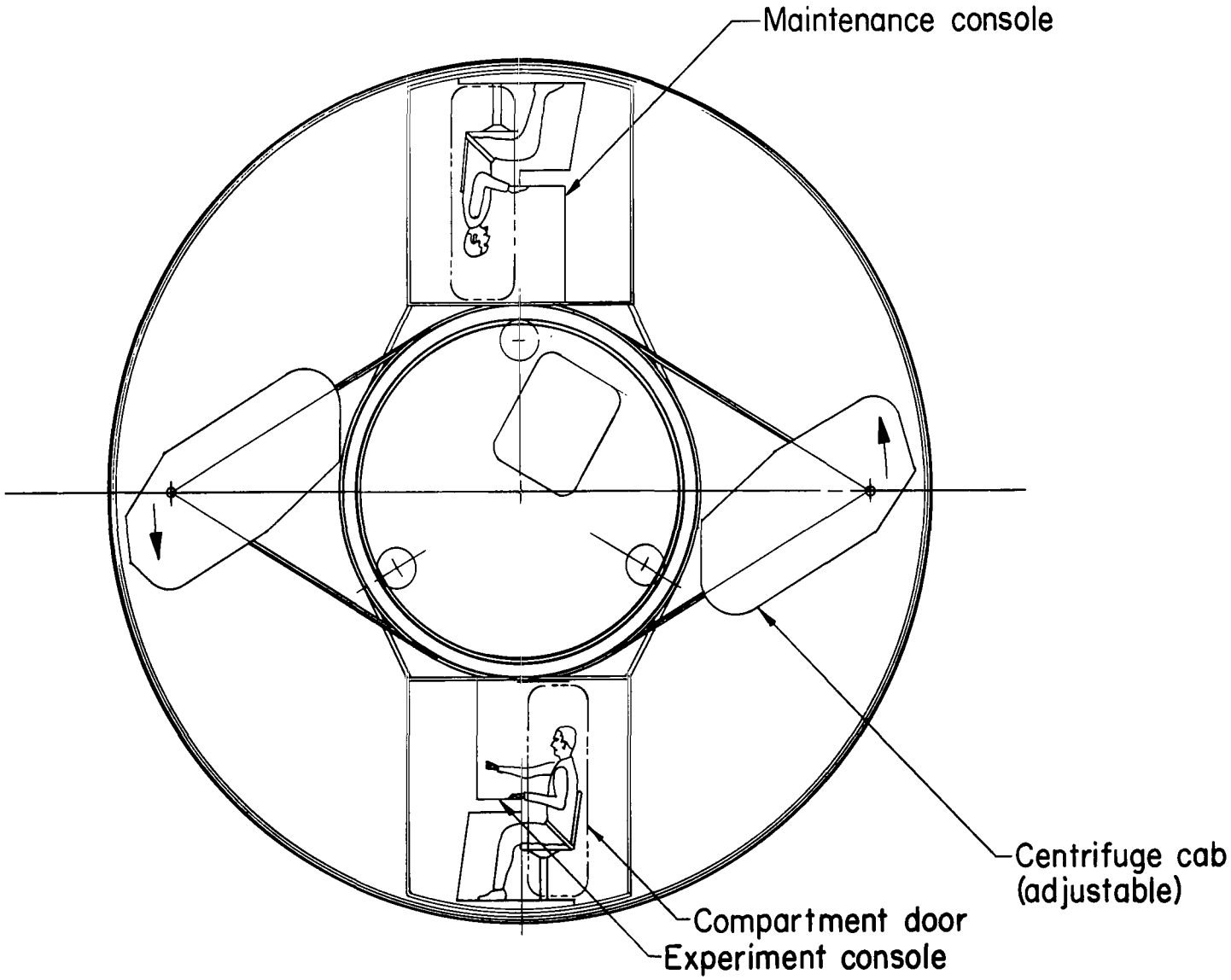


Figure 9.- MORL dual-spin-console concept.

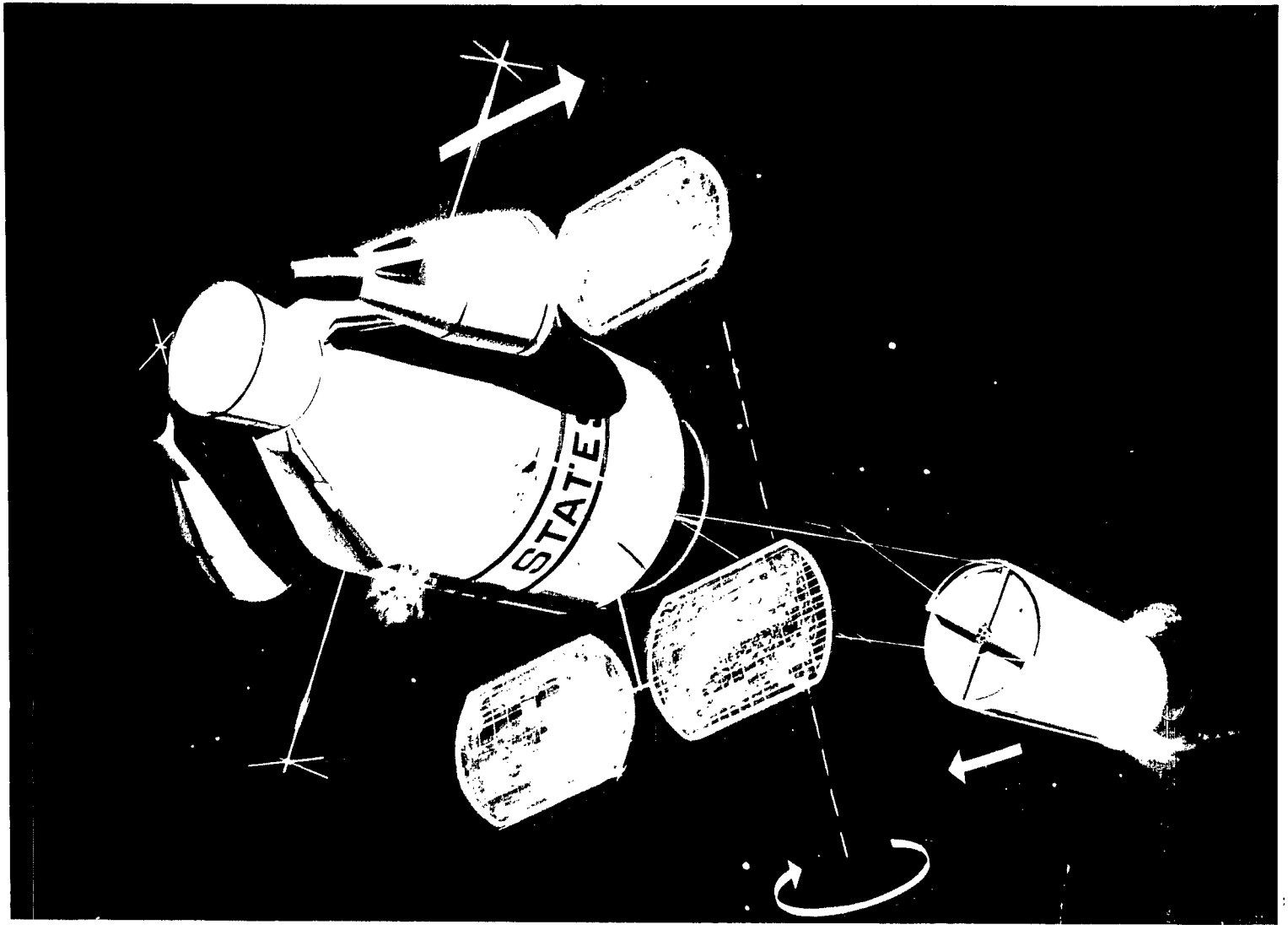


Figure 10.- MORL in spinning mode.

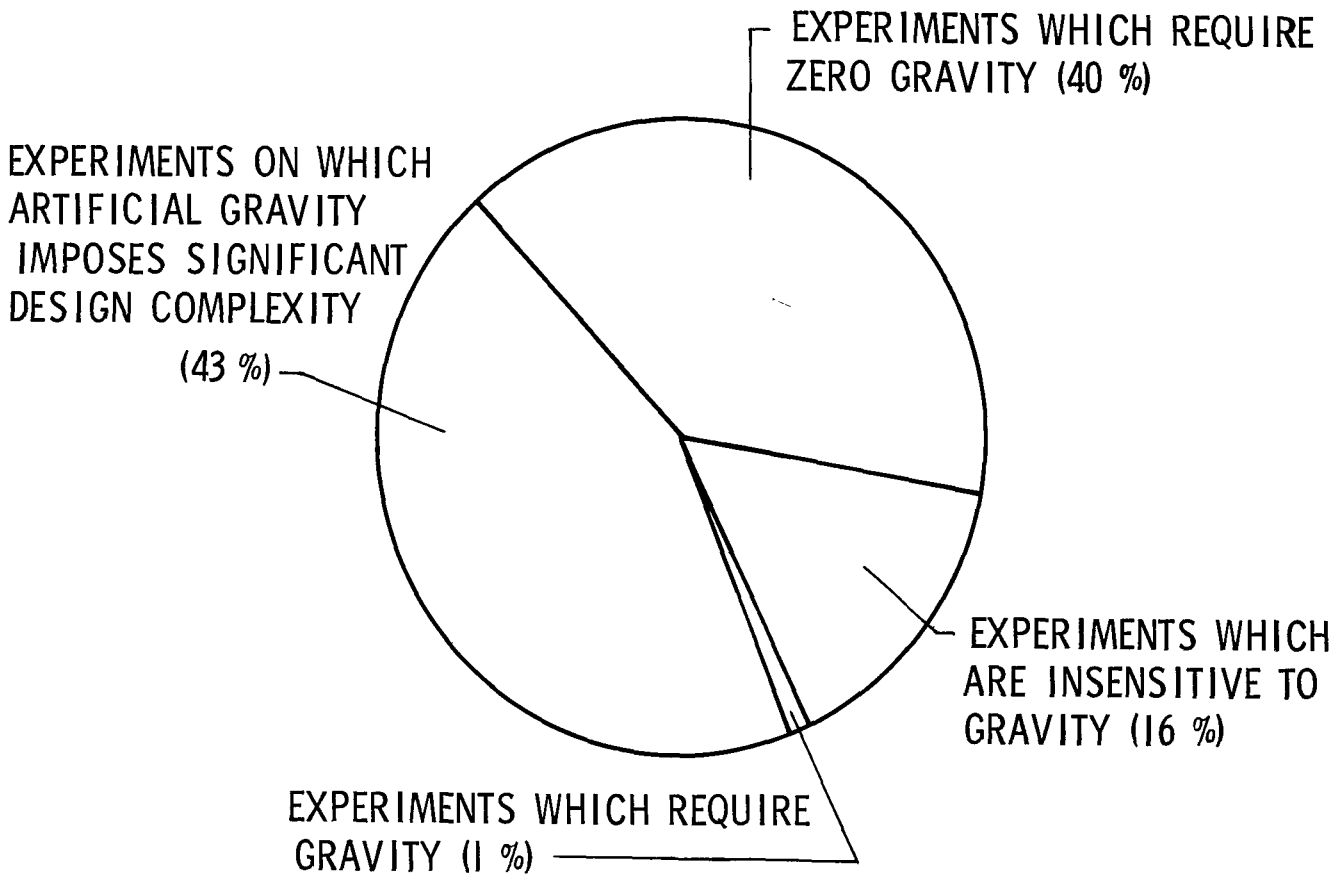


Figure 11.- Typical earth orbital experiment program. (From ref. 4.)

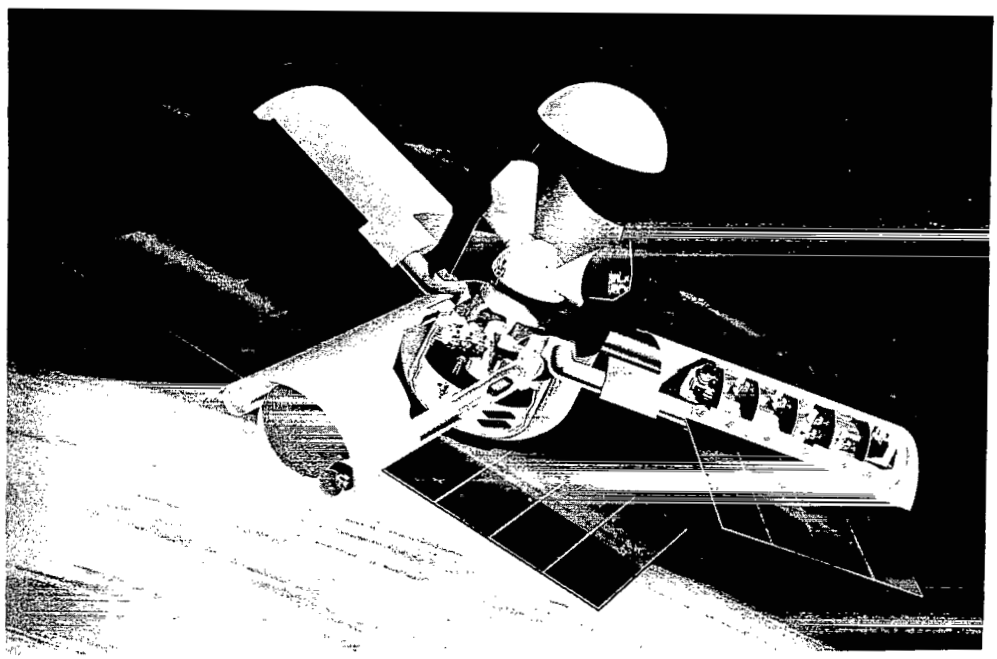


Figure 12.- Three-radial-module configuration of a large, rotating, manned orbital space station.

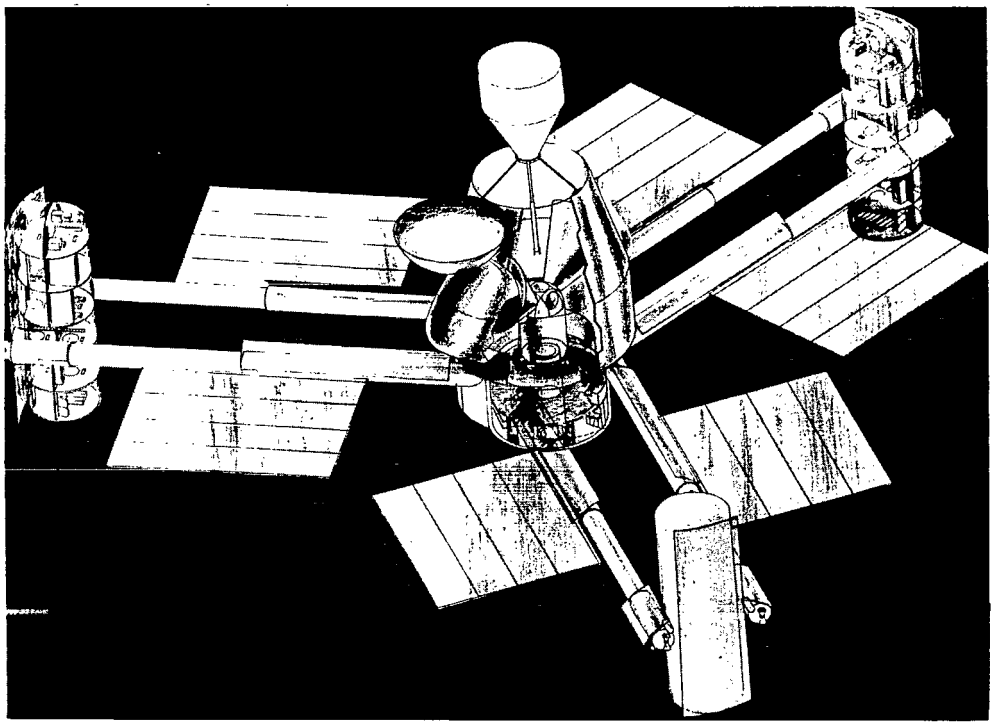


Figure 13.- Three-axial-module configuration of a large, rotating, manned orbital space station.

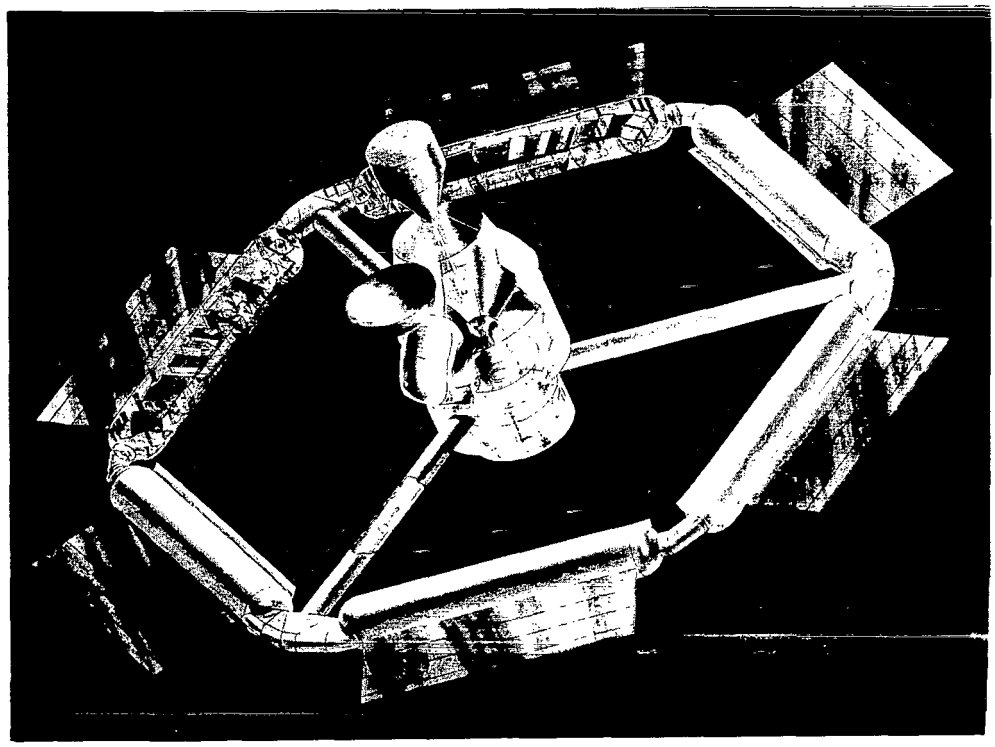
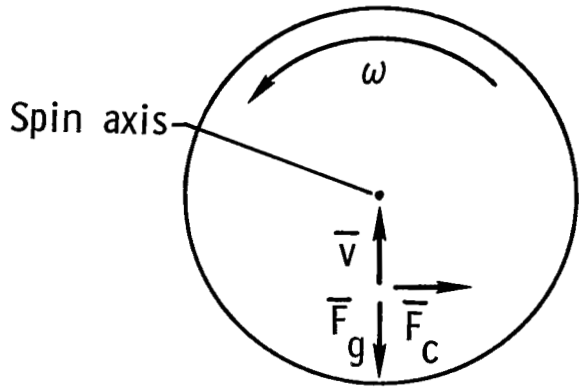
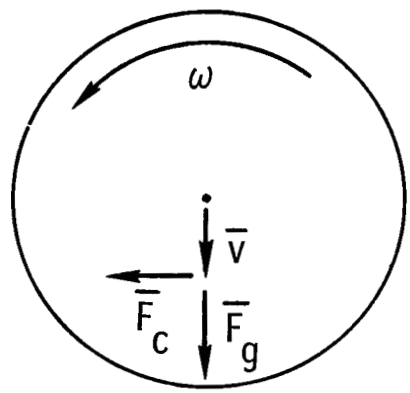


Figure 14.- Six-tangential-module configuration of a large, rotating, manned orbital space station.

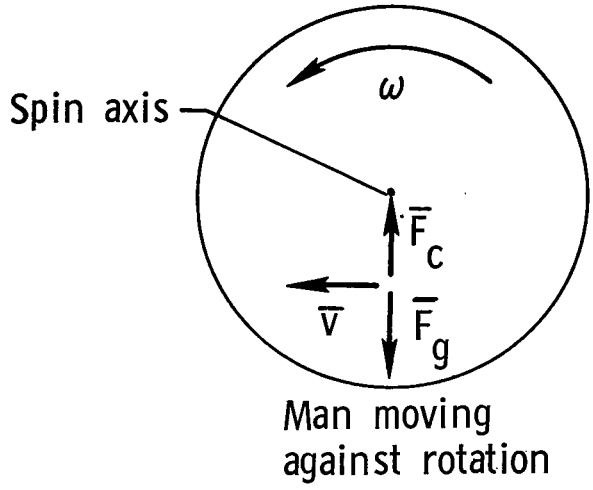


Man moving
toward spin axis



Man moving away
from spin axis

Figure 15.- Coriolis force during radial movement.



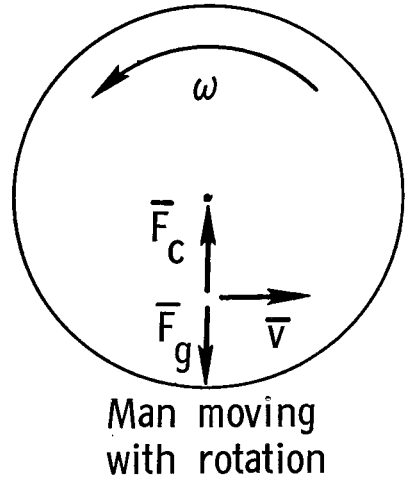


Figure 16.- Coriolis force during tangential movement.

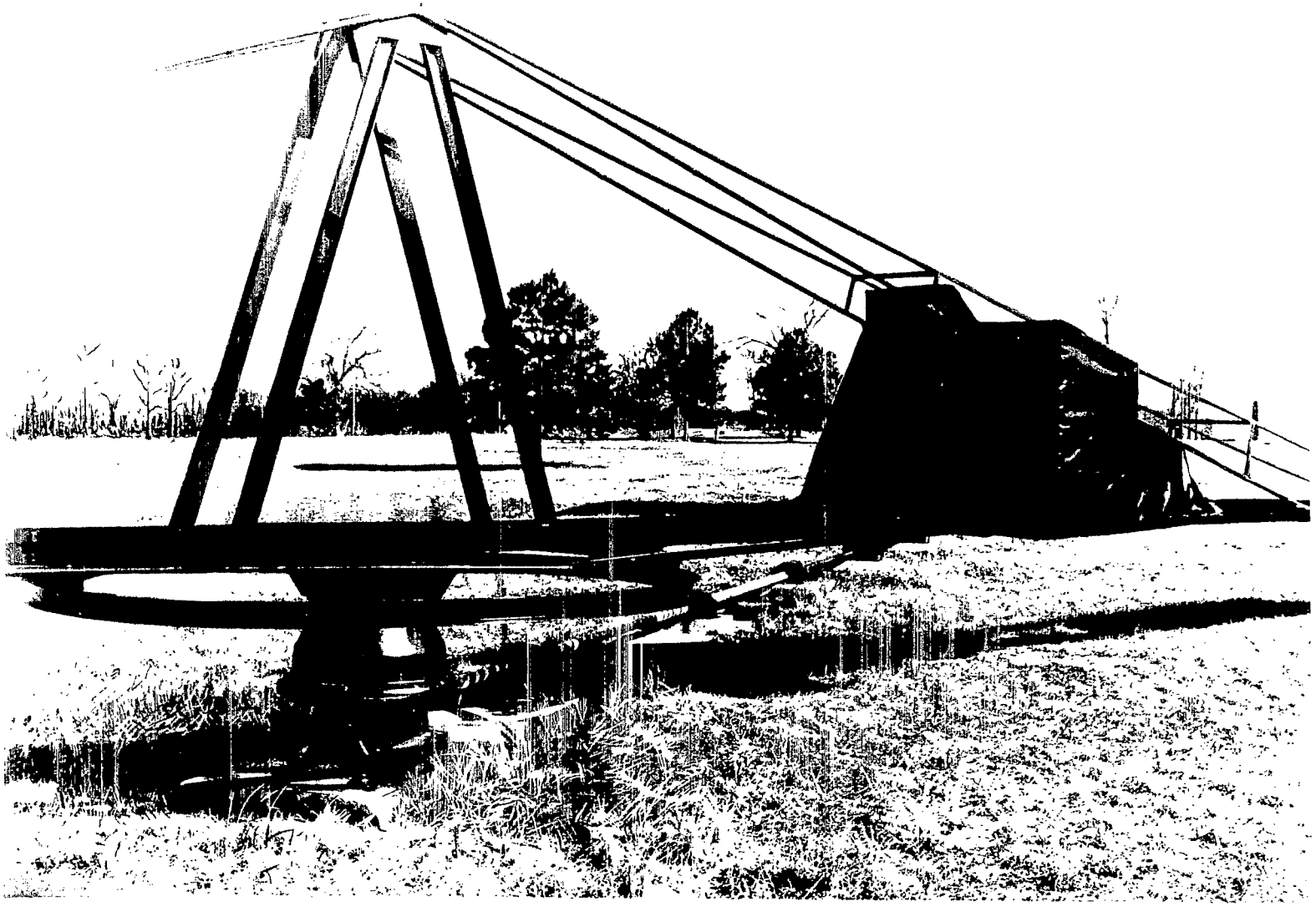


Figure 17.- External view of the rotating vehicle simulator at the Langley Research Center.

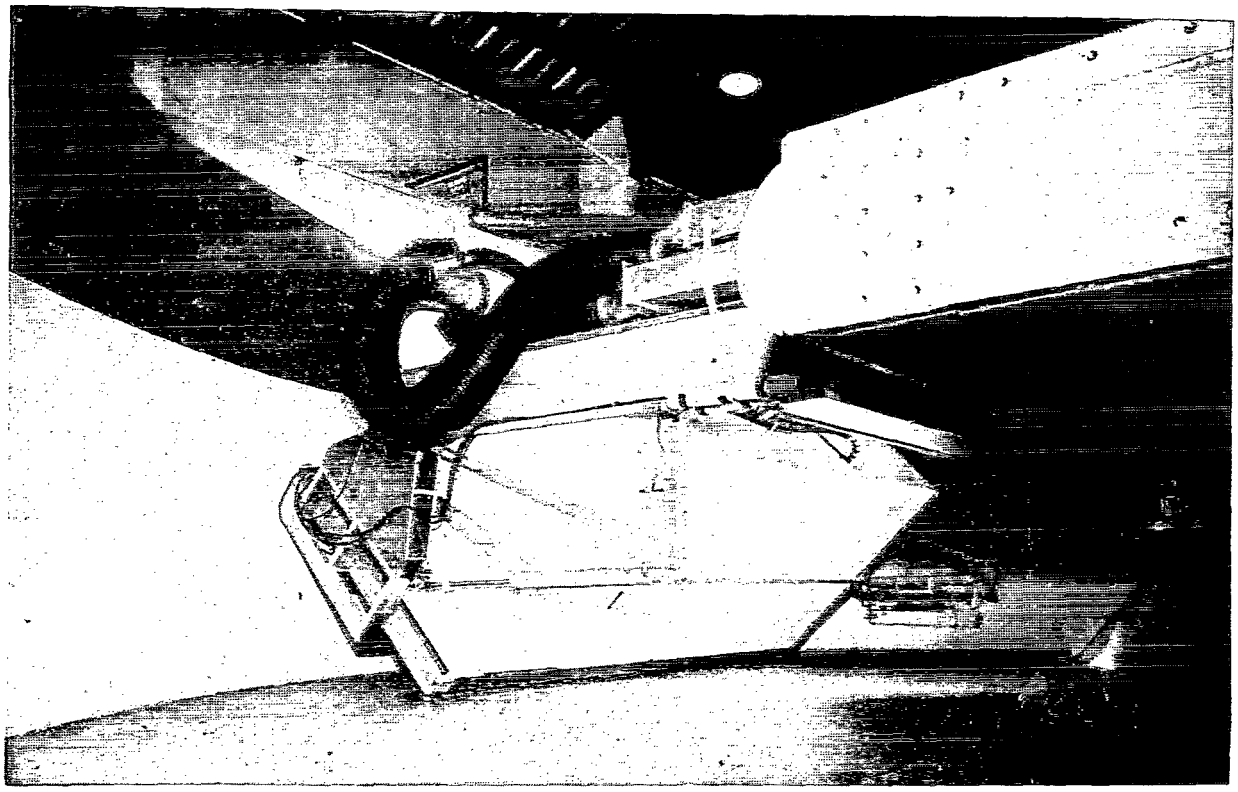


Figure 18.- General Dynamics rotating space station simulator.

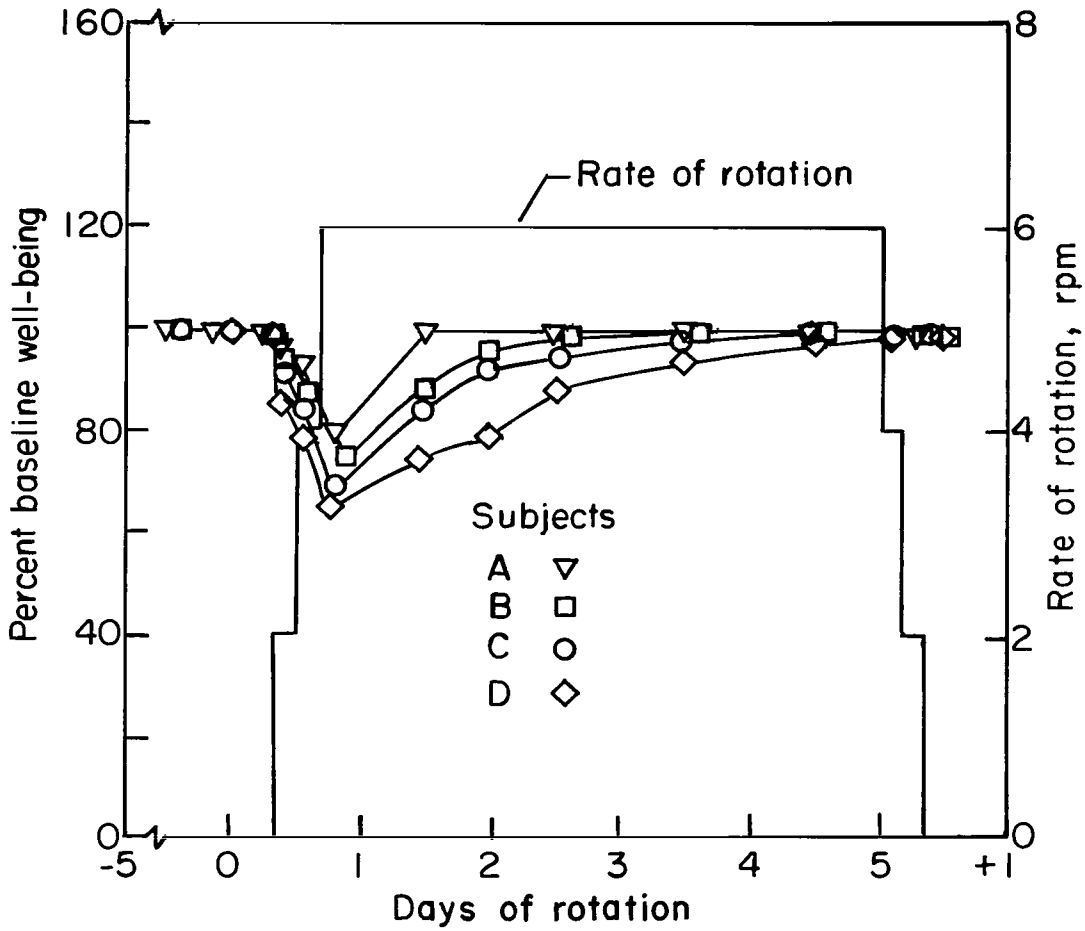


Figure 19.- Percent baseline well-being as a function of days of rotation in the General Dynamics rotating space station simulator. (From ref. 39.)

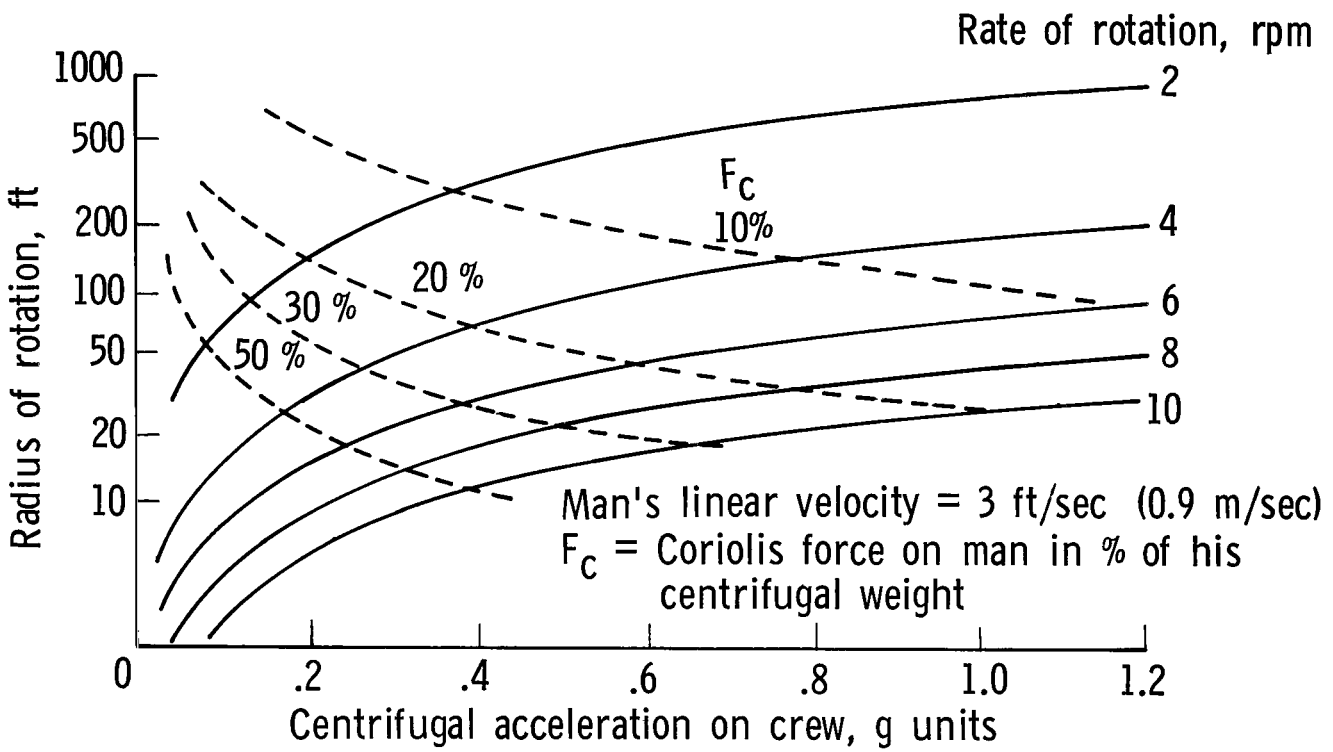


Figure 20.- Coriolis force in percent of centrifugal acceleration. (From ref. 38.)

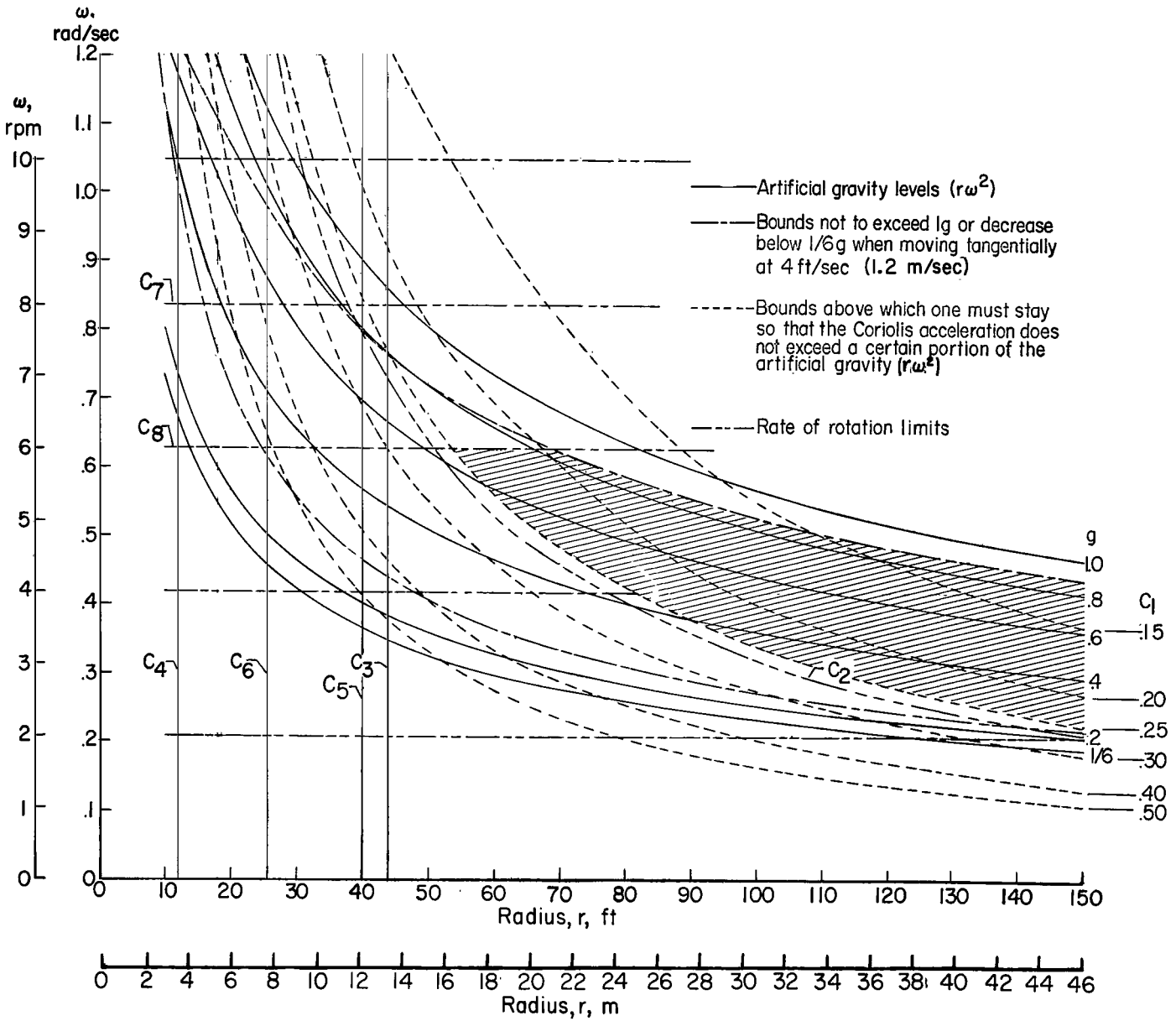


Figure 21.- Design envelope for manned rotating space vehicles.

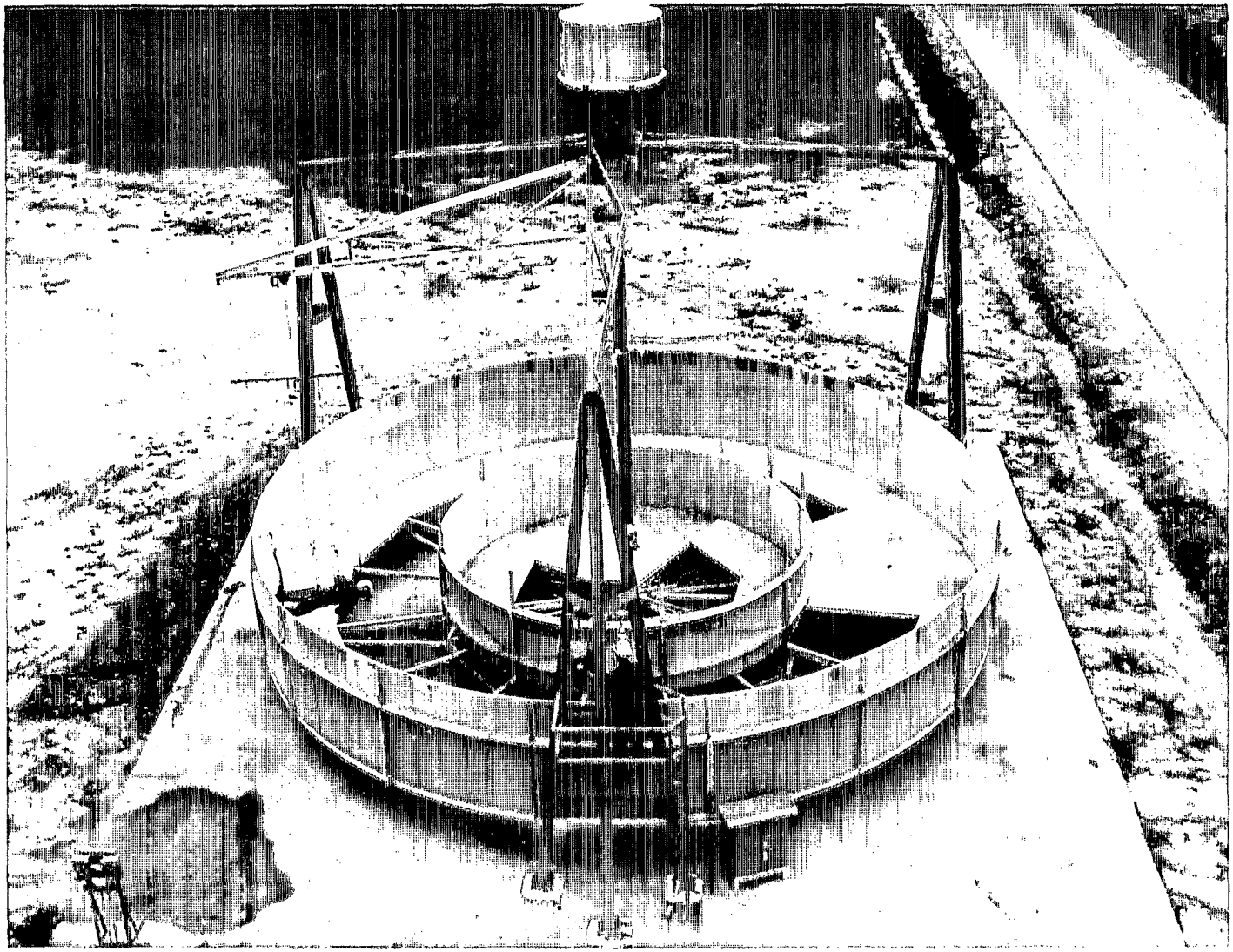


Figure 22.- Rotating space station simulator at the Langley Research Center.

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