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# SOME SELECT PHYSIOLOGICAL, ANTHROPOMETRIC, AND HUMAN ENGINEERING DATA USEFUL IN VEHICLE DESIGN AND LOGISTIC PROBLEMS OF SPACE FLIGHT OPERATIONS

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# SOME SELECT PHYSIOLOGICAL, ANTHROPOMETRIC, AND HUMAN ENGINEERING DATA USEFUL IN VEHICLE DESIGN AND LOGISTIC PROBLEMS OF SPACE FLIGHT OPERATIONS

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# I. INTRODUCTION

Technical investigations into the many facets of space flight, particularly where man is concerned, have prompted queries regarding man's tolerances, measurements, volume requirements, and metabolic processes. This report merely tabulates specific data that are useful to engineers in advanced design of space vehicles, space stations, and the associated logistics problems. By far, all data available have not been presented. Had this been done, an extremely large volume would have resulted. It is hoped that future reports will provide more data as they are collected and analyzed.

There are many sources from which data are available and, in most cases, the data do not exactly coincide. These differences are small. However, the information tabulated herein can be used as typical of the present state of knowledge.

These data were compiled for mission planning and preliminary design purposes.

## II. PHYSIOLOGICAL

### A. Metabolic

Table 1. Metabolic Data (1)*

| Substance | Input (lb/day) | Substance | Output (lb/day) |
|---|---|---|---|
| Oxygen | 2.0 | Oxygen | - |
| Carbon Dioxide | - | Carbon Dioxide | 2.2 |
| Food (dry) | 1.5 | Fecal Solid | 0.2 |
| Water (in food) | 2.6 | Water Vapor (sweat) | 1.1 |
| Water (in drinks) | 2.2 | Water Vapor (expired air) | 0.8 |
| | | Urine | 3.3 |
| | | Fecal Water | 0.3 |
| Total | 8.3 | | 7.9 |

Note that the total input is 0.4 lb greater per day than the output. This is accounted for in the growth of hair and nails, and loss of matter. Also, there is 0.7 lb of water formed in food metabolism. Although the total input of all liquids is 4.8 lb, the total output is 5.5 lb. These amounts are for an average man doing moderate work in the Earth's atmospheric environment; they are based upon a 3000-calorie diet. No safety factor for either input or output is included.

Figures 1, 2, and 3 are included merely to reveal the magnitude of the logistics problem of supplying astronauts with food, oxygen and water. Figure 1 is based upon everything being supplied from Earth, at the rate of 8.3 lb/day/man as noted in Table 1. Figure 2 is based upon all of the food and oxygen being supplied, along with 10% of the water requirements, at a rate of 3.62 lb/day/man. It is assumed that 90% of the sweat, urine, and expired water vapor produced by the crew members can be reclaimed through properly designed mechanical equipment. Fecal water (0.3 lb) is not included for it would be easier to store the feces, or dispose of them overboard, rather than pay the weight penalty of reclaiming such a small quantity of water. The 10% loss is figured in leakage, mechanical efficiency of the equipment, and use of air locks.

If it is assumed that 50% of the food can be grown on board and 90% of the water regenerated, Figure 3 results. In this case, it is assumed that 0.75 lb/day/man of dry food would be supplied from Earth. Thus, a total of 2.87 lb/day/man would have to be "flown in." The 50% figure was selected because this offers a reduced logistics problem,

*Reference

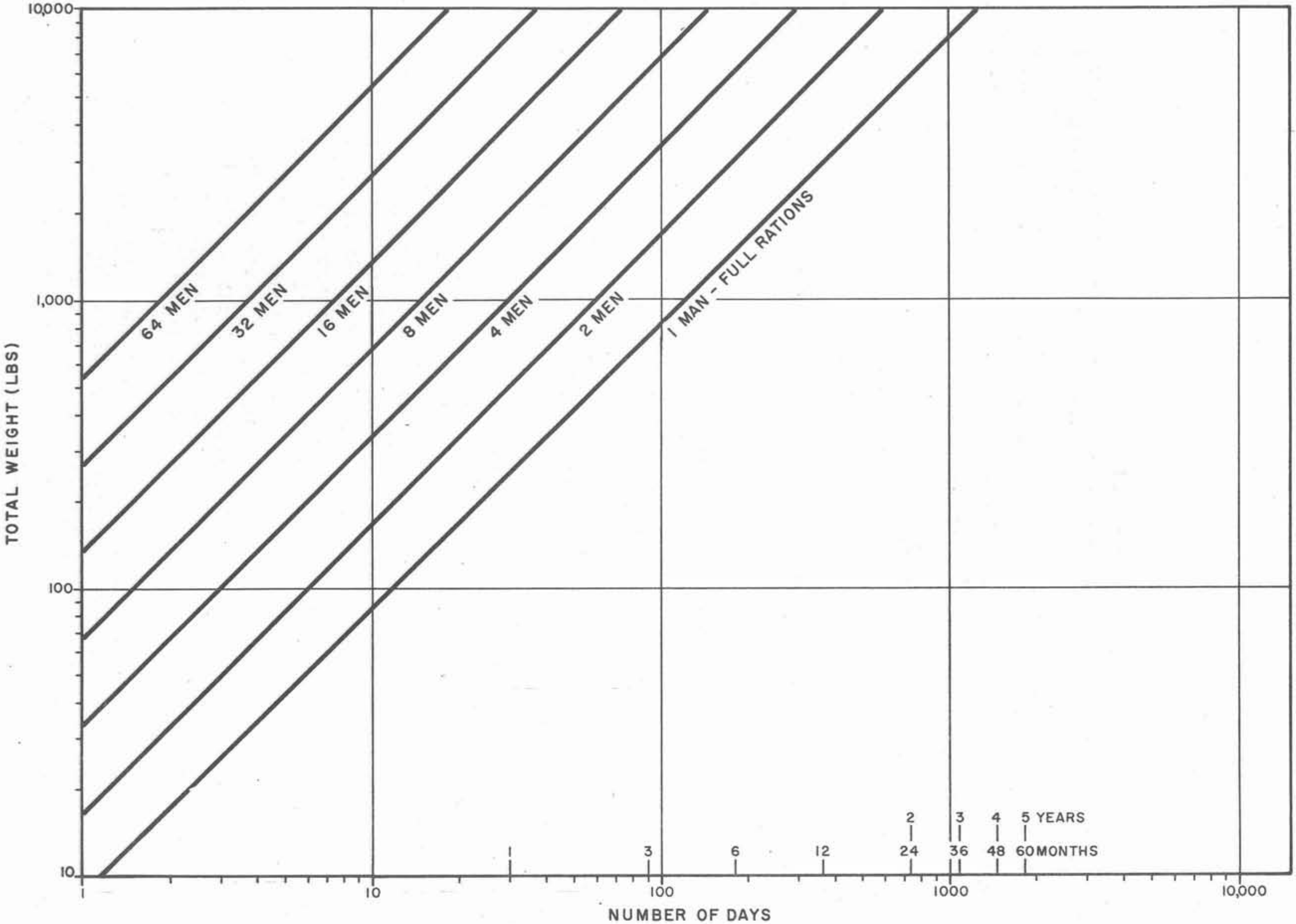



FIG. I WEIGHT OF FOOD, OXYGEN AND WATER WHERE EVERYTHING IS SUPPLIED

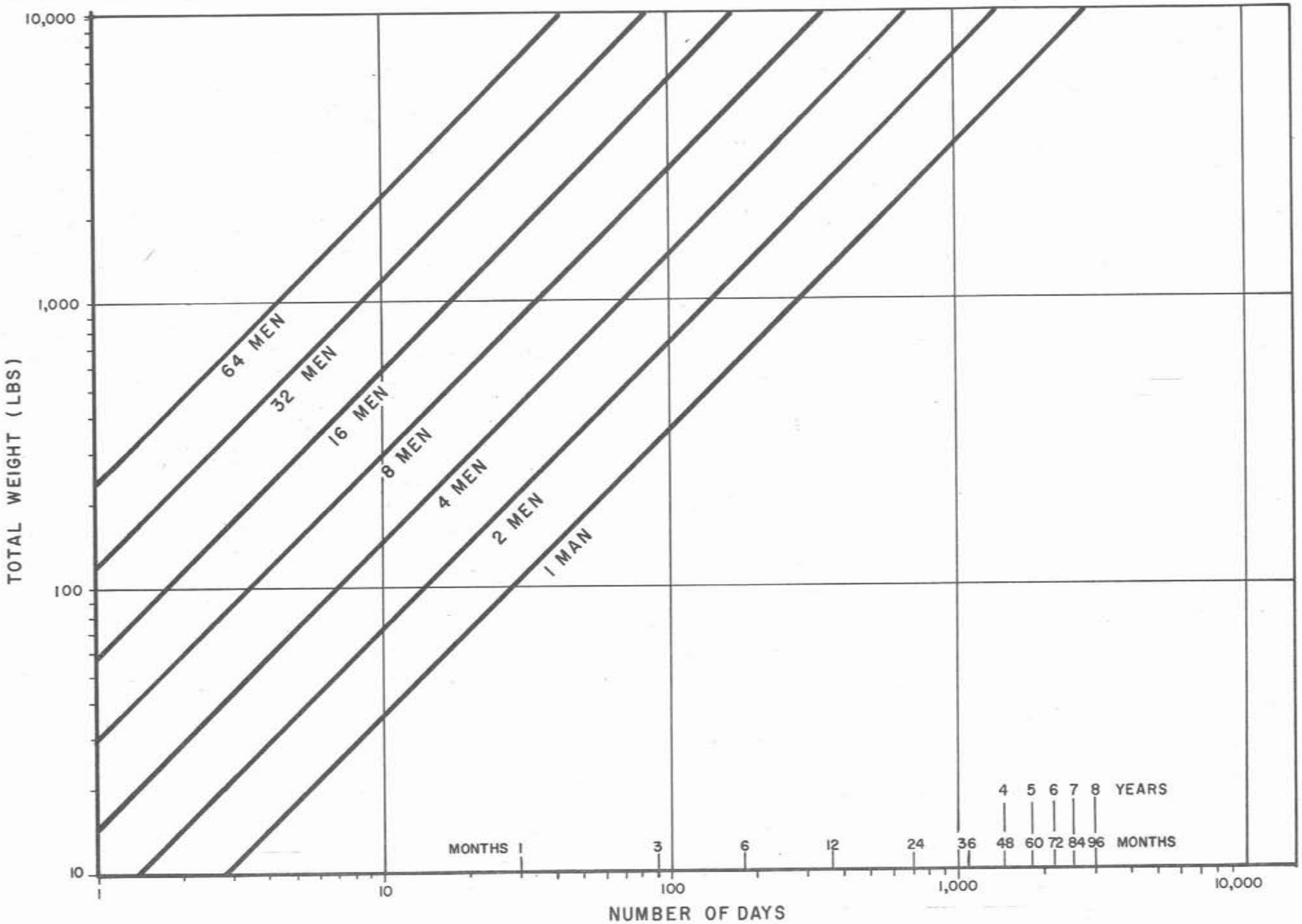



FIG. 2 WEIGHT OF FOOD, OXYGEN AND WATER WHERE 90% WATER IS REGENERATED

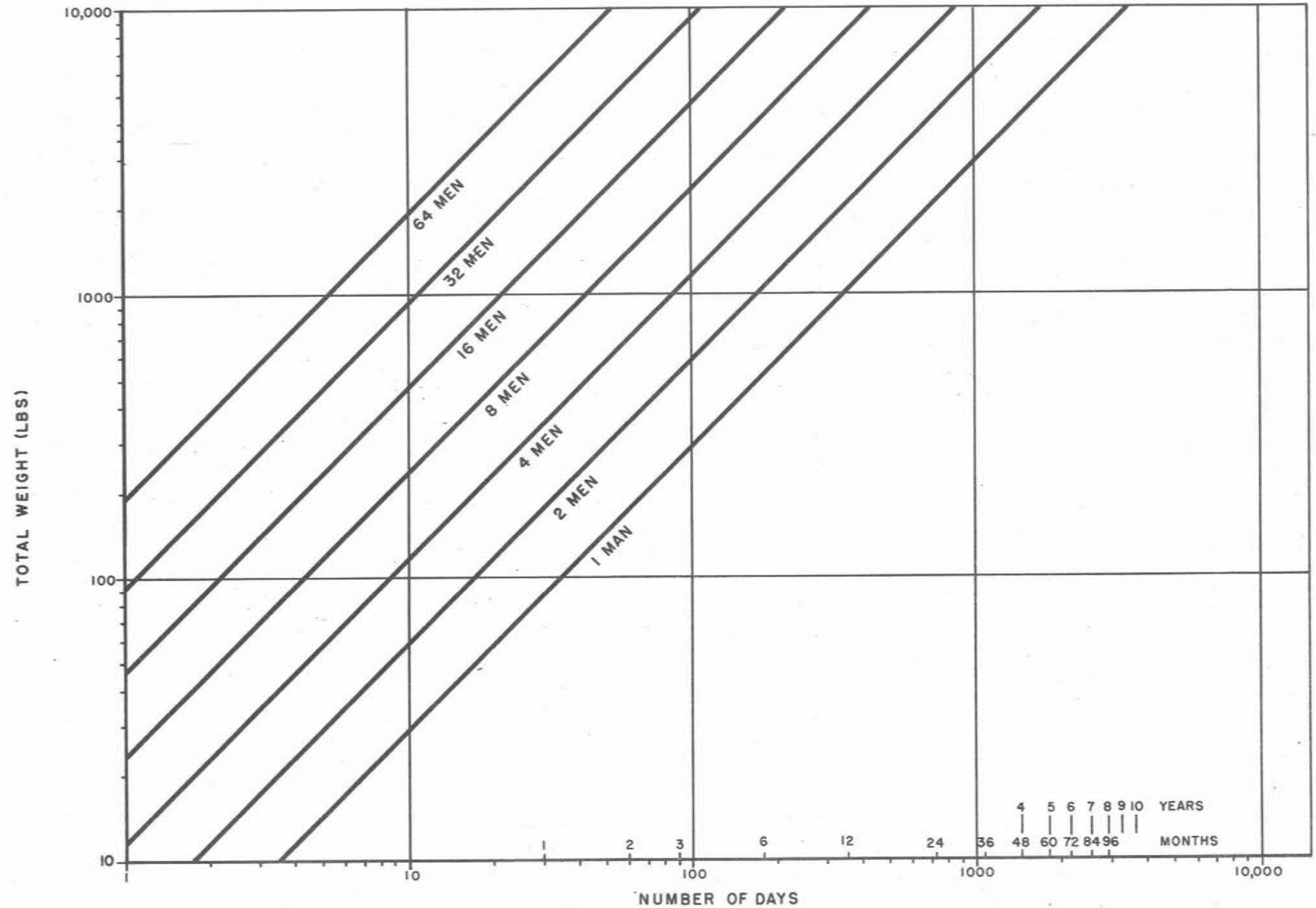



FIG. 3 WEIGHT OF FOOD, OXYGEN AND WATER WHERE 90% WATER IS REGENERATED AND 50% FOOD IS SUPPLIED

provides a greater variety of foods, and appears to be feasible within the next 10 to 15 years. Oxygen was not considered as an element for regeneration, since the presently available equipment for doing this is not too advanced. However, equipment could be developed within the next 5 to 10 years, if a high priority program were developed.

There is a 56.5% weight reduction from Fig. 1 to Fig. 2, and a 65.5% weight reduction from Fig. 1 to Fig. 3. No safety factor has been included in arriving at these curves. If one is desired, it is recommended that 1.5 be used.

B. Air Temperature, Relative Humidity, Ventilation

1. Air Temperature

Table 2. Air Temperature Necessary for Thermal Balance (2,3)

| Temperature (deg F) | Tolerance |
|---|---|
| 160 | Tolerable for about 30 minutes |
| 120 | Tolerable for about one hour, but is above physical or mental activity range |
| 85 | Mental activities slow down, responses are slow, errors begin, complex performance begins to deteriorate. |
| 75 | Heavy physical labor begins to be more fatiguing |
| 65-72 | Optimum |
| 50 | Physical stiffness of the extremities begins |

2. Relative Humidities

Table 3. Human Tolerance to Relative Humidities

| Humidity (%) | Tolerance |
|---|---|
| 15 or less | Drying of the external fluid, under the eyelid and covering the eyeball, occurs. The mouth and nose membrances also dry out (4) |
| 30-70 | Found comfortable by most people (2) |
| 50 | Normal or optimum (3) |
| 90 | The highest temperature endurable approaches normal body temperature of 98.6°F (4) |

3. Ventilation Data

a. Room:

The optimum movement of air within a room is between 15 and 25 ft/sec (5). At an air movement rate of 20 ft/sec the following ambient air temperatures and man's heat output are appropriate, assuming that the necessary clothing for thermal balance is worn.

Table 4. Ventilation Data

| Condition | Heat Output (BTU/hr) | Temperature (deg F) |
|---|---|---|
| At rest | 400 | 70 |
| Moderate activity | 1000 | 58 |
| Vigorous activity | 4000 | 28 |

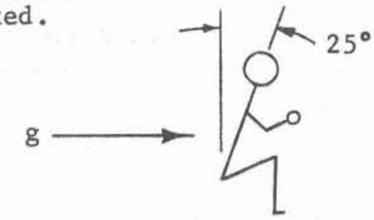
b. Pressure Suits:

Wright Air Development Division's requirements for future ventilating garments (worn under the pressure suit) are 10 cu ft/min at 5 lb/sq in. suit pressure. Inlet temperatures are 45-65°F to handle ambient cabin temperatures of -65°F to 200°F (6). Available garments have a flow rate of 13 cu ft/min at 70°F (3).

C. Acceleration

Recent data on forward and backward acceleration reveal man's tolerance to high acceleration. Forward and backward acceleration are graphically defined as follows:

The optimum position for forward acceleration, using seats similar to those found in fighter-type aircraft, presently appears to be with the spine and head tilted at 25° to the accelerating direction and the legs sharply flexed.

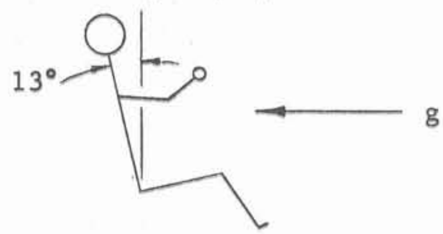



In this position, without a g-suit, the following g-forces are tolerable:

Table 6. g-Tolerance to Forward Acceleration (7)

| Force (g) | Tolerance Time | Results |
|---|---|---|
| 12 | 5 sec | Limited by blackout |
| 10 | 23 sec | Limited by loss of peripheral vision, and breathing difficulty |
| 8 | 60 sec | Hindrance to the free ingress of air into the lungs, and fatigue of abdominal breathing |
| 6 | 3.5 min | |
| 4 | 12.8 min | |
| 3 and below | Limit undetermined | - - - - - |

The optimum position for backward acceleration, again using aircraft-type seats, appears to be in the normal seated position with the head and trunk erect and the thighs perpendicular to the spine.



In this position, without a g-suit, but with full-restraint harness to hold the crew in the seat, the following g-forces are tolerable:

Table 6. g-Tolerance to Backward Acceleration (7)

| Force (g) | Tolerance Time | Results |
|---|---|---|
| 12 | 4 sec | Limited because of restraint system discomfort, leg pain, and breathing difficulty |
| 10 | 12 sec | |
| 8 | 41 sec | Limited because of restraint system discomfort, general fatigue, vertigo |
| 6 | 83 sec | |
| 4 | 4 min | |
| 3 and below | Limit undetermined | - - - - - |

The data of Tables 5 and 6 are plotted in Fig. 4. It is readily seen that the difference of tolerance time between forward and backward acceleration is relatively small. Improved design of restraint harness could reduce this difference so that the curves would almost coincide. The important point is that if re-entry deceleration can be held within the bounds of Fig. 4, it may not be necessary to rotate the seat, or locate the seat so the crew is facing opposite to the flight direction. The crew can be facing forward which is the desirable position.

More advanced work is in progress at the U. S. Navy Aviation Medical Acceleration Laboratory (AMAL) for NASA. Their work evolves from the use of contour seats molded to fit the individual's body in a supine, or semisupine, position. Particular attention is given to chest support to facilitate breathing. This support is reflected in Fig. 5 by the raised portions between the chest and arms. Using this type of seat and a g-suit, a peak of 20.7 g has been obtained (8). Time at this peak was approximately 2 sec with a total time of 52.5 sec. Figure 6 reflects the acceleration time curve for this run. More recent information indicates that 25 g have been obtained in the AMAL centrifuge, in a total time of 40 sec (9). The wave form was similar to Fig. 6 only the slope was steeper and the base shorter. Since these last tests, unofficial information indicates that 27 g have been achieved with some speculation that the maximum has been approached, using the contour seat. During these runs it was necessary for the subject to hold his breath past 16 g. Higher g-forces would not permit breathing. To attain this level, the subjects required prior centrifuge training.

The subjects used in the AMAL centrifuge runs were able to operate a small right-hand control stick. A thumb operated switch also

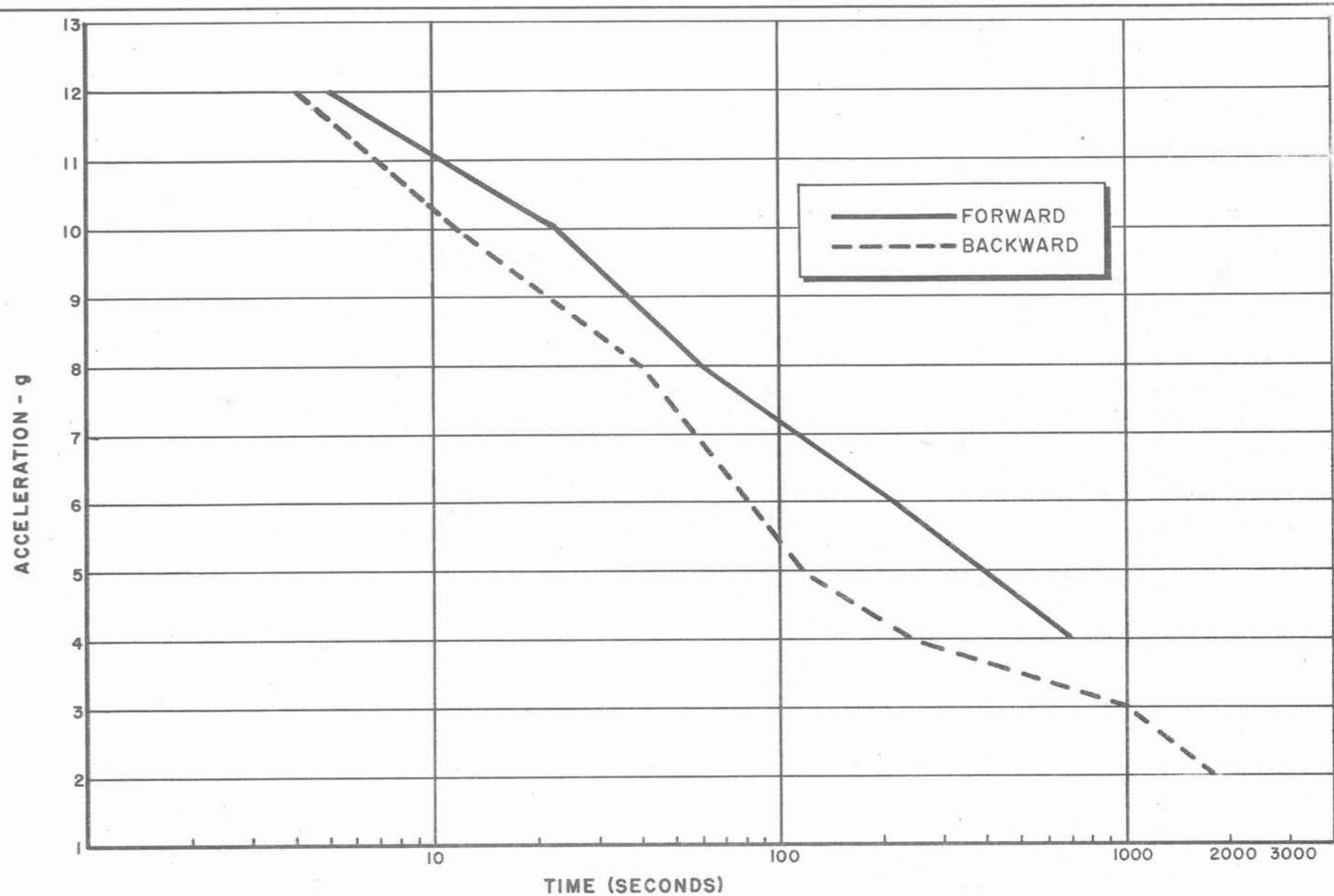



FIGURE 4. COMPARISON OF TIME TOLERANCE TO FORWARD & BACKWARD ACCELERATION (7)

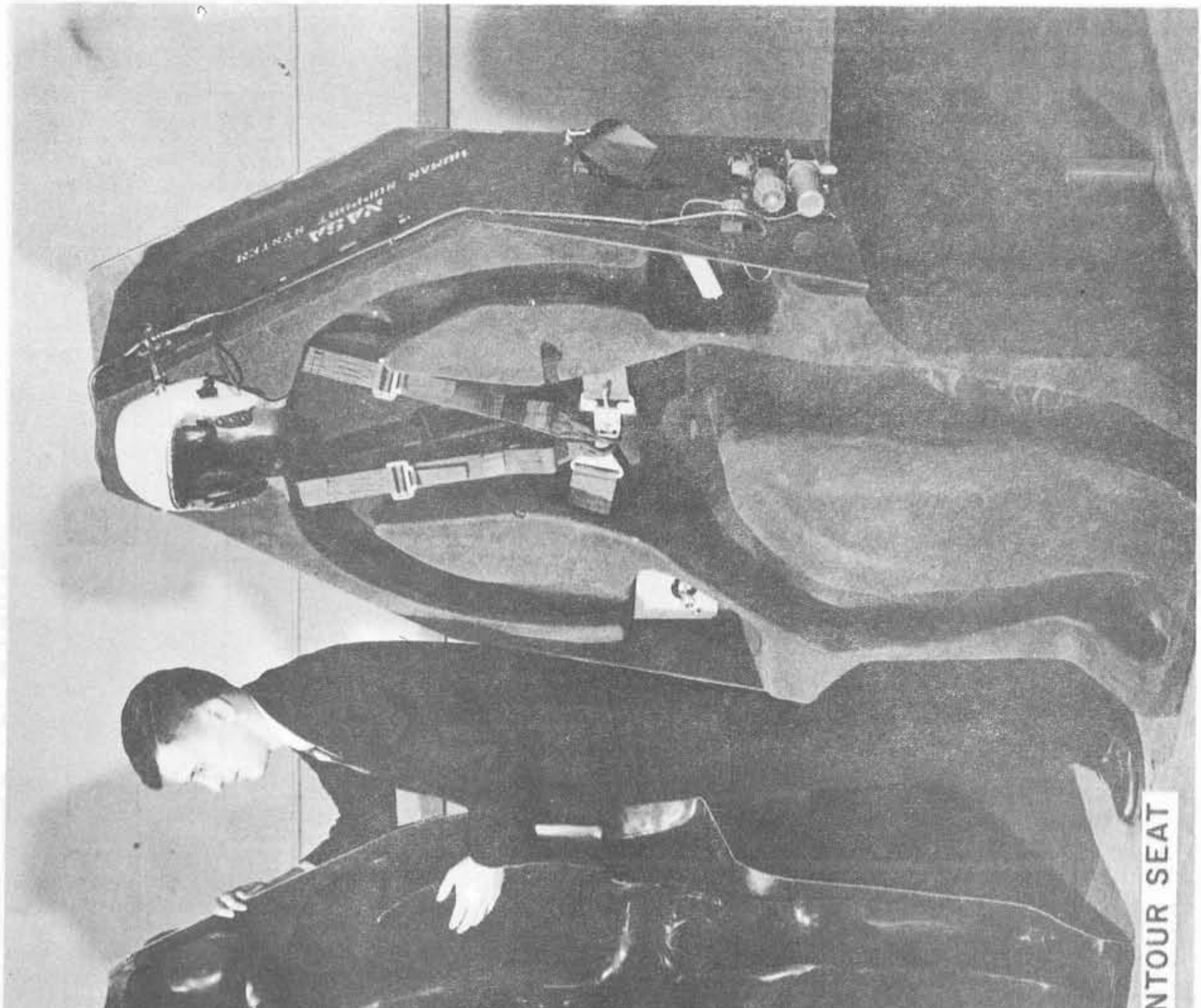


FIG 5 - NASA CONTOUR SEAT

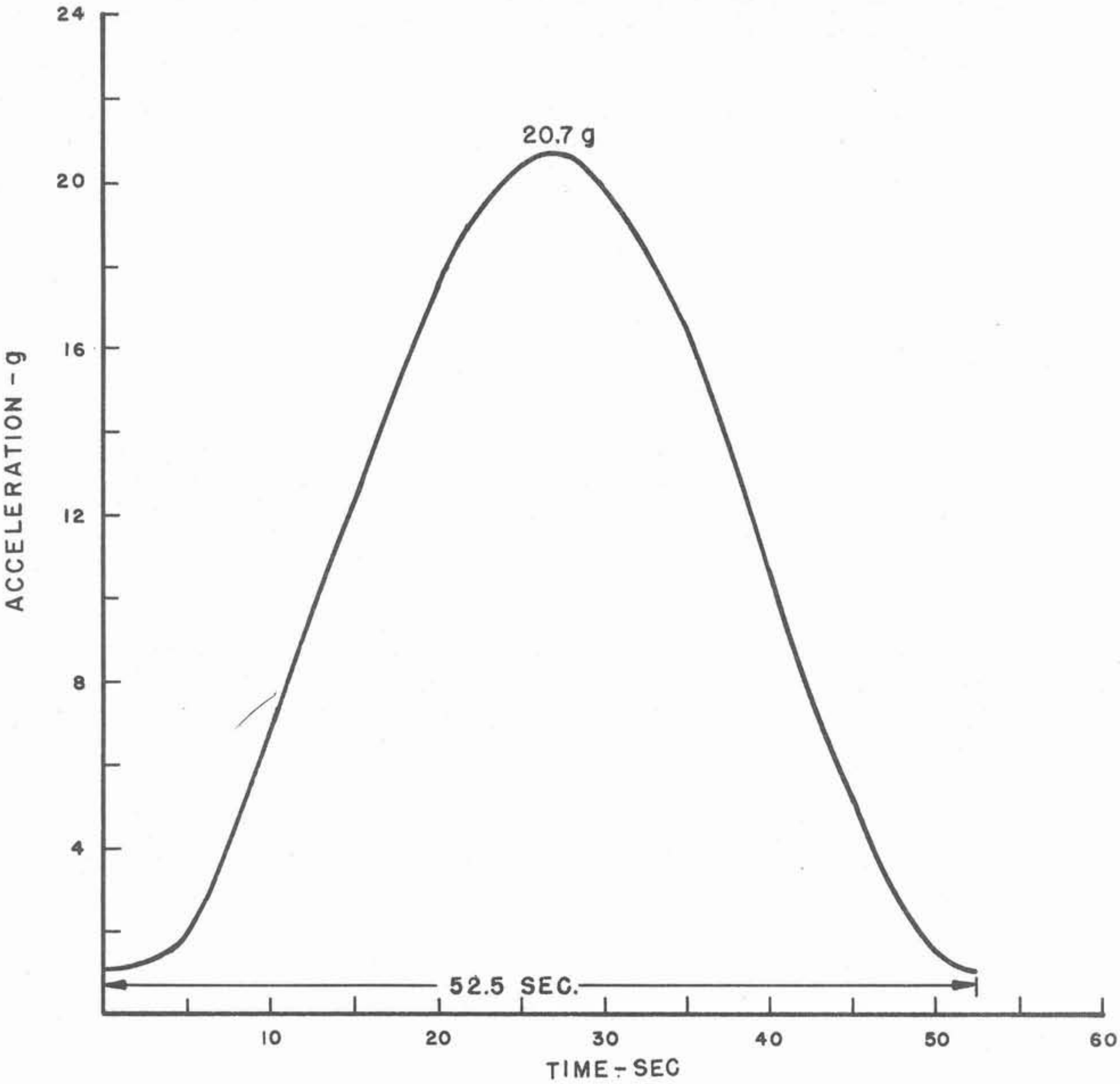
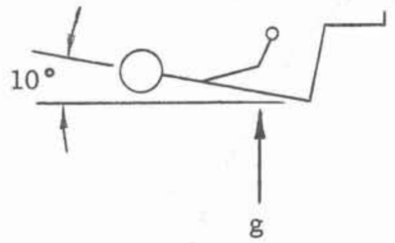



FIG.6 ACCELERATION-TIME HISTORY USING CONTOUR SEAT

was used. Blackout was not experienced. Breathing became difficult only at the higher g-loads, 16 and above, as compared to the 10-g limitation experienced during the tests noted in Tables 6 and 7. Disorientation did not occur during the runs. All of this research indicates that a pilot could perform certain tasks at high g-levels if he had centrifuge training.

The optimum body angles, using the contour seat in a supine position for forward acceleration, presently appear to be in the position shown below.




When the contour seat is used, the thigh angle in relation to the spine is apparently not a critical factor. No data are available on backward acceleration in the contour seat using restraint harness. Thus, there is no way to compare the backward acceleration merits of NASA's contour seat with the aircraft-type seat.

D. Radiation

The human tolerance to X and gamma radiation is not easily determined. It is subject to much investigation and alteration. For general planning purposes, the following total body radiation doses are considered reasonable.

Table 7. Total Body Radiation, Single Exposure (10,11)

| Dose (Roentgens) | Results |
|---|---|
| >500 | Survival is practically impossible |
| 300-500 | Might escape death |
| 100-250 | Survival is probable, nausea |
| 25-100 | Relatively minor affects, always curable |

It is considered that 0.3 R/week is the permissible dose for humans over a normal lifetime (3).

E. Weightlessness

Parabolic flights in T-33 and F-94C aircraft have resulted in periods of virtual weightlessness for 30 to 40 seconds (3). Tests presently under way at the USAF School of Aviation Medicine have produced weightless periods of 60 seconds in the TF-100 aircraft. A C-131 and F-104, which are being used at the Wright Air Development Division, will produce 15 seconds and 90 seconds of weightlessness, respectively.

The general results of these tests are:

1. No difficulty is encountered while drinking or eating, provided the food is in a paste or semi-solid condition and is forcefully injected into the mouth.

2. The majority of one test group, about 66%, enjoyed the experience and showed no symptoms.

3. Those individuals who developed symptoms of autonomic disturbance, indicate that a correlation exists between these symptoms and proneness to motion or airsickness.

4. Experienced pilots are natural choices for aircraft or rocket flights where weightlessness is involved.

5. No difficulty with prolonged periods of weightlessness is presently anticipated provided the crews are well selected and have received some training in equipment designed to produce the weightless state. It is not possible to specify the length of the "prolonged period" since orbital experimentation is required.

6. Individuals must be anchored or restrained in some manner when applying a direct force or torque to an object.

7. Flexing of the extremities does not appear to be a means of locomotion or maneuvering under weightless conditions.

F. Work - Rest Cycle

Experimentation recently completed by the USAF School of Aviation Medicine proved that a work - rest schedule of 4 hours on and 4 hours off was quite successful (12). The subjects adjusted quite rapidly. They remained in a sealed cabin for seven days with no decrement in performance.

Further tests using other work - rest schedules are under way, but the results are not yet known. Until new data are available, it is best to use the 4-on and 4-off cycle for logistic and work schedule purposes, if the planner feels this type of schedule is desirable. However, the individual's normal earth-bound work - rest cycle of 8 hours on and 16 hours off should not be overlooked as a possible schedule. Practically no adjustment would be required of the individual, but more crews would be required to do the same job.

G. Carbon Dioxide Tolerance

The normal sea level partial pressure of $CO_2$ is approximately .03%. Obviously, this quantity has no adverse physiological effect upon the human being in day-to-day operations. However, as this percentage increases, several symptoms occur depending upon the individual's tolerance to $CO_2$. These are excitement, headache, drowsiness, weakness, dizziness and muscular weakness. High concentrations can result in coma or death.

Table 8. Effects of $CO_2$ Concentration (13)

| Concentration (%) | Effects |
|---|---|
| 2 | Initial effects are first noticed; breathing becomes labored |
| 4 | Depth of respiration is greatly increased |
| 4.5-5 | Breathing becomes labored and distressing to some individuals |
| 5-10 | The body organism fails to respond or combat the effects of $CO_2$ |
| > 10 | Overall marked deterioration and an inability to take steps for self-preservation |

Where flight times greater than several hours or one day are necessary, it is generally considered that the $CO_2$ level should remain 1% or below. This will provide a safety factor of 3, if the submarine practice of using 3% $CO_2$ as the upper limit for prolonged exposure is used as a basis.

## III. ANTHROPOMETRY OF FLYING PERSONNEL

The most important physical measurements of the male body are shown in Fig. 7. Measurements from the 5th to the 95th percentile are covered. If it is desired to place an emergency escape switch so that 95% of the male population can easily reach it, the distance should be 29.7 inches. This is the functional arm reach of the 5th percentile which is the smallest. If it is desired to obtain adequate head clearance in the cockpit of a space capsule in the seated position for 95% of the male population, then 38.0 in. should be used. This is the sitting height of the largest, the 95th percentile. For any application, additional space must be provided for helmets, parachutes, shoes, padding, etc.

The internal volume or dimension requirements for space capsules and space stations should be based upon the largest per cent of male population - the 75th to the 95th percentile. This will provide some safety factor and reduce the height problem so that selection of astronaut candidates will not be a critical one.

BODY DIMENSIONS OF FLYING PERSONNEL
(Inches)

| | Percentile | | | | |
|---|---|---|---|---|---|
| | 5th | 25th | 50th | 75th | 95th |
| STANDING | | | | | |
| A. Overall Height | 62.5 | 67.5 | 69.1 | 70.7 | 73.1 |
| B. Eye Height | 60.8 | 63.1 | 64.7 | 66.3 | 68.1 |
| C. Shoulder Height | 52.8 | 55.0 | 56.6 | 58.0 | 60.2 |
| D. Waist Breadth | 9.4 | 10.0 | 10.6 | 11.2 | 12.3 |
| E. Hip Breadth | 12.1 | 12.7 | 13.2 | 13.7 | 14.4 |
| SITTING | | | | | |
| F. Sitting Height | 33.8 | 35.1 | 36.0 | 36.8 | 38.0 |
| G. Shoulder Height | 21.3 | 22.5 | 23.3 | 24.0 | 25.1 |
| H. Eye Height | 29.4 | 30.6 | 31.5 | 32.3 | 33.5 |
| I. Elbow to Finger Tip | 17.6 | 18.3 | 18.9 | 19.4 | 20.2 |
| J. Buttock-Knee Length | 21.9 | 22.9 | 23.6 | 24.3 | 25.4 |
| K. Popliteal Height | 15.7 | 16.5 | 17.0 | 17.5 | 18.2 |
| L. Knee Height | 20.1 | 21.0 | 21.7 | 22.4 | 23.3 |
| M. Biocromial Dia. | 14.6 | 15.3 | 15.8 | 16.3 | 16.9 |
| N. Elbow to Elbow Breadth | 15.2 | 16.3 | 17.2 | 18.2 | 19.8 |
| O. Hip Breadth | 12.7 | 13.4 | 13.9 | 14.6 | 15.4 |
| P. Knee to Knee Breadth | 7.2 | 7.6 | 7.9 | 8.2 | .8.8 |
| REACHES | | | | | |
| Q. Maximum Reach | 35.4 | 37.3 | 38.6 | 39.9 | 41.7 |
| R. Functional Reach | 29.7 | 31.3 | 32.3 | 33.4 | 35.0 |

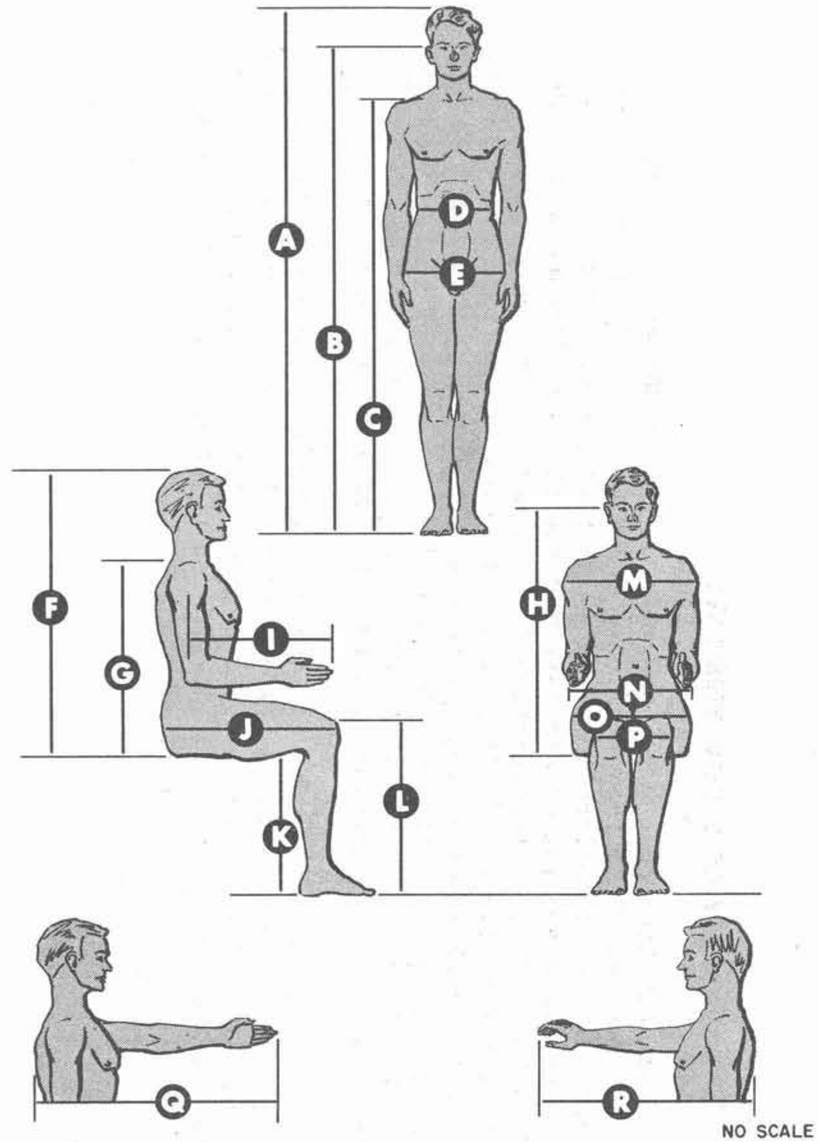



FIG. 7 ANTHROPOMETRIC MEASUREMENTS OF FLYING PERSONNEL (14)

## IV. HUMAN ENGINEERING

### A. Contour Seats

Basically, there are three types of seats available for space operations: the standard aircraft ejection seat, a light weight net contour seat, and the NASA molded contour seat. The aircraft seat is not acceptable for the high accelerations encountered during lift-off and reentry. The net seat, being developed by the USAF, has been tested with human subjects to 16 g. The NASA contour seat has been tested with human subjects to 25 g. This seat provides more positive support for the chest, thereby permitting higher g-loads. It is possible, however, that the net seat will be able to support a human being at higher accelerations. This remains to be seen since the test program has not been completed. The net seat is about half as heavy as the contour seat - 8 to 10 lb as compared to 20 lb. It is attractive from a weight standpoint, but has not yet demonstrated maximum acceleration protection. Until additional data is available, it is recommended that space requirements and weight analyses be based upon the NASA contour seat.

Figures 8 and 9 reflect a 95th-percentile man, dressed in a full-pressure suit (which is inflated) and positioned in a contour seat. Both figures are drawn at 1:20 scale, and are suitable for determining space requirements in manned space vehicles. Either figure may be cut out and pasted on heavy-gage paper, or used as a pattern to make plastic models. Flush mounted eyelets should be used for the joint connection of Fig. 9.

Figure 8 is drawn in a fixed condition where the legs and back angles are in the optimum position for maximum forward acceleration and short duration flight (less than 8 to 12 hours). Figure 9 is drawn for a variety of body positions from standing vertically to having the legs sharply flexed. If longer flight times are involved, the crew should have the capability of selecting a more comfortable position where the spine and thigh bones form an angle of 103° similar to that designed into chairs and aircraft seats. There will be instances where space will not permit use of the optimum position and other body angles will have to be used. Once assembled the model of Fig. 9 is a very useful tool in determining human space requirements in a variety of vehicle designs, since the contour seat is hinged at the knee and the leg joints. This model offers the additional advantage of having arms with the fingers closed for determining useful or functional reaches.

Pilot control, if desired, is achieved by locating the control stick at the pilot's right hand position.

### B. Noise

Considerable research has been conducted to determine the effects of noise upon a human being. Even though much progress has been

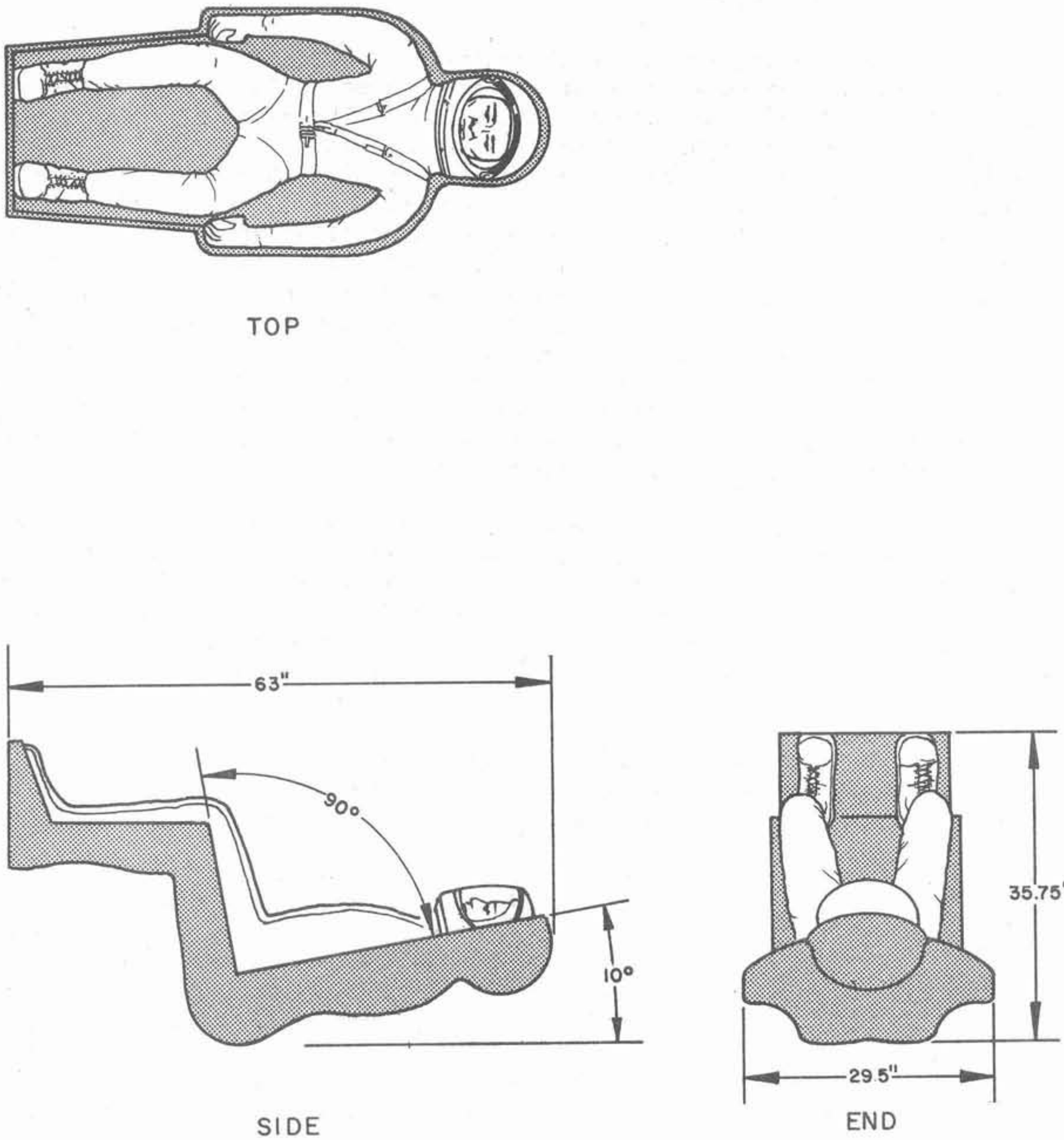



**FIG. 8 ASTRONAUT SCALE MODEL–OPTIMUM POSITION–CONTOUR SEAT**
**SCALE 1:20**

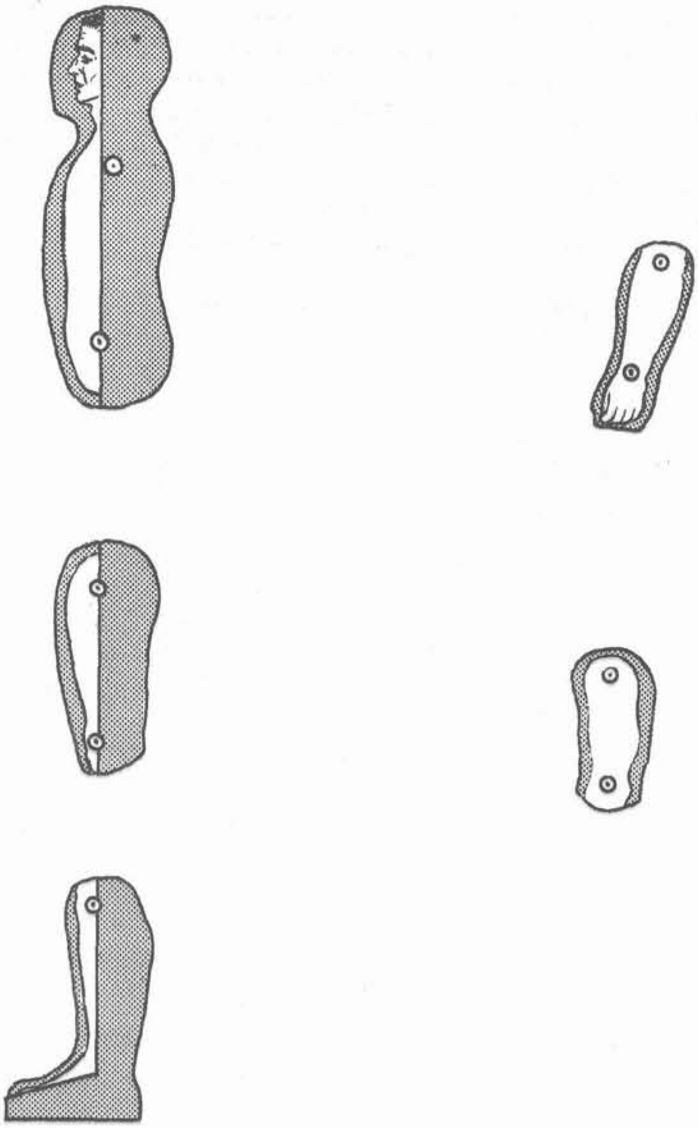


FIG. 9 ASTRONAUT SCALE MODEL-FLEXIBLE POSITION-CONTOUR SEAT
SCALE 1:20

made, there still is disagreement among the experts as to exactly how much noise is too much. This level, however, can be sufficiently estimated so that safe engineering designs can be accomplished for practically all occupations. Where individuals use ear plugs, or other sound-retarding devices, most high-intensity noise areas can be worked in continuously (8 hours/day). Difficulties in establishing exact noise-level tolerances are primarily due to variations of hearing acuity within the population. Some of these variations are due to age, sex, noise levels in the working environment, and general variations in individual ears.

Table 9 reflects data that are generally typical of the population.

Table 9. Noise Levels and Associated Results (2,15,16)

| Noise Level (db) | Results |
|---|---|
| 10 | Some speech sound can be detected, but words not determined |
| 15 | A small percentage of the words become detectable |
| 40 | Almost maximum speech intelligibility is attained |
| 46 | Talking as softly as possible |
| 60-66 | Normal voice level |
| > 80 | Distortion within the ear becomes a contributing factor in reducing speech intelligibility |
| > 85 | Continuous exposure over long time periods results in permanent hearing impairment |
| 86 | Talking almost as loudly as possible |
| >100 | Speech intelligibility decreases slightly |
| 120 | Hearing becomes uncomfortable |
| 130 | A feeling sensation begins to occur |
| 140 | Auditory pain |
| 150 | Stimulation of many senses, nausea, great ear discomfort even with the best protective devices |
| 160 | Severe breakdown of psychomotor performance |

The effect of noise on worker performance, and in generating fatigue cannot be stated exactly. Some data collected on early tests indicated that noise reduced worker performance and induced fatigue. However, later experience indicates that the workers are quite adaptable to noise and that its effects can be overcome considerably to achieve normal, or nearly normal, work performance in short periods of time. Indications are that noise will reduce human productivity, although no positive proof is available. Regarding the problem of fatigue, the human body has a tendency to adapt, physiologically, to acceptable noise levels ($<120$ db) after short periods of exposure. Even though some people may complain that noise is fatiguing, there appears to be no conclusive scientific proof (15).

The annoyance of noise is still another problem. It can be stated, when considering intensity independently of frequency, that loud noises are more bothersome than low ones and that intermittent noises are more annoying than steady ones. Noises in the high-frequency ranges are more annoying than those in the middle or lower ranges. People adapt to the annoying characteristics of noise; however, it is not presently possible to establish tolerance limits regarding these characteristics.

Noise can be reduced about 20 db at 1000 cps, or less, with ear plugs. More sophisticated devices will provide 30 to 40 db reduction in noise intensity at 3000 to 8000 cps. Pressure suit helmets will reduce noise by 20 db at the high frequencies, and 10 db at the lower levels (16).

It is generally agreed that for continuous exposure the noise level should be below 85 db. During launch conditions of manned rocket vehicles, 140 db can be tolerated for a few seconds only; above this, blurring vision, nausea, dizziness, or poor time perception may result, thus endangering the success of the mission.

C. Vibration (2,16)

Design limitations of low-frequency vibrations are shown in Fig. 10. These limitations are not necessarily a standard since a wide variety of data are available that do not agree because of variables in test environment and test personnel. However, the data presented in Fig. 10 are considered adequate and safe for design purposes.

Depth perception is reduced between 25 to 40 cps, and again between 60 and 90 cps. In other words, the ability to estimate distance is impaired. Reading proficiency is generally reduced at low-vibration frequencies similar to that found in a car. Personnel in a seated position are more adversely affected by vertical vibrations. In the prone position (on the stomach) horizontal vibrations, transverse to the body, are more disturbing. It can be assumed that the same is basically true

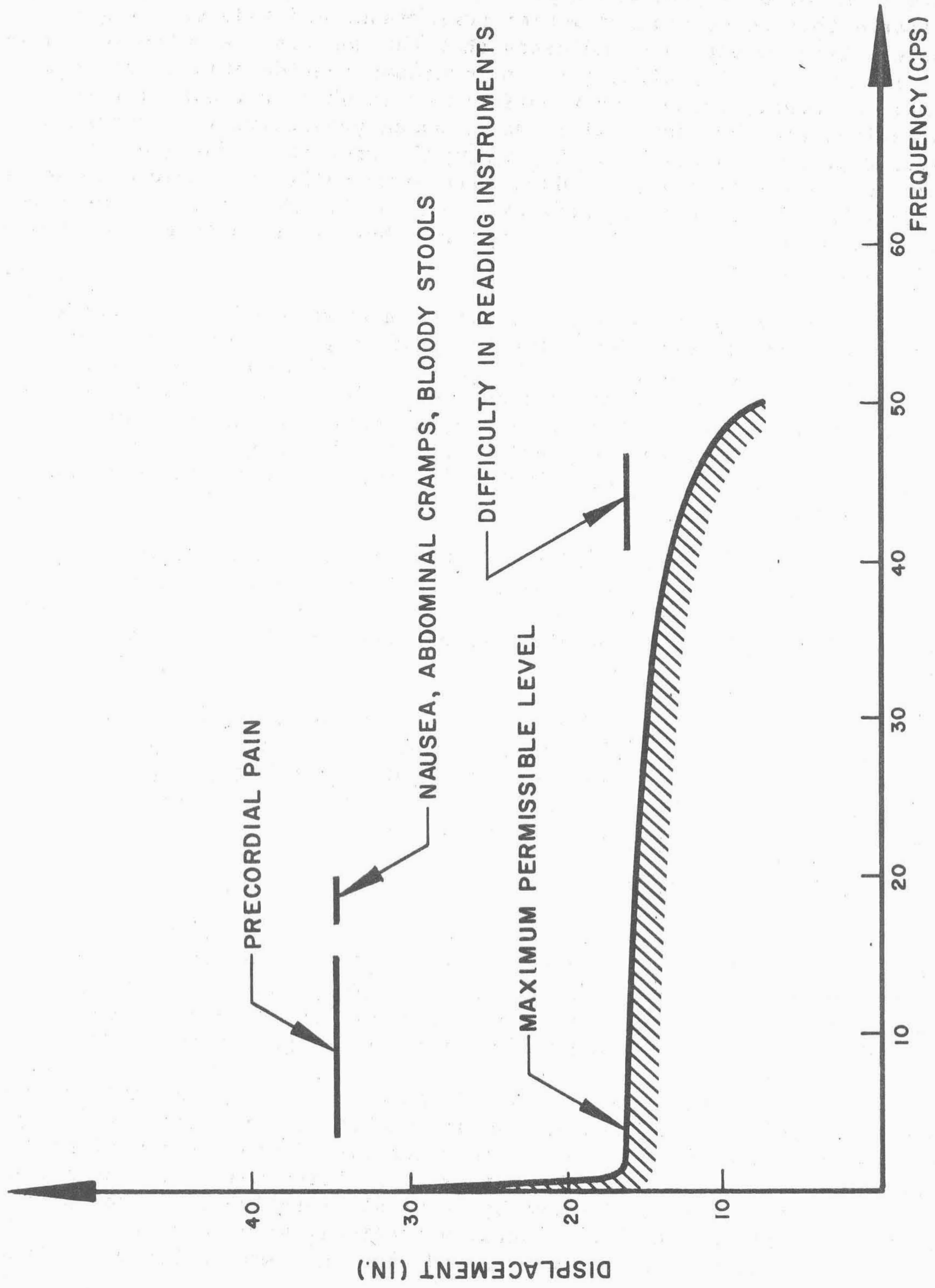



FIG 10 LOW FREQUENCY VIBRATION LIMITS ON HUMANS IN MANNED VEHICLES

in the supine position. Regardless of the position, mental and physical tasks are affected and, in some cases, internal damage can be done at high-frequency, low-amplitude vibrations. Engineering knowledge is well advanced in the vibration area. Thus, discreet use of shock and vibration equipment will greatly reduce the effects of vibration.

## V. SOME OPTIMUM REQUIREMENTS FOR MANNED SPACE VEHICLES

The data that have been presented specify desirable ranges for reliable performance of the human operator in practically every case. If the desirable ranges are selected, a set of optimum conditions evolves (Table 10).

Table 10. Optimum Requirements

| | |
|---|---|
| **Metabolic (at 3000 cal/day)** | |
| Oxygen intake | 2.0 lb/day |
| Food intake | 4.1 lb/day |
| Water intake | 2.2 lb/day |
| $CO_2$ output | 2.2 lb/day |
| Water output | 5.2 lb/day |
| Fecal output | 0.5 lb/day |
| **Engineering** | |
| Temperature | 65-75°F |
| Humidity | 50% |
| Cabin air ventilation | 15-25 ft/sec |
| Noise, continuous | < 85 db |
| Noise, short time (sec) | 140 db |
| Vibration | < 25 cps at .15 in. displacement |
| **Physiological** | |
| Acceleration position | Supine |
| Maximum acceleration in supine position | 25 g for 2 sec |
| Radiation exposure for normal lifetime | 0.3 R/week |
| Radiation exposure, total body, short time | 25-100 R |
| Work - rest cycle (hrs) | 4 on, 4 off |
| Astronaut height | 75%-95% |
| Astronaut weight | 200.8 lb at 95%<br>176.6 lb at 75% |
| $CO_2$ Concentration | < 1% |

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