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ESTABLISHING A HABITABILITY INDEX FOR SPACE STATIONS AND PLANETARY BASES

by

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FOREWORD

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ABSTRACT

Satisfaction of the physiological needs are the prime requisites for assuring man's performance in a short-duration mission. Many authorities feel that longer-duration missions will require essentially only an increase in requirements proportional to the length of the mission, based upon short term figures. The authors contend, on the other hand, that long-duration stays in space may require much more elaborate provisions for assuring the upkeep of morale and performance. This paper establishes the essential habitability needs that allow man to perform for long periods of time. An evaluation of studies concerning habitability requirements is made. The important periods of habitability are discussed, and an habitability index will be established. An hypothetical mission is used as an example, showing the length of stay as a function of payload weights, and habitability features through the use of an habitability index.

INTRODUCTION

MEANING OF HABITABILITY

"The more modern the ship and the greater the need for intelligence in her crew, the more objectionable she seems to become in point of quarters for the men, until we have about reached the point where it is well to call a halt on certain disastrous tendencies in the direction of the utter disregard of what intelligent men are capable of putting up with. . . . it will be best to point out some changes which are needed in the internal arrangements and discipline of our ships, in order to secure the creature comforts to the men under all conditions of service, and thus render the ships habitable and attractive. The physical condition of the men, when it comes to action or to conditions of war, is of greater moment than the. . . extra knots . . . for which we are asked to sacrifice so much."

This quotation is not the work of a human factors specialist in space-cabin design, nor that of a modern naval architect. It was written in 1891 by Ensign A. P. Niblack of the U. S. Navy, as part of an essay concerning the habitability problems aboard Navy vessels (Reference 1). In relation to the living standards of the era, concern for habitability as a means of augmenting crew performance must have been considered throughout naval and, now, space history. However, each generation of designers in their zeal for getting the most with the least, and packing the greatest into the smallest (or lightest), frequently forgets the essential factors of habitability and needs to be reminded.

The operation of a permanent space station or lunar base for a prolonged period of time depends upon the ability of each crewman to perform the tasks assigned to him. For short durations, man will tolerate fairly primitive environmental situations as long as the physiological essentials are provided. For long durations, however, more than these frugal conditions are required to assure that optimal performance will be maintained. System design initiated with a habitability as the unifying concept will not only insure performance, but also assist in maintaining crew morale. A beneficial fallout of the philosophy will be individual motivation to increased duration of tours—a factor that may well decrease total mission costs.

What, then, does habitability mean? Webster defines habitability as the capability of being inhabited by a tenant of the class ordinarily occupying such a dwelling. The key to this definition is the class of the tenant, that is, he is provided with that to which he is accustomed. Thus, habitability includes those characteristics which determine the over-all environment of the individual for the space vehicle these include compartment design, atmosphere and thermal control, food and water, gravitation, radiation protection, personnel hygiene, control of noise and vibration, etc. Habitability also implies an environment that approaches a comfortable earth situation.

HABITABILITY AND SPACE SYSTEMS

Man's future requirements for life in a space vehicle will be based upon (1) space flight duration, (2) nature of the mission and the tasks to be performed, (3) numbers of men involved, and (4) the distances to be traversed. His needs will change as the programs alter and enlarge.

In the past, most engineering interest in the matter of space environmental requirements has been concerned with sustaining man as a passive passenger in space flights of minimal duration. The concept of providing man with an environment to promote his role as an active performing unit in extended missions has been neglected. Although the emphasis on survival and minimum sustenance represents an important first step in the development of manned space and lunar operations, engineering planning for a long-duration mission must consider the environmental requirements for man as an efficient functional component. (Reference 2).

As space programs develop, the following distinct types of manned space systems are expected to be in operation: (1) small single or two-man cabins for up to several days duration orbital flight; (2) multi-manned vehicles with an approximately 2 week mission duration; and (3) space stations and planetary bases. Long duration habitations in space will at first be centered about space stations and lunar bases. Logistics support vehicles will transport personnel and equipment from the surface of the earth to manned, artificial space stations. These manned space stations will orbit at an altitude of approximately 300 miles, circling the earth about every two hours. Lunar bases will initially be established for exploratory purposes, but will probably be expanded for long-duration basing.

It thus becomes apparent that the life support problem could range from one of relative simplicity to one of utmost complexity, depending on the operational requirements of the mission. We have succeeded in putting man into short-term orbital flights lasting several hours. Since the durations were short, and the altitude relatively low, radiation was not regarded as a significant problem. Moreover, with only one passenger, the support was relatively simple in relation to the more complex problem of sustaining future multi-inhabited space stations.

In summation, it appears that space programs will dictate the nature of the life support problems as based upon length of mission wherein (1) short trips in days or weeks will permit designing the space capsule and its internal environment with a minimal degree of comfort for humans—present only in a passenger capacity; (2) medium-length trips for establishing lunar bases or space stations requiring marked improvement of habitable provisions; and (3) extended-duration space-station keeping, lunar basing, or planetary missions necessitating a duplication of man's comfortable terrestrial environment.

These advanced projects involve a variety of space stations and planetary base concepts, all of will depend upon adequate consideration of habitability factors to insure success of operation. Therefore, the question the designer must answer is: "What must be designed into the system to provide adequate habitability?" To answer this, the factors which influence habitability must be clearly identified. They can then be translated into usable design, procedural, and operational requirements. This paper is concerned with a brief consideration of these habitability factors, but primarily with a method of providing a means of comparing one space system design to another, and also to an optimum baseline standard—thus the HABITABILITY INDEX.

FACTORS AFFECTING HABITABILITY FOR LONG DURATION MISSIONS

GENERAL CONSIDERATIONS

It is essential to consider habitability factors because they may have an important effect on man's performance level. A decrease in man's effectiveness could result in an over-all deterioration of system efficiency. A lack of habitability, such as a sleepless night due to heat or cramped, airless quarters, can play a significant role in reduced efficiency. High noise levels often significantly impair coordination, which would obviously decrease efficiency. (Reference 2)

Naval operations, distant early-warning sites, polar IGY activities, and laboratory experiments have provided much information relative to the requirements for the psychological and physiological well-being of man. Reports of these activities are pertinent to long-term space missions because they include verified data regarding manned operations in remote locations under adverse environmental conditions, or confinement and other stresses in controlled experiments. Earth-based activities, no matter how isolated or how well simulated, cannot approach the remoteness or finality of a satellite or lunar base. However, these studies provide some indication of a base line for habitability requirements. (Reference 2)

The basic habitability factors that can be determined for any given spacecraft are (1) environmental control, (2) nutrition and personal hygiene, (3) gravitational conditions, (4) living space and (5) crew work-rest cycles and fitness programs.

This paper assumes the explicit requirements of safe and reliable life support systems. The extent to which people can endure spaceflight is directly related to their confidence in the system. Long-duration spacecraft should use separate pressure compartments, as well as other techniques, to reduce the chances of aborting an entire mission if only a portion of the spacecraft is damaged, and also to increase a crewman's confidence in the mission.

A final factor related to habitability—one which is often overlooked—is total system cost. Figure 1 is a trend chart without precise quantities, although the shapes of the curves are reasonably accurate and illustrate that the limitations on cabin dimensions can range from unusual atmospheres and high-g forces to minute crew compartments. It is not only evident, but historically true, that the more complex and stressful a vehicle is, the more training a crew must undergo to operate the system. Pressure chambers, centrifuges, zero-g flights, egress trainers, etc., are becoming very expensive. Selection programs are also very expensive. If the constraints for this meticulously evaluated program are reduced, the vehicle costs will go up. However, it is believed there is a crossover point, where it no longer pays to destroy habitability. A most important consideration in this regard is the duration of a crewman's tour in space. Strict attention to habitability provisions can be a means of motivating the crewman to accept extended tours, thus drastically reducing overall mission costs.

TIME

It is not possible to define factors affecting habitability except in relation to time. The longer the flight, the more essential the provisions for habitation become. The lower the habitability index, the greater the probability that man cannot effectively endure extended missions. Although this is apparently true, aerospace literature abounds with exceptions. Public opinion concerning spaceflight would be less favorable if 50 percent of all astronauts suffered major psychological and physiological symptoms during every long-duration space flight. An expert's advice, explaining that the symptoms were due to the spacecraft design, would not be needed; nor would it help if it were explained that a man on the ground exposed to the same constraints would suffer identical symptoms. Therefore, when new space programs are planned, new spacecraft are designed, and research conducted, the level of habitability designed into the system must be commensurate with the full range of anticipated mission durations. Theoretical and experimental studies of controlled confinement situations have indicated many factors that influence habitability, and are amenable to hardware design requirements such as the volume or area which may be habited by man; the comfort of the environment; the visual, aural, and tactual inputs; the life sustenance provisions; the sanitation facilities; and the nature of the tasks required of man.

ENVIRONMENTAL CONTROL

Atmosphere

All atmospheric factors must be maintained within a range. Even though slight deviation from this range is tolerated, human performance is apt to be adversely affected. Even a slight amount of anoxia can produce sleepiness and performance decrement. Exposure to toxic products for any length of time may cause deficient performance, even though no physical harm occurs. As long as the partial pressure of oxygen is maintained at 160 mm Hg, then total pressure of only about 3 psi need be maintained for short durations. However, the physiological effects of remaining for many months in an atmosphere of pure oxygen at low pressure are uncertain, and reliable information is needed. Although the physiologic necessity for nitrogen is questionable the question for a need for some diluent gas (such as nitrogen, helium, or neon) is presently quite controversial. The physiological and physical benefits to be gained by using a diluent gas probably far outweigh any drawbacks. For long duration missions, a diluent gas is expected to be standard. Present knowledge of the optimal composition of a mixed gas atmosphere is by no means satisfactory, and much work remains to be accomplished. It appears, however, that a total pressure of 7.0 to 10 psia should be adequate.

Carbon dioxide levels should be maintained below 5 millimeters of mercury. However, this may not be so critical at lower pressure levels. In emergency conditions, greater concentrations of carbon dioxide can be tolerated without serious performance impairment. One study has shown that man can perform fairly efficiently in an emergency situation in carbon dioxide levels as high as 20 millimeters of mercury for 60 days (Reference 3).

Toxic product control is an important and critical problem of atmosphere regulations. Many items considered neutral under normal conditions emit products that may become toxic in a sealed system. Examples of sources of toxic emanations are carbon dioxide, paint, human flatus, lubricants, and carbon monoxide from cigarette smoking.

The early detection of toxic products is a necessity in a sealed system. The development of some specific techniques will be required for each space system. The problem of the removal of atmospheric contaminants can be alleviated by several means of controlling toxic products. Among these are utilization of products with low toxic contents, total enclosure or isolation of toxic materials, control or elimination of dusts and solid particles, and washing gases from the air with scrubbers. Also, the air may be completely recirculated through filtration systems, especially for removal of radiation particles, control of ionized air, and deodorization.

Thermal Control

Numerous studies show that high temperature and humidity adversely affect performance, decrease morale, and may even be a factor in accident susceptibility (Reference 1, 4). Temperature and humidity should be maintained within the comfort range for minimum water vapor production and maximum personnel efficiency. This comfort range will vary somewhat, depending upon the work conditions, humidity, and rate of air movement. In general, an effective temperature of 71 F (range 68 to 74 F), a relative humidity of 30 to 70 percent, and an airflow of 15 to 40 feet per minute are recommended. Effective temperature has been derived from studies on the effect of humidity, ambient temperature, and air movement upon the subjective feeling of temperature.

NUTRITION AND PERSONAL HYGIENE

Nutrition

A varied, palatable diet is an important morale factor, especially during protracted periods of isolation or other stress. A survey of numerous studies made during the past 20 years leads to the conclusion that man rarely is content to survive on dry food or food concentrates for more than a brief period. Dill and Menninger (Reference 5, 6), and many others, have indicated that palatability and variety are prime requisites in food planning, not only because of the physical needs, but also because of the strong emotional values associated with food during long periods of isolation. The impact of individual experiences and cultural patterns on appetite and food habits is enormous. Bondy and Dill (Reference 7, 5) suggest that a lack of appealing food over a long time can become a severe stress and may even be a factor in precipitating a mental or psychoneurotic breakdown. It may be a serious error to stress nutritional requirements and to neglect flavor and appearance. Many a nutritional but unappetizing meal has been discarded by troops in combat areas because the monotony of the food was intolerable. The need for water for physiological requirements is obvious. Water for other purposes is discussed below.

Personal Hygiene and Other Water Needs

Personal hygiene and sanitation must be rigidly controlled. In isolated bases, especially where boredom or stress is commonplace, there is a tendency for hygienic standards to deteriorate.

Authorities in the fields of group morale, health, and welfare agree that an adequate water supply for personal hygiene is essential (Reference 8). Although highly motivated people might endure short rations of water for an indefinite time, it has been demonstrated that an adequate water supply contributes immeasurably to optimum performance. Navy experience has shown that insistence upon personal cleanliness, together with an adequate water supply, is a vital morale factor (Reference 1, 8). Faucett and Newman (Reference 12) indicate that, over a long period of time, the deprivation of sufficient water for showers and cleaning has been cited as a condition of stress which may foster fatigue or even mental breakdown (Reference 3).

Probably the most vital reason for demanding personal cleanliness for a group restricted to a small area is the prevention of infection, disease, and contagion. One only needs to study the records of submarine patrols in World War II for supporting evidence (Reference 8). Actual water requirements for various organizations differ considerably, but the minimum for military groups seems to be about 10 gallons per man-day, with recommendations as high as 150 gallons. Table 1 lists water requirements for various organizations. A general breakdown of water use aboard ships is shown in Table 2.

Table 1. Comparison of Water Requirements

Organization	Gallons Per Man-Day
IGY polar expedition	11
Military advanced bases (World War II)	
Allied	10
United States	25
U.S. Air Force	
Permanent bases	150
Advanced bases	75
U.S. Navy	
Permanent bases	100
Advanced bases	25 to 50
Surface vessels	25
Submarines	20
Space System Recommendation	6

Table 2. Consumption of Fresh Water Aboard Ship

Use	Gallons Per Man-Day
Drinking	0.5 to 1.0
Kitchen	1.5 to 4.0
Washing	5.0 to 20.0
Laundry	5.0 to 10.0

Estimates of other water needs for space systems are much lower because of the expected efficiency of bathing techniques, i.e., bathing garments, etc. Regenerative water systems and artificial g or planetary g will allow more nearly normal washing techniques.

Noise, Vibration, Radiation, Illumination

Other environmental factors need be only briefly mentioned. It is well known that excessive noise levels are physiologically harmful and that lower levels may produce performance decrement (Reference 1). Similar impairments have been shown in relation to vibration.

Radiation protection is an unqualified essential. Although low levels of exposure may be tolerated, any exposure that produces performance decrement may have a serious aftermath. Therefore, radiation above accepted permissible levels is considered inhabitable. Based upon acceptable levels of radiation exposure for industrial workers at one extreme, and data from several industrial reactor accidents on the other, limits of acceptable dose for astronauts can be derived. It is assumed that the astronaut will be allowed the same total lifetime dose during his sparce career as an industrial worker during his working lifetime. It is expected that structural shielding will provide a fairly low level of ambient radiation, and that for periods of high solar flare activity, personal protection or other techniques may be used.

The provision of proper illumination, and the careful selection of interior colors for use in space systems can contribute much to an efficient work environment, and to improved habitability of living areas. Voluminous information on problems of internal lighting effectively demonstrates the importance of proper illumination on visual acuity, visual health, and work effectiveness. Recommendations for appropriate illumination levels for various task requirements in the home, office, and factory have received widespread publication (Reference 2).

GRAVITATIONAL CONDITIONS

Zero-G

The influence of zero-g on habitability is subject to debate. Some maintain the inconvenience of anchoring objects and the strangeness of the situation will produce many complaints, regardless of the innocuous effects zero-g may have for long duration. Others see zero-g as a great convenience and insist the novelty of the situation will greatly relieve boredom. Regardless of the correct view, the factors that enable a consistent orientation reference for the crew will provide for improved habitability.

Except for weightlessness, the majority of the bioastronautic problems to be encountered during lunar space flights can be simulated and studied. The effects of chronic exposure to zero-g will not be fully appreciated until the early orbital flights of Mercury, Gemini, and Apollo are completed. The successful completion of the initial Mercury orbital flights are now part of space history, and detailed analysis of several hours exposure to weightlessness has been undertaken. It appears that the astronauts incurred no permanent pathological damage during these flights. The psychophysiological responses to prolonged unrestrained weightlessness are still not known. The Russian cosmonauts withstood several days of weightlessness, seemingly without untoward effect. Again, data are lacking. Other methods of approach to weightless study have been prolonged water immersion, bedrest, and extrapolation of effects in short parabolic aircraft flights. Some bioastronautic specialists have speculated that there may be a significant deterioration of cardiovascular function during long exposure to zero-g, with consequent reduction in tolerance to accelerations and decelerations encountered in maneuvers, lunar landing, and especially reentry and return to earth. Several devices to help offset cardiovascular accommodation to weightlessness have been described, but whether or not this type of approach will be useful must await evaluation of the early orbital missions.

A spacecraft operating without artificial gravity should be designed to have a consistent vertical alinement within any given compartment. The phenomenon of "down is where my feet are", found in zero-g research aircraft led some authorities to suggest that the spacecraft cabin could be efficiently arranged if the crew were oriented at different angles with respect to each other. However, optimizing such arrangements becomes almost impossible because of the innumerable combinations that must be evaluated. The cost of this program would detract from more important factors which require careful analysis. There are numerous reasons to justify a consistent vertical orientation for many missions, especially earth orbital types.

Many human tasks require judgements concerning various relationships. If, by judicious application of the supposed advantages of optimum zero-g efficiency, the crew faced continually varying reference planes, judgement would almost certainly be poor, unless aided by special provisions. Good design practice suggests selecting a single reference plane permitting alignment of the interior to be consistent with this selected plane. The possible sacrifice in surface area would be more than recovered in design efficiency and habitability. In addition to maintaining a consistent orientation in the zero-g spacecraft, palatable foods that will not crumble or linger in the air of the cabin must be prepared. Any food that does remain in the air should be removed by an efficient air flow system.

Airflow of sufficient velocity to be easily sensed is a generally undesirable condition. But in the zero-g spacecraft, air movement can be used to keep stray objects out of the mouths and noses of the crew, and can add to the variety of sensations important in confinement. In early flights, the crew should be given the option to regulate air movement. Separate compartments with various airflows can be used to add another dimension variety in the zero-g space station.

Artificial-g

An artificial-g spacecraft can be used to eliminate many of the inconveniences of the zero-g spacecraft. However, if a number of considerations are not given close attention, an artificial gravity station could cause more problems than it solves.

Spacecraft rotation seems to be the only practical means of creating a constant force environment. Spinning humans creates dizziness and interferes with their neuralmuscular coordination. There is however, a definite combination of rotational velocities and rotational radii that would be acceptable to man. People quickly adjust to rotations of up to 4 rpm, and can adapt themselves, though not so quickly, to velocities up to 10 rpm. Ice skaters often achieve speeds of 50 rpm, but the axis of their rotation is through the center of their bodies, and only small forces are applied. The 10 rpm upper limit has been derived from research where subjects were at a distance from the axis of rotation. It was found that recovery from rotation takes as long, or sometimes longer, than the original adaptation period.

Numerous rotating space station concepts have been suggested by governmental and industrial personnel. Many of these involve rather distorted visual fields, unless steps are taken to break up the visual scene into areas consistent with crew orientation. Figure 2 shows the length of visual compartments that could be used in torus, hexagonal, and basic space station shapes. The curves for the wall angles are for angles with respect to the man's vertical as he stands in a space station. If corners are broken up and curved surfaces are used, the 12-degree angle might be acceptable. The 3-degree value is near threshold of distortion for tilted rooms when judgements aren't aided by cues due to objects placed near the corners.

Limiting visual distortion in rotating spacecraft greatly aids habitability. It should be mentioned that dizziness can be caused by rotating the visual field without the actual physical rotation of man. This factor suggests that viewing ports, placed on the rim, should include counter-rotating mirrors (or similar devices) to cancel the apparent rotation of the external scene.

Figure 3 summarizes the influence on humans of rotating spacecraft configurations. The report by Loret (Reference 9) is an excellent basic work for those interested in investigating the human factors aspects of rotating space vehicles.

Lunar and Planetary-g

The lunar one-sixth g may produce some physiological adaptation similar to that expected with zero-g. In general, however, the effect of this reduced g will probably be quite pleasurable and readily offset by learning and fitness programs. Except for the case of motion, there should be no special habitability effects.

LIVING SPACE

One of the major factors of interest in space cabin design is the suitability of a particular configuration for extended habitation, and, consequently, the amount of living space provided. Many surveys and studies have been made during the past thirty years for the purpose of evaluating living area requirements. It has been shown that cramped living quarters with little privacy can cause fatigue and poor morale, with a consequent lowering of performance efficiency. Kahn and Kalez (Reference 10, 11) opine that inadequate quarters and physical discomfort have been cited as factors leading to fatigue and breakdown in combat pilots. Inadequate housing was considered as one of the major causes of breakdown in concentration camps. Results of the Navy habitability (Reference 1) survey indicate that adequate space and privacy are important factors in the maintenance of morale. The results of the personnel opinion poll taken during this survey show that, next to atmospheric conditions, living space requirements were considered most important. Regarding the IGY polar expedition in 1957-58, Siple (Reference 12) stated that the ample living space provided for each man helped to solve the psychological problems of prolonged confinement, the relatively large area assured a measure of privacy, and the extra servicing necessary allowed less time for idleness.

It is suggested, therefore, that volume is an important element of man's basic needs. However, this is obviously an oversimplification, because the important point is that many other factors can approach normal earth-like conditions if volume is sufficient. The following major factors can approach earth-like conditions when they are given sufficient volume:

1. Movement - The ability of the body to move freely and travel to different locations

2. Sensory variety - Changing sounds, smells, tastes, and visual experiences (volume permitting separate compartments of varied decoration and functions)

3. Privacy and social protocol - The choice of companions within limits; a division of labor which results in a fairly set protocol for interperson relations; the option for privacy

4. Accommodative body functions - The ability of mechanisms, such as the refocus from far to near objects (voice volume, muscle coordination, and hearing are controlled by their relative distance to objects)

In the small spacecraft, everything with which the man interacts is at a fairly constant distance with the exception of very close or very far visually perceived objects. A large volume permits a continuation of normal accommodative reactions to distance.

Figure 4 describes the extremes of habitability. The craft on the left cannot be expected to perform the same missions as the monster on the right, but the cost of the huge vehicle would require a great return in performance. The optimum spacecraft for long-duration missions will be more spacious than the two-man experimental capsule, but smaller than the city in orbit, suggested by the artist.

The Navy habitability survey serves as the basis for recommendations for minimum space requirements per man, based upon the needs of the individual and the use of the area. For quarters used for sleeping, study, and leisure activities, a minimum of 90 square feet per man, including 40 square feet of unincumbered area, was recommended. The IGY polar expedition facility allowed nearly 100 square feet per man in the sleeping area alone. Table 3 shows various living area recommendations.

Table 3. Comparison of Gross Living Area Requirements

Organization	Gross Square Feet Per Man	
IGY polar expedition	100	
Royal Navy	19	Seamen
	40	Petty officers
	60	Officers
U.S. federal prisons	48	Regular
	70	Honor
U.S. Maritime Service	16 to 30	Seamen
	20 to 30	Rated seamen
U.S. Navy		
Barracks	50	
Vessels	20	Seamen
	90 to 130	Officers
Space System—minimum habitable recommendation	90	

In order to evaluate the habitability features of various space cabin configurations from a physiological viewpoint, three confinement studies in simulated space cabins of differing configurations were conducted at North American Aviation, Inc., Space and Information Systems Division over the past two years (Reference 13). The hypothesis of the investigators was that a cabin allowing a large living area and other habitable features would show little, if any, physiological differences from a normal life situation with a relatively sedentary occupation such as that of an office worker. On the contrary, life in very small cabins would reflect drastically reduced levels of metabolism and cardiovascular response almost commensurate with bedrest situations.

All three simulators were wooden mock-ups of a particular vehicle design. The first cabin study used a mock-up of a small, conical-shaped cabin with an exterior volume of about 450 cu ft, providing a living volume (volume for human occupancy) of 200 cu ft, and living space of 39 sq ft. Three men were confined there for a period of seven days. This cabin is designated Cabin A. Another study involved a space cabin mock-up with a cylindrical configuration, Cabin B, which had an external volume of about 3500 cu ft, an interior living volume approximately 1500 cu ft, and living space of about 150 sq ft. Four subjects were confined in this study for seven days. Cabin C, the third cabin studied, was disc-like in configuration, with an external volume of approximately 3200 cu ft, an interior living volume of about 1600 cu ft, and a living space of about 400 sq ft. Two men were confined in this mock-up for a period of four days. The various mock-ups provided the following living space per man: Cabin A, 13 sq ft; Cabin B, 37 sq ft; and Cabin C, 200 sq ft. In all three studies, the subjects were confined continuously for the period indicated, without any outside contact except by intercom at programmed intervals. In each study, a simulated space mission with a scheduled work-rest regimen was carried out. All requirements for eating, sleeping, personal hygiene, and investigative procedures were provided on board. Although the mission profiles differed, the biomedical and physiological aspects of each were similar and comparisons can be made. Control stations where psychological and physiological investigators continuously monitored each simulation were located immediately adjacent the mock-up.

Determining the metabolic requirements of the subjects offered a means of assessing the various activity levels occurring in each cabin. Comparing the values for the 70-Kg man in each study it is seen that the energy needs varied considerably. Since the amount of activity determines the energy requirements, it is apparent that activity levels within these cabins might vary markedly, even though the mission tasks were similar. In Cabin A where movement, and consequently, activity were reduced to a minimum, the energy needs were almost those of the bedrest state (2300 Kcal per man-day). In Cabin B, because room size space was available for movement, activity increased accordingly, but the activity was still on the lower limits characteristic of a sedentary occupation (2550 Kcal per man-day). Cabin C, on the other hand, with a large amount of free space, allowed activity levels well within those of the average office worker (2800 Kcal per man-day). Figure 5 shows a curve based on these data that relates activity to living space per man. It is interesting to note that the figure of 90 sq ft of living space per man, recommended for long duration missions, falls on the upper limits of this curve.

Confinement within these various cabin configurations produced no evidence of physiological impairment; however, changes similar to those of a bedrest state were noted in the very small cabin.

The general activity level of the crew as measured by mean caloric expenditure is related to the living space per man provided by the cabin. The energy expended in the very small cabin was near the bedrest activity level while that in the very large cabin was in the light office work range. On this basis, an area of about 90 sq ft per man for space cabin simulation or 700 cu ft per man for actual space cabin conditions, would be optimum for long durations.

CREW WORK-REST CYCLE AND FITNESS REQUIREMENTS

Work-Rest Cycles

Work-rest cycles still require much concern for adequate crew duty planning. The optimum work-rest cycle and scheduling arrangements for space missions must be determined from both future research and early manned satellite operations. Since work-rest cycling is an important item of habitability, some discussion is warranted here; however, because of the controversial nature, lack of substantial data, and specificity to mission, no concrete recommendations can be made.

Tasks that the man executes must not only be sensible but also contribute to the total mission. Many of the problems associated with work-rest cycles and related schedules can disappear from the large, multi-man, multi-mission spacecraft whenever designers and planners determine what is required for a successful mission. The establishing of a time factor to perform these predetermined functions would then allow a crew to schedule their own work-rest cycles, so long as total system output did not fall below certain specified limits.

In extended space and lunar operations, the metabolic cycle and the consequent periodicity of proficiency will require considerable attention for three reasons. First, and underlying the other two, people appear to be committed to the diurnal rhythm. It can be shifted, reversed, lengthened, and shortened, but neither broken nor eliminated. Second, there will be no none of the common referents of the natural sequence of day and night in an extraterrestrial environment. Consequently, a day-night cycle must be effectively simulated within the space environment. Third, synchronization of work and sleep schedules of the crew must be maintained for periods of several weeks or months. The degree that a simulated day-night cycle can be synchronized with work-sleep schedules is dependent upon what the system requires of the human component—the nature of the functions, the load these functions impose, and the temporal distribution of this load. When work-sleep schedules are not synchronized with the accustomed physiological day-night cycle, fatigue results. This becomes cumulative, and the final result is a drastic deterioration of proficiency.

Weightlessness may reduce the requirement for sleep. If wakefulness and productive activity are maintained by the total sensory input reacting upon the human, and if under subgravity conditions the total sensory input is substantially less than under normal conditons, how will this reduction in input modify the ratio of work to sleep? Will the ratio be more or less than that normally characteristic of a proficient individual? These questions are as yet unanswered. It is interesting to note, however that the Russian cosmonaut Nikolayen indicated a need for six hours sleep and Popovitch for seven or more hours at one sleep-period (Reference 14).

In order to maintain morale and high performance for a long duration, a schedule most closely resembling a normal earth day should be instigated. This would provide 8 to 12 hours of work activity, 4 to 8 hours of free or leisurely activities, and an 8-hour sleep period. From the results of several work-rest cycle studies, many believe that two 4-hour sleep periods per day may be more desirable subjectively than an 8-hour period. This regime also merits consideration. The suggestion for ad-lib work-rest cycles within mission constraints may be the most productive of all, however.

Recreation and Fitness

Adequate provisioning for leisure hours and relaxation is an important factor for enhancing personnel morale, although the type of nonsedentary activity will be dependent on the area limitations of the space station or lunar base. For long-term space missions, a facility for physical exercise is essential. A planned training and conditioning program will be necessary to maintain physical fitness and help reduce cardiovascular and musculoskeletol deterioration. Sedentary and semisedentary activities will also be required.

Provisions for entertainment media such as motion pictures, television, and radio will be important both for relaxation and as informational contacts with earth. The opinion survey conducted in the Naval habitability studies revealed that both officers and enlisted men rated entertainment highest in importance among the recreational facilities afforded ship personnel of the Atlantic Fleet. Space on lunar stations should also include library facilities, and individual compartments should be designed to facilitate reading, writing, and pursuit of individual hobbies or interests. Opportunity and equipment for personal scientific interests should also be made available (Reference 1 and 2).

Fatigue

In space operations, fatigue is the same problem as in conventional operations of a critical nature. Fatigue can be prevented by habitability design, work-rest cycling, pharmocologic augmentation, and adequate leisure time.

The fatigue in space or lunar operations is not foot-pounds-of-expended-energy type. Instead, it is the fatigue associated with the depressive effects of sleep deprivation, or prolonged commitment to skilled or semi-skilled tasks, and the subsequent inclination or ability to continue those tasks. Manifestations of these depreciative effects consist of decrement in proficiency (such as impaired judgement, slower decision time, and decline in alertness), increased variability of proficiency, degradation of attitudes and feelings, and various metabolic changes. It has repeatedly been found that the effects from prolonged commitment to a particular task are not completely dissipated by a normal period of sleep. When the individual again resumes work, he gives every indication of being completely rested, but as work continues, the beginning or proficiency deterioration occurs sooner than during the previous work period, and progresses at a faster rate.

The most dangerous aspect of fatigue is the low order of correspondence between the fatigued individual's actual level of proficiency and what he believes it to be. The man is aware of his fatigue—general tiredness, boredom, and vague discomforts—but he is not aware of his proficiency loss. Despite the fact that his proficiency may have deteriorated to unacceptable levels, he may believe—he may even argue with considerable vehemence—that his proficiency has not changed. Thus, he elects to continue working. The danger of this short of decision is reflected in the number of fatal automobile accidents that occur late at night and early in the morning.

Small Group Dynamics

The space station or planetary or lunar base crew will probably be established along military lines. The sociology of military organizations generally is of operational efficiency. The intent of this information is to provide some insight on the premise that the needs of a group are greater than that of the sum of its individual members. However, the nature of these systems may result in disharmony and lack of cohesiveness among the specialists. Specialists have different training in connection with their fields, and they will have different egocentric feelings and values. The value assigned by an individual to his speciality is often not the same as the value that the organization assigns to his work.

Early in the planning phases of the program, pictures of the space station or planetary base organization must be constructed as a sociological entity. This concept will lead to adequate crew selection, orientation and training programs, and will provide sensible inputs for team-type approaches to work and work-cycle planning.

HABITABILITY INDEX

GENERAL

The engineer and human factors specialist concerned with advanced programs is confronted today with a variety of space cabin and planetary base systems for which he must establish design requirements. Often, guidelines for human needs are established, but in many cases they remain inadequate. Frequently, tolerance limits and optimum levels only are listed and the "grey" area between them is barely considered. The whole human system, then taken as an aggragate, is seldom considered but, rather, looked upon as a group of unrelated items.

A frequent complaint voiced by these designers is that there is no method of comparing various systems from a human occupancy standpoint, and there is no optimum standard against which to measure their particular design recommendations. Based upon the discussions presented in the preceding sections, it is the purpose now to suggest a means by which one system can be compared to another, to itself over varying time periods, and to an ideal system. The technique to be used is to establish an index for human factors requirements -- a Habitability Index. In presenting the human factors data, several points must be borne in mind. Tolerance limits given need not necessarily be considered lethal-points, but most often represent either a level at which severe performance decrement is expected or where physiologic damage occurs. The area outside tolerance levels must be considered as an inhabitable zones index measurement. For nearly all the items considered, exposure time is an important factor; however, most tolerance levels decrease rapidly in a short period and become constant for long duration exposure. Some factors, living space and anoxic acclimatization, for instance, change over a much greater time period. Since long-duration systems are under discussion, short term effects are not presented herein.

Until Habitability Indices are determined for the many real and proposed systems, and numerous comparisons made against actual operations, it is not possible to predict system success or failure at any given percentile value. Rather, the Habitability Index can only provide a comparison guide for establishing optimum and near optimum space system designs, or be used as a method of comparing contemporary programs.

METHOD

The technique used is the establishment of an "index number" by a variation of the method of "weighted average of relatives." For each habitability factor considered, a minimum or maximum tolerance and an optimal level is given -- all items being listed for continuous exposure. The final result allows comparison of various space system designs either by individual item (such as pCO_2), by subsystem (such as environmental control), or by total system.

For each item of the system under consideration, a relative value (percentage) is determined between the design or operative value established and the optimum value listed. In order to equate the wide variety of factors, the minimum (or maximum) tolerance is considered as zero and the optimal level as 100. The value for any particular system is some percent between zero and 100. Carbon-dioxide may be cited as an example. The maximum tolerance level of pCO_2 for a long duration is 20 mm Hg and the optimal level is less than 5. If the system design allows a level of 8 mm, then the relative value is the difference between 8 and 20, divided by the difference between 5 and 20, or 12/15 x 100 = 80%. Thus for this particular system the carbon-dioxide limit is 80 percent of the optimum standard.

Once the individual relative values are established, they are averaged by major groups: environmental control, nutrition and personal hygiene, gravitation, living space, and crew work-rest cycles and fitness. These major group values provide good comparison points to other space systems.

The Habitability Index for the total system is finally determined. Each major group values is multiplied by a weighting factor - environmental control x 4, nutrition and personal hygiene x 2, gravitation x 1, living space x 2, crew work-rest cycles and fitness x 1.

The weights were established for individual items in each group and by group importance to performance and health. The sum of these weighted averages is then divided by 10 (weight total) to determine the Habitability Index. The index for the Optimum Standard System (all optimal values) is 100%. Figure 6 is an example of a data sheet for Habitability Index determination.

EQUATIONS

The method described above may be expressed for clarity as follows:

1. Find relative value (RV factor, E.G. - Oxygen (pO_2)

$$RV = \frac{P_a - P_t \times 100}{(P_o - P_t)}$$

where

P_a = actual measure, P_o = optimal level, P_t = tolerance level (minimum limit)

Note: When P_t (maximum limit) then $(P_t - P_o)$

2. Average group, E. G. - Environmental control (oxygen, CO_2, etc.)

$$\overline{RV} = \sum \frac{RV}{N}$$

where

N = number of items

3. *Find Habitability Index* by averaging weighted group averages

$$\text{HABITABILITY INDEX} = \frac{\sum(\overline{RV} \times q)}{\sum q}$$

where

q = weighting factor

CELENTANO-11

HABITABILITY DATA FOR INDEX DETERMINATIONS

Most of the following tables and charts represent adaptation of data relative to habitability factors from materials and sources discussed in preceding sections. Some of these are obviously based on scanty data and revision is expected. Although the data chosen may not be broad enough or complete enough in scope, it is provided to allow initial habitability indices to be made.

Figure 6 is an example of a data sheet to assist in Habitability Index determinations.

1. Environmental Control

a. Oxygen requirement - Table 4. Tolerance limit is lower limit. Assumes diluent gas with total pressure of 7.0 to 10.0 psia for durations over one month.

$$\text{Over one month: } RV = \frac{\text{Total pressure system (psia)}}{7.0 \text{ psia}}$$

(with maximum of 100%)

b. Carbon dioxide - Table 5. Tolerance limit is physiological impairment.

c. Temperature - Figure 7. Optimum level is 71 F (average).

d. Humidity - Figure 7. Optimum level is 50% (average).

e. Noise - Figure 8. Optimum level is speech and sleep levels. Tolerance limit is deafness risk level for continuous, and discomfort level for short period (5 minutes).

f. Vibration - Figure 9. Tolerance limit and optimum level are upper and lower limits of unpleasant region respectively.

g. Radiation - Table 6. Considered inhabitable (zero percent) above permissible limits.

CELENTANO-12

Table 4. Effect of Oxygen Pressure on Performance and Tolerance (Continuous Exposure)

EFFECTS (pO_2 mmHg)	VOLUME PERCENT O_2			
	21	30	50	100
OPTIMUM	160	162	170	190
MAXIMUM TOLERANCE	460	460	460	460
UNIMPAIRED PERFORMANCE				
UPPER LIMIT	240	250	275	300
LOWER LIMIT	115	120	130	160
ACCLIMATIZED (4 WEEKS)	60	81	120	150

(Adapted from Reference 2)

$$\text{Over one-month } RV = \frac{\text{Total Pressure of System (psia)}}{7.0 \text{ psia}}$$

(Maximum RV = 100%)

Table 5. Carbon Dioxide Effects (Continuous Exposure)

EFFECT	PARTIAL PRESSURE (mm Hg)
PHYSIOLOGICAL IMPAIRMENT	> 20
DISCOMFORT ZONE	10 - 20
BORDERLINE	5 - 10
OPTIMUM	< 5

(Adapted from Reference 2)

Table 6. Radiation Exposure Dose Limits

Critical Organ	Minimum Life-time Dose (REM)	Average Yearly Dose (RAD)	Average Dose for 30 Days (RAD)	Maximum Permissible Single Acute Emergency Dose (RAD)
Skin of Whole Body	1630	231	25	500
Blood Forming Organs	271	54	5	200
Feet, Ankles, & Hands	3910	559	50	100
Eyes	271	27	3	100

h. Illumination - Table 7

$$RV = \frac{\text{Actual level}}{\text{Recommended level}}$$

2. Nutrition and Personal Hygiene

a. Nutrition - Table 8

b. Water for nutrition and for personal hygiene - Table 9

3. Gravitation

a. RV data - Table 10. Estimates are assumptive.

b. Artifical - g curves - Figure 12.

1. PGV is pseudo gravitational vehicle - an ideal artificial-g system.

2. The shaded area is the human factors design envelope.

3. RV for physiological need is same as for lunar-g.

CELENTANO-13

Table 7. Recommended Levels of Illumination for Various Tasks or Situations

Task or Situation	Recommended Illumination Level in Footcandles
Halls and Stairways	5
Washrooms	10
Shops, offices, and typical living area	15
General office work	25
Most severe living compartment tasks	25-30
Most severe tasks encountered in workday situations	40-50
Accounting, bookkeeping, drafting	$\left[RV = \frac{\text{Actual Level}}{\text{Recommended Level}} \right.$
(Adapted From Reference 17)	

Table 8. Nutrition

Food Item	Provision Weight (Lb)	Per Man-Day Energy (Kcal)
Optimum provision Perishable or frozen items	5.0	2800
Equivalent palatable dehydrates	1.3	2800
Tolerance limit Solid dry food item	1.3	2800
Survival - 6 months	0.6	1300
Survival - 1 month	0.1	460

Table 9. Water

Water Need	Amount per Man-Day
Optimum provision Personal hygiene and nutrition	50 (6 gal) (or equivalent cleansing system)
Tolerance limit Nutrition only	6
Survival - 1 month	1.5

Table 10. Gravitation

Condition	Time (Months)	Relative Value (%)
Zero G		
No fitness program	0.5	100
	> 0.5	? (Est. 80)
	> 6.0	? (Est. 50)
Fitness program	1.0	100
	> 1.0	? (Est. 100)
	> 6.0	? (Est. 80-100)
Lunar-G (one-sixth)		
No fitness program	1.0	100
	> 1.0	? (Est. 80)
Fitness program	12.0	100
Artificial-G		
Physiological need	Same as Lunar-G	
Physical benefits (within Human Factors area on Loret Graph)	12.0	$\frac{\text{G-level of system}}{.5g}$

(4.) RV for physical benefit = $\frac{\text{g-level of system.}}{0.5g}$

(0.5g considered to be practical optimal level: MAX. RV 100 percent)

4. Living Space

a. Volume per-man requirements - Figure 10.

b. Area per-man requirements - Figure 11. Cabins one to four refer to proposed space systems. Cabin five is an idealized cabin.

5. Crew work-rest cycles and fitness.

RV - Table 11. Estimates are assumptive.

Table 11. Crew Work-Rest Cycles And Fitness

Condition	Time (Months)	Relative Value (%)
Work-Rest Cycle		
8 on -16 off (4 on - 8 off)	12	100
8 on - 8 off (4 on - 4 off)	1	100
	6	? (Est. 80)
	12	? (Est. 60)
Recreation	12	100
Fitness Program	Same as Gravitation	

EXAMPLES

Example 1.

Optimum One-Year System

Factor	Value	RV
1. Environmental control		
pO_2 (total 7 psia)	160 mm	100
pCO_2	<5 mm	100
Eff. Temp. (Avg)	71 F	100
Humidity (Avg)	50%	100
Noise - general area	50-60 db	
Sleep area	30-40 db	

CELENTEADO-15

	Value	RV	
Vibration - amplitude	<0.001 in	100	
frequency	<2 cps	100	
Radiation	Basic permissible	100	
Lighting - all area	recommended	100	
		100	$\overline{RV}$
2. Nutrition			
Food - mixture perishable & dehydrate	5 lb	100	
Water	50 lb/day	100	
		100	$\overline{RV}$
3. Gravitation			
Artificial-g	0.5g		
or zero-g	with max fitness program	100	$\overline{RV}$
4. Living Space	700 cu ft per man	100	$\overline{RV}$
5. Crew Work-Rest Cycle			
Work-Rest Cycle type	8-16	100	
Recreation	adequate	100	
Fitness	complete	100	
		100	$\overline{RV}$

then:

$$\overline{RV}_1 \times 4 = 400$$
$$\overline{RV}_2 \times 2 = 200$$
$$\overline{RV}_3 \times 1 = 100$$
$$\overline{RV}_4 \times 2 = 200$$
$$\overline{RV}_5 \times 1 = 100$$
$$\sum \overline{RV} = 1000$$

Finally: Habitability index $= \frac{1000}{10} = 100\%$

Example 2. Six-month Earth Orbital System

Six man cabin with 2400 cu ft living volume.

Factor	Value	RV
1. Environmental Control		
pO_2 (Total pressure 5psia)	160 mm	71.50
pCO_2	< 8 mm	80.00
Eff. temperature	75 F AVG.	71.50
Humidity	50	100.00
Noise - general area	70 db	75.00
Vibration	imperceptible	100.00
Radiation	below permissible	100.00
Lighting	adequate	100.00
	$\overline{RV}$	69.70
2. Nutrition		
food-mixture	dehydrate 75	75
	20 lb/day	32
	$\overline{RV}$	54

CEL-GNTAJO-10

Factor	Value	RV	
3. Gravitation			
Zero-g	fitness program	100	$\overline{RV}$
4. Living Space	400 cu ft per man	36	$\overline{RV}$
5. Crew Work Rest Cycles			
Work-rest cycles	4 on, 8 off	100	
Recreation	adequate	100	
Fitness		100	
		$\overline{100}$	$\overline{RV}$

then:

$$\overline{RV}_1 \times 4 = 278$$

$$\overline{RV}_2 \times 2 = 108$$

$$\overline{RV}_3 \times 1 = 100$$

$$\overline{RV}_4 \times 2 = 72$$

$$\overline{RV}_5 \times 1 = 100$$

$$\sum \overline{RV} = 658$$

Finally: $\text{Habitability Index} = \frac{658}{10} = 65.8\%$

CONCLUSIONS

Habitability design is an important factor of any space system. It can influence man's success or his failure. Since it imposes such influence, methods have been established for testing habitability factors, such as gravitation, living space, and personal hygiene.

The following conclusions enumerate the vital importance of Habitability Indexes.

1. Design of space systems for long-duration missions must include adequate consideration of habitability factors. Maintenance of crew performance, increased tour duration, and decreased mision cost can be effected with habitability design.

2. The essential factors of habitability which influence man's performance in a space system are environmental control, nutrition and personal hygiene, gravitation, living space, and crew fitness and work-rest cycles.

3. Tolerance limits for performance as well as for physiologic damage can be established for many of the habitability factors.

4. Applying the mathematical technique for an index of numbers to these habitability factors, a Habitability Index can be established.

5. This index allows comparison of one space system to another and to an optimum, standard space system.

6. Using habitability data presented in this paper, Habitability Indexes can be established for any space system.

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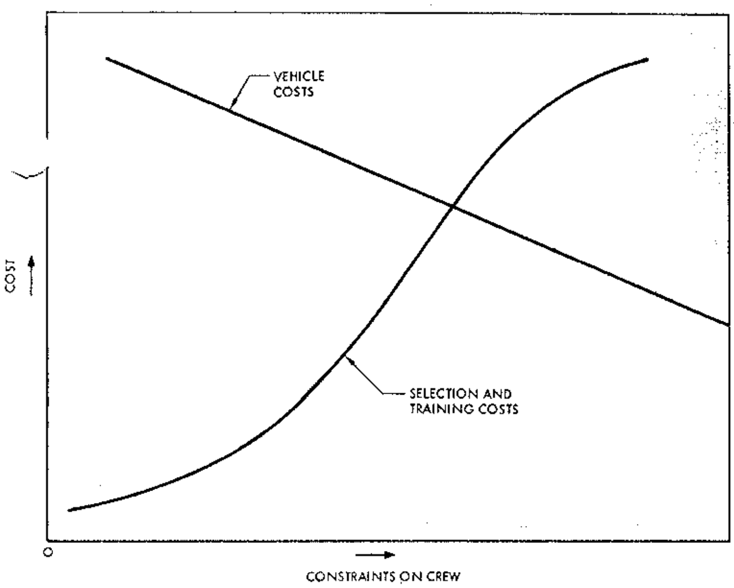


Figure 1. Crew Constraints Versus Training Cost Trends

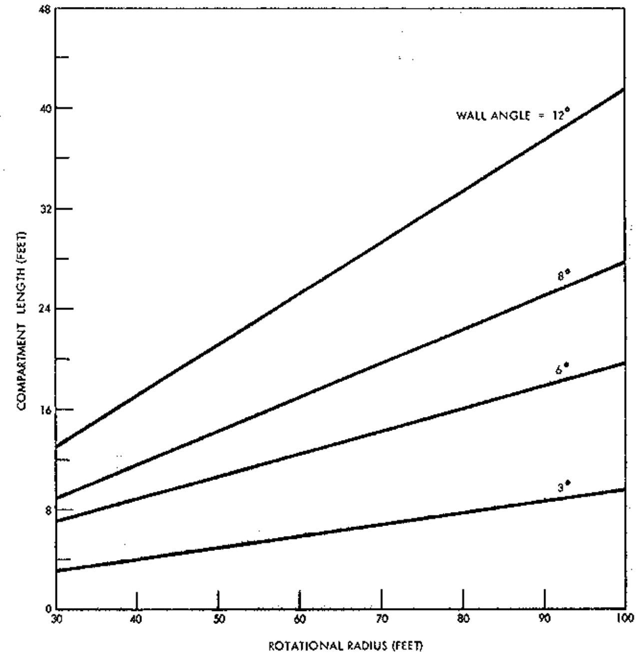


Figure 2. Compartment Length Considerations

CONFIGURATION	ILLUSIONS	TANGENTUAL MOTION	RADIAL MOTION	VOLUMETRIC RESTRICTIONS	REENTRY VEHICLE ACCESS	GRAVITY VARIATIONS
1 TORUS OR WHEEL	1	1	2		2	2
2 AXIALLY EXPANDED DUMBBELL	2		1		2	2
3 SPOKE WITH PARALLEL MODULES	2		1		2	2
4 SPOKE WITH IN-PLANE MODULES	2	2	1		2	1
5 CYLINDER OR DUMBBELL WITH RIGID SHAFT	1	2	1	1	1	1
6 DUMBBELL WITH FLEXIBLE SHAFT	1	2	1	1	1	1
7 LARGE TANK	1	1	2		2	1
8 SPHERE	1	1	2		2	1

MAJOR PROBLEM 1 PROBLEM 2

Figure 3. Configuration Influence on Human Factors Problems

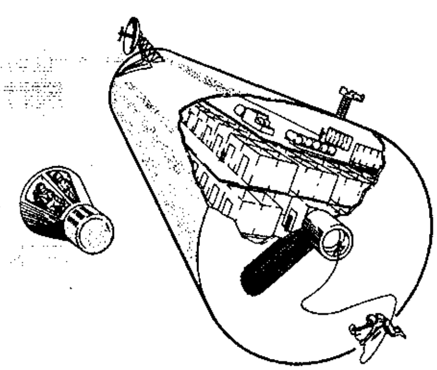


Figure 4. Habitability Factors

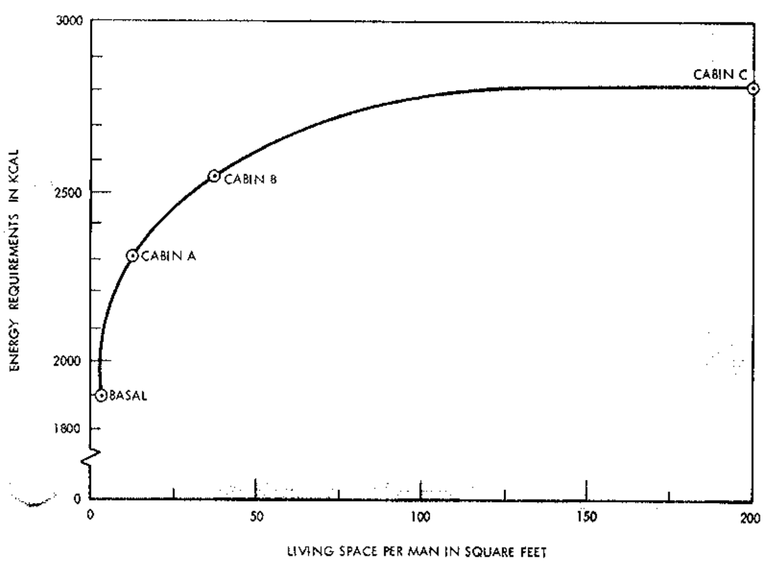


Figure 5. Effect of Living Space Upon Energy Requirements of a 70-Kg Man

HABITABILITY INDEX DATA SHEET

	RV	WEIGHT VALUE	COMPUTATION
1. ENVIRONMENTAL CONTROL		4	
ATMOSPHERE - PO_2, PCO_2	____		$RV_1 \times 4$ = ____
THERMAL EFF. TEMP. HUMIDITY	____		$RV_2 \times 2$ = ____
NOISE	____		$RV_3 \times 1$ = ____
VIBRATION	____		$RV_4 \times 2$ = ____
RADIATION PROTECTION	____		$RV_5 \times 1$ = ____
LIGHTING	____		TOTAL = ____
AVERAGE	____		
2. NUTRITION-PERSONAL HYGIENE		2	
FOOD	____		
WATER	____		
AVERAGE	____		
3. GRAVITATION	____	1.	HABITABILITY INDEX = TOTAL / 10 = ____ %
4. LIVING SPACE	____	2	
5. CREW WORK - REST CYCLES AND FITNESS		1	OPTIMUM STATION VALUE 100%
WORK-REST CYCLE	____		
RECREATION	____		
EXERCISE	____		
AVERAGE	____		

Figure 6 Habitability Index Data Sheet

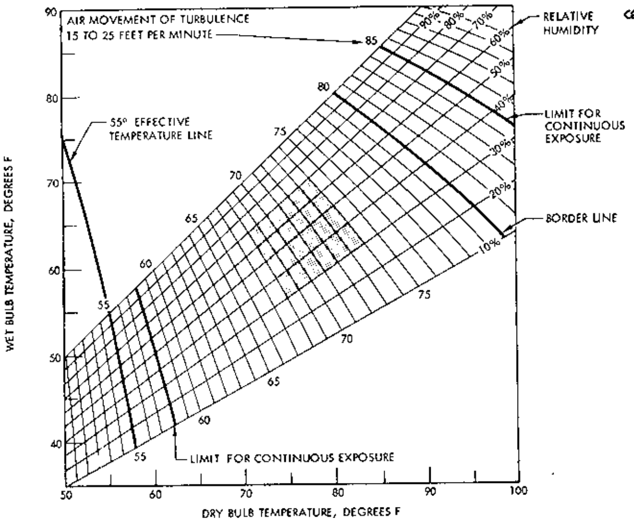
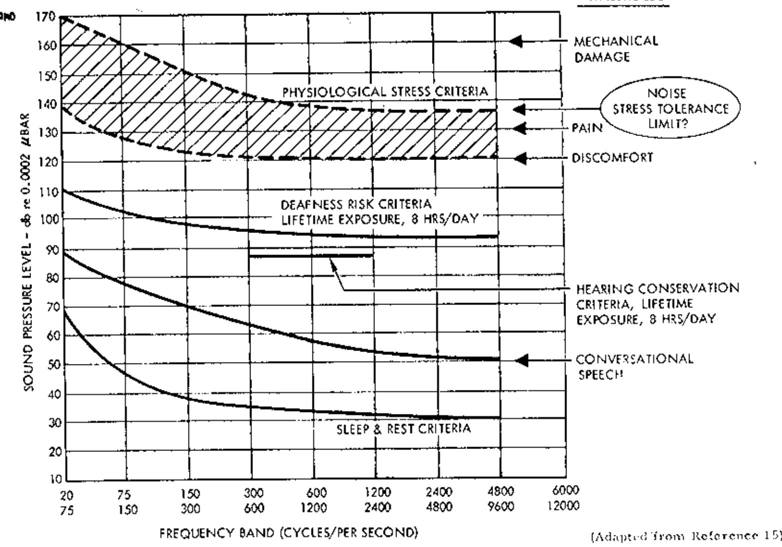


Figure 7. Comfort Zones

(Adapted from Reference 16)



(Adapted from Reference 15)

Figure 8. Tolerance Criteria for Noise

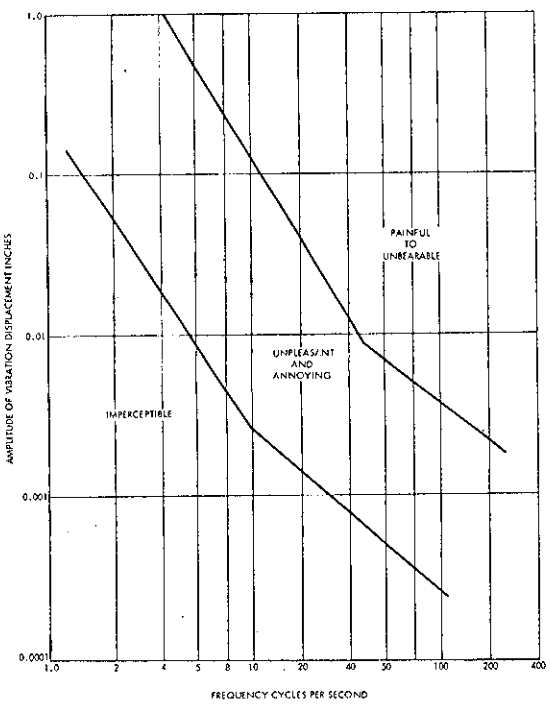
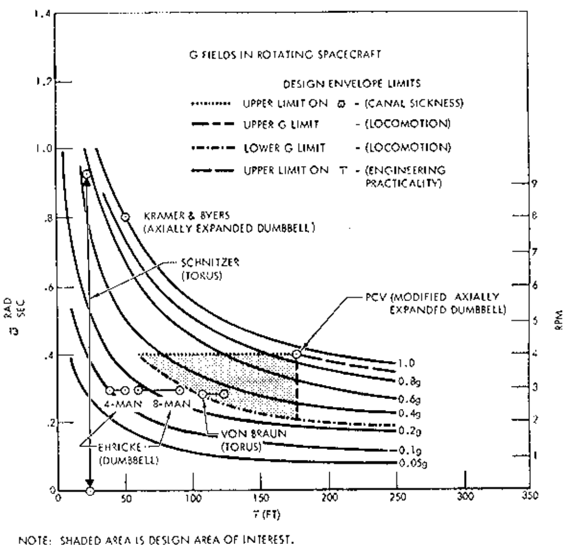


Figure 9. Limiting Vibrations Levels



NOTE: SHADED AREA IS DESIGN AREA OF INTEREST.

(From Ref. 9)

Figure 10. "G" Fields in Rotating Spacecraft

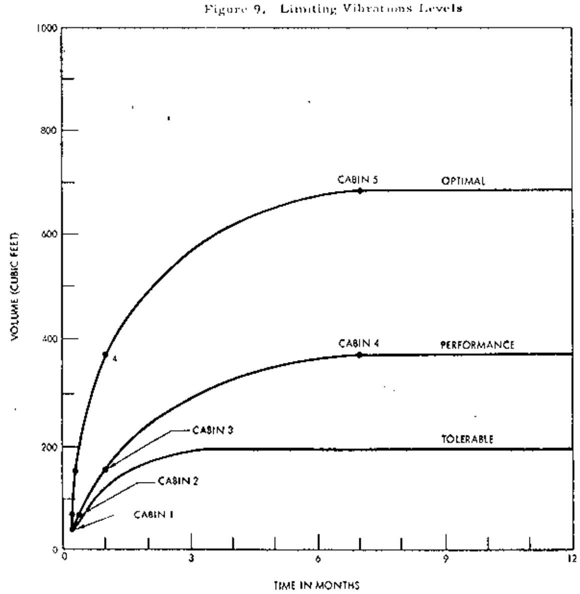


Figure 11. Living Space Per Man (Volume)

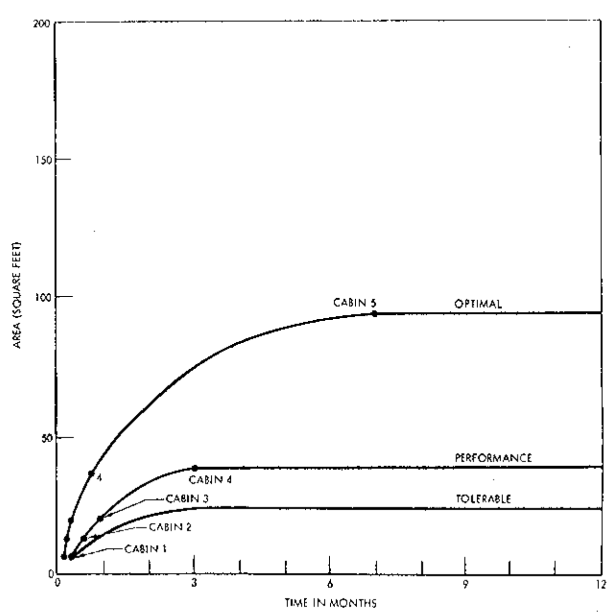


Figure 12. Living Space Per Man (Area)