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DESIGN REQUIREMENTS FOR MANNED ORBITAL AND LUNAR BASES

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Summary

Satisfaction of his physiological needs is the prime requirement for assuring man's performance in a short-duration space mission. Many authorities feel that long-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 considerations regarding the most efficient use of man in an actual space environment presume that all of the environmental requirements for human existance have been provided. These needs can be satisfied through appropriate design requirements, established early in the developmental program, so that man can exist and operate satisfactorily in an orbital or lunar base environment. This paper describes the essential habitability needs that allow man to perform for long periods of time.

Introduction

Design requirements for manned orbital vehicles and lunar bases must be predicted upon: space flight duration; nature of the mission and tasks to be performed; and numbers of men involved. These needs will change as the programs alter and enlarge. In the past, engineering interest in space environmental requirements has been concentrated on 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, that is, a habitable environment.

Space programs will dictate the nature of the life support systems, based upon whether the mission is: a short trip, in days or weeks, which will permit designing the space capsule and its internal environment with a minimal degree of comfort for humans; a medium-length trip for establishing lunar bases or space stations requiring marked improvement of habitable provisions; or an extended-duration space-station orbit, lunar basing, or planetary mission necessitating a duplication of man's comfortable terrestrial environment. Advanced projects involve a variety of space station and lunar base concepts, all of which will depend upon adequate habitability factors to assure success of operation.

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 isgnificantly impair coordination, which would obviously decrease efficiency.[1,2]

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.[1,2]

The basic habitability factors that can be determined for any given spacecraft are: environmental control; nutrition and personel hygiene; gravitational conditions; living space; and crew work-rest cycles and fitness programs.

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, in the unacclimatized individual, 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 requirement 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 orbital and lunar 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 with special emphasis upon total pressures of 5.0, 7.0, and 10.0 psia, constituents of O_2/N_2, O_2/Ne, O_2/He, or combinations thereof.

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.[3]

Toxic product control is an important and critical problem of atmosphere regulation. 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. Among these are utilization of products with low toxic content, total enclosure or isolation of toxic materials, controlled leak rate, and washing gases from air with scrubbers. Also, the air may be recirculated through filtration systems, especially for removal of 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.[4,5] Temperature and humidity need to be maintained within the comfort range for minimum water vapor production and maximum personnel efficiency. This comfort range varies 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[6] and Menninger,[7] 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[8] and Dill[6] suggest that a lack of appealing or palatable 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. 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 need to 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.[9] 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.[1,9] Faucett and Newman[3] 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.

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.[9] 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. Estimates of these water needs for space systems are much lower because of the expected efficiency of bathing techniques, bathing garments, etc., and are in the range of 4 to 6 gallons per day. 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 product performance decrement.[4] 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 space crewman will be allowed at least the same total lifetime dose during his space career as an industrial worker during his working lifetime. An increase in the allowable dose has a significant effect on cabin design. 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.[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 prolonged orbital flights are completed. The successful completion of the initial Mercury orbital flights are now part of space history. Evidence of cardiovascular adaptation is apparent in reports of post flight venous pooling which rapidly disappeared. Apparently no other problems were encountered during these short orbital flights. The Russian cosmonauts withstood several days of weightlessness, seemingly without untoward effect, but data are lacking. It is obvious, however, that a biomedical research program for the express purpose of studying the effects of prolonged exposure to weightlessness is a vital requirement for early orbital research.

Other methods of approach to weightless study have been prolonged water immersion, bedrest, and extrapolation of effects in short parabolic aircraft flights. 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 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.[1] 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.[1] A most important design consideration is the provision of protective features such as removal of sharp corners or projecting equipments to prevent injury during unrestrained motion.

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 quickely adjust to rotations of up to 4 rpm, and can adapt themselves, though not so quickly, to velocities up to 10 rpm.[1] 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.[1] 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.[1] The report by Loret is an excellent basic work for those interested in investigating the human factors aspects of rotating space vehicles.[10]

Lunar-g

The lunar one-sixth g may produce some physiological adaptation similar to that expected with zero-g. The effect of this reduced g could be quite pleasurable and readily offset by learning and fitness programs. Except for the ease of motion, there should be no special habitability effects. Design requirements specifically must consider this ease of motion and involve safety provisions.

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[11] and Kalez[12] cite inadequate quarters and physical discomfort 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 survey indicate that adequate space and privacy are important factors in the maintenance of morale.[4] 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 IGY polar expedition in 1957-58, Siple 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.[13]

Surveys such as the Navy habitability study serve as the basis for recommendations for minimum space requirements per man. 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.

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.[14] 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. Another study involved a space cabin mock-up with a cylindrical configuration 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. The third cabin studied, was disk-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. These mock-ups provided 13, 37, and 200 sq ft/man of living space respectively. 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. In the small cabin where movement, and consequently, activity were reduced to a minimum, the energy needs were almost those of the bedrest state (2300 Kcal per 70 Kg man-day). In the middle sized cabin, 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 70 Kg man-day). In the large cabin, 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 Kg man-day). 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, and other data cited, an area of about 90 sq ft per man for space cabin simulation or 700 cu ft per man for actual space cabin conditions is recommended as optimum for long durations. When large crew numbers are involved, however, this volume need should decrease because of the increasing availability of unoccupied space.

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 none of the common referents of the natural sequency 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 id 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 conditions, 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.[15]

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 orbital or lunar base missions, a facility for physical exercise will be required. A planned training and conditioning program may be necessary to maintain physical fitness and help reduce cardiovascular and musculoskeletol deterioration.

Provisions for entertainment media such as motion pictures, television, and radio may 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 invididual compartments should be designed to facilitate rading, writing, and pursuit of individual hobbies or interests.[1,2]

Fatigue

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

The fatigue in orbital or lunar base 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 judgment, 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 sort 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 orbital station 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.

Conclusions

1. 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.

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

3. 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.

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

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