HABITABILITY ISSUES IN LONG-DURATION UNDERSEA AND SPACE MISSIONS

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13 ABSTRACT

Habitability issues are coming increasingly to the fore as U.S. technology continues its rapid advancement. Man now must live and work in small habitats, both for undersea and space exploration, for extended periods of time. His well-being and productivity during the long missions of the future will be greatly affected by the extent to which proper habitability principles are incorporated into the design of the systems.

This report reviews a number of studies in the area of habitability. Emphasis was placed on extracting from these studies that information most relevant to any long-term mission in confinement. It is concluded that, whereas the basic laws of habitability are known, there is much yet to be learned concerning development of social structures in small groups in relative isolation, planning for necessary hygiene needs, development of proper work spaces, and construction of internal and external communications systems. With respect to testing for habitability and the documentation of habitability principles, the space program was found to be considerably more advanced than was the program for undersea missions.

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HABITABILITY ISSUES IN LONG-DURATION UNDERSEA AND SPACE MISSIONS

Introduction

The technology needed to keep man contented and comfortable, and thereby, hopefully, motivated and effective, during long-term missions in confined habitats requires some improvement. Reports from the Gemini and Apollo space missions as well as the Sealab, Tektite, and other undersea projects, indicate the elements of these environments which collectively make them "habitable" are often less than optimum. This appears to be due partly to a lack of appropriate technology; in some measure, however, it certainly is due to unavoidable circumstances. That astronauts, for example, had to grapple for as long as two weeks with a waste management system that was anything but aesthetically pleasing was not the outcome of any deliberate plan to relegate the health or comfort of the crew to a low order of priority. In the initial development and design of small habitats, whether intended for undersea or space exploration, primary attention has rightfully gone to keeping man alive and functioning in a system whose principal purpose is to achieve a specific operational goal. Habitability issues are always, and always must be, dealt with after feasibility of a system has been demonstrated. These issues have not been ignored; they have been postponed.

Now that the feasibility of both space and undersea vehicles has been clearly demonstrated, the time has come to turn to the problems involved in keeping man motivated and effective for long periods of time in habitats in which one is certain he can be kept alive and well. Studies of the habitability of confined spaces have, in the past, dealt primarily with the needs of a single individual or a group of individuals in a particular restricted-volume environment. It is the purpose of this report to transcend specific cases and to consider basic elements which govern habitability and which are applicable to any number of individuals whose missions include confinement for long-term excursions, either into space or under the sea. It is assumed that the reader is familiar with the Gemini and Apollo spacecraft configurations and the missions conducted in these craft, either through direct involvement in some phase of mission planning or development or as a result of exposure to the extensive publicity received by space missions. He may, however, be less familiar with undersea projects, of which there have been a greater variety, both in terms of mission profiles and habitat structures. For this reason, an appendix to this report has been included which provides a brief description of the principal undersea habitat missions in the United States (Appendix A).

This report reviews a number of studies in the area of habitability. Emphasis has been placed on extracting from these studies those findings which are relevant to any long-term mission in confinement. The differences that mission constraints create have, however, not been disregarded. The authors have endeavored to bear in mind that the space and undersea environments are at best analogous, and to avoid the snare of considering an undersea habitat little more than a submerged space capsule. Mission differences are very real and do have an impact on associated habitability considerations.

Perhaps the essential similarity between the recent undersea and space missions rests with the fact that they are conducted by men who are trying to achieve lofty goals which were previously unachieved and unachievable. These men are, by nature and by necessity, single mindedly determined to succeed by "overpowering" what would appear to almost anyone else to be insurmountable odds. "Overpowering" inadequacies in the habitability of their microcosmic homes seems, by comparison, an insignificant issue. In addition, man is physiologically an adaptive creature and can alter his physical and physiological habits for some period of time with no measurable effect. Although both astronauts and aquanauts have done just this, and their missions have been spectacularly successful, their comments both during and following missions indicate quite clearly that certain elements of their environments which were merely irritating in the short run might have had seriously degrading effects if their missions had been substantially longer. For long-duration missions in the future, habitability factors may well become as important as engineering issues and must be given full attention in designing space vehicles and undersea habitats intended for long-term occupancy.

A "Definition" of Habitability

The concept of habitability is an elusive one. Barnes (1969) points out the difficulties in defining habitability when he states that "The concept of habitability of a space can have no reasonable definition apart from the requirements of the individual to be housed within the space. It is the interaction between the patterns of requirements of the individual and the characteristics of the space which determines the level of habitability." Fraser (1968) attempts a somewhat more specific definition. Habitability, for him, describes the qualities of an environment as related to the acceptability of that environment for man. In fact, in one sense it is a measure, although all too frequently a qualitative one, of the suitability of an environment for occupancy for man. Habitability, Fraser continues, is not an absolute term. There is no ultimate standard of habitability. It must be considered relative to the duration and the purpose of occupancy. Furthermore, the standards demanded will vary markedly according to the previously established customs, practices, and habits of the occupants.

In a continuing discussion of the definition of habitability, Fraser considers that the term habitable refer to that equilibrium state resulting from the interactions among the components of a man-machine-environment-mission complex which permit man to maintain physiological homeostasis, adequate performance, and acceptable social relationships. On the basis of this interactive model, the attributes of habitability, then, are those attributes of man, and his interactions with the other components of the system, which influence the resulting equilibrium state in a manner that renders it more or less acceptable to man. Thus, since man provides the reference criteria for human habitability as well as being a component of the system, only those interactions which directly involve man are significant in the creation of habitability. The attributes then can be considered in terms of factors involving man alone, factors determined by man's response to his environment, factors arising from man's interaction with the machine, vehicle, or dwelling, and those developing in relation to the requirements of the mission.

The last points in Fraser's definition, those which stress the interaction of man with the machine and with the mission, are of great importance. This is particularly true for the mission interaction. The nature of the mission and the role of the human operator in accomplishing this mission are very influential in determining the acceptance which will be accorded a vehicle and its components. For example, if the work requirements during the mission are both meaningful and extensive, life within a confined undersea habitat or spacecraft will be more acceptable than if the role of the aquanaut or astronaut is essentially that of a spectator passenger in transit. In the latter case, considerably more attention must be given to habitability issues in the design of the craft.

Habitability, according to Johnson (1969), is considered to be comprised of the following nine principal elements:

1. Environment--composition, temperature, and movement of the respirable atmosphere; acoustic, lighting, and radiation levels.

2. Architecture--geometric arrangement of crew quarters, work areas, companion ways; stowage and equipment mounting provisions.

3. Mobility, restraint, and equipment handling; the kinematics of locomotion and restraint, and the evaluation of mechanical aids and routines.

4. The fare, its stowage, preparation, serving, eating arrangements, and facilities; includes drinking and rehydration water.

5. Clothing and personal accouterments--shirtsleeve garments, personal articles, and notions.

6. Personal hygiene--body waste collection, body cleaning and grooming.

7. Housekeeping--house cleaning, debris control, refuse disposal, laundering, restocking; steward duties.

8. Communication--intravehicular only.

9. Off-duty activity provisions--conducive environment, certainly, and possibly exercise and entertainment equipment.

The above list is comprehensive and provides a good overview of habitability elements, although certain of the elements might be defined somewhat differently and expanded. For example, the capability and feasibility of communications between the spacecraft and Earth also may be an important feature in determining habitability. In addition, the emphasis on off-duty exercise and entertainment equipment might reasonably be increased. Recent research sponsored by the National Aeronautics and Space Administration dealing with the use of off-duty time, to be discussed in detail later, indicates this topic will represent a serious element in determining the habitability of long-duration missions and may well prove to be one of the most critical.

Operator Considerations

Habitability is not just a function of the characteristics of the living and working areas of a spacecraft but depends instead on the interaction of the occupant and his surroundings. This interaction, in turn, can be as varied as the personal characteristics and personality of the occupant. This point was demonstrated in a study by Jerdee (1966) who attempted to determine whether the behavior he was studying (attitudes toward a number of job related factors in an industrial setting) was a group phenomenon or an individual phenomenon. He found no differences among the attitudes of the various groups of workers and concluded that in research on job attitudes the more promising unit of study appears to be the individual rather than the work group as a whole. The individual characteristics of the occupants will play an important role and should, if possible, be assessed and used during the design of vehicles for long-duration missions.

Data Sources

The first space or undersea mission where time is counted in years rather than days will represent a unique event in the annals of man. The stress variables, particularly those arising from isolation and confinement, will be of a different order than have ever been experienced before. Yet the fact that the conditions encountered will be unprecedented cannot prevent intelligent planning for such missions. Means must be built into the system for minimizing any disruptive forces that might arise through time as a result of the close quarters, the repetitive work operations, and the intimate circumstances of crew endeavor. A careful examin^tion must be made of other analogous human experiences which can in some manner shed light on the problems likely to occur.

A number of data sources are relevant to some extent to the problem of habitability of future spacecraft and undersea habitats. These are:

1. *Industrial and Commercial Design.* Design engineers working toward the development of industrial facilities and commercial products have formulated a number of rules intended to maximize the interaction between the consumer and the product. These rules deal with such aspects as color effects, noise control, structural balance, movement of individuals and information within a facility, and anthropometric considerations. With respect to equipment operation and the proper utilization of the human in systems, especially military systems, there are a number of sources which present "human engineering guidelines" for use by the equipment designer (Woodson & Conover, 1964; Singleton, Easterby, & Whitfield, 1967; Morgan, Chapanis, Cook, & Lund, 1963;

McCormick, 1957). The rules presented in these documents are intended to maximize system effectiveness and, since habitability obviously is a factor contributing to effectiveness, deal with habitability to some extent. However, because habitability considerations are not the primary point of interest, these texts fail to provide *definitive* guidelines for the design of long-duration habitats. In addition, the rules formulated are based on extensive research using, for the most part, the normal American adult male as the research subject, who differs in some important respects from the select astronaut and aquanaut population. "Laws" which govern industrial and commercial situations must, therefore, be considered only partially applicable.

2. *Small Group Hazardous Missions.* There are a number of instances in which small groups of men have attempted to deal with hazardous and hostile environments for substantial periods of time. Records of these ventures are useful in documenting the long-term response of man to this type of ordeal. Unfortunately, however, relatively little in the way of systematic recording of the effects of habitability variables has been accomplished, although limited information is available. Table 1, adapted from a report by the Grumman Aircraft Engineering Corporation (1968), lists briefly the principal characteristics of a number of small group hazardous missions.

Table 1

Selected Missions to Remote Areas

Mission	Crew Size	Duration/Hazards
Remote radar sites (Dewline)	Approx. 25 men per site	Duration varies but no less than 12 mos. Severe isolation and close social confinement. Hazards due primarily to cold weather.
Operation Deep Freeze (Antarctic)	8 – 267	Duration = 8 mos. to 2 years. Absolute isolation during winter mos. with close social confinement. Hazards associated with getting lost in cold, fire and collapse of habitat.
Submarine Triton	180	84-day mission continuously submerged. Crew isolated and closely confined in vehicle of unknown capability. Crew uncertain of mission objectives.
Explorations and expeditions	1 or 2 men to parties of hundreds	Durations vary from short to extremely long times. Confinement and isolation varies. Extreme range of exposure to hazardous conditions.
WWII bomber crews	1 to 12	Crews confined and isolated periodically throughout tour. Flack, ditching in ocean, fire, and system failure.
WWII submarines	Average 75	Patrols up to 80 days. Severely confined and isolated. Subject to air attack, depth charges, life support failure, collision, etc.
Shipwrecked crews	1 to many	Duration varied-extreme isolation. Occasional extreme confinement. Drowning, mutiny, starvation, inability to be rescued.

(Adapted from Grumman Aircraft Engineering Report, 1968)

Sells (1966), in attempting to arrive at a model for studying social systems appropriate for long-duration space voyages, compared eleven well-known "microsocieties" with that postulated for the extended duration space ship. The comparison systems chosen by Sells were:

- Exploration parties
- Submarines
- Naval ships
- Bomber crews
- Remote duty stations
- Professional athletic teams
- Industrial work groups
- Shipwrecks and disasters
- POW situations
- Prison society
- Mental hospital wards

These systems were compared for similarity with respect to objectives and goals, value systems, personnel complement, organization, technology, physical environment, and temporal characteristics. Submarines were found to be most similar overall to the space ship situation but to match it most closely with respect to goals, value systems, and organization than any other variables. In terms of overall closeness of fit, submarines, exploration parties, and bomber crews are considered to have social systems most similar to those of an extended duration space mission. Industrial work groups and shipwreck and disaster situations are most dissimilar. It is of interest that the latter situations are nevertheless frequently cited as significant literature sources for the resolution of space-mission oriented problems without concern for the appropriateness of such generalization.

The work of Sells would indicate that the most profitable route to follow in the study of space and undersea habitat social systems and the variables which influence these is investigation of lengthy submarine cruises. Dillehay (1967) reviewed the literature concerning performance during Fleet Ballistic Missile submarine system cruises. In general, he found that overall success of the mission has not been a variable reported in research on submarine systems. Some specific aspects of success, such as efficiency of performance of duties and overall individual performance as rated by petty officers and officers, has been investigated, but these have usually been included in complex criterion measures involving other kinds of variables. The available data, however, suggest that efficiency of performance is not related to length of submersion.

Dillehay found no studies that dealt with interpersonal processes or group structure as a function of time submerged, operational variations, or other features of submarine activity. Nor is information available which would indicate the relation between habitability factors and successful performance during these missions. It appears that, while the initial design of ballistic missile submarines included a careful consideration of those factors likely to make the submarines most habitable for extended cruises, there has been little if any work done on the subsequent evaluation of these factors.

3. *Man in the Sea.* The most ambitious United States man-in-the-sea projects to date are represented by the Sealab and Tektite programs. Tektite I is perhaps the most important venture in terms of habitability and represents a cooperative multiagency/industry/university program placing four marine scientists, under saturated diving conditions on the ocean floor under 50 feet of water for sixty continuous days (*Naval Research Reviews,* 1969a). It involved the Departments of the Navy and Interior, the National Aeronautics and Space Administration, and the General Electric Company with assistance from the Coast Guard, the University of Pennsylvania, and other government, industry, and academic organizations. It was under the overall cognizance and management of the Chief of Naval Research. Among its principal objectives were psychological and physiological studies of crew behavior, marine scientific investigations, and advancement in undersea technology and engineering.

The Tektite I mission* was conducted at a carefully selected isolated site near St. John, Virgin Islands, from 15 February to 15 April 1969. This was the longest period for which human beings have lived under saturated diving conditions utilizing a nitrogen/oxygen mixture for a breathing atmosphere. During the experiment, data were collected daily from each aquanaut, including blood and microbiological samples. Sleep patterns and other behavioral data were monitored continuously from the surface. The aquanauts engaged in scientific activities, involving marine biology and geology, ranging up to 1,000 feet away from the habitat for several hours daily.

The basic Tektite habitat, as shown in Figure A-3, Appendix A, consists of two interconnected cylinders, 18.1 feet high and 12.5 feet in diameter, mounted on a base structure (*Naval Research Reviews,* 1969a). Each of the cylinders contained two compartments. The left side housed the crew quarters on the lower deck, with the bridge or control room above. The right cylinder connected with the left by means of a 4-½-foot diameter transfer tunnel running from the bridge to the upper half of the right cylinder, the engine room. The lower half of the right hand side housed the wet room which was continually left open to the sea for easy access in entering and leaving the habitat. The right side of the habitat also supported a five-foot high, two-foot diameter cupula mounted on top of the cylinder for additional observation purposes.

Within the left cylinder, the crew quarters contained a small galley, bunks, stowage for personal gear, and entertainment equipment consisting of radio and television facilities. An emergency exit hatch and scuba equipment were located in the crew quarters. The bridge served a dual purpose: (1) as the control center for the habitat system and (2) as a work area for the scientists. The

*Additional information concerning the habitability problems associated with this and other U.S. undersea missions will be found throughout this report in the appropriate sections.

engine room contained the larger items of the environmental control system, the primary transformers, switch gear, and the large freezer for food storage.

Since the wet room was always open to the base, and therefore directly to the sea, it was the only compartment not having controlled humidity; it housed the scuba gear, for use by the crew while conducting experiments outside the habitat, and an outlet for recharging the scuba bottles. In addition, it contained a laboratory including a wet sink where the scientists could perform specimen preparation. It also contained a hot shower. The interest of NASA was in the extent to which a small group of men could live and work effectively individually and as a crew in confined quarters and under stressful conditions for a long period. While most of the data relating to the Tektite projects are under analysis at this time, certain information is available. For instance, during a recent press conference, the question was raised as to how much longer the aquanauts thought they could have stayed down. Mr. Richard Waller, one of the aquanauts, replied, "Well, I don't think any of us really know but I would say that we certainly could have stayed down a lot longer than we did." (*Naval Research Reviews,* 1969b). While this indicates that a motivated individual can tolerate extended residence under Tektite-type conditions, it does not necessarily mean that habitability conditions were optimum or even acceptable.

The Tektite II mission has now also been completed and involved eleven missions of shorter duration (6 to 20 days). One of the objectives of this mission was to investigate in a more thorough manner the basic dimensions of habitability. Table 2 lists the habitability areas which were studied during this program.

Table 2

Habitability Research Areas for Tektite II

Item	Extension
1. Food	Acceptability, freeze dried, wet pack, frozen steaks and sauces, equipment for preparation and eating, eating habits and patterns.
2. Sleep areas	Size and shape, privacy, frequency of use, how used.
3. Storage area	Personal area—size and location. Universal area—size and location.
4. Work area	Personal area—size and location. General area—size and location.
5. Off-Duty activities	Eating, sleeping, recreation, type, location, frequency, individual and group.
6. Illumination and decor	Work areas, recreation areas, private and sleep areas, eating area.
7. Housekeeping	Allocation of tasks, efficiency, frequency.
8 Mobility	Ability to move about within habitat, equipment and transfer.
9. Privacy needs	Territoriality (how expressed), space needs, frequency of use of private areas.

(From Deutsch, 1971)

4. *Ground-Based Simulation.* Over the last decade, there have been a number of ground-based simulation studies in which subjects have been confined within a small cabin for an extended period of time. A number of such studies are cited in the Grumman Aircraft Engineering Corporation Report (1968). For the most part, these simulation efforts have been concerned either with studying the effects of a particular gaseous atmosphere or with an assessment of human response to lengthy confinement. Habitability issues were given little attention beyond the provision of the basic necessities of life.

One of the most elaborate, and most recent, of the ground-based simulation studies was conducted by the McDonnell-Douglas Astronautics Company (1969) as a test of oxygen and water reclamation components in a regenerative life support system. In this test, four college students spent 60 days in a space cabin simulator, about 12 feet in diameter and 40 feet long. As one part of this program, a general assessment of habitability features was conducted. Table 3 presents the results of a habitability scale in which subjects scored various items according to the level of annoyance they produced. A 3 point scale was used with no annoyance scored as zero and extensive annoyance scored as three. The numerical value assigned to each item for a given test date represents the sum of the ratings assigned to that item by the four crewmen. Therefore, the maximum possible annoyance score assigned to any one item for any one day would be twelve. The entries in Table 3 show a rather consistent response to each of the habitability items throughout the period of the simulation.

The results of the 60-day study were supported in large measure by a later and more extensive simulation lasting for 90 days (Jackson et al., 1972). In this study, crewmembers elaborated to some extent on those features of the habitat affecting privacy requirements. The chamber provided only about 90 square feet of floor area for each man. Nevertheless, crew remarks indicated that privacy provisions were satisfactory. Privacy was viewed by the crew as ability to separate oneself from others, but not necessarily in a physical sense. At times, all four crewman were located in the same area and were engaged in individual activities requiring no interaction with other personnel. At these times, the crew indicated that their privacy needs had been satisfied.

5. *Man in Space.* Some of the most meaningful data concerning habitability, for present purposes, come from space flights to date. Johnson (1969) provides the following account of habitability factors in the three vehicles of the United States manned spacecraft program. The habitable world of the lone *Mercury* crewman for one day in space flight was 50 cubic feet, half of which was filled with equipment. His respirable atmosphere was 5 psia pure oxygen. He was often too warm or too cold. The crewman was suited in a pressure garment which he could not remove. He was seated in a closely fitted couch and his knees were drawn up and his feet were drawn back farther than was comfortable. He could not straighten up. Personal hygiene provisions were primitive indeed. The crewman more often than not were wet with their own urine. There were no provisions for defecation. Fortunately none were needed. The crewman was much too busy or

enthralled with his circumstances to be concerned with off-duty equipment. The longest flight time in this program was 22 hours.

Table 3

Habitability Scale

ITEM	DATE				TOTAL
	3/6	3/20	4/3	4/17	
1. Trouble sleeping	5	5	5	7	22
2. Food	4	6	6	6	22
3. Noise	5	4	5	5	19
4. Lack of water for washing	4	4	5	3	16
5. Lack of exercise	4	3	5	4	16
6. Behavior of others	3	2	4	4	13
7. Toilet facilities	4	2	3	3	12
8. Boredom	3	2	4	3	12
9. Bunks	3	3	3	3	12
10. Crowding in the chamber	3	2	2	4	11
11. Temperature and humidity	2	2	4	3	11
12. Lights while sleeping	3	2	3	3	11
13. Worries about the outside	3	1	3	3	10
14. Lack of privacy	2	2	3	3	10
15. Dirt	3	2	3	2	10
16. Smells	1	2	3	4	10
17. Not able to concentrate	2	2	2	1	7
18. Physical symptoms	2	1	1	1	5
19. Lights while awake	1	1	1	2	5

(From McDonnell-Douglas Astronautics Company, 1968)

The *Gemini* crewmen had enough room, a total pressurized volume of 80 cubic feet, so that alternately they could stretch a bit and wiggle in and out of their pressure garments. However, they had to sleep, eat, and manage their personal hygiene more or less in their individual couches. Their sleep was disturbed somewhat by their on-duty partner and by spacecraft operational activity. Their food was dried and had to be rehydrated. It was nourishing enough, but could be eaten only from squeeze tubes. Personal hygiene equipment consisted of a roll-on, cuff-type urine collector and a plastic defecation bag. Dry and premoistened wipes were used. In all, defecation procedures left a good deal to be desired. The crewmen returned dirty, smelly, needing shaves, dehydrated, and suffering weight loss. After 14 days of space flight, often they remarked that they had few secrets between them.

The *Apollo* command module cabin was much larger than the Gemini cabin, having a total pressurized volume of 360 cubic feet. As has been seen on television, there is enough room in the Apollo command module to allow the crewmen to interchange positions, and even to practice acrobatics. There is also sufficient space for sleeping and personal hygiene activities. The food has been improved, but it is still almost all freeze dried. It can be rehydrated either with hot or cold water, but the hot water is not very hot nor is the cold water very cold. However, improvements are being introduced gradually.

The Apollo crewmen can spend almost all of the mission in shirtsleeve garments, but the garments are still just what is left after the pressure suits are taken off. Apollo urine and feces collection equipment is approximately the same as was the Gemini equipment. The crewmembers of the Apollo 10 mission did, at least, have shaving equipment. Generally, personal hygiene equipment is being rapidly improved. However, for all practical purposes, the habitability provisions of Apollo are still primitive.

In the late 1970s, the United States is likely to undertake space missions of much longer duration than were the Apollo and Gemini missions, and with larger crew complements. Although missions to date have been quite successful, Johnson points out that it is neither in the interest of the crew nor their performance to subject them to the spartan accommodations of our present spacecraft. Spacecraft habitability must afford a measure of comfort and convenience not unlike that provided by surface facilities.

Measurement of Habitability Variables

In his review of habitability variables, Fraser (1966) notes that there have been a few attempts to develop a quantitative habitability index, primarily one by Celentano and his colleagues, who propose an additive model of habitability in which several factors, namely, environmental control, nutrition and personal hygiene, gravitation, living space, crew fitness, and work/rest cycles are known and can be expressed quantitatively. With appropriate weighting and mathematical manipulation of these variables, an index is obtained. Unfortunately, as Fraser notes, the application of this index is limited to a simple additive model in which the range of all parameters is known and quantifiable, and for which exist recommendations or specifications relating to optimal levels and permissible maxima or minima.

In Fraser's evaluation, it is doubtful if much is to be gained by developing indices of habitability in the current state of the art. Many of the factors involved are not quantifiable, and many of those that are quantifiable cannot be expressed with the precision and accuracy necessary for the purpose.

In the long run, he feels, any index of habitability probably will give a false sense of precision and validity in that after various arithmetical manipulations, a single hard number is applied to what are frequently only opinions. It is probable that a more meaningful appraisal of habitability would be obtained by a skilled subjective and objective assessment of all of the factors involved, followed by exercise of the best informed human judgment.

Although there seems to be little point at this time in attempting to achieve a single index of habitability, there remains a need to understand the relative contribution of the different variables in situations in which habitability begins to deteriorate. It is of great importance that insight be gained as to those parameters which are most significant during long periods of operation in closely confined quarters. The necessary research to provide these data has not been accomplished.

Indoctrination Training

A notion central to the consistency theories of human consciousness and behavior (and to many common sense approaches to psychology) is that the individual tries to keep his internal beliefs (his attitudes), his verbal statements, and his gross behavior in agreement with one another (McGuire, 1968). While, in fact, the individual may often fall short of this goal, he is still regarded as being motivated in this direction in the interest of economy, aesthetics, etc. McGuire also states that a person's initial belief, or attitude, should become more resistant to subsequent forces acting to change this attitude if he is somehow made to commit himself to it. Still more committing than announcing one's belief publicly is to behave in some costly and irretrievable manner on the basis of that initial belief.

Kiesler, Collins, and Miller (1969) have examined the experimental evidence concerning the relationship between behavior and attitude, in an attempt to define those variables which influence or inhibit attitudinal change. They find that most of the evidence at this time suggests that it is possible to predict behavior from attitudes but without a great deal of precision. They suggest that situational differences, norms, and expectations can vary while an attitude remains constant. These differences in norms for behavior create differences in behavior unrelated to the attitude--which runs counter to the usual notion that behavior is a more "valid" measure of attitude. In short, it seems that although a fixed attitude will not necessarily result in a precise behavioral pattern, it will provide a general context within which that behavior occurs. McGuire (1968) in reviewing the work of a number of individuals attempting to formulate techniques for instilling strong, positive attitudes, notes that individuals appear to adhere to a given belief to the extent that they see it as instrumental to the attainment of positively balanced goals.

The above analysis of the relationship between attitudes and behavior is directly relevant to the problems which will be faced by astronauts and aquanauts during long-duration missions. It is axiomatically true that weight and volume constraints will preclude the building of any spacecraft, at least in the foreseeable future, which will be as comfortable and habitable as earthbound structures can be made to be. Volume limitations also place restrictions on undersea vehicles. This means that men and women will have to "learn to live with" certain components and aspects of their immediate environment. This they will do on the basis of positive attitudes developed prior to mission initiation. However, the long-term success of this accommodation will depend on the nature and strength of attitudes built before the mission concerning the habitat, the crew, the equipment, and most importantly, the goals of the mission. Careful attention must be given to these issues during intensive indoctrination and training programs. If crews are allowed to leave feeling that some component, such as the waste management system, is of borderline adequacy or could be improved with more work, the irritant quality of this component could be magnified manyfold during the mission and cause severe problems all out of proportion to the actual nuisance value of the component. The inculcating of proper and lasting attitudes is of the utmost importance.

In extrapolating to the situation of long-duration missions, the above analysis of attitudinal effects on behavior would imply that if the goals of the mission can be maintained as strongly and as directionally during the course of the mission as at its beginning, this will serve to produce concurrent attitudes which will allow astronauts to override any problems during the mission dealing with the acceptability of habitability factors.

Physical Factors Influencing Habitability

Crew Volume Requirements

An important topic with which to deal in assessing habitability requirements concerns the minimum space per crewmember which is required. It has been established in a number of investigations that if working and living spaces are too small, serious consequences will result. A slight infringement on space requirements will result in minor performance degradation and minimal discomfort, easily overcome by the adaptive human for reasonable periods of time. For long durations, however, it is likely that the effort expended in overcoming this irritant will increase and the disruptive feature of too little space will grow until it becomes quite noticeable. Correspondingly, a serious lack of space will produce problems almost immediately.

Fraser in 1966, summarized the work to that time concerned with establishing volume requirements for extended residence in enclosed quarters. These results are presented in Figure 1 and, in some instances, extrapolate volume requirements for up to 400 days of residence. Fraser notes that, although the volume requirements per man cannot be specified with any degree of authority, it would seem that for durations of 300 to 400 days, or perhaps beyond, the absolute minimal acceptable volume for multiman operations would be in the region of 200 to 250 cubic feet per man; the acceptable would be about 350 to 400 cubic feet; and the optimal about 600 to 700 cubic feet, utilizing the volume for all purposes related to living conditions. If optimum habitability is considered the goal, design requirements for long-duration missions should be based on the optimal level of 600 to 700 cubic feet per man. In any event, the curves of Figure 1 clearly show the need for more volume per man as a function both of increasing time and increasing crew size.

Eberhard (1966), in studying the minimum crew volume requirements for the Air Force Manned Orbiting Laboratory, combined certain available data points with industry projections, as shown in Figure 2. This figure is extrapolated to a mission duration of 1,000 days and indicates that for a mission of this duration 700 cubic feet of free volume per man would be a requirement. This is in keeping with the assessment made by Fraser of volumetric requirements for a mission duration of 300 to 400 days, and perhaps suggests that 700 cubic feet of free volume represents something of an upper limit to this curve and thus becomes independent of mission duration.

Earth-based studies of spacecraft volumetric requirements may, however, present a distorted picture because of the impossibility of simulating one critical dimension—zero gravity. The volume of the Apollo command module was only 360 cubic feet. Yet, according to Apollo astronaut Allan Bean (1971) this volume was adequate. This he attributes to the enhanced facility for movement in the weightless state. For example, whereas a doorway of less than standard height is obstructive on earth, the ability to move in a swimming manner in zero gravity would make even a 3 foot hatch more than adequate in a space cabin. It is imperative that designers of future space vehicles consider the effects of this aspect of the space environment when planning living and work space volumes and use it to advantage.

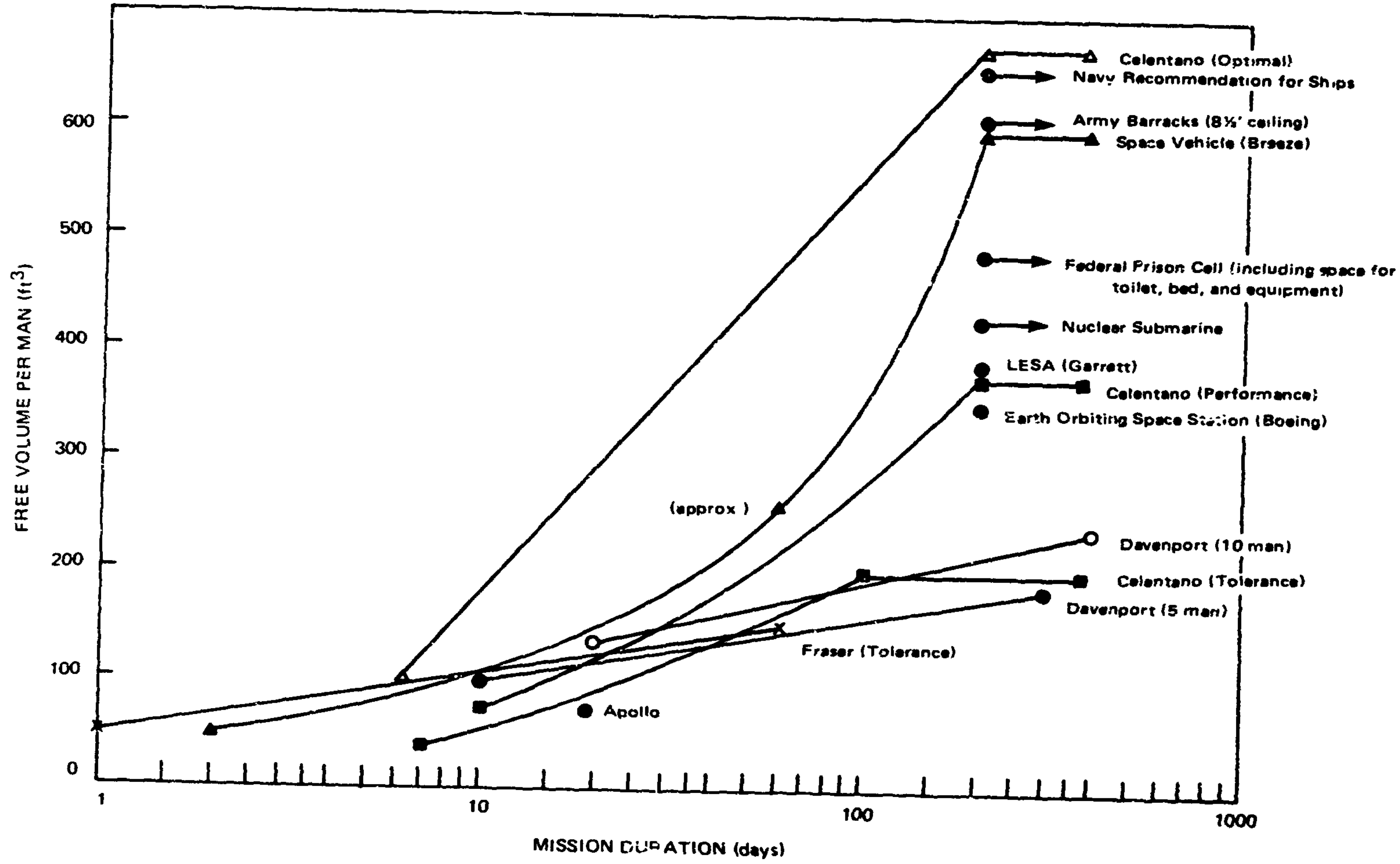

Figure 1. Recommendations for Living Space in Prolonged Space Missions

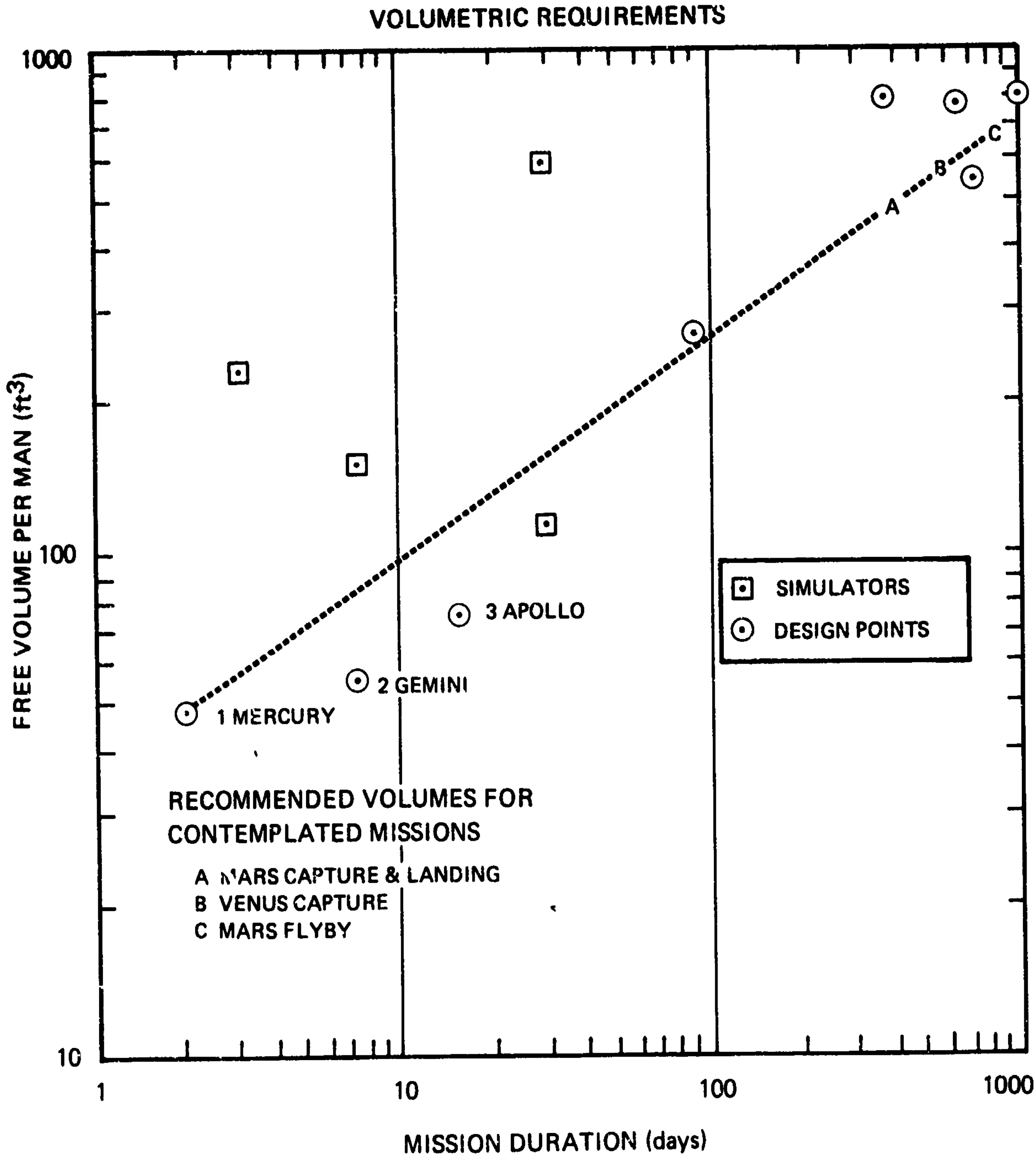

Figure 2. Free Volume Recommendations Based Upon Simulator Data and Various Mission Design Points. (Adapted from Eberhard, 1966)

Arrangement of Space

The simple establishment of free volume requirements, as pointed out by Barnes (1969), means little when related to the actual design of a spacecraft. Meaningful research must begin with individual areas or compartments in the craft and should first analyze how many men will use the area, what functions they will perform there, and how the area will interact with other compartments in the craft. In short, specification of free volume becomes meaningful only when meshed with a functional analysis of the spacecraft areas involved. Volume/function studies for each type of compartment will reveal the design requirements and minimum volume necessary for that type of compartment.

Fraser (1966) notes that a functional analysis, i.e., the mode of utilization and configuration of available space, can be examined from several different points of view. However, certain ground rules can be assumed. Thus, space must be provided for the conduct of tasks relating to the mission, to vehicle management, and to biomedical support. Space also is required for rest and off-duty time, for dining and food management, and for hygienic provisions. Therefore, it is convenient to think of configuration in terms of functional units relating to these activities, although it should be realized that functional units are not necessarily topographical units. In other words, the volume allocated to one unit need not necessarily be located in one region of a vehicle.

To meet the various requirements, Fraser suggests that four functional units might be delineated, namely:

1. Work unit: for the conduct of operational tasks, vehicle management and biomedical support.

2. Public unit: for use in dining, food management, communal recreation, leisure, and exercise.

3. Personal unit: for sleeping, personal privacy, and personal storage.

4. Service unit: for toilet purposes, laundry, and public storage.

Based on industrial research using spacecraft models and full-scale mockups, Fraser suggests the following relative volumes of available space which might be occupied by each functional unit:

Work unit:	40%
Public unit:	25%
Personal unit:	20%
Service unit:	15%

The suggested proportions are considered approximate and in each case would be influenced by the requirements of the mission and the capacities of the vehicle and the dwelling, and would need to be determined empirically by analysis of the requirements and the use of models and mockups.

One of the principal complaints concerning both the Sealab II and Tektite I missions was the need for more laboratory space and better designed work areas around the entry hatch. Design of habitats for future missions should reflect the need for work areas compatible with the needs of the users. Where possible, storage area should not encroach on work or laboratory spaces, and maximum effort should be made to make storage spaces in otherwise wasted spaces.

In another functional analysis, Barnes (1969) provides a slightly more extended breakdown of facilities which should be located within the spacecraft as follows:

1. Command and control center
2. Sleeping and living quarters
3. Eating/recreation/relaxation facilities
4. Hygiene/waste control facilities
5. Lab space/repair area
6. Intercompartmental passageways

The recommendations provided by Barnes further suggest that flow analyses be made of the movement of people among these various locations within a craft. He suggests that crew quarters should be near the command area, scientists quarters near the laboratory space, and that all sleeping quarters should be in relatively quiet parts of the spacecraft and close to hygiene facilities. This flow is equally applicable to undersea habitats.

Sleeping areas should be designed to give privacy; however, only with all systems considered. To accomplish this, the Sealab II aquanauts were provided draperies, but these shut off gas circulation. Consequently, a carbon dioxide buildup resulted in the bunk area, causing unpleasant and potentially unhealthful sleeping conditions. Another design problem reported as irritable by the crewmembers was that both the Tektite I and Sealab II habitats were at a slight tilt. Provisions should be incorporated in the design of an undersea habitat to allow for leveling after it has been secured to the ocean floor. Lunar surface astronauts have also reported being disturbed by listing. Apollo 14 crewmen had difficulty sleeping between EVA periods, partly attributed by them to a seven degree starboard list of the lunar module which had been brought to rest on irregular terrain. The crewmen were sufficiently disturbed to look out the window several times during the sleep period and used a hanging upright plumb bob for reassurance that the LM was not starting to tip over. Another problem reported from Sealab was the design of the bunk area table, which, when open, prevented anyone from being in a bunk. This small oversight may have been a primary cause of undue fatigue.

Storage/Equipment Access

An important feature in the design of functional areas, particularly working areas, is the provision for storage and access to equipment, tools, and supplies. This is part of a design process which all too frequently takes place during the latter stages and consequently results in storage and access modes which are less than optimum. As a complicating feature, additional equipment may be added after the design of the vehicle is frozen, thus forcing engineers to provide storage facilities in areas which are unsuited on the basis of any kind of functional analysis. This has been true in the development of military aircraft, in which items of personal protective and survival equipment have been added at a later time, resulting in major problems of storage and access within the cockpit area.

Storage facilities should be planned as an integral part of the functional analysis process which outlines the major work activities and movements of the crewmen. In spacecraft and sea habitat design, this inevitably will pose problems due to the limited areas which are available for this purpose. For this reason, spacecraft designers are now resorting to quick snap devices, such as velcro clamps, which can be moved about as the crewmen desire and which allow tools to be hooked into a fixed location between periods of use.

In the provisioning for and location of tools, attention must be given to the general maintenance philosophy under which craft are being developed and the amount of crew time likely to be involved in maintenance activities. If maintenance tasks, however routine, are to occupy any significant part of the work day, the configuration of the craft as well as the location of tools and supply spares must take this into account. Table 4 (Calderon, 1968) presents estimates of maintenance and checkout time requirements for the crewmen of a large orbiting space station. This table indicates that the subsystem requiring most attention will be the environmental control/life support system, with this unit requiring over 1-½ man hours per day of attention. In all, almost five man hours per day must be devoted to maintenance and checkout operations. With such demands, it will be advisable to structure these activities and the location of the required tools and equipment so that these efforts can be accomplished with maximum ease and least conflict with the general layout and operation of the spacecraft.

Privacy and Territorial Needs. Areas also must be provided, in all likelihood in the sleeping quarters section, suitable for the storage of personal equipment. If a part of the sleeping section can be set aside for each individual's personal equipment, it may serve to satisfy the "territorial needs" of the individual. Fraser (1966) identifies the territorial need in the human, often termed a "privacy need," as a fundamental one, although no studies have been accomplished to indicate how much space, or what configuration, is necessary to satisfy this territorial need. However, the ability to store one's private and personal possessions in an undisturbed location appears to be one of the critical ingredients in meeting privacy and territorial needs.

Table 4
Maintenance and Checkout Time MORL-11A Space Station

Subsystem	Average Man-Hours/Day
Onboard test and maintenance	0.21
Ferry-resupply craft and cargo module	0.36
Stabilization and control	0.71
Propulsion	0.14
Structural and mechanical	0.86
Communication and telemetry	0.71
Electric power	0.36
EC/LS	1.36
Total	4.71

(From Calderon, 1968)

Personal Hygiene Facilities

It is critical that facilities be appropriate for, and designated for, the performance of personal hygiene activities. The American culture is oriented toward excellent performance in these areas and, if performance is hindered by lack of suitable facilities, the perceived habitability of the spacecraft will suffer. Barnes (1969) indicates hygiene facilities should perform the following functions:

1. Washing (crewmen, clothing, equipment)

2. Collection, processing, and the disposal of body wastes (urine, feces, vomitous, mucous, whiskers, nails, hair, etc.)

3. Collection and disposal of food processing debris, unused food, waste paper, etc.

4. Provide an area for personal grooming.

In establishing facilities for these functions, care must be taken that the facilities are more than simply adequate. As Fraser (1966) notes, the question of personal cleanliness has both social and physiological connotations. Our culture is cleanliness oriented, with the criteria of cleanliness being largely social in nature, namely, odor and appearance. Thus, strong social demands are made on the individual to give, at least, the impression of cleanliness. Merely because the demands are social does not mean, however, that they can be ignored. It may be possible to train people, in concert, so that the normal social demands assume minimal significance, but the underlying social pressures might still break through to exert an unwanted influence at a time when morale is already low from the summation of other stresses. It is indeed unlikely that reduced standards of personal hygiene *per se* are going to affect the performance capability of the individuals concerned, or the outcome of a mission. Reduced standards of personal hygiene, however, can lower the overall habitability of the environment; and conversely, if an adequate standard of personal hygiene is maintained, the overall habitability of the environment is relatively enhanced.

Johnson (1969) states that, although facilities must be entirely appropriate, they need not embrace some of the more exotic schemes proposed to date. Johnson observes, for example, that the old fashioned hand-held wash cloth is entirely satisfactory for most purposes. The wash cloth will not tear easily, it can get at almost all areas of the body, and it can be used over and over. The terrycloth towel is preferred for drying. Lint is not expected to be any more of a problem in the spacecraft than anywhere else, and the rough texture of the two cloths is thought to be beneficial.

The Apollo 10 crew first discovered that it was possible to shave in space with shaving cream and safety razor. It has not been found to be necessary to use a motorized device with a vacuum attachment to collect whiskers. Lather collects whiskers, and the astronauts wipe the lather off with a tissue, a technique, as Johnson notes, which is several thousand years old.

Cleaning and general housekeeping duties present a different problem in the undersea habitat. The complaint which arose in both the Sealab and Tektite missions was that scientists felt too much of their time was spent in cleaning duties and recommended that the crew include one member who could take over all the cleaning and cooking duties.

Mobility

Ever since the Gemini flights called attention to the kinematic problems of mobility and restraint, it has been apparent that zero gravity space flight requires the development of an engineering rationale to deal with crewman mobility and restraint as rigorously as with any other space flight kinematic activity (Johnson, 1969). During the development of this rationale, a number of specific locomotion aids have been suggested, developed, and tested, as shown in Figure 3, as possible means of lessening the rigors of work, particularly during extravehicular activities. Experiences during early Gemini EVA periods showed energy expenditures for such activities to be excessive. Part of this was attributed to the lack of appropriate restraint and locomotion aids for the EVA work.

Loats, Hay, and Morris (1969) recently conducted an extensive simulation study to determine the applicability of various restraint and locomotion aids related to the performance of a variety of critical intravehicular tasks. Table 5 shows the types of restraints and aids which were studied in relation to four classes of tasks, appropriate for the spacecraft environment. In assessing the performance represented by these categories, specific tasks were developed, averaging approximately ten minutes in length, and the various combinations and versions of the restraints and locomotion aids evaluated.

Figure 3. Zero G Locomotion Aid and Restraint Apparatus

Table 5
Relationship of the Task Categories to the Candidate Restraint and Locomotion Aids

Locomotion Aids	Task			
	General and Housekeeping	Equipment Operation	Cargo Handling	Maintenance
Handrails around station perimeter	–	x	x	x
Handrails (portable type)	–	–	x	–
Handrails-walking combinations	–	x	x	x
Pressure walking between surfaces	–	–	x	–
Soaring	–	–	x	x
Handholds	x	x	x	x
Velcro sandals	x	x	x	x
Restraints				
Chair and seat belt	–	x	x	x
Positive foot restraints	x	x	x	x
Toe traps	–	x	x	x
Handholds	x	x	x	x
Waist tethers (2)	x	x	x	x
Single flexible strap	x	x	x	x
Handrails around station	–	x	x	x
Velcro sandals	x	x	x	x

(From Loats et al., 1969)

Results indicated that, in general, handholds both specifically designed and naturally occurring should be used whenever possible since they act as combination locomotion aids and restraints, and there is no task efficiency lost due to restraint erection procedures. The subsequent addition of a peripheral hand rail in the mockup used in this investigation proved a singularly effective restraint concept. Specific handholds on cargo do not appear necessary unless the cargo size is large. Velcro is an exceptionally good restraint for attaching small hardware and containers to work tables, but does not provide a necessary restraint to counteract body forces produced by the subject both in fixed location work and in movement. Waist tethers were the most effective aids for the exercise tasks since they provided a compromise between freedom of motion and overall body fixity.

Soaring and combination handhold-soaring proved to be the most effective locomotion aid, especially over the short to medium distances. A center erectable handrail proved to be the most effective locomotion aid for certain cargo transfer tasks. This was chiefly due to the fixed path implicit in this task and due to the needs of the subject to supply countertorque in order to maintain a preferred body attitude during the cargo transport.

Equipment operation and maintenance tasks appear to be feasible in all gravity levels investigated within this study. For the most part, the tasks can be performed with minimum restraint and locomotion aids. Long-duration operations at data and work consoles necessitate the use of a chair-seatbelt system. However, optimum space allocation dictates that this chair-seatbelt should be adjustable and capable of being stowed when not in use, to minimize interference with the subject.

Precision maintenance tasks are easily performed at standing work stations, particularly when the stations are provided with the toe-trap type foot restraint. These work stations also benefit from laterally located handholds on the work station. It was found that the work station should be liberally provided with velcro attachment pads for retention of tools and other small parts.

Garments

Perceived habitability is likely to be influenced by the kind of personal garments worn by astronauts or aquanuats as they work and relax in their habitats. Current spacecraft, as represented by the Apollo vehicle, and certainly all future spacecraft will provide what has become known as a "shirtsleeve environment" to the fullest extent possible. Pressure suits will be worn only during critical mission phases and during periods of extravehicular activity. During routine phases of the mission, astronauts will wear shirtsleeve garments. However, as Johnson (1966) notes, these shirtsleeve garments are not expected to be what is left over after removing pressure garments. The shirtsleeve attire is not expected to be much different from that found to be comfortable and convenient in current earthbound activities. Minor modifications will be required to suit the zero gravity environment and certain styling can be expected as an article for space wear. The list of acceptable materials used in garments will be limited since these articles must be flame retardant, easily cleaned, wear resistant, and capable of holding reasonable shape.

Johnson recommends both long sleeved and short sleeved shirts and a jacket since he anticipates that thermal comfort may represent some problem during the course of a mission and particularly when moving from one area of the spacecraft to another. This problem is compounded in the undersea habitat using helium as a component of the atmosphere due to its property of accelerating heat loss. Johnson does not recommend the one piece type of coverall garment, however, since it compounds personal hygiene procedures. In the zero gravity environment, pockets will need closures, like zippers; and long sleeve shirts and long trousers will need knitted cuffs or the equivalent. Slipper socks probably will do for footwear, provided the soles, the sides of the foot, and the toe are covered with a rubber-like material to protect the foot, to develop greater friction than is possible with plain socks, and to provide greater wear resistance. The rubber-like material will have to be well ventilated, though, to prevent excessive sweating. In any case, the slipper sock should be readily laundered and dried.

With intra-habitat garments, as with all items of personal attire, facilities must be available for cleaning as required. Whether this requirement dictates a complete laundry capability will depend on the number of crewmen and the length and type of mission.

Illumination

By and large, astronauts and aquanauts will live under conditions of artificial illumination during the full extent of a long-duration mission. The effectiveness and general quality of this illumination will be an important determinant of the habitability during the mission. Proper lighting of equipment and display systems is an obvious concern and is dealt with extensively in such texts as the *Human Engineering Guide to Equipment Design* (1963). The data provided in sources such as this have been considered relatively standard for a number of years and will be reflected in lighting techniques for equipment to be included in the spacecraft. While the use of proper display lighting is a central issue in determining the effectiveness of the displays, it is of lesser importance in assessing overall habitability. However, it is worthwhile at this time to review a list of recommendations provided by Urmer and Jones (1965) regarding effective spacecraft illumination, even though the bulk of attention is devoted to equipment lighting. Their recommendations are that:

1. White light illumination be provided for most mission phases.

2. The intensity be variable from 0.1 m-L to about 40 m-L with the highest intensity for launch only.

3. An intensity of 10 m-L to be provided as the maximum value for nonlaunch conditions.

4. Provisions be made to turn off all internal lights, with critical instruments being self-illuminated, particularly to allow easy maintenance of interior/exterior balance.

5. Flexible flood lights be provided to produce extreme contrast effects by "washing out" shadows.

6. Red filters (6400 Angstroms) be provided for dark-adaptation for all light sources.

7. Transilluminated displays be shielded to prevent their being masked by high-intensity light sources.

8. Lights, indicators, and self-illuminated instruments be located to prevent reflections from windows and other instruments.

9. Filters or shutters be provided for the windows to reduce undesirable illumination.

10. Filters or shutters be readily operable, using electrical switches if necessary, to aid the astronaut in programming light to achieve light levels.

11. Color and intensity of caution and warning lights be considered, as they influence ambient illumination levels and dark adaptation, particularly for the dark side of the Earth.

12. The reflectivity of suits, equipment, and interior paints be used to increase the evenness of illumination.

13. Inadvertent light leaks, particularly from high intensity light sources, be identified and corrected before the mission for each spacecraft, to insure that low levels of interior illumination and dark-adaptation can be maintained.

14. The color of critical markings and legends be designed such that they can be seen when red lighting is used.

Spacecraft habitability will be influenced by the color and character of the general illumination as well as the decor and fixtures. Fraser (1966) provides a summary of illumination of important general illumination characteristics, drawn largely from the 1949 review by M. A. Tinker of lighting effects on submarine habitability. Fraser notes that the most effective vision occurs when brightness contrast ratios are no greater than three to one. At the same time, however, for decorative purposes, some contrast is desirable. Lack of variation tends to be monotonous and undesirable. Good decorative schemes cannot be readily achieved with a one to one ratio. The blending of highlights and shadows adds attractiveness to the living space, and can be better achieved with high ratios, while still remaining within acceptable limits.

With respect to color schemes, it is known that distinctive preferences exist. Numerous studies have shown that the preference for six common colors is blue, red, green, violet, orange, and yellow, in order of decreasing acceptability. Although the dominant wavelength or hue is significant in the determination of color preference, luminance (or reflectance) and purity, are also important. The appeal of a color increases with increasing luminance until the comfort limit is exceeded, following which there is an increasingly violent loss of appeal. Somewhat similarly, appeal increases with increase in purity up to the spectrum limit in many individuals, although a substantial number do favor weak, unsaturated colors. Fraser notes, however, that the increase in affective value noted in these circumstances is in relation to tests with very small areas of color; it is probable that when areas are large, as in compartment walls, these factors do not apply.

In an unreferenced study by Washburn, cited by Fraser, the pleasingness of 19 saturated colors, 18 tints or pastels, and 18 shades was measured. On the average, the tints were most pleasant, the shades next, and the saturated colors least. The size of the colored area had some influence on appeal. With saturated colors, the small areas were preferred but the large areas of tints and shades were preferred. In saturated colors, red, orange-red, and green-blue were most preferred, while yellow and yellow-green tended to be disliked. The most pleasing tints were blue, blue-violet, violet, and red-violet. Tinker, himself, found that with the exception of yellow-green, any color was preferred over the achromatic surfaces of black, white, and gray, while there was a suggestion that tints were more pleasant than saturated colors or shades, and that in larger areas tints were more acceptable than colors. While "pleasingness" may not be directly relatable to crew effectiveness, it does, however, contribute to overall habitability.

In addition to appeal, or affective value, colors would appear to influence emotional responses, as is evidenced by the epithetical terms applied to them such as sober, hot, heavy, dry, juicy, voluptuous, sensual, insipid, brutal, tranquil, and discordant. Some colors appear cool, tranquilizing, and restful; these are the blues, greens, and violets, which are appropriately used in rest and recreation areas. Red, orange, and yellow are considered exciting, and stimulating to work, and are found appropriate for work areas, while in general lighter colors are considered cooler than dark colors.

With respect to color harmony, or the juxtaposition of colors, studies have shown that the affective value of a combination of colors is highly dependent on the affective value of the component colors, although the result is not strictly additive. Where the composition is complex, as in a painting, the pattern of the composition exerts more weight than do the colors themselves, even if the composition is abstract.

Unsaturated complimentary colors, however, would appear to provide the best harmony for complimentaries. Strong and saturated complimentaries in apposition tend to produce an impression of discordance, which may be aggravated by the impression of flutter resulting from afterimages of each color projected onto the neighboring color as they are fixated serially. Hues tend to harmonize best that are separated either by small or large hue intervals rather than by intervals of intermediate value. However, small areas (e.g., trim) of discordant or unpleasant color may be introduced for interest and to heighten by affective contrast the pleasantness of other colors, while some lightness variation will assist in reducing monotony.

Thus, in general, for optimum habitability, color should provide both reflecting surfaces and pleasing combinations. Saturated colors and colors of low reflectance should be avoided on large areas; tints of appropriate color should be used instead. A proper proportion of reflectance should be maintained on consoles, panels, instruments, floors, ceilings, and walls. Variety and color of decoration is desirable. To maintain a pleasing environment, with appealing contrasts, different colors should be used in the same compartment, and still different combinations in other compartments. Tints and light greys possess several advantages, they make a compartment appear more spacious and ceilings appear higher. Some of the favored colored tints are buff with umber, ivory, cream, blue, coral, and peach. Flat or matte surface paints should be used to avoid specular reflection. A light that enhances warmth and softness of colored objects is desirable and furthermore illumination should be such that it does not markedly alter the color of natural objects, e.g., skin, complexion, and food.

Within these limitations, Fraser concludes that a variety of colors can be selected for the interior of spacecraft and space dwellings. Cool, work-stimulating colors are recommended for the work area, with bright contrasting accents on trim; warm, relaxing colors are recommended for public rest and recreation areas, again with contrasting accents and trim; while subdued, "homely" colors will be appropriate for personal areas. General lightening of color values will assist in providing brighter interiors with a lower level of illumination. The latter, as much as feasible, should be indirect, diffuse and nonglaring.

Noise Control

The internal noise levels of a spacecraft and undersea habitats can be quite high at times. Figure 4 presents the time history of the internal noise in a Mercury craft during the 70 seconds following liftoff. This shows that the sound level exceeded 140 dB during the period of maximum dynamic pressure. Although launch noise levels are somewhat atypical when considering a long-duration mission, there will be other times when internal noise can be quite high as during course correction phases. During normal power off flight, noise levels will of course be much lower although not negligible. For most of the mission, noise will come through the operation of spacecraft subsystems and communications equipment. This type of noise can be controlled either through appropriate shielding or by operating the equipment only at times when the noise will not be disruptive to other crew activities such as resting or sleeping.

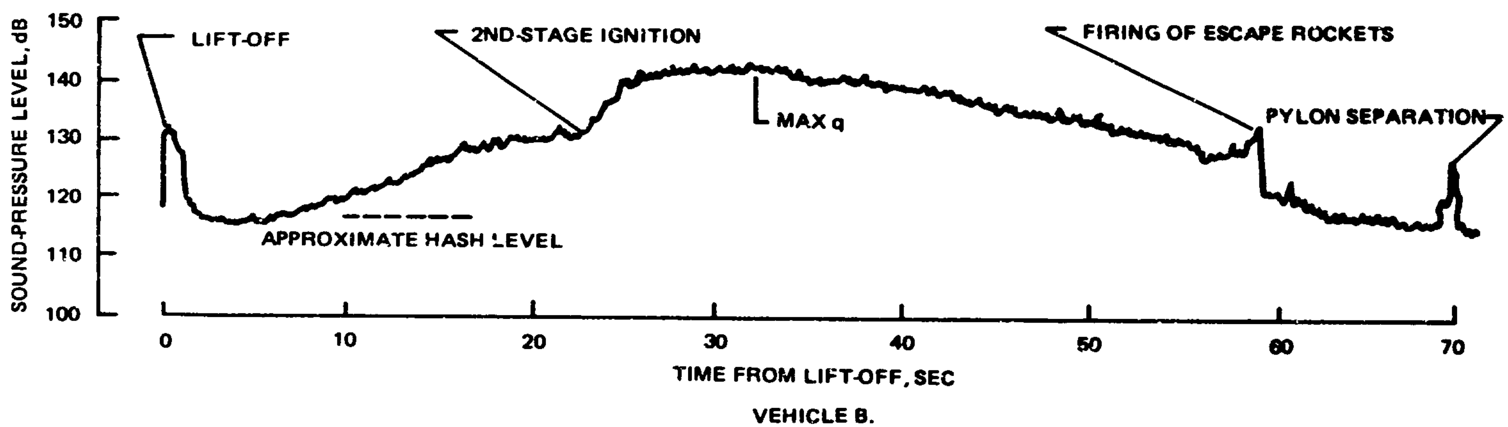

Figure 4. Time History of Overall Internal Sound-Pressure Levels

Efforts should be made in the design of the spacecraft to separate areas of high and low noise levels. Such areas as sleeping quarters, communications centers, and areas in which intensive work must be conducted should be given special acoustical treatment. Figure 5 shows noise ratings associated with various sound pressure levels, ranging from ratings of very quiet to those of intolerably loud. It is of interest to note that sound levels judged quiet in private office spaces are quite different from those judged quiet in general offices. It is apparent that the context within which the judgment is made has considerable influence on human perception as to what is quiet.

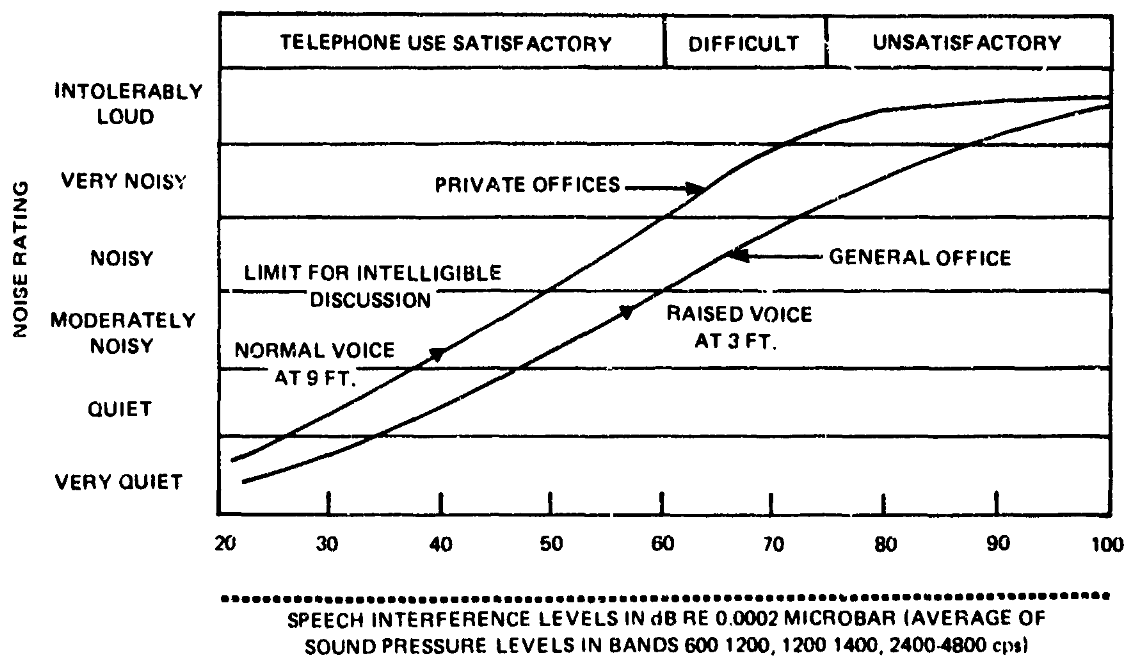

Figure 5. Acceptable Noise Levels

Whereas every effort should be made to control undesired noise, attention also should be given to the provision of desired sounds for personal enjoyment. Music should be available on an individual basis in sleeping, resting, and recreation areas. It also probably would be desirable to preselect the available music so as to be compatible with the personal tastes of the crewmembers.

Physical Conditioning Equipment

The problem of the physical cardiovascular deconditioning is a significant one during even relatively brief space missions. Physical deconditioning is obviously much less of a problem in undersea habitation, but some programs of physical conditioning might be beneficial, especially for long missions, both from a physical and a psychological point of view.

Extended space flight implies more than a change in the condition of the musculoskeletal or cardiovascular system (Weber & Gatts, 1969). It incorporates elements of general health such as appetite or state of nutrition, anxiety or state of baseline muscular tension (as related to physical conflict), oxygen consumption and metabolic level. However, inasmuch as these latter variables have been under careful control during the space flight program, it can be assumed that the deconditioning effects which have been found, primarily in the cardiovascular system, represent an adjustment of the body to weightless conditions. The extent of cardiovascular deconditioning and exercise capacity losses in the initial Apollo flights has been documented by Berry (1969). He found that the crewmen of the Apollo 7 and 8 flights had highly significant increases in heart rate and decreases in blood pressure in response to lower body negative pressure tests administered immediately postflight. Berry concludes that the space flight situation does create some modification of the cardiovascular system resulting in increased pulse rate response to a stress of the lower body negative pressure type, increased lability of the blood pressure, decreased pulse pressure and loss of electrolytes. Berry (1972) reported this latter situation, if it included a marked potassium ion loss, may well be responsible for the cardiac arrhythmia as seen in one spacecrew.

Weber and Gatts (1969) suggest that the only useful or effective approach toward the prevention of physical deconditioning is weight bearing or some exercise program for use in zero gravity conditions which simulates weight bearing. Berry (1972), on the other hand, feels provision of dietary electrolyte supplements may be critical. While the exact nature of physical exercise equipment most appropriate for inclusion in long-duration space missions is as yet undefined, provision for such equipment should be made. Exercise facilities should be incorporated into the general design of the spacecraft and sea habitats, in such a manner as to provide the least conflict with other features of the craft which influence its habitability.

Social Factors

Crew Structure and Composition

In all multimanned space flights and undersea habitat missions, there has been a fixed crew command structure. There is a clearly defined chain of command, with the Commander exercising ultimate authority and the other crewmembers assigned positions as a function of their particular role in the mission. This spelling out of positions has proven quite effective. There is at present no evidence to suggest that an equally clear command and organizational structure will not be required in later missions in which crew size may grow to a dozen or possibly even 100 men. The presence of an effective organization, even though only a few individuals may be involved, creates an orderliness of operation which in turn makes the entire situation more tolerable.

Spacecraft and sea habitats must have effective internal and external communication systems. An appropriate internal system is indispensible to orderly and effective work performance. In addition, it adds to habitability considerations if means are provided for an individual to communicate from some remote area in the craft readily with an individual who may be in another section. The structure of the system must be such, however, that communications between two members do not disturb other members of the crew.

There is also an obvious requirement for an effective external communication system, capable of providing voice contact with the spacecraft while it is in deep space and with the submerged undersea habitat. The ability to talk directly with friends on Earth may be especially important to the mental stability of astronauts and aquanauts and thus make their environments more habitable. An issue remaining to be resolved, however, is the possible need for management of news and items of personal information. In the event of very distressing news, such as that pertaining to the death of a member of the immediate family, it might be advisable to withhold the information until the completion of the mission. However, this is an issue which supervenes normal habitability concerns.

Finally, in any consideration of crew composition, one must arrive at some philosophy as to how to handle the sex issue. This obviously is an issue which must be approached with some caution, regardless of the circumstances. It is quite possible, in any event, that lack of normal heterosexual relationships could cause a significant buildup of emotional tension during missions lasting for a year or more. The resulting unsettling effect could serve to undo all other efforts directed toward making environments habitable. For this reason, some attention should be given to the possible use of crewmembers of both sexes, presumably comprised entirely of married couples.

Dining Factors

The preparation and service of food during long-term missions may prove to be the most significant parameter affecting habitability. During Project Tektite, in which four scientist aquanauts lived and worked in a submerged station for 60 days in a habitat amounting to approximately 500 cubic feet per man, it was found that ever increasing importance was attached to mealtime activities. Dining became a major social event of the day and was a time during which experiences of the day were shared and problems discussed. The act of food preparation itself became a major source of recreation for at least two of the four crewmembers.

Weber and Gatts (1969) provide an excellent review of the considerations involved in developing a food service program for long missions. They note that if food is to be a positive motivating factor, the crewmember must be given the privilege of choice and the menu must be constructed so that there is no monotony. Consideration of cycling in a menu is, in itself, not sufficient. Subvarieties of the offerings must be included. This is illustrated by the fact that most restaurants have approximately 15 to 20 menu selections.

Dried food can be used in all cases where human acceptability (all factors considered such as appearance, texture, and taste) would not be affected. Frozen or thermostabilized food should be considered where the technique can be most advantageously employed to preserve quality. Those foods for which the fresh would be most desirable should also be considered.

Concepts must be developed for cooking and baking equipment. Equipment will be selected from the standpoint of food variety, equipment complexity, power consumption, and space and weight considerations. Figure 6 shows a microwave oven under test for possible use in space.

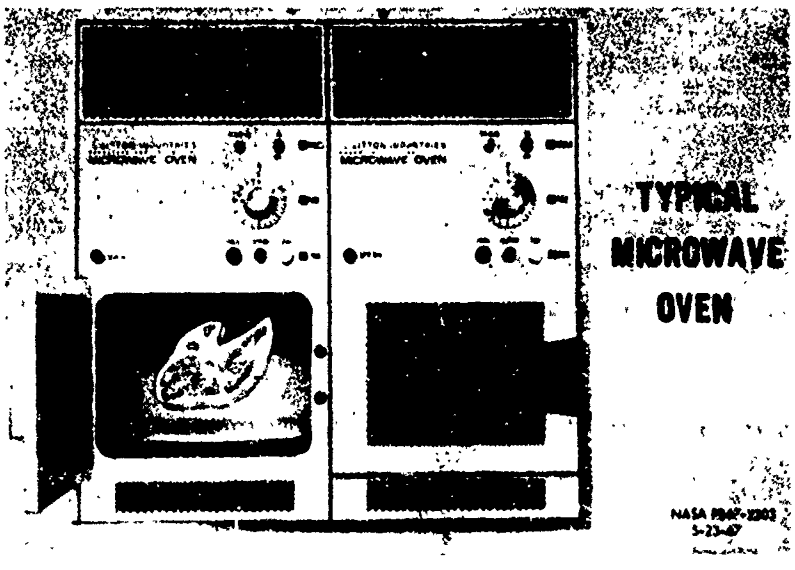

Figure 6. Cooking Conventional Foods in Zero G

In any meal planning operation, the planner is limited by the small number of different basic food types. Great variety is achieved only by varying preparation methods. For this reason, consideration must be given to a variety of cooking methods such as boiling, broiling, frying, baking, etc. An effort should be made to select cooking equipment and techniques that provide food with a familiar appearance and flavor. For example, if microwave cooking is used for meat preparation, means should be studied to obtain the surface searing necessary for appearance and flavor.

Various heat sources, such as microwave and solar heating should be considered. The feasibility of pressure cooking and baking to provide reduced cooking time and greater food varieties should be investigated. Consideration must be given to means of elimination of venting of cooking odors, smoke, steam, and grease to prevent contamination of the space base atmosphere. Cooking utensil design must consider ease of cleaning to insure sanitary food preparation. Special consideration must be given to cooking utensils and food heating equipment to provide proper restraint and positioning of food under the zero gravity condition. The lack of convection under zero or low gravity must be compensated for in equipment design. Because a choice of entrees, deserts, etc., for each meal would be desirable, a tradeoff of varieties versus requirement for additional equipment must be made. The ultimate goal is a good serving system that adds to the overall enjoyment of the dining experience. The achievement of this goal will contribute very significantly to spacecraft habitability.

The preparation of food in the high pressure environment of underwater habitats presents some unique problems:

1. Frying of food is prohibited because of the release of acrolein.

2. Certain foods such as toast, when burned, release carbon monoxide which, even in small concentrations, at high pressures can cause severe problems.

3. Because helium is a constituent of the underwater habitat environment, new safety procedures must be incorporated. Since the pressure in some of the deep habitats may be as high as 18 atm (at 600 feet), cooking times are considerably less than normal and boiling points much higher. The boiling point of water in Sealab II was approximately 330°F. Thus, burn accidents are much more serious. It also appears that the chance of occurrence of such accidents is increased. Due to the thermal characteristics of helium, heaters and stoves with heating coils may be at red hot temperature yet not be the glowing red which signifies danger.

Under a consideration of specific eating techniques in space, Weber and Gatts note that an ordinary knife-fork-spoon utensil set would be desirable under zero gravity conditions since this coincides exactly with earthbound habits. Such utensils may still be acceptable if cohesive foods are selected and prepared with gravies or sauces that possess adhesive properties. Beverages could still be consumed from cups or glasses but with the added requirement for straws or mouthpiece lids. If table manners can be relaxed, the simple expedient of using the fingers to eat many foods would be natural.

Provisions for control of spillage and crumbs, as well as for the application of condiments and seasonings such as mustard or pepper, will present definite problems in zero gravity. Required body restraints should be minimal, allowing a large degree of torso freedom over the eating surface to reduce sloppiness. The use of bite-sized prepared foods would alleviate many problems and is completely feasible for certain foods.

A final, and by no means inconsequential, topic concerning food deals with its acceptance by individual crewmembers. Food preferences, and the acceptance of specific food items are highly individual matters. In the preparation of menus for long missions, considerable care should be taken to determine the food preferences of individual members and to stock food supplies on that basis.

The recent 60-day manned test of a regenerative life support system (McDonnell Douglas, 1968), conducted within a closed chamber, provides some of the best information to date concerning food acceptance and its importance during life in an enclosed cabin. The four crewmembers in this test were provided with four basic menus, which were presented on a rotating basis for six days each week. These menus provided approximately 2400 to 2800 calories per day in four nutritionally balanced meals each consisting of from four to six food items. Once each week, the subjects were provided with a complete dinner prepared by the staff of the executive dining room. These meals, passed into the chamber in thermal storage plates, were equivalent to high quality restaurant food. A representative dinner included a prime cut of steak, a large baked potato, sour cream, salad, rolls and butter, fresh milk, and dessert.

Before the start of the test, crewmen were given the menu for the freeze dried food and were informed that they would also receive the weekly dining room meals. They were encouraged to eat all foods presented, but were not required to do so since no balanced food studies were planned and the evaluation of the basic diet was to be qualitative. Furthermore, they were not restricted from varying the planned menus. During the first half of the study, they were not required to report specific departures from the menu.

All subjects initially agreed that the freeze dehydrated food was acceptable. However, their average daily consumption decreased during the first few weeks of the test. The subjects reported that many of the food items that were acceptable before the test lost appeal as the experiment progressed. This was not apparent to the experimental staff members who sampled the rejected food in limited quantities. Certain food items were frequently rejected. Planned menus were modified by interchanging food items. Particularly favored food items such as shrimp cocktail, fruit cake, brownie bites, and peach bars were saved and traded to other crewmembers. Large quantities of powdered milk and powdered orange juice were consumed to supplement the freeze dehydrated diet.

After a few weeks of testing, the crew began to experiment with basic food items: potato soup was rehydrated with minimal water and consumed as "mashed potatoes," beef was mixed with peas, and bacon bites were mixed with "mashed potatoes." Toward the end of the study, a small refrigerator was passed into the chamber to cool reclaimed potable water. This opportunity was immediately utilized for further food experimentation: hot gelatin drink was rehydrated with fruit cocktail bars to produce a jellied salad; and powdered orange juice was rehydrated to produce fruit flavored ice cubes.

The Friday meals, when the restaurant quality meal was served, became extremely important to the crewmembers. Time was often referenced to the day of the dinners and agitation developed among the subjects if the dinners were not delivered on time. It is extremely difficult to estimate the impact which these meals had on continued acceptance of the basic diet. While unquestionably a positive morale factor, as indicated by the expression on the face of the subject in Figure 7, it is suspected that the obvious comparison served to make the freeze dried food even less acceptable.

Figure 7. "Quality Meal" During McDonnell-Douglas 60-Day Life Support System Test

Leisure Time Activities

A topic relating to habitability that becomes of considerable importance when planning for lengthy missions concerns the incorporation of appropriate facilities, equipment, and procedures for leisure time activities by crewmembers. Because of the confining nature of the spacecraft and undersea habitats and the constant contact with the same crewmembers, particularly for small-sized crews, the identification of adequate off-duty or discretionary activity requirements for space stations, bases, and interplanetary spacecraft is necessary (Eberhard, 1969). In his recent study of this problem, Eberhard reviewed the status of off-duty time and discretionary activity requirements for longer duration space missions and surveyed potential crewmember acceptance of various discretionary activities. He found that, whereas various NASA mission and other studies scheduled 1.5 to 3 hours a day of off-duty time (scheduled and unscheduled), it might be in excess of 12 hours a day. This would be a function of lessened sleep time requirements, inadequate work opportunities, and maintenance contingency time that might not occur during latter stages of a long-term mission.

Eberhard reviewed a number of investigations of the activities of individuals held in relative confinement for some period of time. These included studies of shelter evaluations, missile site crewmen, laboratory investigations, antarctic expeditions, and space simulation studies. The following summary of activity findings was presented:

1. Men in confinement prefer work to free time.

2. There is a higher incidence of abnormal symptoms among men in confinement without adequate work opportunities than with those who have such opportunities.

3. Discretionary activities should depend upon the free choice of each crewmember.

4. Confined individuals create some free time activities of their own.

5. Off-duty time and activity patterns of isolated groups differ from those of the general population; furthermore, the activity patterns of the individuals in confinement change over time.

6. Talking, reading fiction, watching movies, and television are the most frequently performed activities by confined groups.

7. Men in confinement take almost twice as long to eat as men in the general population.

8. Exercise was necessary in an infrequently performed activity for all of the adults studied.

9. Interest in educational activities is highly individualistic; however, it is generally sought infrequently.

10. Individuals who regularly use religion, or those who do not, adjust best to confinement.

11. Activities such as painting, playing cards, chess and checkers, are relatively infrequently mentioned by most of the individuals studied.

12. Recreational facilities have historically been the source of significant morale problems for confined groups.

A questionnaire was administered to thirty astronauts at the NASA Manned Spacecraft Center to assess their preferences for off-duty activities and the use of off-duty equipment. Eberhard presents the results of this assessment in Tables 6 and 7, with each table indicating the ranking of items most preferred to least preferred. The information in these tables represents the best data available at this time concerning the desired structure of off-duty activities. However, the data were obtained on the basis of verbal report rather than as a result of direct observation of off-duty activities under actual confinement conditions.

Table 6
Rank Order Preferences of 30 Astronauts
for Present Off-Duty Activities

Present Off-Duty Activities	Rank
Job related activities	1
Reading	2
Physical exercises	3
Studying or coursework	5
Playing sports	5
Listening to records, etc.	5
Family activities	7
Watching TV, movies, etc.	8
Being alone	9
Technical writing	10.5
Religious activities	10.5
Personal writing	12
Resting, relaxing, or doing "nothing in particular"	13
Eating snacks	15
Model building, etc.	15.5
Playing card games	15.5
Painting, sculpting, photography	17.5
Playing board games	17.5
Playing gambling games	19
Playing musical instrument or singing	20
Stamp, coin collecting	21

(From Eberhard, 1969)

Table 7
Rank Order Preferences of 30 Astronauts for Off-Duty Equipment for Spacecraft Utilization

Equipment Usage in Spacecraft	Rank
Viewports of spacecraft	1
Physical exercise equipment	2.5
Record or tape player	2.5
Books	4
Sports equipment	5
AM or FM radio	6
Newspapers	7
Magazines	8
Photo equipment	9
Radio equipment for personal communication	10
Television set	11
Writing supplies	12
Playing cards	13
Board games	14
Musical instrument	15
Dice	16
Model building kits	17
Painting/Drawing supplies	18
Stamp or coin collecting	19

(From Eberhard, 1969)

Conclusions

Habitability is an intangible and yet very meaningful issue in the design of spaces in which humans must live and work. Habitability has been defined in many ways, with the definitions being as broad or as restricted as the specific topics one wishes to consider. For present purposes, habitability is considered in its broadest sense, and covers all issues relating to the living environment which bear upon the comfort, happiness, motivation, and effectiveness of the occupant of the environment.

In many instances, it is difficult to separate matters of habitability design from the more direct issues of engineering design. If a subsystem of a habitat fails, for example, the waste management system, the entire structure loses a good bit in terms of habitability. However, this is considered a reliability problem, one dependent on engineering design and not really a habitability consideration. From the point of view of habitability, the waste management system may be excellent, albeit unreliable.

Issues underlying habitability can be complex and are always interrelated. An engineer working with habitability problems must understand all systems in a structure in order to deal appropriately with individual issues. For example, provision for privacy in an underwater habitat would call for curtains around bunks or sleeping enclosures. However, it has been found that this can lead to an undesirable carbon dioxide buildup. Obviously, either an appropriate tradeoff must be made or a new design-for-privacy initiated.

The following sections present broad conclusions developed from a review of recent missions in space vehicles and underwater habitats. In general, it was found that habitability engineering is more advanced for space activities than for those underwater. However, there remain a number of habitability problems related to both environments, some of which could become severe. These should be considered before structures are developed in which individuals will live and work for *long* periods of time.

Habitability Design Principles

The basic principles relating to design for habitability are well known. There is a fund of data describing such topics as optimum illumination levels for various activities, proper procedures for noise control, and appropriate use of color in sleeping, resting, and working spaces. The principal design problem is one of adapting this type of data to a structure which will be located in a highly unusual external environment such as deep space or beneath the surface of the ocean. However, the general design principles are available and represent an excellent starting point from which to begin the necessary design tradeoffs with engineering constraints.

Habitability Issues

Social/Behavioral Factors. To date, the crews involved in both space and undersea missions have been extremely work-oriented, and have shown little inclination for any other activity, with the exception of sleep and self-maintenance. As the length of missions increases, however, the confinement factor in their habitats will undoubtedly become more troublesome, and result in a greatly increased need for diversionary activity. Consequently, leisure activity must be given primary consideration, on both an individual and group basis, as a factor highly relevant to overall mission success.

Certain behavioral patterns among the crew and in relation to mission support personnel have become evident during both space and undersea missions. In large crew complements such as found in undersea habitats, there has been a degree of "grouping" by experience levels, occupation, etc. This, in turn, has produced resentment by those who feel excluded. In both types of missions, there have been varying degrees of "annoyance" with mission control and/or topside personnel. These patterns must be considered and evaluated in the premission planning sessions related to crew selection, support personnel selection and training, layout of "social" areas, scheduling of work, etc.

Workspace Layout and Scheduling. Workspace layout is one of the paramount problems in underwater habitats. Results from the Tektite missions have demonstrated that the single most important variable relating to habitability was the degree to which the aquanauts found the habitat to be supportive of their scientific and engineering tasks. Predesign habitat planning should consider the following questions. (1) How often will the space be used? (2) Will other crewmembers be waiting to use the area? (3) Will they be comfortable while waiting? (4) Does the layout reflect time spent and the importance of a certain space? In undersea missions, laboratory areas and water entry areas have produced the most severe problems. Spacecraft, as they become larger, may show similar problems when they begin to serve less as transportation vehicles and more as workshops.

Tektite II crews engaged in a great variety of scientific studies and spent widely differing periods of time at different activities (work, sleep, leisure, self-maintenance). These missions demonstrated, for example, that the collection of different samples will require different types of laboratory and storage arrangements (e.g., geological versus biological samples). Work schedules, in terms of time in the water and amounts of energy expended in gathering these samples, may vary greatly, necessitating leisure time and rest time scheduling changes. If future habitats are to continue to be used for a series of successive missions involving a wide range of mission profiles, careful forethought must be given to optimizing the facilities for the entire spectra of mission objectives as well as various crew requirements.

Personal Demands. When provisions for personal needs, such as food preparation, waste management, hygiene, maintenance, warmth and privacy, fail to meet expected standards, they can become a cause of morale decline and performance degradation. Repairs and/or alterations to the equipment which aid in fulfilling these requirements has proved necessary in almost all underwater habitat missions. This work is, at best, difficult to accomplish under mission environmental conditions, and the equipment's temporary loss may have a detrimental effect on morale as well as the overall scientific objectives of the mission. Careful premission testing in simulation facilities would isolate many of the human factors as well as basic engineering problems associated with these requirements and allow for premission remedial action should any system prove inadequate.

For space missions, considerable attention is being given to waste management and personal hygiene systems as longer flights, such as Skylab, are planned. Even here, however, weight and volume constraints generally cause the operational system to be less pleasing than one might desire. There is a continuing need for research to improve present technology in this field and to develop new concepts which are altogether different from those on which present systems are based.

Communications. Inner-habitat communications will become more important as the complexity of habitats increases. Of all space or sea habitats, the Tektite habitat is the most compartmentalized, yet, there has been only a minimum of inner-habitat communication problems. External communication created more difficulties. Video links have been successfully relied upon but these need further evaluation to establish the extent to which they can be used before privacy is seriously compromised. What information should be relayed must be evaluated. One of the lowest rated characteristics of the Tektite habitat was the paucity of news from topside. Space crews have also been troubled by both the amount and type of communications during certain missions. Engineering design to improve on the "Donald Duck" speech in a helium environment is imperative if there are to be effective communications with deep ocean habitats.

Habitability Testing

To date, there has been no systematic testing of the various parameters likely to influence underwater habitability. Many habitability problems are highly interrelated with basic engineering systems, yet receive only post-design attention. It is important that these issues be identified in advance of system design so they can be dealt with appropriately as the system is constructed. The optimum method for determining those issues which could have a significant effect on the success or failure of a mission would consist of:

1. Careful analysis of all available habitability data related to engineering technology—e.g., architecture, electrical systems, waste systems, etc.

2. Use of laboratory full-scale models to evaluate tradeoffs while testing various arrangements and their subsequent acceptability.

3. Use of a full scale model under semi-submerged conditions; e.g., one in which the entrance hatch is underwater, but in which the habitat spaces are above water and at atmospheric pressure.

For all practical purposes, divers would use the habitat as if it were submerged at saturation depth. Several distinct advantages would accrue from the use of such a testing configuration. The habitat could be constructed of wood or some other inexpensive material which could readily be reshaped to experiment with different volumetric requirements. Costly boilerplate fabrication would be unnecessary and no pressure testing would be needed. Future aquanauts, scientists, and habitat engineers could be safely trained under conditions which closely simulate the conditions in which they would ultimately work.

Data Sources

The documentation of habitability design principles for space vehicles took a significant step forward with the publication in 1971 of the *Habitability Data Handbook* by the NASA Manned Spacecraft Center. This handbook is a collection of data in six volumes concerned with the following subject areas: mobility and restraint, architecture and environment, housekeeping, food management, garments and ancillary equipment, and personal hygiene. The handbook is intended as an integrated data source for use in habitability system planning and design, intersystem tradeoffs, and interface definition.

There is no habitability data handbook for underwater systems comparable to that published by NASA for space systems. Data relating to underwater habitats derived from programs such as the Tektite series appear in many reports and in many forms. Prior to the design of habitats for long-term undersea residence, relevant habitability data, of which a reasonable amount now is available, should be collected and organized into a single source document. Such a document would be of considerable value to design engineers as future underwater activities are planned and systems constructed.

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APPENDIX A

Major U.S. Undersea Habitat Missions

Sealab I & II, Tektite I & II and Aegir were selected for inclusion in this appendix because each of these missions represented a new dimension in undersea exploration and consequently offered some unique problems in underwater habitability.

Sealab I

Description of Habitat

The Sealab I hull was fabricated from two cylindrical minesweeping floats. The habitat is 40 feet long and 8 feet, 11 inches in diameter. (See Figure A-1.) The habitat is divided into two compartments; one 31-foot compartment is utilized as a living space, the other 9-foot compartment serves as a utility space. Normal entry into the habitat is provided by a 30 by 36 inch hatch extending three feet below the hull and four feet above the hull. Two ports are provided on each side for viewing purposes.

Description of the Mission

The Sealab I mission housed four men at a depth of 193 feet for 11 days. The mission was conducted from 20 July to 31 July 1964, off Argus Island near Bermuda. The main objectives of this mission included: (a) to confirm shore laboratory investigations of the physiology of saturation diving, (b) to determine the characteristics and suitability of undersea habitats for the support of swimmers performing various tasks in offshore water, and (c) to determine man's efficiency in the performance of various tasks while living under saturation conditions. This mission was conducted by the Office of Naval Research, in conjunction with other U.S. Navy activities.

Habitat Environment

The atmosphere in the habitat consisted of a 79% helium–4% oxygen–17% nitrogen gas mixture. Carbon dioxide buildup was controlled using lithium hydroxide (LiOH) in two electrically powered CO_2 scrubber units. Relative humidity was maintained near 72% utilizing two dehumidifiers and the temperature was maintained at around 85°F. Lighting for the habitat was provided by deadlights in the counter and table areas.

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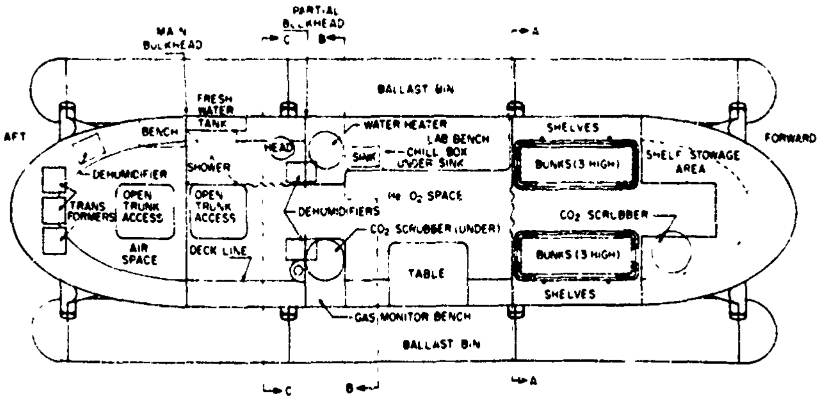
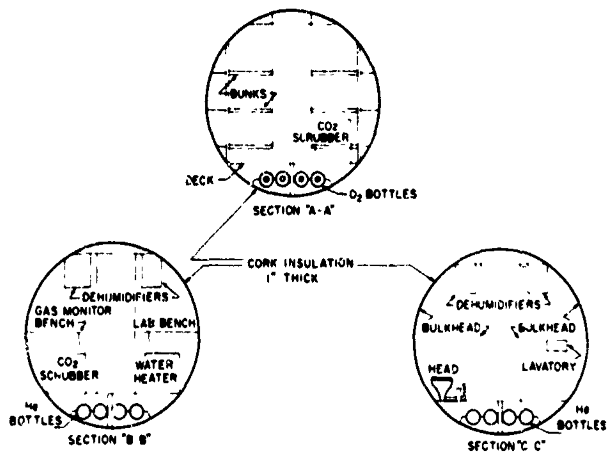


(a) Top View



(b) Cross-Section Views at Intervals Marked in (a)

Figure A–1. Selab I Interior Arrangement From ONR Report ACR-108

Sealab II

Description of Habitat

The hull of the Sealab II habitat is 57 feet long with a 12-foot outside diameter. (See Figure A-2.) It is capable of withstanding an internal working pressure of 125 psig. The hull is provided with 11 view ports and with three access openings. The main entry hatch is on the bottom and is approximately four feet in diameter.

Description of the Mission

The Sealab II mission housed three 10-man aquanaut teams for 15 days each; one man spent 30 continuous days, another spent 30 days in two discrete 15-day periods. The habitat was maintained at a depth of 205 feet off the California coast from 28 August to 10 October 1965. The main objectives of the mission were: (a) to determine man's general ability to do useful work at a depth of 200 feet in a realistic ocean environment under saturated diving conditions, (b) to determine the physiological changes in man resulting from extended diving, (c) to measure performance and determine work degradation or improvement, as compared to surface diving operations, and as a function of dive time, (d) to determine stressful conditions and their effect of the group interaction of the aquanauts. This mission was conducted by the Office of Naval Research as a part of the man-in-the-sea task of the Deep Submergence Systems Program.

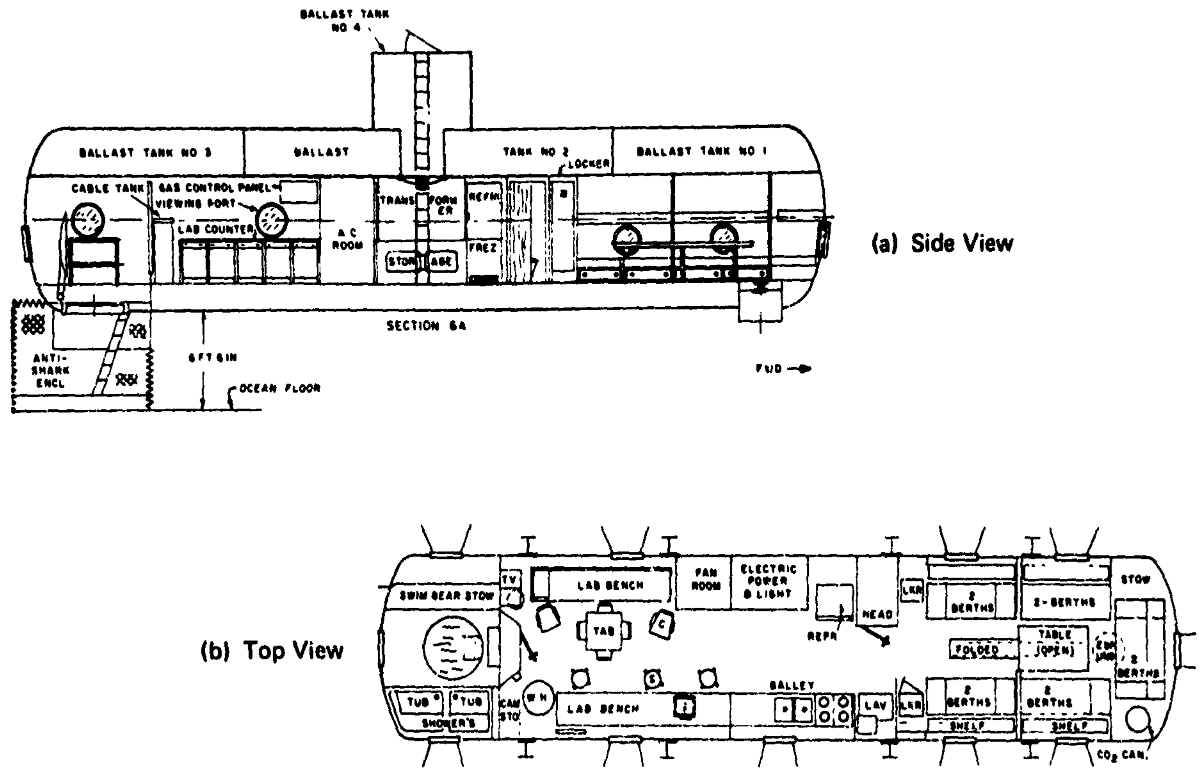


Figure A–2. Sealab II Interior Arrangement From ONR Report DR 153

Habitat Environment

The atmosphere in the habitat contained 78.1% helium–4.5% oxygen–17.4% nitrogen. Relative humidity ranged from 60 to 92 percent. Air temperature ranged generally from 80 to 90°F. CO_2 buildup was controlled by means of a scrubber system utilizing canisters of LiOH. Carbon monoxide removal was not included in the plans for this mission, however, when levels of 20 ppm or more were detected–some LiOH canisters were replaced with Hopcalite and silica gel for catalytic oxidation of the CO_2. Hydrocarbons and odors were controlled by the use of large filters of activated charcoal in the atmospheric recirculating system. The lighting system throughout the habitat consisted of 40–100 watt appliance lamps. The number and location of the lighting fixtures for illumination were in accordance with the average foot-candle values specified in Table I of section 9640-2 General Specifications for Ships of the Navy.

Reference

Project Sealab Report. An experimental 45-day undersea saturation dive at 205 feet. ONR Report ACR-124, March 8, 1967.

Tektite I

Description of Habitat

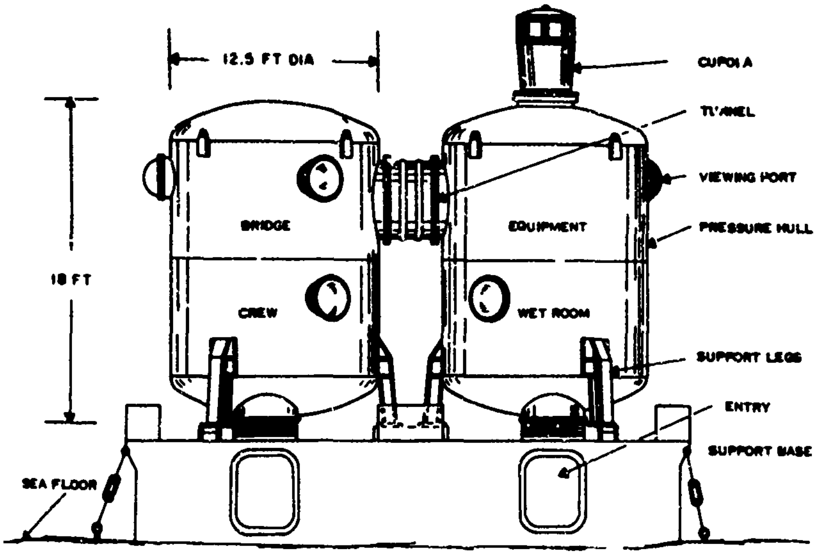
The Tektite I habitat consists of two pressure hulls having a maximum diameter of 12.5 feet and a maximum height of 18 feet. These pressure hulls are attached upright to a rigid base, and connected by a pressurized cross-over tunnel. (See Figure A-3.) The cylinders are divided into two compartments each; bridge, crew quarters, equipment room, and wet room. Six viewing ports and a cupola were provided for observation purposes. Hull structures were designed for a maximum operating pressure of 33 psig. Normal entry into the habitat was provided by an open 4-foot diameter entry trunk in the wet room.

Description of the Mission

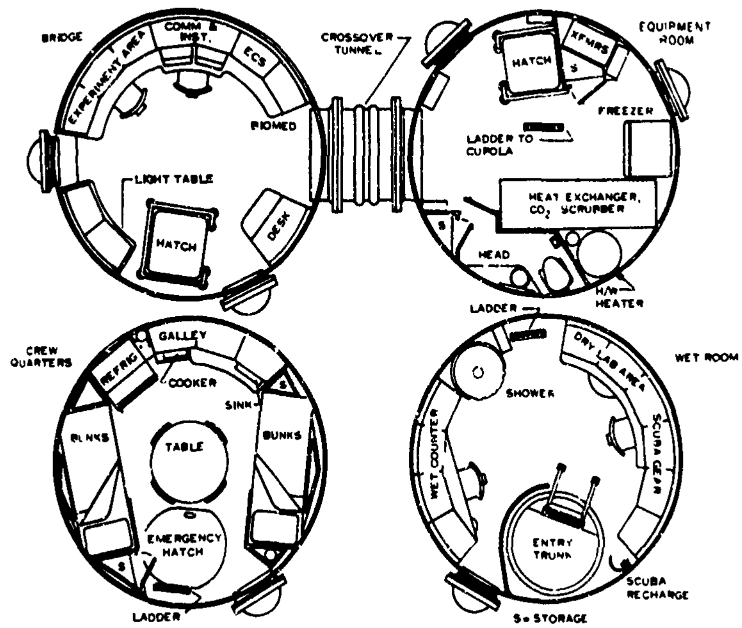
The Tektite I mission housed four men for 60 days at a depth of 43 feet in the Virgin Islands. The mission was from 15 February to 15 April 1969. The main objectives of the mission were: (a) to study the behavior and effectiveness of a small group of highly trained men to real work under stressed, isolated conditions, (b) to study biomedical responses of men living under high-nitrogen partial pressure saturated conditions in the marine environment for an extended period, (c) to conduct meaningful marine science research from an undersea habitat. This mission was conducted under the overall cognizance and management of the Chief of Naval Research.

Habitat Environment

The atmosphere in the Tektite I habitat contained a mixture of 92% nitrogen and 8% oxygen. Carbon dioxide was removed by a Baralyme scrubber system. A thermal control system maintained the habitat air temperature at 80°F and the relative humidity at between 42 and 60 percent. The interior lighting systems consisted of four ceiling fixtures in each compartment to provide area illumination. These lighting fixtures could be continuously controlled from maximum to zero intensity with a dimmer switch. Supplementary lighting fixtures were used to provide additional illumination where necessary. Charcoal filters were used to remove noxious odors and noise abatement was assisted by the use of acoustic ceiling tiles.



(a) Side View



(b) Top View

Figure A-3. Tektite I & II Habitat. (From ONR Report DR 153)

Reference

Project Tektite I – A multiagency 60-day saturation dive. ONR Report DR 153, January 16, 1970.

Tektite II

Description of Habitat

The Tektite II facilities were basically the same as the Tektite I facilities. The only exception being for this mission there were five crewmembers which necessitated a folding cot where the habitat engineer slept.

Description of the Mission

The Tektite II experiment consisted of 11 missions ranging in length from 6 to 20 days with the habitat at a depth of 50 feet. For 10 of the missions the team was made up of five men and for one mission was made up of five women. The objectives of the missions were varied ranging from equipment checkout to behavioral studies to scientific studies including almost all phases of oceanography. This mission was conducted under the overall cognizance and management of the U.S. Department of the Interior.

Habitat Environment

The environment for the Tektite II missions was basically identical to that for the Tektite I mission.

Reference

Tektite II – Scientist-in-the sea. U.S. Dept. of the Interior, August, 1971.

Aegir

Description of the Habitat

The undersea habitat Aegir consists of three interconnected pressure vessels. (See Figures A-4 & A-5). The cylinders internally measure nine feet in diameter and 17 feet in length and serve as living and laboratory compartments. Although each vessel has its own access hatch in the water, normal entry is made via the 10-foot diameter central sphere which serves as a diver staging and buoyancy control area.

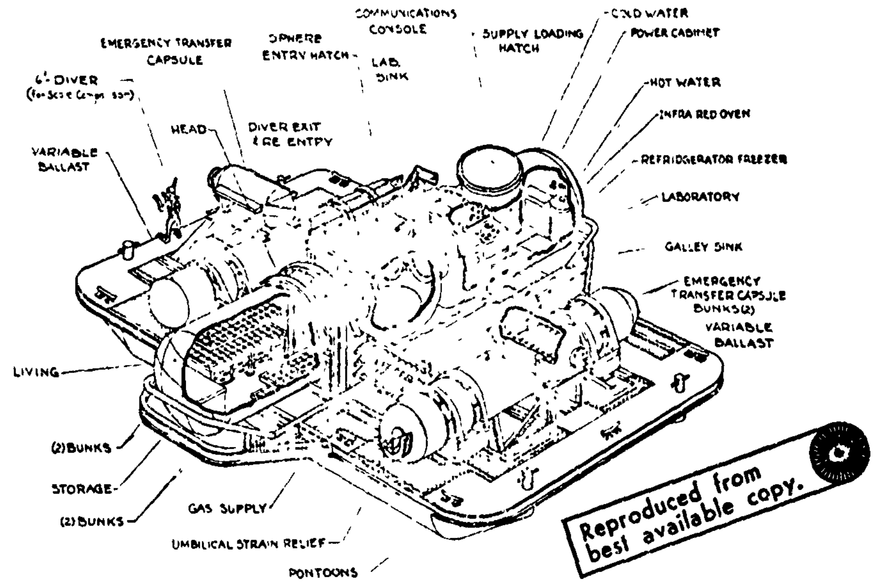


Figure A–4. Aegir and Support Vessel

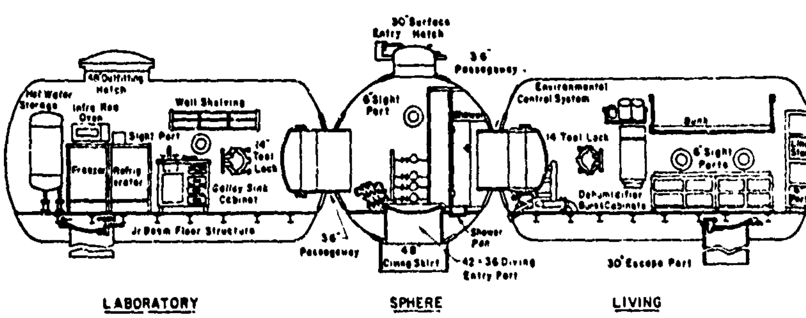


Figure A–5. Aegir Interior Arrangement

Description of the Mission

The Aegir mission housed six men for five days at a depth of 516 feet in Hawaiian waters. The mission was conducted in June 1970. The main objectives of the mission included a general test-out of systems and equipment along with some experiments the Navy had planned for Sealab III. The mission was conducted by the Makai Undersea Test Range.

Habitat Environment

The atmosphere in the habitat was a mixture of 91% helium, 7.2% nitrogen, and 1.8% oxygen. Temperature and humidity were conventionally monitored and controlled by ten household type electric heaters and dehumidifiers. These two parameters produced the greatest problem during the mission. Shortly after landing on the bottom, the habitat interior temperature dropped nearly to ambient (70–80°F) and remained there during the mission. The dehumidifiers, which also did not function as planned, were unable to maintain relative humidity below 80 percent on the bottom.

Reference

Personnel communication and segments of reports supplied by the Makai Undersea Test Range, Makapuu Point, Hawaii.