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ABSTRACT

This paper presents an "Inquiry by Design" approach to the problem of architectural design for the crew habitat of an interplanetary vehicle. This habitat must meet a range of difficult requirements to protect the crew's health and safety during the approximately 6 to 12 month voyage each way. It must provide a habitable environment that affords the crew privacy, group activities, recreation, exercise, communications, training facilities, and health care. It must incorporate countermeasures against prolonged exposure to zero gravity and shielding against radiation from solar flares and galactic cosmic rays.

The design research involves the investigation of a prototype interplanetary habitat that incorporates substantial radiation shielding for the crew quarters and a human powered, short-arm centrifuge for zero gravity countermeasures. It includes private crew quarters, life support system, stowage and equipment volumes. This *inquiry by design* exercise explores the habitat components subsystem by subsystem to find the challenges that emerge for integrating them. This exercise in designing an optimized interplanetary habitat reveals some key design and engineering issues for NASA to consider in developing a Mars vehicle.

INQUIRY BY DESIGN

The concept of "Inquiry by Design" presents an approach to research whereby the designer seeks to learn about a design problem by developing design solutions to it. To paraphrase John Zeisel's approach, a design solution comprises a "hypothesis" about a problem, that reveals the deeper character of the design problem [Zeisel, 1981]. The approach involves analyzing the design problem to create a design problem definition that decomposes into a set of distinct design issues. The design researcher creates a set of propositions to test how to address each issue. These propositions add up to a compound "hypothesis" about the design problem and how to resolve it.

In this paper, I present the problem first with its component issues, then the design solution with its propositions, and an evaluation of what this "inquiry by design" approach teaches us. Another way to view inquiry by design is a "what if" approach. For example, *what if* it is necessary to take the requirement for radiation protection seriously? Or, *what if* it is necessary to provide zero-gravity countermeasures?

DISTINCTION BETWEEN PLANETARY AND INTERPLANETARY HABITATS

Before delving into the design research issues and propositions for the interplanetary habitat, it is important to understand what characteristics it shares with the problem of the surface habitat, and, what is more important, which issues make the two habitat applications distinctly different from each other. A great deal depends upon whether the designer intends the habitat to serve also as a planetary surface habitat in addition to serving as a transit habitat between the Earth and a destination planet, which in most recent thinking is Mars.

The central design research problem for both planetary surface and interplanetary vehicle habitats is how to optimize their design for the unique application for which the designer intends them [Cohen, July 1996; Cohen, Sept. 1996]. The specific operational and functional requirements for surface and vehicular habitats are in fact radically different. It is vital to understand those differences and their implications for choice of habitat configuration, structure, materials, outfitting, operations and the overall impact upon mission architecture. The key planning decision lies in the allocation of functions between the interplanetary and surface habitats, and the appropriate candidate architectural plans, sections, elevations, adjacencies, connectivities, and functional separations for each habitat application. For example, in contrast to interplanetary habitats, surface habitat design must include a broad range of site planning considerations.

This habitat system optimization goal means how best to incorporate the functional components within the different gravity orientations, how to protect against the relevant environmental hazards, and how to respond to the operational imperatives for each application. The two situations differ profoundly. The interplanetary vehicle habitat must support the crew for two voyages of at least six months in zero gravity, accommodate countermeasures against zero gravity such as the human powered centrifuge, operate life support in an essentially closed system, and protect the crew from radiation hazards including solar protons and galactic heavy ions. In contrast, the Mars surface habitat must perform in .38 G to accommodate a major mass and volume demand to support the science laboratories, and crew quarters for a sojourn of 600 days on the surface, afford dust protection, support frequent EVAs for scientific field work, and may operate with an open loop, in situ resource utilization (ISRU) enhanced life support system. However, there is no need to impose any of these surface features upon the interplanetary habitat, nor, conversely, is there a need to impose the interplanetary features upon the surface habitat. It will be vital to optimize both habitats to minimize the extraneous burden of accommodating functions unnecessary to each portion of the mission, and instead to maximize the accommodation of the necessary functions for each portion.

THE PROBLEM OF THE INTERPLANETARY HABITAT

The interplanetary habitat is a unique and fairly complex design problem. For the purpose of this design research, the interplanetary habitat is just that: part of an interplanetary vehicle that crews assemble in low Earth orbit (LEO) and then injects on its trajectory to Mars. Upon arrival at Mars, the vehicle goes into a Mars orbit. The crew transfer to a descent/ascent vehicle and descend to the Mars surface where they live in a surface base habitat that arrived separately from the interplanetary crew vehicle. When the crew finishes their sojourn on the Mars surface, they ascend back to orbit in the descent/ascent vehicle, rendezvous with the orbiting interplanetary vehicle, and then inject on the Earth return trajectory. Upon returning to Earth, the interplanetary vehicle either goes into LEO where it can rendezvous with a shuttle, space station or other vehicle or the crew use Apollo or Soyuz type vehicles to make a ballistic entry to return directly to the Earth's surface.

Given this scenario, the interplanetary habitat faces the demand of supporting a Mars crew of typically six or eight members for six to eight months outbound to Mars, then going into a dormant state for up to about 600 days, then supporting the returning crew for up to a year on the return voyage.

DESIGN RESEARCH ISSUES

These considerations yield a set of nine leading design research issues: pressure vessel structure, radiation protection, living quarters, zero-gravity countermeasures, crew privacy & group activities, stowage, circulation, integration into the interplanetary vehicle, and habitat size. For each of these issues in the design problem decomposition, I present a corresponding proposition for a design solution. Although these issues may resemble "requirements," they differ from requirements because they pose the question "What is the nature of the problem they embody and what are the connections between them?"

1. PRESSURE VESSEL - What is the optimum shape and structure for the Habitat pressure vessel? Because all space habitat architecture is pneumatic, the pressure vessel structure is often the first consideration in a design. In the case of the interplanetary habitat, the surface area to volume ratio is important for minimizing structural mass, minimizing surface requiring thermal insulation, and minimizing the surface for radiation protection.

2. RADIATION PROTECTION - Is it possible architecturally and geometrically to protect the crew from radiation exposure? Radiation exposure is one of the greatest potential hazards to crews in transit through interplanetary space. This design effort must take seriously the recommendations of the experts on radiation protection, who seem to converge on an agreement that interplanetary crews need substantial protection on the order of 30gm/cm^2 shielding against galactic cosmic rays (GCRs) [Townsend, Nealy, Wilson & Simonson, Feb 1990, p.8, and Cohen, July 1996]. How to introduce this shielding mass and volume emerges as a major architectural and engineering challenge.

The radiation protection question has such far-reaching implications that it requires greater explication than the other design issues.

Galactic Cosmic Rays (also known as HZE particles) consist of the nuclei of atoms (primarily helium, manganese, iron, xenon, and argon) traveling across the galaxy from many stars. They are spatially isotropic so that shielding a spacecraft against GCRs requires an omnidirectional enclosure around the crew [Simonson & Nealy, 1991, Feb, p. 9]. GCRs are relatively constant compared to SPEs, although the strength of their flux waxes and wanes with the solar cycle, so GCRs tend to vary inversely with the incidence of SPEs. At solar minimum (quiet part of the solar cycle) GCRs are strongest but at solar maximum (active part of the solar cycle) the GCRs are weakest as the solar wind pushes them away. However, even the weaker GCRs at solar maximum pose a significant hazard. The main cause for the concern about GCRs is that their radio biological effectiveness in tumorigenesis is ***thirty times as great*** as a unit dose equivalent of solar particles, [Fry, 1987]. For this reason, it is advantageous to provide omnidirectional shielding to the crew habitat on the interplanetary vehicle, instead of providing just a solar storm shelter.

Campbell & Harris [1992] calculated that the GCR exposure for an unshielded vehicle of 1 gm/cm^2 is 62.85 cSv per year in interplanetary space at 1 astronomical unit from the sun during Solar Minimum. For a 180 day (half year) transit to Mars, this unshielded dose would be 31.4 cSv, perilously close to the National Council on Radiation Protection (NCRP) annual limit, considering all the uncertainty factors. Townsend, Wilson, Nealy [1988, p. 7] indicate their uncertainty about the GCR spectrum at up to 50%, with a consequent dose uncertainty of up to 70%. They translate this radio biological uncertainty factor into a shielding requirement of 25g/cm^2 against GCRs. Fry shows that 30 gm/cm^2 serves as a fairly effective barrier to GCRs. Campbell and Harris calculated that in interplanetary space during solar minimum when the GCR flux is at its greatest, the shielding thickness must be 50 gm/cm^2 to limit the annual dose to 31.4 cSv or 15.7 cSv for a 180 day transit. Townsend, Nealy, Wilson & Simonson's [1990, Feb., p. 8] calculation for GCRs during solar minimum indicates that 30g/cm^2 of aluminum reduces the annual dose to 35.2 cSv or 17.6 cSv for a 180 day transit.

Prompt Effects from GCRs In addition to these findings within the literature that NASA has published, there are significant concerns about so-called "prompt" effects of radiation, particularly from GCRs (HZEs). The most recent survey publication on radiation from the National Research Council's Space Studies Board [1996, p. 26] explains:

> "The concern about HZE particles is that the energy deposition may be significantly different from that of radiation qualities for which we have some radiobiological understanding. One particle of very high Z and energy can traverse a number of contiguous cells. There is a very dense ionization in the inner part or core of the particle track, with secondary particles and delta rays extending to neighboring cells. . . ."

The Space Studies Board [p. 26] expressed particular concern about the effects of HZEs upon the central nervous system (CNS):

> The effects of HZE particles on the CNS include (1) cellular effects, including biochemical changes, (2) functional changes; and (3) late effects, especially DNA repair deficiencies.

In addition to these HZE effects, the Space Studies Board expressed concern about a variety of effects from a diversity of radiation types. Specific cellular effects of possible concern that the Space Studies Board cites include effects to the brain, to the respiratory and cardiac nerve centers in the floor of the fourth ventricle. Functional effects of possible concern include impairment of neural networks involved in motor performance, with such effects as impaired balance. Taste aversion is a functional/behavioral effect. Other effects from both low and high linear energy transfer (LET) radiation include cataracts [p. 27], mutations or other heritable effects [p. 28].

The Armed Forces Radiobiology Research Institute - Scientific Advisory Committee [1994] published the proceeding of a workshop in which the participants discussed a comparable range of concerns. Dr. John Lett's comments indicate [p. 5]:

> "The study concluded that some photoreceptor cells were killed and degenerated rapidly. The data suggest that there could be a loss of photoreceptors along the path of Fe [iron] nuclei. *Consequently, lesions from local tracks of Fe particles in the brain of an astronaut could cause degeneration and loss of function within the duration of a Mars mission."* [emphasis added]

Other items of concern in the Armed Forces Institute Workshop include cataracts [p. 6], "forebrain damage" [p. 7], possible changes to the hippocampus gland [p. 9], and taste aversion, [p. 13].

One of the most striking experimental results among the few experiments with HZEs on animals is the effect upon the sperm-producing cells. Sapp, Philpott et al [1992] reported their results from irradiating mice from a variety of sources, then examining their sperm producing tissues under an electron microscope to count the damaged cells. They found very substantial differences between the effects of x-rays and the smaller HZEs on the one hand and the effects of Fe nuclei on the other hand [p. (2)181]:

> "The loss of spermatogonia due to irradiation is readily apparent. . . . It is evident that killed and damaged cells are rapidly removed post-irradiation since virtually all Type B spermatogonia are absent; . . .
>
> . . . At radiation levels of 0.10 Gy [1 Gray = 100 RAD] and less, spermatogonial response is similar, for X-ray, Helium, Neon and Argon radiation, as reflected by survival in Stage 6 tubules 72 hours post-irradiation. Approximately one-fourth of all spermatogonial cells are lost at the 0.10 Gy dose level. Irradiation with *Iron, however, results in a dramatic decrease in surviving spermatogonia. Almost one-half of all spermatogonia are lost at the very low 0.01 Gy exposure level."* [emphasis added]

In light of this accumulating evidence and concern, it will be difficult for space habitat designers to brush off health and safety concerns about radiation. This *design hypothesis* about an interplanetary habitat attempts to take the radiation safety data seriously, and to respond with an appropriate standard of care.

3. LIVING QUARTERS - Is it feasible to create habitable living space within an interplanetary vehicle? Given a volume of living space shielded against GCRs, creating habitable living quarters becomes the next challenge. The geometry of this volume must make a workable transition from the pressure vessel shell and the shielding mass to a suitable configuration in which to create the living environment. The key features of this living environment include a perceptually consistent up-down orientation, appropriate scale and usable dimensions, attachment hard points for mounting floors and partitions, utilities, and other such accommodations.

4. PRIVACY & GROUP ACTIVITIES - Can the Habitat accommodate both private and common activity areas? Given a suitable envelope in which to construct crew living quarters, it is vital to provide both individual private and group activity areas. The private areas include individual crew cabins and hygiene facilities. The group areas include the wardroom (dining area) galley, exercise and recreation areas, medical treatment areas (which may also share commonality in part with private cabins) and work areas.

5. ZERO-GRAVITY COUNTER-MEASURES - Is it practical to incorporate countermeasures against extended exposure to weightlessness? The prolonged journey in interplanetary space implies extended exposure to weightlessness, which can have severe detrimental effects upon crew health, including loss of bone mass, loss of muscle mass and cardiovascular deconditioning. It is necessary for the habitat or vehicular design to incorporate effective countermeasures against these effects of weightlessness [Grymes, Wade & Vernikos].

6. STOWAGE - Is it feasible to provide adequate and accessible stowage for all the consumables, equipment and infrastructure the crew will require? Supporting the Mars crew for 12 to 18 months in the interplanetary vehicle will require a considerable volume of stowage for consumables of all kinds and for a wide variety of equipment. The consumables may include food, water, make-up oxygen and other gases and clothes.

7. CIRCULATION - How can the design provide ingress, egress, and access to all parts of the habitat without wasting precious volume? The crew must be able to enter the habitat and to exit it for transfer to other vehicles including the descent/ascent vehicle. The internal circulation must afford convenient, non-interfering access to all portions of the habitat.

8. INTEGRATING HABITAT INTO VEHICLE - How is it possible to integrate the crewed interplanetary habitat into the interplanetary vehicle? The habitat must be capable of being integrated into the interplanetary vehicle ensemble, including an aerobrake, ascent/descent vehicle, fuel tanks, engines, and a structural system that holds them all together.

9. HABITAT SIZE - What is the appropriate and necessary size for the interplanetary habitat? All the above design issues converge upon the question of what is the appropriate size and mass for the interplanetary habitat. Sizing this habitat has, in turn, a profound ripple effect throughout the Mars mission architecture.

THE CANDIDATE PROPOSITIONS AS DESIGN HYPOTHESIS

For each of the issues stated above, the *inquiry by design* approach suggests the following design propositions. Taken together, the design propositions constitute a design hypothesis in response to the issues in the design problem decomposition.

1. SURFACE AREA TO VOLUME: SPHERICAL PRESSURE VESSEL - A spherical shell geometry is the most efficient shape for minimizing the ratio of surface area to volume. Implementing a spherical shell presents the benefit of minimizing the mass of pressure vessel structure, the surface

area requiring insulation, and the living envelope needing radiation shielding. This design proposition advocates such a spherical shell. FIGURE 1 shows this spherical pressure vessel with two pressure ports for hatches at opposite poles.

2. RADIATION PROTECTION: WATER SHIELD - The leading difficulty in installing a substantial quantity of radiation protection within a habitat arises in launching it to LEO. Since the radiation shielding is likely to weigh in the range of tens of metric tons of mass, it becomes problematic to incorporate it into the habitat pre-launch on the ground. It is also problematic to install a large mass of rigid shielding in the habitat while in LEO. The proposed solution is to employ water shielding, with a thickness of 30cm as recommended by Townsend et. al [Townsend, Nealy, Wilson & Simonson, Feb 1990]. This design proposition calls for installing water tanks in the habitat, configured to provide shielding, but to launch it to LEO dry. After achieving LEO, one or more "tanker" craft launches (could be by Space Shuttle) will bring the water to the habitat, to which it will pump the water, filling the tanks and providing shielding. Preliminary calculations indicate that the mass of this water would be approximately 42.3 metric tons with a 7m outside diameter [Cohen, July 1996, p. 7, shows 46mT for a 7m inside diameter for the water shield]. This mass and volume of water shielding makes the greatest impact upon the habitat design of any of the design propositions, and it causes a profound ripple effect throughout the entire system architecture, with large effects on the launch masses.

Truncated Octahedral Geometry for Water Tanks The design of the water shielding tanks is pivotal in creating a workable shielded interplanetary habitat. This design proposition suggests a geometry based upon the Archimedean solid known as the regular truncated octahedron, which consists of eight hexagonal faces and six square faces. The edge of the square is the same as the edge of the hexagon. The hexagon is triangulated into six triangular sub-faces. The square is triangulated into four triangular sub-faces There would be two shapes of modular tank, corresponding to the two faces: eight hexagonal tanks and four square tanks. The tanks would be made of aluminum or stainless steel. The square faces would be capable of incorporating an opening for crew circulation, ventilation or to pass utilities through the water shield wall.

FIGURE 2 shows each of these tank geometries with filleted edges. This geometry has the advantage of no acute corners that would be difficult to weld and fabricate, and where corrosion or degradation of the weldments would be more likely to occur.

This array of tanks would enclose the living quarters, affording the crew radiation shielding protection whenever they were inside, during the normal course of their daily routine. The inside clear dimension is 6.3 to 6.4m and the outside dimension is 7.0m. FIGURE 2a shows the truncated octahedral geometry of the water tanks.

The next geometric alternative to the truncated octahedron was a dodecahedron with twelve pentagonal faces, possibly with some truncation to create a set of smaller (hexagonal) faces, but the dodecahedral geometry placed these vertices or truncations of them in non-orthogonal and difficult to manipulate locations. The dodecahedron's pentagonal faces have the advantage of all obtuse internal angles, but a secondary framework would require rigidized vertices as the dodecahedron is not naturally self-rigidizing.

A spherical shape may seem like a logical solution, but there would be many difficulties associated with making a single double-sided spherical shell tank, even with interior partitions. A spherical trigonometric solution may work, but the spherical gores would be most advantageous as a spherical truncated octahedron.

Structural Struts to Connect Water Tank Vertices to Pressure Vessel Shell The key interface between the truncated octahedral water tanks and the outer pressure vessel shell is a set of struts that will connect the vertices of the truncated octahedron to hard points on the pressure vessel structure. The corners of the water tanks meet at these vertices, and it remains to be seen whether they require a framework following the edges of the truncated octahedron to hold them in place, or whether the water tanks can provide sufficient stiffness and strength within their own structure to allow a "frameless construction." In either case -- framed or frameless -- the truncated octahedron would make its structural connection at the vertices. These radial struts would require a considerable degree of linear elasticity -- like a shock absorber -- to allow the spherical pressure shell to expand and contract without introducing high local stresses into it at the connection points. FIGURE 2b shows the array of structural struts radiating from the truncated octahedral vertices.

Eliminate "Solar Storm Shelter" The traditional concept of a "solar storm shelter" that could also provide GCR protection has always been misguided. The typical envelope for a solar storm shelter affords four to eight m^3 volume, to which the crew would retreat during a two to three day flare. However, GCRs occur in a constant flux, and it is completely unrealistic to expect a crew of six to eight to live in a volume with a maximum of one m^3 per person for a year. Such an arrangement would surely maximize the detrimental effects of confinement, lack of privacy, and interpersonal stress. Also, the proposal that the crew should simply sleep in the storm shelter -- receiving protection for about 1/3 of the voyage -- are almost as unrealistic because it negates privacy for the crew members almost as completely.

Placing the complete living quarters inside the water shield eliminates the need for a separate "solar storm shelter. Instead, the 6.4m diameter water shield will protect the crew during their normal day from the steady bombardment of GCRs, and also provide solar storm protection, while affording them a reasonable volume for the living environment.

3. CREW QUARTERS INSIDE THE WATER SHIELD - Configuring the crew living quarters inside the water shield leads to demands on several attributes of this design proposition: installing a transverse floor deck to create usable volumes, providing crew passage through the transverse deck, and the ability to utilize the deck as an equipment accommodation and support system. The transverse deck would connect to selected interior truncated octahedral vertices of the water tank system, and thereby transfer its structural loads to the radial struts that tie into the structural pressure vessel. FIGURE 3 shows this transverse deck as described in the three paragraphs below.

Transverse Floor Deck Creates Usable Volumes Implementing a transverse floor deck divides the crew living environment volume into "upper" and "lower" levels. The upper level would contain the crew living quarters including the private cabins, the wardroom, galley, and perhaps some recreation areas. The lower level would accommodate the zero-gravity countermeasures and some recreation activities.

Crew Passage through the Deck To afford the crew direct passage from the lower to upper levels, the transverse deck includes a through passage. The location of this pass-through affects the usability of the floor area on the deck above and influences the circulation pattern and the utilization of both upper and lower levels. The choice of location is between the center or edge of the deck. In this design proposition, the through passage appears at the edge of the transverse deck.

Deck as Equipment Support System The transverse deck must be sufficiently deep and robust to accommodate equipment in two ways. First, it must accept the recessed installation of equipment, utility distribution and stowage. Second it must support the surface mounting of equipment and interior space-dividing partitions. The floor deck structure may be a rigid, flat space frame, capable of distributing the loads to its edge where it would meet the "space truss" created by the water tank system. The depth of the deck appears here as .3m, but functional stowage requirements may drive it substantially deeper -- perhaps as deep as 1m.

4. CREW HABITABILITY ACCOMMODATIONS ON UPPER LEVEL - The installation of crew living quarters on the upper level of the habitat makes it possible to make maximum use of the largest available floor area. The inside faces of the water shield create a

sloping "ceiling" that will help lend visual interest and a dome-like effect over this level of the crew quarters, which may enhance up-down orientation. FIGURE 4 illustrates the features described in the three paragraphs below.

Private Cabins Each crew member will need an individual private cabin [Connors, Harrison, & Akin, pp. 82-90]. For married couples, it may be possible to arrange adjacent cabins, with a common wall that is collapsible or removable. This design proposition clusters the private cabins together, although there may be a very good argument in sound isolation, for distributing them around the habitat, separated as far apart as possible.

Hygiene Facilities The Hygiene facilities seem to fall somewhat naturally among the private accommodations. However, if the upper level volume has too many demands upon it, it may be possible to locate the hygiene facilities elsewhere -- either in the lower level volume or outside the water shield in the stowage zone.

Group Activities, Wardroom & Galley The design of the group activities area, which include the wardroom, galley and associated recreational facilities, requires a great deal of care in planning and implementation as Nixon, Miller & Fauquet demonstrated in their study for the Space Station Wardroom [Nixon, Miller & Fauquet, 1989]. The wardroom must serve as a multi-purpose area for eating meals, holding meetings, conducting video conferences, hosting press briefings, disassembling and repairing equipment, and possibly performing medical treatment [Stuster, pp. 61-62].

5. ZERO-GRAVITY COUNTER-MEASURE: HUMAN-POWERED CENTRIFUGE ON LOWER LEVEL - This design proposition argues that it is neither practical nor necessary to spin up an entire spacecraft to provide artificial gravity as a countermeasure to weightlessness. Instead, it adopts the Human Powered Centrifuge (HPC) developed by the Life Science Division at NASA-Ames Research Center as a solution to proved short duration, high gravity centrifugation as a countermeasure. Please see FIGURE 5a for a photograph of the prototype HPC at Ames. This design approach installs the centrifuge in the lower level of the living environment. Please see FIGURE 5b for a view of the HPC installed in the lower level of the interplanetary habitat. The Human Powered Centrifuge provides both centrifugation and exercise for the crew member who uses it in the supine bicycle ergometer position to pedal the drive system. It can accommodate a second subject who benefits from the centrifugation but does not pedal the drive system.

6. STOWAGE INSTALLATION ALONG INSIDE OF PRESSURE SHELL - Since free volume inside the water shield will be very precious, this design proposition states that anything that does not have a very strong argument for being inside it should be located outside the water shield envelope. The considerable volume of stowage thus belongs outside the water shield. All the stored provisions for the long voyage out to Mars and back to Earth would reside in a stowage system along the inside of the pressure vessel, across an open passage zone from the water shield.

This stowage zone would accommodate life support equipment, including physical chemical systems and bioregenerative systems such as plant growth chambers. Anything that needs only infrequent crew attention could go into this stowage volume. It is possible that some or all of the hygiene facilities would best go in this stowage zone also. If the interplanetary crew have an extravehicular capability, the EVA space suits and their servicing support systems would reside in this stowage volume. The mass of stowed supplies and equipment will contribute added shielding to protect the crew against radiation. FIGURE 6 shows an isometric view of the stowage volume isolated from the rest of the habitat configuration.

7. CIRCULATION - An efficient and not overly extensive circulation system is a key to effective crew access, ingress, and egress throughout the habitat. The key elements of this design proposition for such a system are the pressure hatches through the primary

pressure vessel structure, the pass-through in selected square faces of the water shield tanks, and the appropriate rotation of the water shield relative to the other geometries to ensure non-interference between the orthogonally positioned square faced tanks with pass throughs, and the transverse deck within the living environment. Initially the square faced-tanks were at 90° vertical and horizontal. By rotating the water shield on the order of 20° out of plane with the transverse deck, the circulation pattern avoids some interferences and creates new and interesting relationships among the elements. FIGURES 8 and 9 afford a view of some aspects of this circulation system

Pressure Hatches The Habitat includes two pressure hatches situated at the opposite poles which appear here at top and bottom of the habitat. Each pressure port has a Space Station-like hatch door, 1.25m square, with rounded corners, that translates out of the way for the crew to bring bulky equipment through. These pressure hatches open into the circulation zone between the water shield and the stowage. It is intentional that the pressure hatches do not line up with the square face pass throughs in the water shield, which may require supplemental water shielding tanks in the stowage volume. Also, the stowage volume areas just inside the pressure hatches serve as a kind of ante chamber for stowing and staging equipment to be used outside the hatch.

Water Shield Pass-Throughs The water jacket pass-throughs that occur in the square faced water tanks should be large enough to allow passage of any equipment needed inside the water shield. The inside edge is rounded to allow crew members to slip through easily. It would be possible to install a non-pressure hatch in this square opening if so desired.

Orthogonal Clear Passages The design of the circulation system includes a system of clear passageways at right angles to each other in which there is no stowage. The effective clear width along these meridians is 1.4m to accommodate the movement of large and bulky items. FIGURE 6 shows both the stowage volume and these circulation passage zones.

8. HABITAT INTEGRATION IN VEHICLE CONFIGURATION - Integrating the habitat into the larger vehicle ensemble stands out as the most difficult integration challenge. The considerable unknowns that emerge as assumptions of "best guesses" comprise a large part of this challenge. This design proposition for vehicular integration of the Habitat takes a conservative approach in the sense of relying on concepts that are already fairly well described and well understood. The design concept is to order these elements from bow to stern in a clear sequence: aerobrake, habitat, descent/ascent vehicle, fuel tanks, and engines. FIGURE 7 shows a sketch of this approach, which will require substantially more effort to achieve confidence in it as a successful design solution.

9. HABITAT SIZING AND INTEGRATION - FIGURE 8 shows the interplanetary habitat with the relevant dimensions. The outside diameter of the structural pressure sphere is 10m. Several inhouse studies indicate that a 10m diameter is within reason for an interplanetary habitat. FIGURE 10 presents a view of the integrated habitat, with all the systems discussed above in their places

EVALUATION OF THE "DESIGN HYPOTHESIS"

The totality of this interplanetary habitat design constitutes a hypothesis about how to provide a habitat that takes seriously the leading safety constraint of effective radiation shielding, in addition to meeting all the other commonly agreed requirements.

RESOLVED ISSUES - This design hypothesis succeeds in resolving some of the design issues raised in the design problem decomposition. These resolved issues include: the spherical habitat, water shielding architecture and geometry, private cabin geometry, structural support of the water shield, and the installation of the Human-Powered Centrifuge.

Spherical Habitat is feasible and workable This *design hypothesis* shows that a spherical habitat is feasible from the viewpoint of interior utilization, even though the "shielded" volume does not extend out to the pressure vessel walls.

Water Shielding is Architecturally and Geometrically Feasible The biggest design challenge was to find a way to package the water tankage that works architectural, geometrically, and structurally. The truncated octahedral geometry provides a feasible solution, with the caveat that it would be necessary to place the tanks inside the pressure vessel before welding it closed along its meridian or equatorial seams. The presence of such a large quantity of water may provide a resource to the life support system.

Structural Support of Water Jacket is Feasible at Vertices As a corollary to the truncated octahedron, the geometry lends itself to structural support at the vertices. This consideration is essential for demonstrating structural feasibility. The caveat is that the system must avoid creating local high-stress concentrations in the outer aluminum pressure vessel structure. With empty tanks, the launch loads will be low, but the aerocapture loads with the filled tanks may be high.

Irregular Sleep Cabin is Not a Problem The rotation of the water shield tankage about the living environment creates some irregular geometric faces, areas and volumes, which lead to irregular shapes and dimensions in the partitions between the private crew cabins. Although this will pose a challenge to the craftsmen who install these partitions, it is not a problem for the interplanetary crew. The Skylab cabins designed by Raymond Loewy and Associates were all different, non-standardized shapes, which gave each crew cabin a small element of intrinsic individuality and character [Man-System Integration Standard, p 8-18].

Feasible to Install the Human Powered Centrifuge Another important finding of this exercise is that it is feasible to install the Human Powered Centrifuge in such an interplanetary habitat (and probably in almost any other one with sufficient volume. Essentially, what the HPC requires is a circular cross sectional area through the volume to accommodate the 150" (3.84 m) rotational diameter, plus surrounding structure.

UNRESOLVED ISSUES AND SHORTCOMINGS - Although this inquiry by design showed that it is possible to resolve several of the leading design research issues, there were many more -- albeit less prominent ones -- that remain unresolved. These unresolved issues include the secondary water shields, non-vertex structural connections, depth of stowage volume, irregular faces of the rotated truncated octahedron, stowage zone as a single loaded circulation zone, usefulness of the lower level crew quarters, radial strut interference in the circulation zone, lack of windows, and the integration of the habitat into the interplanetary vehicle.

Provide Secondary Water Shield Panel At Pass-Through Assuming that a non-pressurized hatch door in the water jacket shield is largely unnecessary, and it there is one, it will not be a 30cm water shield, raises the question of whether to install supplemental shielding in the stowage volume opposite the pass-through.

Structural Connections to Water Shield Difficult if not at Vertices While it is good to have major structural connection points on the water shield tankage at the vertices, because these vertices will occur in very irregular locations on the rotated water shield, it would be useful and valuable to have structural connection points elsewhere on the truncated octahedron. However, this design neither anticipates nor provides for these secondary structural connection points. The solution would appear to necessitate a secondary structure overlaying the tanks, with secondary, triaconation-like gussets or stiffeners running from the vertices to the center of each triangular face, creating an additional structural geometry.

Dimensions Of Stowage Volume: Insufficient Depth? The design proposition offers a stowage volume depth of .4m, (15.625"), considerably less than the standard closet depth of 24" (.6m) in American homes, and even smaller in comparison to the .9m (36") deep Space Station racks. While this depth of stowage may be sufficient for some items, it will not suffice for many others. Thus it may be necessary to make some portions of the stowage volume much deeper, expanding it into the circulation zone between the water shield and the stowage. For some purposes, like a hygiene facility or a navigation work station, it may be advantageous to extend this expansion all the way across the 1m circulation zone. It will be important to calculate the volume of stowage required to support the human mission to Mars.

Rotated Water Shield Trunc-Octa Creates Irregular Faces Although rotating the water shield tankage does not create a problem in the private crew cabins, it may create difficulties almost everywhere else. By introducing this variance into the system, it may make the installation of equipment much more difficult throughout the rest of the shielded living environment, except where it can attach to the transverse deck. It also creates the potential for visual and perceptual confusion about spatial orientation. The rotated trunc-octahedron will conflict visually with the simple up/down geometry of the transverse floor deck and the partitions mounted upon it. This perceptual question requires further attention.

Location of Radial Struts Interferes with the Circulation Zone The array of structural struts that radiate from the trunc-octa water tank vertices intersect the stowage and more importantly the widened circulation zone in an arbitrary pattern, creating possible interferences with through circulation. To avoid these interferences and non-standard intersections of stowage volumes, the designer must exercise great care in selecting the rotational angle for the water shield.

Stowage Zone Is Inefficient as a "Single-Loaded Corridor" In most buildings on Earth, it would be considered very inefficient to "load" a corridor with useful rooms on only one side, unless there was a compelling reason to leave the other wall unused by circulation connections. Such a compelling reason might be to install windows. However, there is no such purpose in the stowage and circulation zones in this Habitat.

Lower Crew Quarters Volume Has Limited Usefulness Although the lower level crew quarters serves admirably to accommodate the Human Powered Centrifuge, this volume is not very useful for anything else. An unfortunate aspect of this design proposition is that it rendered the rest of the spatial volume almost useless as did the Human Powered Centrifuge when installed in the lower level of the Controlled Environment Research Chamber at NASA-Ames. One possible solution is to install an isogrid floor between the centrifuge motion envelope and the upper portion of the lower volume, creating a third level. The size of the volume within the 7m outside diameter water shield is too small to allow this intermediate level, suggesting that either the diameter should be bigger, or the next version should insert a short cylindrical section between the upper and lower 7m diameter hemispheres.

No Possibility Of Windows For Wardroom Or Crew Quarters Perhaps the greatest single shortcoming of this design hypothesis for a habitat is that it precludes the possibility of a window to the outside in the crew living quarters. In virtually every NASA program, the crews have argued for the best windows possible. On Skylab, the 18" (46cm) window in the Wardroom was a major focus of crew attention and activity, and NASA has elevated this success to a standard requirement [Man-System Integration Standard, pp. 8-17, 8-37, 8-38]. In this Habitat, the windows must be located outside the shielded envelope, in the outer pressure shell. It would be necessary to install window work stations in the unshielded volume along the outer pressure shell, for use in rendezvous and docking with other vehicles. This installation of window-workstations would be feasible. It might be possible to strike a balance between a large high quality (such as high definition TV) view screen and a small porthole. This arrangement sets up a potentially paradoxical situation of asking the crew to risk an exposure to radiation for short periods to accomplish high priority tasks at this window-workstation.

Integrating Habitat into the Interplanetary Vehicle Integrating the Habitat into the Interplanetary Vehicle remains the most problematic aspect of this design exercise. None of the design propositions address it adequately. Instead, there needs to be a separate but companion study of integrating the Habitat into the vehicle from the outside inwards toward the Habitat.

Mass of Water Shielding Last but far from least, the mass of the water shield poses a very substantial concern for adding cost and fuel requirements to the human mission to Mars. A conventional rule of thumb is that a kilogram of payload to Mars will add from three to five kilograms of fuel to the mission. In the case of a 42.3 mT mass of water (plus about 3mT for the water tanks to lift it to LEO), the increase in fuel might range from about 127 mT to 212 mT of added fuel. The 45.3mT of water and tankage requires 1.3 shuttle launch equivalents, and the additional fuel to take it to Mars requires 3.6 to 6.0 shuttle launch equivalents, for a total of 4.9 to 7.3 shuttle launch equivalents. With a conservative cost estimate of $400 million per shuttle flight to lift 35mT to LEO, the price of this radiation protection will total from $1.96 billion to $2.92 billion.

If NASA is serious about effective radiation protection for the crew, it will need to confront these numbers forthrightly, analyze them honestly, and find constructive ways to respond to them. Ultimately, NASA will need to factor this cost for radiation protection into the total mission architecture.

CONCLUSION

This exercise in Inquiry by Design was useful in discovering the criticality of certain design issues and the feasibility of design propositions to resolve them. This analysis shows that this interplanetary habitat "design hypothesis" is valid principally to the extent that it is architecturally and geometrically feasible to install a substantial water shield for radiation protection. The analysis also confirms that it is feasible to install a Human Powered Centrifuge for zero-gravity countermeasures. The analysis highlights the challenge of integrating the habitat into a larger interplanetary vehicle ensemble.

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REFERENCES

Campbell, Paul D., & Harris, J. D., (1992, December) Crew Habitable Element Space Radiation Shielding for Exploration Missions, LESC-30455, Houston, TX: Lockheed Engineering and Sciences Company, Contract NAS9-17900.

Cohen, Marc M., (1996) Design of a Planetary Habitat Versus an Interplanetary Habitat, SAE 961466, 26th International Conference on Environmental Systems, Monterey, CA July 8-11, 1996) Warrendale, PA: Society of Automotive Engineers.

Cohen, Marc M., (1996) Habitat Distinctions: Planetary Versus Interplanetary Architecture, AIAA-96-4467, AIAA Space Programs and Technologies Conference, Sept. 24-26, Huntsville, AL, Washington DC: American Institute of Aeronautics and Astronautics.

Connors, M. M., Harrison, A. A., & Akins, F. R. (1985) LIVING ALOFT: Human Requirements for Extended Spaceflight, NASA SP-483, Washington DC: NASA Scientific and Technical Information Division.

Fry, R. J. M., (1987), "Radiation Protection Guidelines for Space Missions," in McCormack, Swenberg & Bücker, Eds, pp. 715-728.

Grymes, R. A., Wade, C. E., & Vernikos, J., (1996) *Biomedical Issues in the Exploration of Mars*, AAS-95-483, pp. 225-239 in Stoker & Emmart, eds, Strategies for Mars, San Diego, CA: Univelt, Inc.

Man-System Integration Standard, Vol. 1, NASA STD-3000, Rev. B, (1995, July) Houston TX: Johnson Space Center.

McCormack, Swenberg & Bücker, Eds, (1987) Terrestrial Space Radiation and Its Biological Effects, New York: Plenum Press, Proceedings of the NATO Advanced Study Institute, October 11-25, 1987, Corfu, Greece.

Nixon, David, Miller, Christopher R., & Fauquet, Regis, (1989, December) Space Station Wardroom Habitability and Equipment Study, NASA CR 4246, Washington DC: NASA Scientific and Technical Information Division.

Sapp, W. J., Philpott, D. E., Williams, C. S., Williams, J. W., Kato, K., Miquel, J. M., & Serova, L., (1992) *Comparative Study of Spermatogonial Survival after X-Ray Exposure, High LET (HZE) Irradiation and Spaceflight,* Advances in Space Research, Vol. 12, No. 2-3, pp. (2)179-(2)189. UK: COSPAR.

Armed Forces Radiobiology Research Institute - Scientific Advisory Committee, (1994, Feb. 10-11) Data Requirements Regarding particle Carcinogenisis in the Space Radiation Environment, *Workshop on Heavy Energetic Charged Particle Radiation and the Central Nervous System*, Bethesda, MD: Armed Forces Radiobiology Research Institute.

Simonson, Lisa C., & Nealy, John E., (1991, Feb) Radiation Protection for Human Missions to the Moon and Mars, NASA TP 3079, Washington, DC: NASA Scientific and Technical Information Division.

Space Studies Board – National Research Council (1996) Radiation Hazards to Crews of Interplanetary Missions: Biological Issues and Research Strategies, Washington DC: National Academy Press.

Stuster, Jack W., (1986) Space Station Habitability Recommendations Based on a Systematic Comparative Analysis of Analogous Conditions, NASA CR 3943, Washington DC: NASA Scientific and Technical Information Division.

Townsend, L. W., Nealy, J. E., Wilson, J. W., & Simonson, L. C., (1990, Feb) Estimates of Galactic Cosmic Ray Shielding Requirements During Solar Minimum, NASA TM 4167, Washington DC: NASA Scientific and Technical Information Division.

Townsend, Lawrence W., Nealy, John E., & Wilson, John W., (1988, May) Preliminary Estimates of Radiation Exposures for Manned Interplanetary Missions from Anamolously Large Solar Flare Events, NASA TM-100620, Hampton, VA: NASA Langley Research Center.

Zeisel, John (1981), Inquiry by Design: Tools for Environment-Behavior Research, Monterey, CA: Brooks/Cole Publishing Co.

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FIGURE 1 The spherical pressure vessel presents the minimum ratio of surface area to volume. The pressure vessel supports the water tank structural by means of radial struts that connect to the vertices of the water tanks.

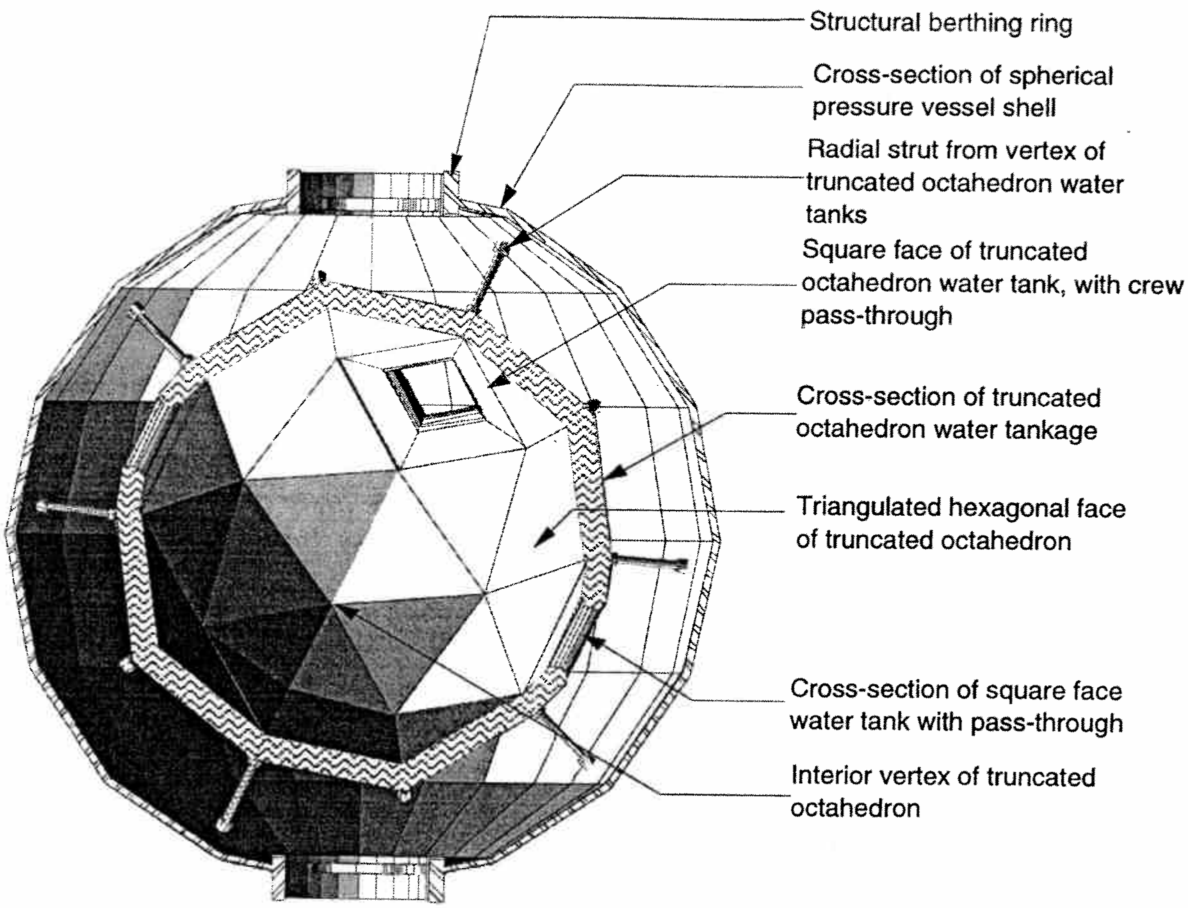


FIGURE 2 "Exploded Perspective" of the three types of water tanks in the truncated octahedron geometry. From left to right: the square face tank with a crew pass-through, the hexagonal face tank, and the plain square tank.

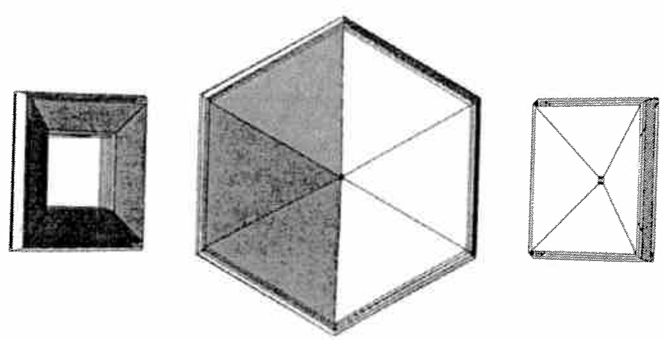


FIGURE 2a The water tank geometry is based upon the Archimedean solid known as the truncated octahedron. The square faces may include pass-throughs for crew circulation, ventilation or utilities. The hexagonal faces are triangulated.

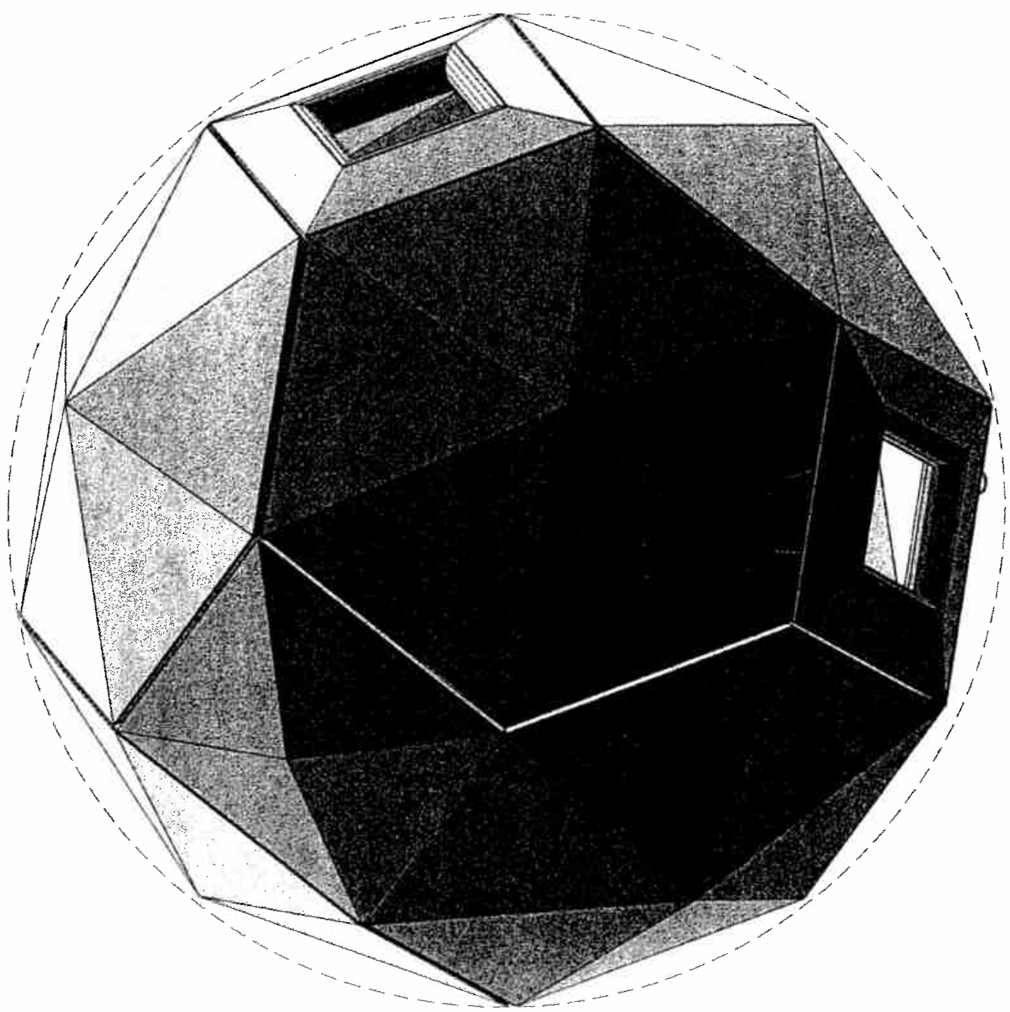


FIGURE 2b The array of structural struts radiates from the truncated octahedral vertices to hard points on the pressure vessel shell.

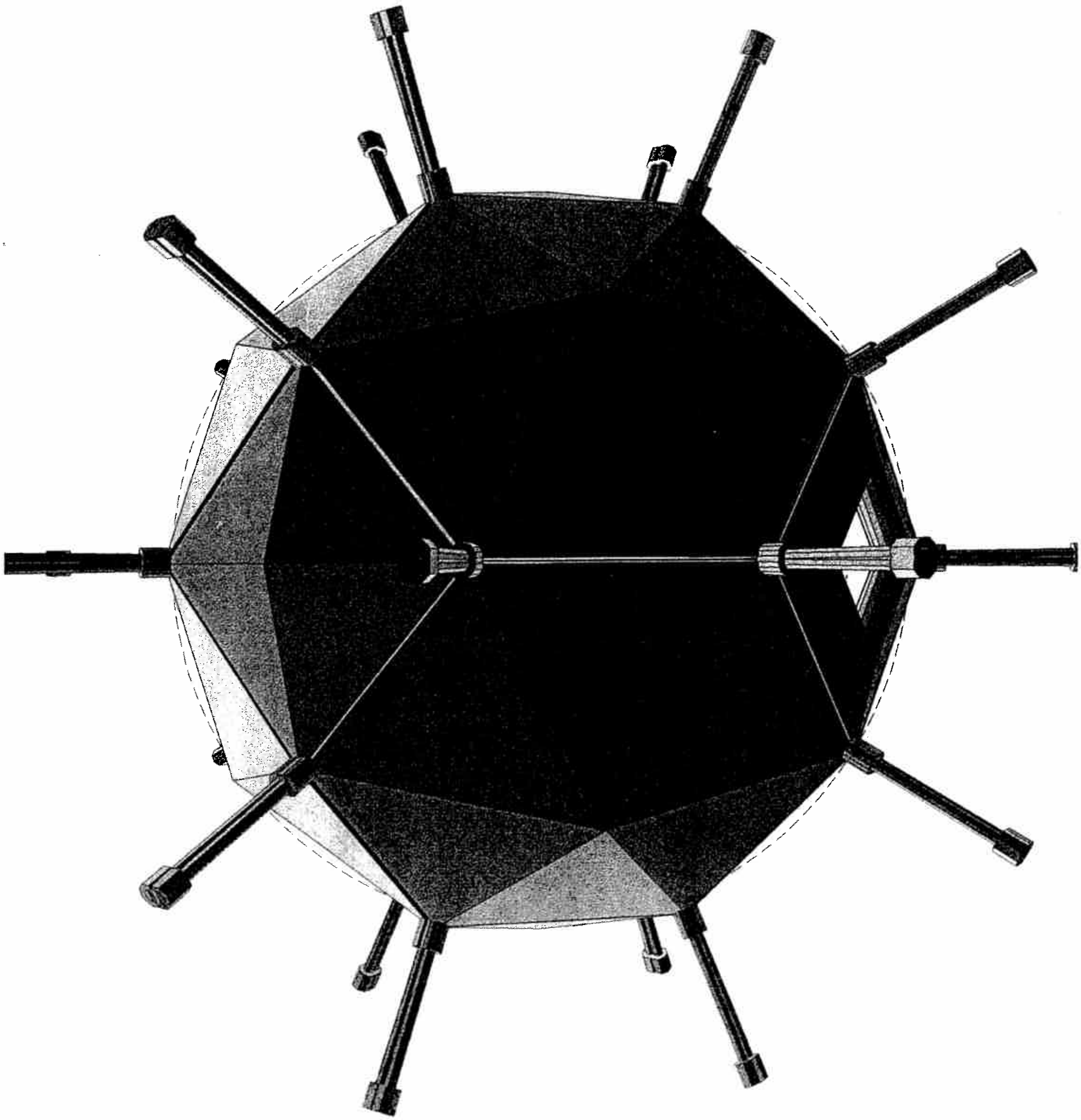


FIGURE 3 The transverse deck within the water shield volume creates usable upper and lover volumes for the living environment.

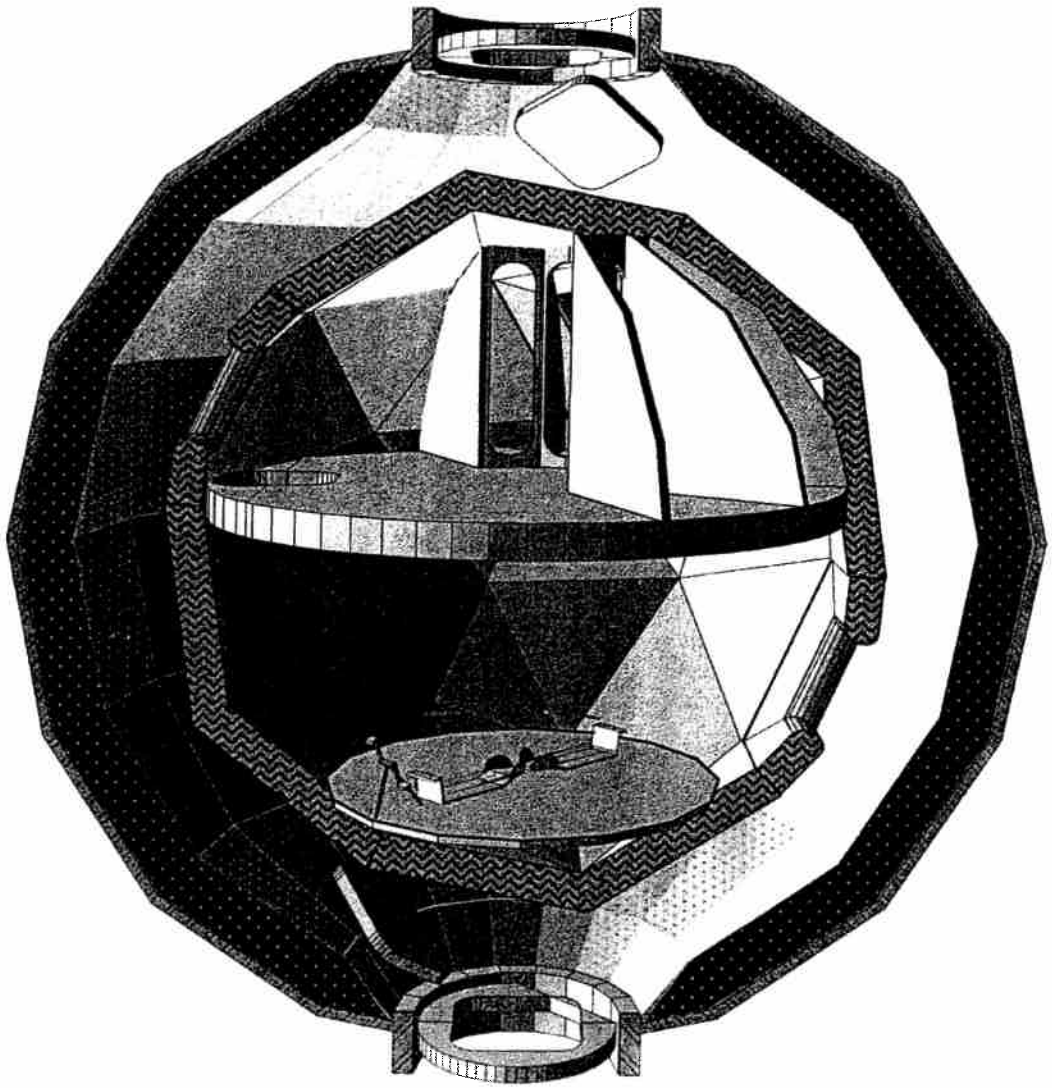
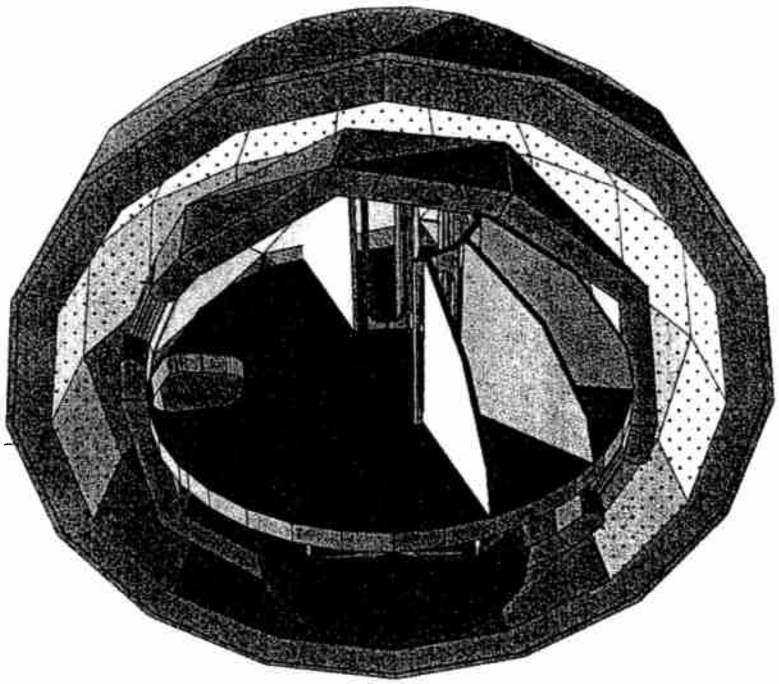


FIGURE 4 The upper level crew quarters would include private cabins, hygiene facilities, the wardroom and galley.



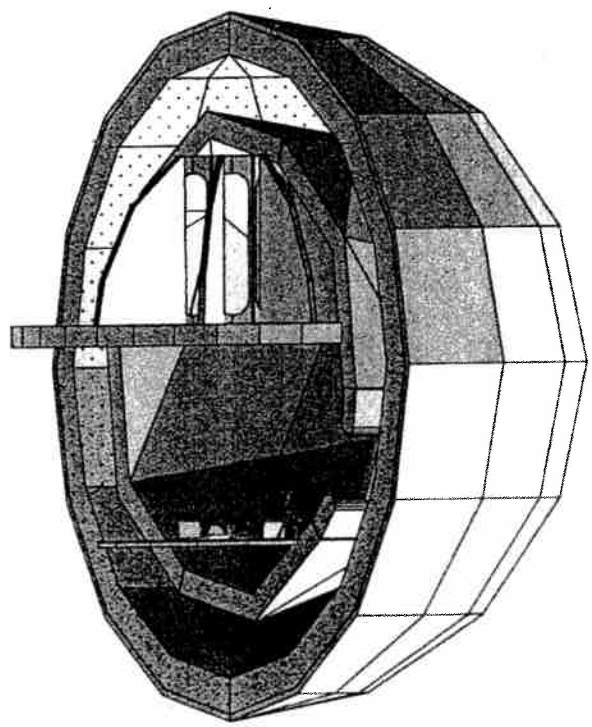


FIGURE 5a Photograph of the Human Powered Centrifuge experimental facility in the lower level of the Controlled Environment Research Chamber at NASA-Ames Research Center.

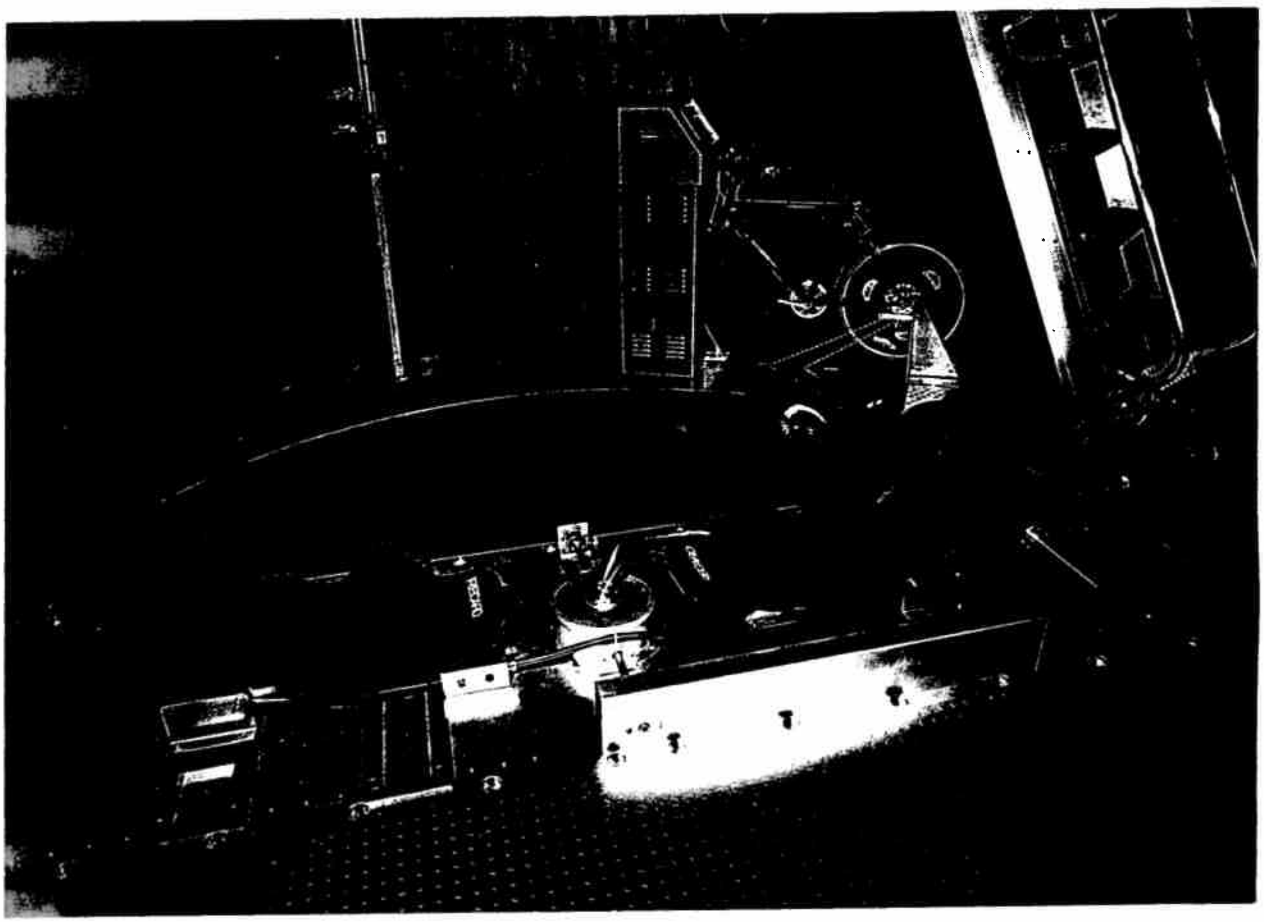


FIGURE 5b CAD view of the Human Powered Centrifuge installed in the lower level of the living quarters of the hypothetical interplanetary habitat.

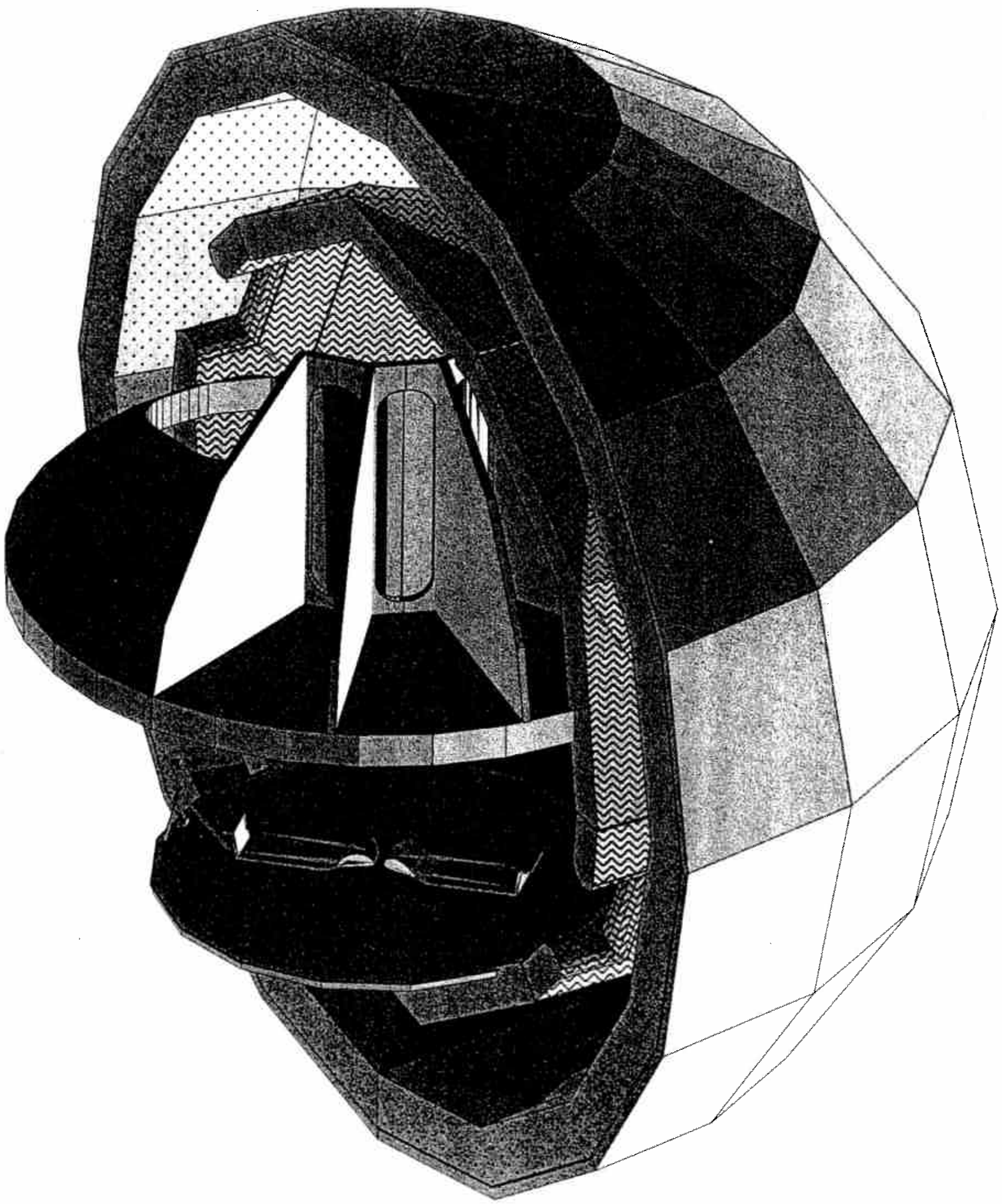
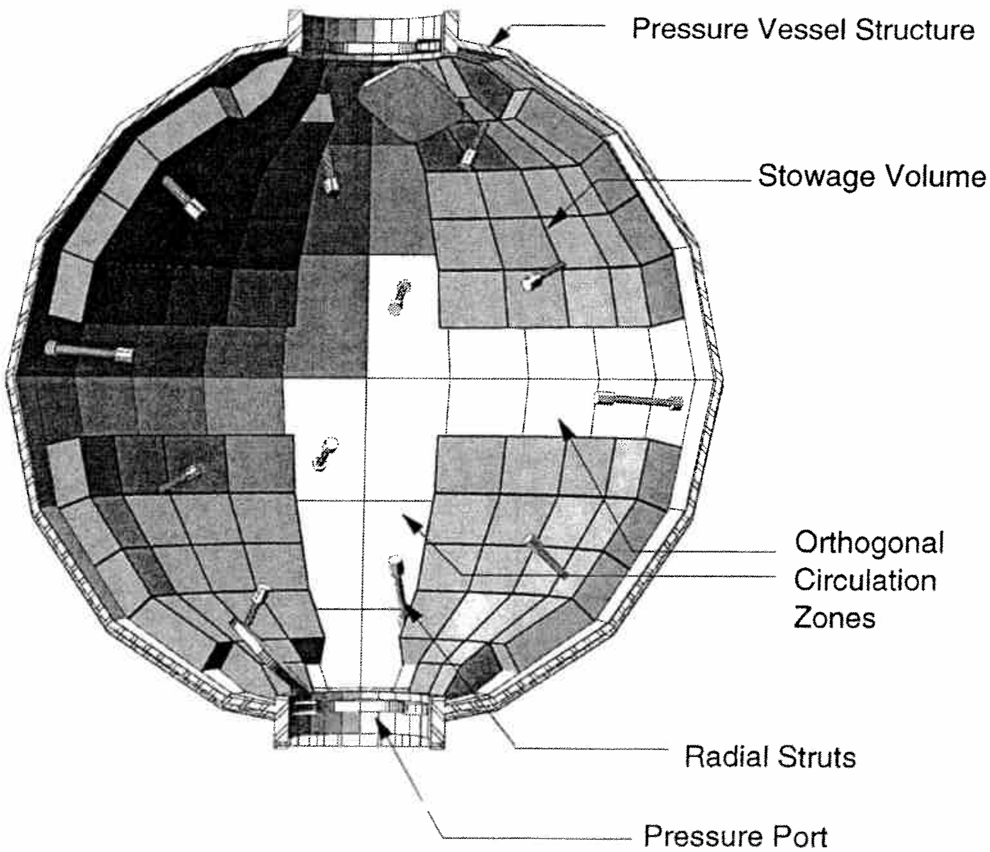


FIGURE 6 The stowage volume will occur along the inside face of the pressure vessel shell, providing both consumables and equipment volume, and also additional radiation shielding for the crew. A widened circulation zone occurs on the orthogonal meridians.



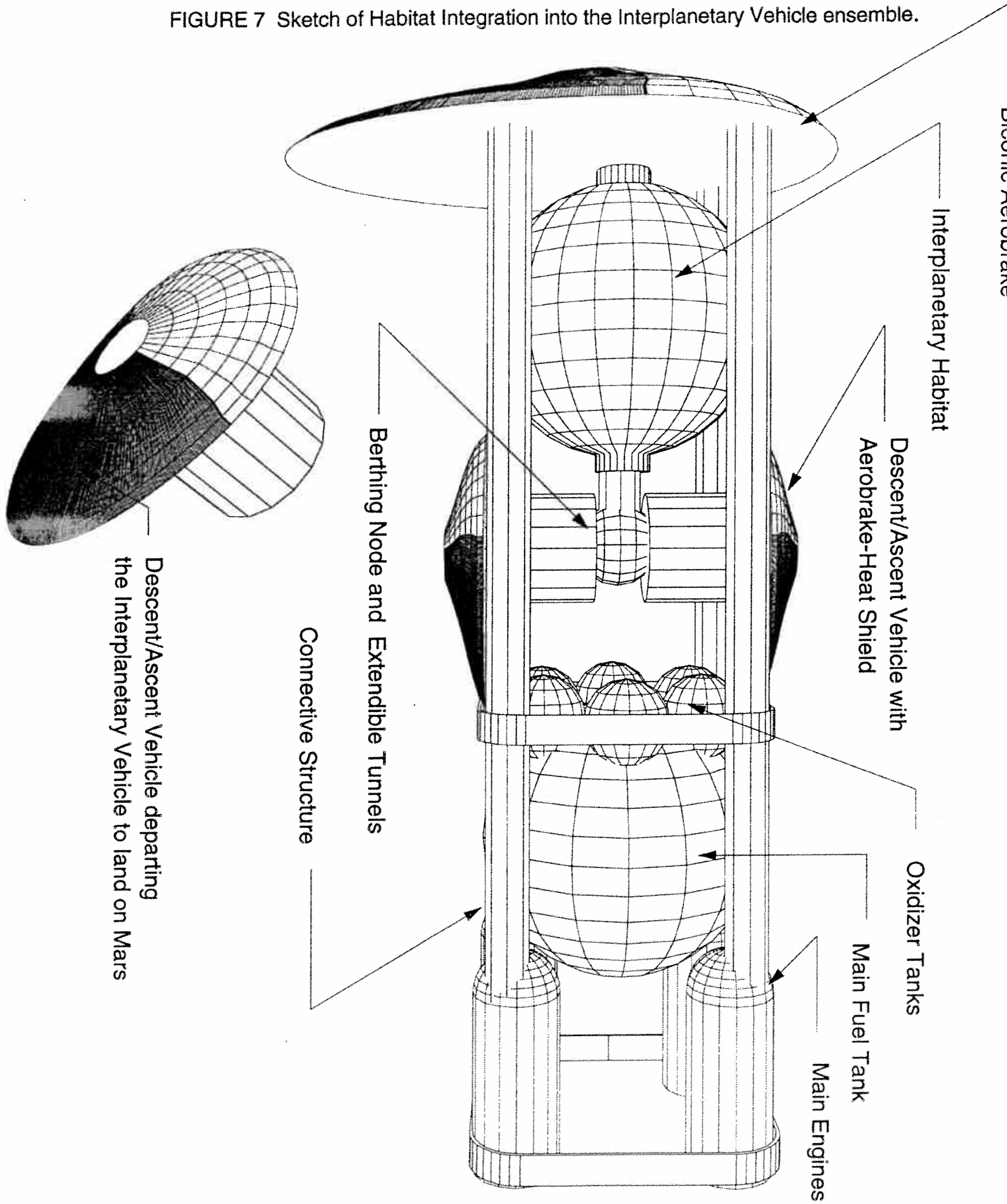
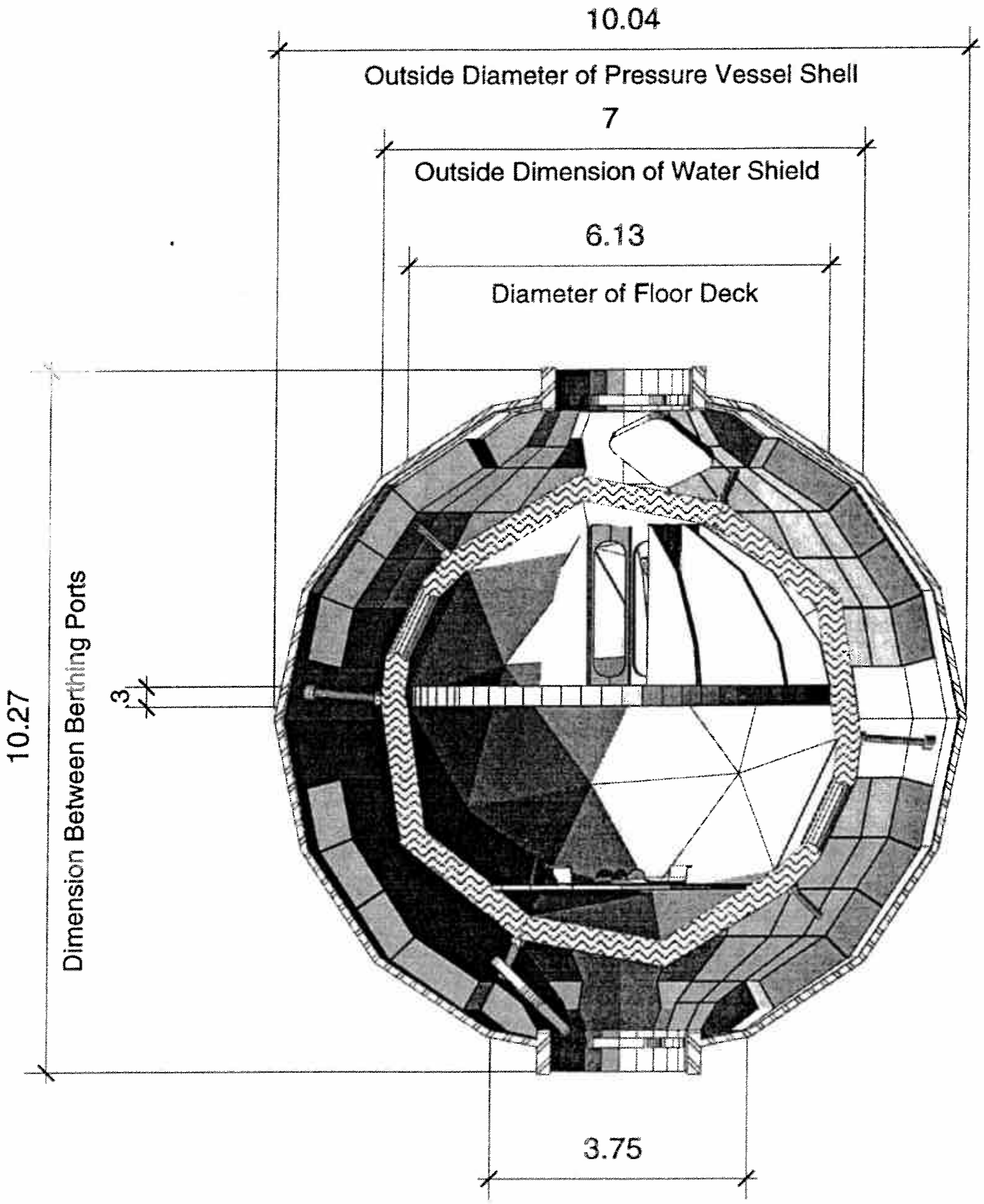


FIGURE 7 Sketch of Habitat Integration into the Interplanetary Vehicle ensemble.

FIGURE 8. Some Key Dimensions of the Interplanetary Habitat.



Dimensions in Meters

Note: Some scaled dimensions may vary from the dimensions stated in the Text

FIGURE 9. An integrated view of the interplanetary Habitat interior. This view shows all the previously described subsystems fititing together. Note the interference from the radial struts in the meridian circulation zones.