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GENESIS II: ADVANCED LUNAR OUTPOST

UNIVERSITY OF WISCONSIN-MILWAUKEE

This study investigated advanced, second-generation lunar habitats for astronauts and mission specialists working on the Moon. The work was based on design constraints set forth in previous publications. Design recommendations are based on environmental response to the lunar environment, habitability, safety, near-term technology, replacability and modularity, and suitability for NASA lunar research missions in the early 21st century. Scientists, engineers, and architects from NASA/JSC, Wisconsin aeronautical industry, and area universities gave technical input and offered critiques at design reviews throughout the process. The recommended design uses a lunar lava tube, with construction using a combination of Space Station *Freedom*-derived modules and lightweight Kevlar-laminate inflatables. The outpost includes research laboratories and biotron, crew quarters and support facility, mission control, health maintenance facility, and related areas for functional and psychological requirements. Furniture, specialized equipment, and lighting are included in the design analysis.

PROJECT GENESIS

In the aftershock of the Space Shuttle *Challenger* disaster in 1986, scientists, professionals, and citizens around the world have been rethinking the role humans should play in space. Current discussion and planning has moved into the arena of long-duration missions and extraterrestrial habitation. On the 20th anniversary of "One giant leap for mankind," President Bush announced a goal to land people on the moon by 2005, and this time to stay. Plans for the near future in space include a permanently inhabited space station, a lunar outpost, and possibly a joint United States/Soviet Union mission to Mars.

Project Genesis is proposed to NASA[1] as a pair of lunar outposts and early-stage, permanently occupied habitats on the Moon. Called *Genesis I* and *II*, these evolutionary outposts will serve both as long-term testbeds for all materials, processes, and development strategies to be employed in a mature lunar colony and as testbeds for all processes to be employed in the exploration and eventual settlement of Mars.

Following guidelines provided by engineers and scientists at NASA's Johnson Space Center (NASA/JSC) and with the advice of aerospace engineers from the Astronautics Corporation of America and Orbital Technologies Corporation, the UW-Milwaukee Space Architecture Design Group has designed two complete habitats: *Genesis I*[2,3] and now *Genesis II*. *Genesis I* was planned for a crew of 8 to 12 persons on rotations of 6 to 9 months with a maximum duration of 20 months, and *Genesis II* for a second crew of 11 astronauts and mission specialists at a different site. For both outposts, crew gender, nationality, and ethnicity are expected to vary as the consortium of world aerospace partners become involved in scientific, architectural, and engineering communication. This paper summarizes the major design criteria and concepts which lead to the development of *Genesis II*[4,5].

GOALS AND PROCEDURE

The project was part of a continuing effort to research and design human settlements for the Moon and Mars. The pedagogic objective is to enhance architectural and architectural/engineering education through establishing an advanced space architecture program that integrates architecture, engineering, planning, environment-behavior (EB) studies, and advanced construction technology. The project also aims to produce information and design solutions useful to the aerospace community, NASA, its prime contractors and subcontractors, and NASA/USRA schools in the area of long-duration habitation design.

The long duration of these planned events requires the involvement of architects, interior designers, industrial designers, planners, and other environmental design professionals in order to ensure environments suitable for human habitation and performance. To date, space design has been the province of the engineer and that profession's highly technical orientation. Long-range planning, systems integration, construction sequencing, and interiors environmentally suitable for humans are all areas in which the design professions have demonstrable expertise and in which they can exercise a positive and much needed influence. Thus has evolved *space architecture*, as the field is becoming known.

The design of *Genesis II* is based on the exploration of different scenarios[6], a facility program[7], the final design document from 1989-90[2,3], and excellent critiques of *Genesis I* offered by NASA scientists and engineers. Additional resources included work on the design and full-scale mock-up of an inflatable lunar habitat[8] and independent study projects to collect and prepare research information[9,10,11].

The process culminated in an integrative design studio in which architects and engineers, from first year undergraduates to first year graduate students worked together to investigate and develop *Genesis II*. Areas of detailed architectural and engineering design investigation included the implications of new lightweight, high-strength materials especially elastomers and thin films; character of the lunar environment; extraction of design relevant information from previous space experience, analogous situations, and simulations; and human factors analysis of the minimum space requirements for different lunar habitation and research functions in 1/6th gravity. The studio was conducted as a professional team project, with the faculty advisor directing the project and the three teaching assistants and other advanced students assuming the role of team leaders for various specialized functions. The class worked as one team, producing one final project, but was subdivided into various teams with specific tasks and deadlines as the semester unfolded. Through all steps, the program stressed the systems approach to design.

LUNAR BASE MISSION OVERVIEW

An advanced lunar must be:

1. Located at an Earth-facing equatorial location.
2. Constructed of lightweight durable materials requiring minimum EVA time.
3. Contained within the next generation of Earth-lunar transport systems: (a) space shuttle system, (b) heavy-lift launch vehicle such as the Shuttle-C with cargo capacity of 69,000 kg and cargo bay 25 × 4.5 m, (c) low-Earth orbit Space Station *Freedom* (SSF) and associated platforms, and (d) the planned dual-use cislunar transport system composed of an orbital transfer vehicle (OTV) and a separate reusable lunar lander that transports construction components to the lunar surface along with crews and logistics.
4. Capable of housing 11 astronauts of different nationalities, genders, and specialties for periods of time up to 20 months with a normal change-out of 6-9 months.
5. Able to provide for all necessary life-support and quality of life systems including (a) anthropometrics and human factors, (b) health and safety, (c) EB issues of isolation and interaction, privacy, personal space, and territoriality, (d) habitability architectural issues in crew areas, crew support, operations of base, and design for productivity, and (e) space biosphere Controlled Ecological Life-Support System (CELSS) and Environmentally Controlled Life-Support System (ECLSS).
6. Built using integrated advanced space construction technology.
7. Responsive to the physics, geology, and natural environment of the Moon and appropriate "urban" design so as to retain the natural qualities of the Moon.
8. Capable of supporting five main mission operations: (a) lunar surface mining and production analysis for lunar oxygen (Lunox), helium 3 (H_3), and other minerals; (b) lunar construction technology and materials testbed for testing high technology construction with inflatables, the use of lunar regolith for radiation shielding, lunar glass, lunar concrete, and sintering techniques using advanced telerobotic systems; (c) CELSS test facility; (d) lunar far side observatory; and (e) human factors and EB research facility to investigate habitability issues on the Moon including ongoing post-occupancy evaluations (POEs).

The first mission to establish the second-generation *Genesis II* outpost, expected to land on the moon between 2005 and 2009, could last as little as 14 days. The astronauts, architects, and engineers will live inside their lunar landing vehicle (LLV) and spend much of each day performing EVA building the outpost. Once all systems, subsystems, and backups have been verified, and the initial IOC has been achieved, expected by 2015, crew change-outs will occur every nine months to a year as the astronauts perform research and manufacturing operations on the lunar surface.

LAYOUT OF THE GENESIS II LUNAR BASE

The proposed design is situated in a lunar lava tube near the Apollo 15 site, located at 3°E 25°N, alongside Hadley Rille at Palus Putredinis (Marsh of Decay).

The site plan is zoned that the hazardous la facility is approximately 3 km to the south an facility is 1 km to the north, the mining facility a zone is 1.25 km to the west, and the solar array field a dissipation radiator field is near the habitat (see Fig. 1). The habitat itself is over a drilled and sintered opening to the safe confines of the lava tube.

Following extensive telerobotic research and exploration, the base will be developed in three stages spanning almost 10 years: (1) emplacement of an assembly facility and the erection of radiation protection truss-work with accompanying regolith covering; (2) integration of the balance of base components, construction of all surface facilities, drilling, exploding, and sintering of the shaft to the lava tube, and lowering and assembling the structural truss-work and initial crew quarters on the base of the lava tube; and (3) final IOC during which two large inflatables are lowered into the lava tube, inflated, and outfitted for expanded crew quarters and research space.

The proposed design is based on the use of Space Station *Freedom*-type hard modules, lightweight structural truss systems, and thin-film elastomer inflatables. The habitat and research areas are situated in the safety of the lava tube, away from radiation, sharp temperature fluctuations, and deadly solar flares. Storage and vertical circulation to and from the surface occurs through a Shuttle-C module installed in the sintered opening between the lava tube and the surface. Only logistics modules and the EVA chamber remain on the surface protected by truss-work covered with a minimum of 0.5 m of lunar regolith. The basic configuration—a giant H on its side—may be seen in Fig. 2. Details, shown in a series of plans and axonometric drawings, of the two-story habitation and laboratory inflatables, the crew support module with mission operations and health maintenance facilities on the bottom of the lava tube, and the logistics and EVA modules on the lunar surface may also be seen in Fig. 2.

As considerable emphasis was placed on the quality of life and the contribution that the designed environment can make to habitability in confined quarters[12], more detailed designs are shown in Figs. 3 and 4 for individual spaces within the

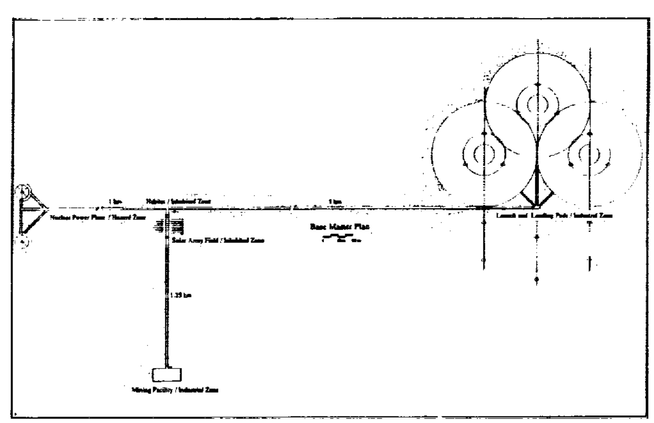


Fig. 1. Site plan for *Genesis II*, showing the launch and landing facility to the right, habitat/research facility near the center, power facility to the left, and mining below. Note: North is to the left.

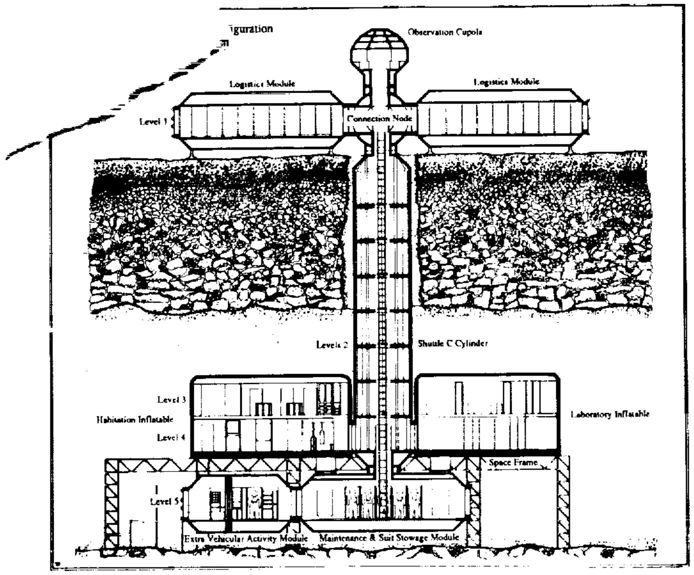


Fig. 2. Longitudinal section through *Genesis II*, showing the Shuttle-C vertical translation and storage module which connects the logistics and EVA modules and observation cupola on the moon's surface with the habitation and laboratory inflatables and mission control/crew support and maintenance/EVA modules on the surface of the lava tube.

a

b

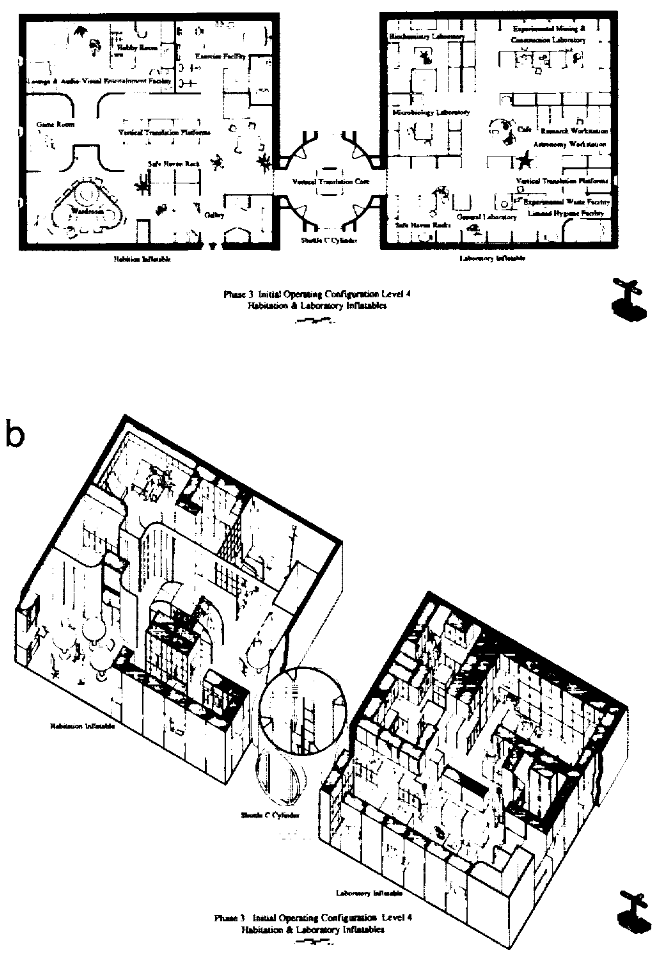


Fig. 3. a and b: IOC plan and axonometric of the lower level of the habitat and research facilities connected through the Shuttle-C circulation core. On the left is the galley, wardroom, a games room, lounge and AV entertainment facility, hobby room, and exercise facility, all arranged around a central atrium and vertical translation platforms up to the crew quarters. On the right are the research laboratories: a general lab, microbiology lab, experimental mining and construction telerobotic laboratory, an experimental waste facility connected with the biotron above and workstations for the lunar far-side observatory and for internal environment/behavior analyses and POEs of the base itself.

crew habitat (e.g., the wardroom/dining room, a game room, the exercise facility, several arrangements of the crew quarters, the personal hygiene facility, a small library, several reading rooms, and a conservatory).

Detailed designs were also developed for mission operation workstations, health maintenance facility, and special furniture designs for the 1/6th gravity body position. Technical engineering details were developed for wall sections, hatch connectors, the lighting system, and the structural space-frame truss work(4).

Finally, as the lunar outpost may need to expand into a more mature lunar colony, the system allows expansion to accommodate increments of 5-6 additional astronauts and mission specialists by adding inflatables along the length of the lava tube.

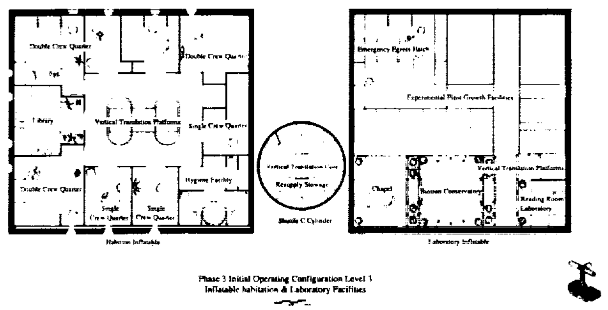
DESIGN ADVANTAGES AND LIMITATIONS

The second-generation *Genesis II* lunar habitat and research facility incorporates many design features, some well established, others yet untried. The principle design criteria influencing the design included safety, using advanced yet near-term technology, replacability and modularity, and minimizing volume and weight at lift-off; yet the driving force in the design was habitability—human factors and EB considerations to provide a reasonable quality of life during long stays in an alien environment.

Habitability criteria affected the design in many ways and places. Living and working spaces were separated, with the living spaces being in the inflatable habitation facility and the working spaces being in the inflatable laboratory facility and mission control on the lowest level of the lava tube. Movement through the Shuttle-C cylinder—the central circulation core—provides some transition between working and living spaces.

The character of the two types of spaces differs greatly (Figs. 3 and 4). The laboratory inflatable is organized in a series of work bays with the extensive biotron upstairs accessible from peripheral translation platforms, while the habitation inflatable is organized around a central atrium and vertical translation platforms linking the two habitation floors. Within the research spaces an effort was made to separate different research functions from each other, while in the habitation area an effort was made to provide social and gathering space as well as visual connections between major spaces via the central atrium.

Balancing social interaction is the need for privacy. Upon advice of our consultants, and based on the research literature(13), the individual crew quarters were made larger than a



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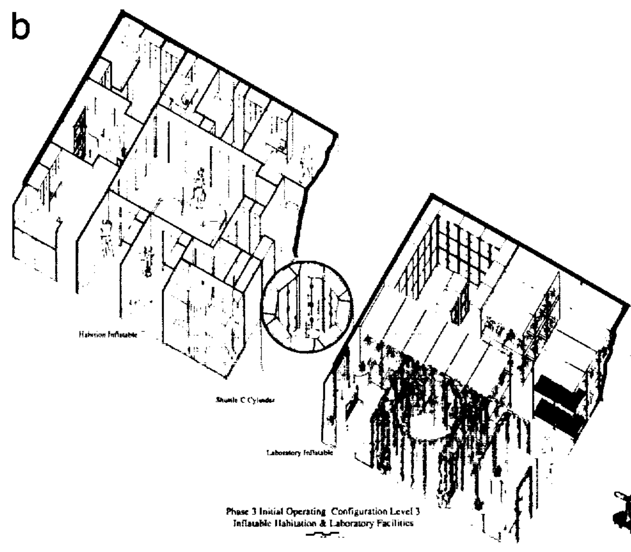

Fig. 4. a and b: IOC plan and axonometric of the upper level of the habitat and research facilities. On the left are a variety of individual and shared crew quarters. On the right is the experimental plant growth biotron. Note also the library, reading room, conservatory, and chapel for individual and small group retreat.

minimum and considerably larger than suggested from current NASA standards for Space Station *Freedom*[14]. A variety of single and double crew quarters were designed to allow choice, and to allow the possibility of an environment/behavior post-occupancy evaluation (POE) of their impacts over time.

To reinforce these private spaces, small spaces were created throughout the habitat for individual or small-group quiet activities, including a library and small games room in the habitation inflatable and a reading room, conservatory, and chapel borrowing from the natural character of the biotron in the research inflatable.

Safety influenced the design in many places, most notably in having dual means of egress from all points of the outpost, for example, the two EVA chambers allowing egress to the surface and to the open end of the lava tube.

The modular kit of parts allows ease of emplacement, interchangability, reconfiguration, and resupply. Pieces were sized to be transported through the hatches and moved from the logistics modules to all parts of the base. To prc flexibility, a module of 1.2 m was chosen. The also makes personalization of individual spaces—cre and research laboratories—easy to accomplish.

Other important design constraints were the use of near-term technology and the minimization of volume and weight. The use of inflatable structures, using the latest in lightweight elastomer laminates, responded to both of these constraints. The technology needed to construct inflatables is not immediately available, but is near enough that it is practical and will be available prior to 2005. Inflatables work as a testbed for experimentation. They also collapse for transportation, resulting in low mass and volume. Once expanded in the lava tube, the inflatable provides a very large volume for its weight and thus greatly reduces the cost of the base.

A major asset of the design is its location inside a lava tube. This protects the base and its inhabitants from solar flares, meteorites, radiation, and temperature fluctuations. The extension of the habitat from the surface level to the base of the lava tube also allows two means of egress with exits on different levels. Use of the natural cavern of the lava tubes will prove cost effective relative to constructing space frames and moving great quantities of lunar regolith for protection. The constant temperature minimizes demands on the CELSS/HVAC system, also proving to be cost effective. EVA operations will be easier, with no worries about cosmic radiation. Finally, expansion is eased by adding additional inflatables without having to remove and provide additional regolith protection.

The natural zoning of the base can be seen as an advantage of this scenario, and a natural outgrowth of using a lava tube. The sensitive habitat and research zones are protected and isolated from the hazard zone of launch and landing, from the industrial manufacturing zones, and from the potentially hazardous nuclear energy zone.

Inside the base, the articulated zoning between work and leisure, and between public and private, mirrors—albeit in a microcosm—the equivalent urban zoning on Earth.

The furniture is potentially a breakthrough in lunar design (see Figs. 5 and 6). While there are no published data on anthropometrics in 1/6th gravity, our interpolations between 1 g and 0 g suggest what we have been calling a "1/6th body position." We have therefore designed a set of 1/6th gravity furniture for work and leisure.

Lastly, the design of *Genesis II* provides a variety of different situations and spaces, different in spatial size and configuration, and different in style and esthetics, with the flexibility to be personalized, allowing for the range of astronauts and mission specialists who will inhabit the base and for their different needs and personalities. The variety and flexibility are set up as an experimental system to enable POE and further refinement both on the lunar base and as input for martian travel and outposts.

AREAS FOR FUTURE RESEARCH AND DESIGN DEVELOPMENT

PDRs by NASA scientists and engineers and reviews offered of the work at national conferences, including the annual USRA conference, have suggested the following limitations and areas for further research and design development:

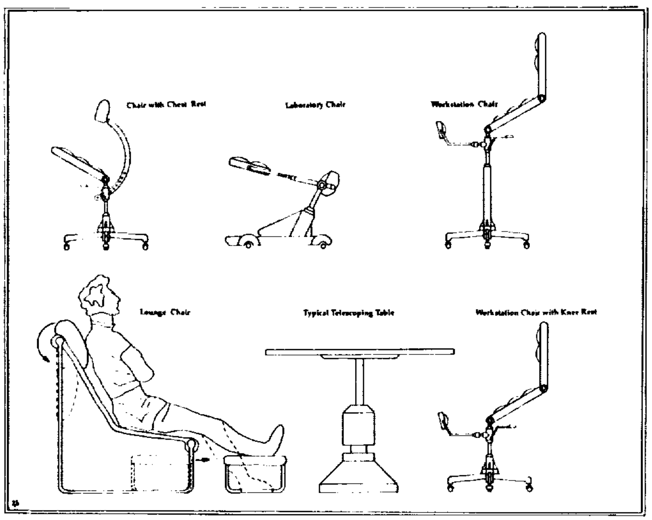

Fig. 5. Proposed experimental furniture designs for 1/6th gravity.

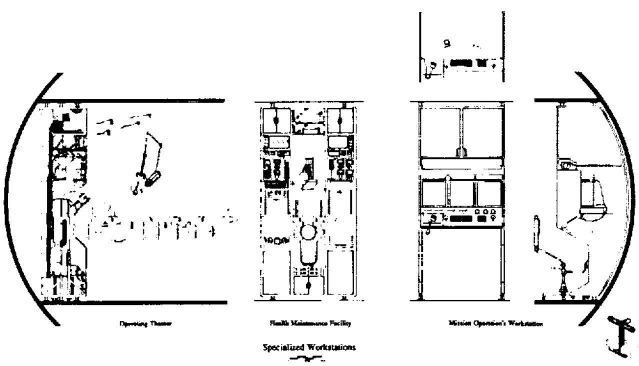

Fig. 6. Typical mission operations workstation designed to accommodate the 1/6th gravity body position. Note: Many other detailed design drawings—health maintenance facility, operating theater, suit maintenance facility, crew quarters, etc. have been developed and are included in the full report[4].

1. The first question is the location of viable lava tubes. Survey missions must confirm locations, and subsequent exploration must determine their structural integrity.

2. Related is the question of how to stabilize the inner surfaces of lava tubes. Structural support systems may need to be devised that can be emplaced in an emergency.

3. Questions have been raised about inflatables, about likely bowing or what is known as the "oil canning effect," and about pressure and stress on their corners. Further study needs to be conducted—perhaps including computer simulations as well as laboratory tests—of the structural integrity of different inflatable shapes.

4. It is hoped that further work will be done on furniture design for 1/6th gravity, and, with NASA's assistance, on testing the furniture anthropometrically and functionally.

5. Some controversy surrounds the notion of providing safety through safe haven racks. Further exploration needs to be done on the relative advantages and disadvantages of save havens as places versus as racks.

6. Questions could be raised about the modularity and relative openness of the plan. Some may question whether modularity leads to a sterile environment. We feel that modularity and the possibilities of interchangability are absolutely critical in an extraterrestrial habitat and research facility. Once these facilities are in place, at considerable expense of launch and EVA construction time, it would be unreasonable to assume no subsequent changes in functional needs, or if there were, that it would require entirely new construction with new parts being transported from Earth. The modular system allows rapid change-outs as functional requirements change between crew change-outs (e.g., different crew compositions—men, women, couples; different mission research functions, etc.). Exploration does need to be done, however, on the relative merits of different modular systems, e.g., hexagonal versus the current rectilinear system.

7. Concern has also been expressed about sound transmission and safety from research accidents in a relatively open plan research facility. Of special concern would be the possible transmission of odors or germs from animal research. Each of the research areas can be isolated from all others in a matter of moments, and could be closed if noise is a problem. Nevertheless, the questions raised about modularity deserve considerable further research and design investigation.

8. The exercise facility will undoubtedly require more sound proofing from the rest of the crew quarters. Exercise machines cause noise and vibration, and require secure structural connections, neither of which has been adequately accounted for in the current design. New forms of NASA exercise countermeasure machines will be explored and incorporated in future work. A separate facility for group recreation may be needed. This will isolate excessive noise and vibrations from the ongoing base functions.

9. Other vibrations may occur from the movement of personnel and the operation of equipment. These vibrations may cause structural problems, and the resulting noise may also lead to an increase in crew member stress.

10. The medical facility on the ground level of the lava tube, very close, but not immediately adjacent to the research areas, may cause some concern. Better emergency circulation connection between the two may be required.

11. Only some attention has been given so far to the equipment needed for construction. Investigations need to be made of the relative merits of drilling, blowing, and laser cutting the hole between surface and tube. The reactions of the lava tube to vibrating machines during construction also needs careful exploration. Weight bearing features of the construction equipment relative to the strength of the lunar regolith over cavernous lava tubes needs careful exploration too. The details of the inflation of inflatables needs to be clarified. The exact equipment needed for construction, and the influence of this on the design itself, deserves further attention.

12. A number of mechanical engineering considerations were not investigated in this design, among them heat dissipation, capacity of thermal radiators, ventilation system, and detailed mechanical analysis.

13. The extensive length of the Shuttle-C translation core between the surface of the moon and the lava tube itself presents cause for concern. Considerable space is devoted to circulation. Movement between base locations must be efficient. In the event of an emergency, the crew must have easy access to safe haven locations. Further investigation needs to be conducted to determine if this is the most efficient circulation solution.

14. Questions could also be raised about the advisability of combining inflatables and hard modules in the lava tube itself. Why not use all inflatables, one might ask, given they have such a great volume to mass ratio? In the spirit of initial exploration, and conceiving the lunar base as a testbed for Mars, this scenario explored the use of both inflatables and modules, and the necessary connectors between the two.

15. Lastly, further attention needs to be given to the overall image of the habitat and research facility. Does the design tell us what we value as humans?

It is our firm belief that NASA should proceed with the lunar/Mars Space Exploration Initiative (SEI) toward the eventual exploration and habitation of both the Moon and Mars. First- and second-generation outposts will need to be developed, refined, and tested. We offer these conceptual designs as beginnings on the path to the eventual habitation of our near planets.

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