4 SUMMARY AND CONCLUSIONS

4.1 CRITICAL DESIGN FEATURES OF GENESIS II

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 cost, i.e., minimizing volume and weight at lift-off, yet the driving force in the design was habitability—human factors and environment-behavior considerations to provide a reasonable quality of life during long stays in an alien environment.

Habitability criteria affected the design in many ways, in many places. A separation was made between living and working spaces, 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.

Furthermore, the character of the two types of spaces differs greatly. 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 mini-atrium and vertical translation platforms linking the two habitation floors. Thus within the research spaces an effort was made to separate the various research functions from each other, while in the habitation area an effort was made to provide considerable social and gathering space—as well as visual connections between all functions—in the central "atrium."

Balancing social interaction is the need for privacy. Upon advise of our consultants, and based on the research literature (cf. summary in Moore, 1990), the individual crew quarters were made larger than minimum and considerably larger than what would be suggested from current NASA standards for Space Station *Freedom* (e.g., NASA STD-3000, 1989). A variety of single of 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 extended time. The crew quarters were outfitted with sufficient persona amenities that a crew member can spend considerable time, if need be, away from fellow crew members.

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

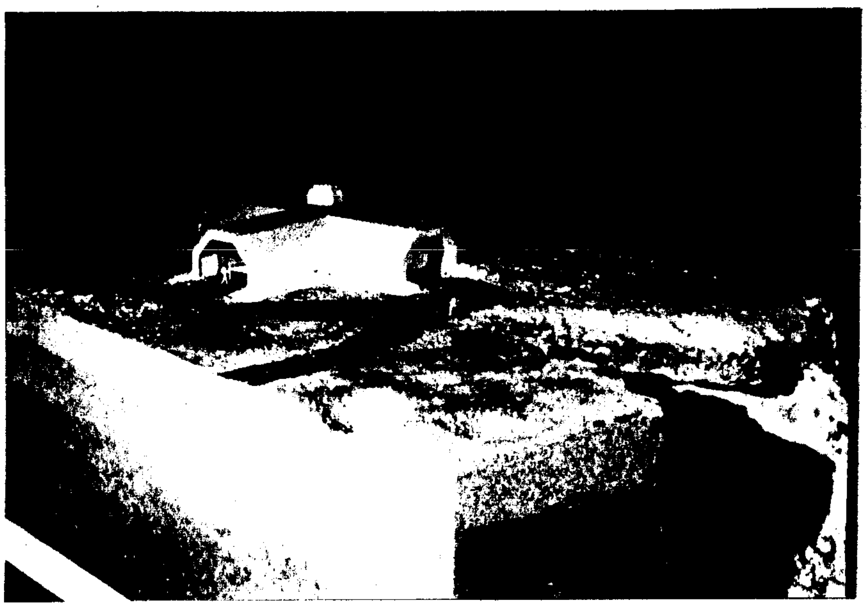

Figure 4-1. The model of the Genesis II Advanced Lunar Outpost. The opening to the lava-tube is on the right. The dark paths on the surface are sintered roadways to help keep dust levels low.

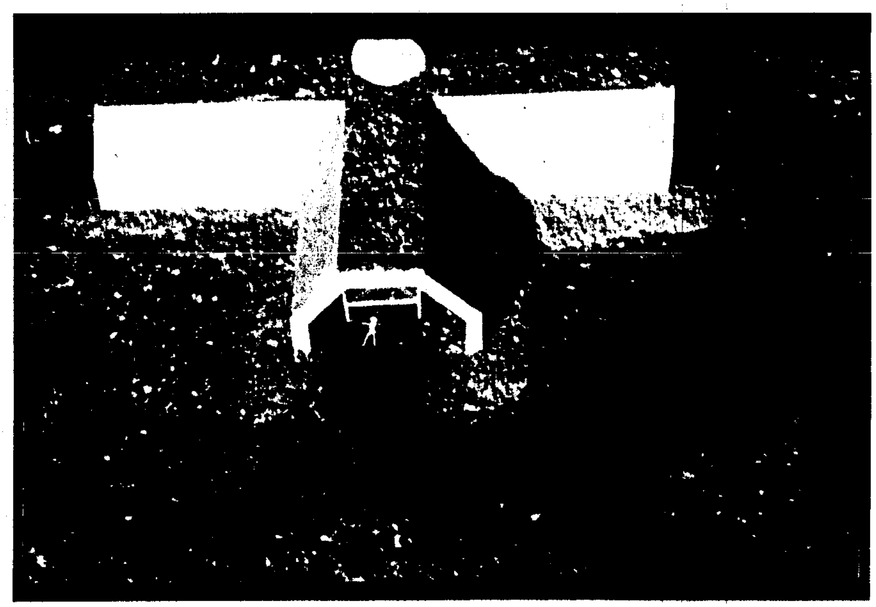

Figure 4-2. An overhead view of the modules on the lunar surface covered with a protective shielding. Note the coupola protruding at the apex of the configuration.

Safety influenced the design in many places, most notably in having dual means of egress from all points of the outpost, including two EVA chambers to allow egress to the surface and/or to the open-facing end of the lava tube and the provision of safe-haven racks throughout the structure.

The modularity of the design allows the crew to reconfigure the interior spaces to their liking. The modular kit of parts allows easy of emplacement, interchangability, reconfiguration, and resupply. All pieces were sized to be transported thorough the hatches and moved from the logistics modules to all parts of the base. To provide maximum flexibility consistent with anthropometrically appropriate design, a module of 1.2 meters and variations thereof was chosen. The modular design also makes personalization of individual spaces—crew quarters 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 light-weight 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 lift-off in 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.

4.2 MAJOR STRENGTHS AND LIMITATIONS OF THE DESIGN

There are advantages and limitations to the design of this lunar base. As in any design, alternatives that offered the greatest advantages were chosen over those with major limitations. Yet strengths and limitations remain. Since this design explored the impact of habitability criteria on lunar bases, design options that favored habitability considerations ere favored over others that had major habitability limitations.

A major asset of the design is its location in side a lava tube. This protects the base and its inhabitants from solar flares, meteorites, radiation, and temperature fluctuations, allowing more flexibility in other aspects of the design. 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. There are other advantages to the use of the lunar lava tubes. 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 facilitated by creating and linking another inflatable without having to remove regolith 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 the lava tubes. 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 zoning of new—and old—towns on Earth.

The use of both rigid and expandable structural systems provides a means of comparing the strengths and limitations of both, extending the experimental testbed function of the base.

The use of inflatables greatly reduces the cost of the base by minimizing mass and volume while providing large spaces easily subdivided according to functional criteria.

Another key design feature, the ability to easily personalize due to modularity, aids in the habitability and the quality of life of the base. As explained immediately above, the modular kit of parts also provides ease of emplacement, change-outs, reconfiguration, and resupply.

The furniture is potentially a real breakthrough in lunar design. 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 as shown in Figure 3.4-1 on page 28. Two members of the team have therefore designed a set of 1/6th gravity furniture for work and leisure, as shown in Figures 3.4-1, 3.8.4.2-1, 3.8.4.3-1, 3.8.5.4-1, 3.8.6- 3, and 3.8.9.1-2, and summarized in Figure 3.8.11-1 on pages 28, 39, 40, 42, 44, and 48. An effort will be made to extend these designs and to test them in a 1/6th gravity chamber in the near future.

Lastly, we feel that the design of the base to have a variety of different situations and spaces, different in spatial size and configuration, and different in style and esthetics, as well as in flexibility to be able to be personalized, provides for the range of astronauts and mission specialists who will inhabit the base and for their different needs and personalities. Furthermore, 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 Martian outposts.

Along with the assets inevitably come the limitations. As the limitations all suggest areas for future research and design development, we will discuss them in this light.

4.3 AREAS FOR FUTURE RESEARCH AND DESIGN DEVELOPMENT

Preliminary design reviews (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:

1. The first limitation—or question for further research—is the location of a viable lava tube. Precursor survey missions must define the location, and subsequent exploration must determine their structural integrity. More information is needed on the location, size, and geologic nature of these forms. After confirmation of their existence, selection criteria will be developed depending on the size, nature, and mission requirements for the base.
2. Connected with the concern about the location of a viable lava tube is the question of how to stabilize the inner surfaces of the tube once found. Structural support systems may been to be devised that can be emplaced in an emergency.
3. Questions have been raised about the inflatable, about likely bowing or what is known as the "oil canning effect," and about pressure and stress on its corners in particular. Further study needs to be conducted—perhaps including computer simulations as well as laboratory tests—of the structural integrity of different inflatable shapes.
4. As mentioned above, further work will be done on furniture design for 1/6th gravity, and, with NASA's assistance, on testing the furniture for functional adequacy and static and dynamic anthropometrics in a 1/6th gravity chamber.
5. Some controversy surrounds the notion of safe havens as 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. Others may question whether modularity necessarily implies an open plan, as in the landscaped office plans of the 1950s through 70s. While there certainly is evidence in the office research literature that modularity is not the panacea that many thought it would be—few changes being made, open plans leading to increased noise and visual distractions—we feel that modularity and the possibilities of interchangability are absolutely critical in an extraterrestrial habitat and research facility. Once facility are in place, at considerable expense of launch and EVA construction time, it would seem unreasonable to assume no subsequent changes in functional needs, or if there were, that it would require entirely new construction with new parts being lifted-off from Earth. While the modular system may not be manipulated often by astronauts and mission specialists during a typical 9-month period, it also 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 proceed, 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 and from the crew support areas in particular. 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 counter-measure 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. Separating the exercise facility will enhance the activities psychologically, providing greater space and freedom to enjoy the reduced gravity.
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 (see Figures 3.4-1 through 3.4-6 on pages 26-27). 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 especially 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, the need for and amount of thermal radiators, ventilation systems, and a detailed mechanical analysis. Such analyses are not normally a part of design schematics, but would need to be explored in detail if this design were taken into detailed design development.
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. It is true that 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 the safe haven locations. Further investigation needs to be conducted to determine if this is the most efficient solution.
14. Question 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 the lunar base being 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?

Having mentioned these limitations and areas for further development, however, 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. We offer these conceptual designs as beginnings on the path to the eventual habitation of our near planets.

Figure 4-3. The entry to the airlock on the lunar surface. The dust-off platform is just outside the airlock module, and the coupola can be seen in the background.

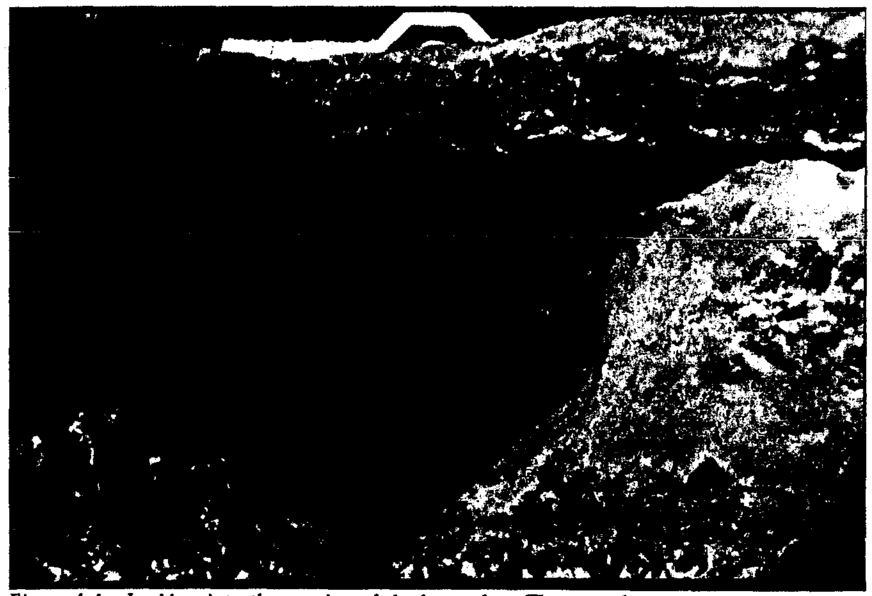

Figure 4-4. Looking into the opening of the lava-tube. The space-frame supporting the inflatables can be seen in the darkness.