5. SUMMARY AND CONCLUSIONS

5.1 CRITICAL DESIGN FEATURES OF *PAX*

A number of design features of the proposed *Pax* permanent Martian base and habitat deserve attention. It is the contention of this research and design group that, based on our preliminary analysis of Martian habitats, these features may be critical for habitat success, and deserve further research and design analysis.

5.1.1 SITE SELECTION

It is proposed that *Pax* be constructed at the Viking 2 landing site, 45 degrees N latitude, 251 degrees W longitude, known as *Utopia Planitia*. The site is near varied geologic surface features important for research. The site is located in the northern hemisphere, away from the origination of southern dust storms during the summer season. The terrain in the immediate area, generally level according to Viking 2 photos, is appropriate for a transportation system and launch and landing facility. The elevation of the site is relatively low with respect to the other features on the surface, thus providing some radiation protection from the accumulated, albeit thin atmosphere. Finally, current theory on water location (Carr, 1986) suggests the search be conducted near the north pole. The site for *Pax* is south of where the northern polar cap advances in the winter season.

5.1.2 BASE LAYOUT

The base layout follows a north-south axis, with the habitat, solar array fields, and radiator fields being in the center, the auxiliary nuclear power plant 2.5 km to the south, and the launch and landing facility 2.5 km to the north. Winds are from the west and south-west; launch and landing patterns will not endanger the habitat, and any possible nuclear residue will be carried away from the base and habitat.

5.1.3 HABITAT BASIC CONCEPT

Schematic design studies were conducted early in the research and design process of this project to explore different base layout master and site planning concepts. The implications of four alternative concept designs were explored, analyzed, and then compared at a PDR. They were:

- hard module habitat partially buried and partially set in the edge of a Martian crater
- inflatable habitat partially buried and partially set in the edge of a Martian crater
- Earth-like technology for Martian surface application
- space-frame construction spanning between crater edges

The advantages and limitations of each concept design were analyzed. An attempt was made to combine the best of each concept design. From the PDR, it was found that there are considerable advantages for surface construction with a combination of hard module and inflatable structures covered with a space frame regolith containment system. This was the integrative concept that was adopted and developed throughout this project.

5.1.4 CONSTRUCTION SEQUENCING

The whole issue of sequencing from initial lift-off from Earth to IOC and NOC is a critical, and early, mission and design decision to be made. Based on our analyses, the advantages of Zubrin's "Mars direct" mission scenario, or mission "architecture" as NASA calls it, became apparent. Adopting large segments of this scenario suggested a split-sprint mission, with cargo transportation and initial robotic emplacement preceding the first landing of humans on Mars. Thus the construction sequencing we have recommended proceeds in seven phases:

1. Landing of two 9-m hard modules as the initial campsite or outpost, followed by six crew members who begin to prepare the site for further development.
2. Excavation of the footprint for the IOC Martian habitat.
3. Landing of two additional 9-m hard modules as the second phase outpost, followed by six additional crew members who begin assembly and raising of the space frame and regolith containment system.

4. Emplacement and inflation of the two 12-m inflatable crew support and laboratory facility modules.
5. Rigid entry module moved from campsite location and connected to the inflatables together with a primary entrance airlock to the habitat.
6. Utilizing a lift and trailer system, the fourth and fifth components, both rigid modules dedicated to greenhouse functions, transported underneath the space frame shelter, and flexible connections attached to the laboratory and crew inflatables.
7. Two additional rigid modules docked: a logistics module, which will serve as an emergency airlock, docked to the crew support inflatable; and a combination laboratory logistics and emergency egress airlock, docked to the laboratory inflatable. This completes IOC.
8. Expansion of the base as necessary to various NOCs, e.g., removal of the crew or laboratory logistics module/airlocks, and excavation and emplacement of an additional 12 m or larger inflatable module.

5.1.5 OVERALL DESIGN ORGANIZATION OF THE HABITAT

There are seven factors that went into creating the basic parti or conceptual framework, governing the overall concept design of *Pax*. They are:

- embracing entry
- a separation of work and play
- circulation efficiency
- dual egress
- central focus in each module or inflatable
- homelike environment
- sense of place

Because *Pax* is to be the astronauts' "home" for two years or more, a designated entrance will mark the "font door" to home. By situating the modules in an embracing formation, slightly set back in the center, the crewmember will have a sense of "moving within." The indented area is intended to mark a focal point in the habitat. The embracing feature is evident in both the plan and elevation of the habitat. From the surface of Mars, entry into the habitat is a sequential process. The crew will enter under the shelter system to the primary airlock. From this airlock, the crew will pass through a dust-off chamber before entering the primary circulation space.

Since the crew does not egress the habitat to conduct IVA, the concept of designing *Pax* through a separation of "work" and "play" can help the crew differentiate their activities. By physically separating the laboratory spaces and crew support spaces, the crew may feel as though they were going to work similar to on Earth. They have the opportunity to "leave work " and "go home" for peace and recreation.

The habitat is organized in an efficient manner. From module to module there are clear linear circulation paths. Time will not be wasted by excessive walking. As discussed in Chapter 3 clear circulation and wayfinding are important in keeping stress levels down. Situating the individual habitat volumes in a straight line would be far too monotonous. *Pax* is formed in a continuous, looped path. This allows for a variety of circulation paths while still being efficient. As an example, vertical circulation is located either in the center of a module or along the perimeter; the horizontal circulation is in the shape of an arc in the crew support module and vertical in the laboratory module.

Dual egress is another important element in extraterrestrial living. In the event of an emergency, the crew must be able to emergency exit any of the habitat volumes in two opposite directions. Two means of egress are required in building on Earth. This should be the same in extraterrestrial situations. Suits and EVA chambers are located in three areas to permit suited egress to the outside.

The entry module acts as the central focus for the habitat as a whole. Creating a central focus in each of the modules and inflatables is considered an important link in making *Pax* livable. It unifies the volume. Each of the five components also have designated focal points in which the crew can gather. Within each volume personalization also acts as a humanizing factor.

The ability for the crew to personalize the spaces can provide for a more productive mission. As discussed in Chapter 3, allowing the crew the luxury of bringing pieces of "home" with them is important in keeping stress levels down. The Martian living environment will be different than that of Earth. Yet the crew should live in a comfortable and familiar way. The crew will be able to bring with them a "sense" of home. For example, the library will be filled with books that the crew has requested, and the crew quarters can each be decorated to suit individual tastes.

In designing individual spaces, the intent is to portray a particular atmosphere. To create a sense of place appropriate to the functions occurring is an important element. For example, the galley should give the impression that it is a galley and not mission operations. The private crew quarters should appear different than that of a laboratory. This may help the crew in adapting to isolated living conditions.

By incorporating all of the aforementioned concepts into the design of *Pax*, it is hoped that living on Mars will be comfortable and provide a productive environment for the crew. Each designed space, discussed in the following pages, integrates design issues and requirements with the intention of making each space productive, habitable, and comfortable.

Pax contains five main components. It consists of three, 9 m hard modules, and two 12.6 m inflatables. Two of the hard modules house the greenhouses and the third is the entry and suit stowage module. The two larger inflatables hold the majority of the functions-predominantly the crew support and the laboratory areas. Three EVA chambers and a logistics module (space station-derived) make up the balance of the habitat.

5.1.6 INTERIOR DESIGN INCLUDING CONSIDERATIONS OF COLOR, LIGHTING, AND MATERIALS

Seldom have lunar and, even more so, Martian designs been taken to a level of design development where the particulars of interior configuration and how the configuration will impact on human productivity and satisfaction can be examined. An important part of our design work, especially in this project for a first Martian habitat, has been to investigate interior architecture and how it impacts on habitability.

The configuration of all the spaces in *Pax* has been described and discussed above, and related to human factors and environment-behavior reasons for design decisions.

But in addition, careful consideration has been given to technical details, color, lighting, and materials based upon color and material design recommendations from NASA-Ames Research Center. The selection of color for *Pax* was based on three activity area definitions. High activity areas contain larger wall spaces in light, lively, warm earth tones and warm pastels. Moderate activity areas e.g., designated work areas, are finished in calm, low saturation colors. Low activity spaces—quiet, cozy environments—are done in light blues and grays.

Pure colors are used rather than drab colors. Bold colors are limited. Shades and pastels are used on larger surfaces. And contrasting colors are used to break monotony.

Pax therefore makes liberal use of gray tones, pale blue-grays, burgundies, taupes, off-whites, silvers, deep blues, and terra cottas. A basic color scheme was chosen for particular spaces, with the effect upon adjacent spaces considered if those spaces flow into one another. A continuity of color was provided from one area to another to relieve the habitat from appearing "chopped up" and discontinuous. Bright colors were used to highlight certain special features, either architecturally or visually. Color also augments the translation pathways throughout the habitat.

Similarly, *Pax* incorporates a number of lighting systems to increase visual stimulation, add variety, and augment the tasks to be performed. Lighting was used to highlight special architectural features in each area of the habitat.

Suggested material usage came from the NASA Man-Systems Integration Standards. Materials will go through sophisticated testing to determine whether outgassing from the product is detrimental to humans or the space environment. Materials were chosen to aid mission activities and tasks. For example, surface materials in the general laboratory allow for ease of the task and easy maintenance. While reflective properties, not contamination and non-discoloring properties, durability and deterioration were considered, a variety of materials with textural surfaces are included to vary the environment and to stimulate the confined astronauts visually and tactually.

5.2 MAJOR STRENGTHS AND LIMITATIONS OF THE DESIGN

Uncountably many decisions go into any design. All decisions that are made have the overall objectives of the design as their driver and, hopefully, empirical research as their justification. Sometimes these design decisions conflict with each other. This design, as in all designs, has strengths and limitations. Following are some of the most notable.

- One of the first strong points is economic in nature. The habitat uses rigid modules that were on-site from the initial exploratory landing. The four pre-landed hard modules make up over half of the habitat. Taking advantage of these saves extra mass that would otherwise need to be delivered.
- Another of the large scale elements of the base that works well is the radiation shielding. Its design allows it to be in place before the modules of the base are put in place, providing shielding during the bases construction. A protected area is provided around the modules giving easy access for maintenance. The structure—being an encompassing space frame—also allows for easy expansion.
- The general zoning of the habitat works very well. Work is separated from leisure, public from private, noisy from quiet, and active from passive. This can be seen in the functions of the individual modules, and in the difference in the floor levels within each.
- Within the habitat, a number of spaces are allowed that provide privacy, a place for a crew member or small group to get away. The crew quarters are the primary place a crew member can escape to. Passive recreation also can allow privacy. The chapel and library are two more areas that allow for this important need for occasional isolation.
- Spatial variety is another way this design excels. Supplementing the rigid modules with inflatable modules adds variety to the spaces that are created. Although all of the enclosures of the habitat are generally the same shape, a number of different types of spaces are created within. While some shapes may be pie shaped, others are rectilinear, and still others are curvilinear. A variation in ceiling height and floor levels helps further to create this variety of spaces throughout the habitat.

Some other issues that made an impact on the design in a positive way include:

- Active recreation is isolated from other functions within the base, preventing excess noise and vibration created in the space from becoming a problem.
- The entry EVA chamber is separated from other spaces, helping to keep dust from spreading throughout the habitat.
- Dual egress is allowed throughout the habitat; there are always two ways of escaping any area.
- The modular rack system allows easy changeout, replacement, and rearranging throughout the habitat, not only at IOC, but if the habitat is expanded to various NOCs.
- Using a number of enclosures (modules) allows containment of trouble areas in the event of an emergency, yet allows large spaces and easy connection of associated functions.
- The loft-type crew quarters make efficient use of vertical space.
- The connection of the crew quarters to the greenhouse allows convenient access to quiet spaces for the crew during off-hours.
- Situating the library and chapel within a greenhouse adds to the comforting environment of all.
- Having two greenhouse modules, each with it's own atmosphere, adds to the scientific benefit and productivity of the base.

There are also limitations, other issues on which the base and habitat could use improvement:

- The habitat may be larger than necessary for 18 crew members. It could be optimized to a smaller volume.
- Spaces exist with no function (e.g., the center of the first floor in the crew support module). While these are desirable aesthetically, they may be extraneous in terms of efficiency, mass at lift-off, and economics.
- Even though the radiation shielding makes views possible, views out of the base are limited to one window in a mission command workstation.
- A drawback of the structure is its complexity. A large amount of mass, hundreds of pieces, will need to be delivered to the Martian surface. The structure will likely involve extensive EVA time in assembling the truss-work.
- Their is an over redundancy of equipment and spaces within the labs; dual functioning could cut down on the amount of space and equipment needed.
- The vertical circulation throughout the habitat needs more thought (e.g., convenience, comfort, practicality, extent of use).

- The nature of the laundry facilities (closet-like) and location (on a major circulation intersection) make it problematic.
- A more direct connection between the galley and wardroom would be desirable.
- The idea of a split-shift within these tight quarters needs more thought.
- The airlock attached to the labs may be used as much as if not more than the entry EVA. This airlock should therefore have suit storage and a preparation area outside of the equipment lock.

5.3 AREAS FOR FUTURE RESEARCH AND DESIGN DEVELOPMENT

A number of areas suggest themselves for future research and design development.

1. More attention needs to be given to the development, and human factors and environment-behavior justification, for design requirements for all scales of Martian campsites/ outposts and permanent bases including their habitats. Some work has been done on this for lunar bases (e.g., Moore, et al., 1992; ongoing work by Joyce Carpenter and Deborah Neubek at NASA-JSC), but as far as we can determine, not for Martian environments.

2. Minimally necessary activity spaces, and their minimally necessary sizes both in terms of m^2 of floor plan and m^3 of volume. Our work to date has suggested a minimally necessary set of laboratory and crew sup[port spaces, but considerably more work needs to be done to refine this list. Similarly, our work to date has begun to suggest possible spatial allocations for each of these spaces (for 12 and 18 crew members), but again, the work has only scratched the surface, indicating the importance of careful human factors analyses—and perhaps terrestrial simulations—of these quantitative requirements.

3. Site location requirements need to be studied more thoroughly, and more quantitative parameters given for each.

4. The implications of different power sources need to be analyzed (solar, nuclear, wind), as well as the implications of all the other factors that influence the overall site plan for the base, including radiator fields, methane production facility, launch and landing facility, mining sites, vehicle storage and maintenance facility, and transportation infrastructure to the immediate base facilities and to remote mining and research facilities.

5. Within the habitat/laboratory zone itself, careful study needs to be given to the overall size of an appropriate habitat/laboratory structure. Various published reports have suggested a range from 227.03 m^2, 349.13 m^2, 552.56 m^2, up to 1,185.03 m^2 for permanent lunar habitats for 18 people. The range itself shouts the need for careful research to begin to narrow the range to acceptable figures.

6. The implications of mining sites, possible industrial zones, and in-site resource utilization on the design of the base, and on the habitat itself, need to be studied.

7. While not studied in the present work, structural and construction systems and material selection must ultimately be integrated with considerations of human habitability. As mentioned in the introduction, the vast majority of work from other labs and centers to date has focused on the engineering aspects of lunar and Martian habitats. The background of our center, our researchers, and our design students, together with the lack of previous habitability research and design efforts for Martian habitats, drove the

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A number of these suggestions have come from our various reviewers, at internal PDRs, and at the presentation of our work at conferences of the American Institute for Aeronautics and Astronautics, American Society of Civil Engineers, and Environmental Design Research Association. We thank all of our colleagues for their insights and recommendations for the continued evolution of our program of research and design.

present enterprise in an attempt to discover some of the ramifications of elevating human factors and environment-behavior considerations in the design decision making process. Ultimately, however, the base is one base, the habitat one habitat, and all habitability, structural, construction, material selection, and economic considerations have to be integrated.

8. The design concepts expressed in this report could be subjected to independent investigation and corroboration. Any design is made up of a variety of design concepts, not just one overarching *parti.* The concepts, sometimes called patterns, are generic, or, at least, the central idea is generic, though the particular form a pattern takes depends on contextual circumstances. These, and other, patterns could be articulated, assessed qualitatively against existing research literature, and then subjected to empirical test in simulated environments (using experimental or quasi-experimental methods). This would result in a series of tested principles that could be applied to the design of any Martian (and perhaps) lunar base and habitat.

9. The implications of the need for flexibility, changeability, and expandability deserve further attention.

10. Studies need to be conducted of bounding platforms, their spacing and sizing, and whether ladders will work for movement of materials in 1/3 gravity.

11. The tradeoff between variety (in spaces, lighting, color, materials) versus cost need to be looked at quantitatively.

12. The implications of the need for mechanical, electrical, and air-handling space, as well as feed and return lines for CELSS operations need to be investigated. In the present design, space is left over for those functions, but no studies have been found on the amount of space needed for different crew sizes and mission profiles, and we have not yet done any such analyses.
13. An efficiency analysis needs to be done to determine the most efficient spaces and subspaces for different mission functions.

14. Trade-off studies need to be conducted on the viability of using conventional architectural principles applicable on Earth, versus near-term technology options, versus less conventional limits of possible technological development.

15. Detailed analyses need to be conducted on how geophysical laboratories would operate on an extraterrestrial body, what functional relationships are necessary, what equipment would have to be housed, even what the most likely mission objectives might be, and their design implications, etc.

16. The implication of different crew compositions deserves study, including volumetric studies, design implications of assuming the 5% Oriental female and the 95% American male, the efficient and creative use of confined spaces, and living accommodations for different mission lengths.

17. The implications of the sociology of small groups over long-duration confinement needs to be understood, and the implications translated into design directives.

18. The implications of designing for flexibility versus designing for specific functions needs to be addressed more clearly.

19. The implications of minimizing crew time possibly devoted to maintenance needs to be considered in future designs.

20. The implications of different images for the likely crew compositions needs to be considered, for example, are high-tech environments appropriate for NASA and related space-agency highly trained, highly self-selected crews, or are more homey, Earth-like environments more appropriate? There is a type of ideological assumption in our work to date, but it has not been tested, that bring home to Mars is appropriate. The importance of this assumption needs to be questioned, Antarctica and other simulation research needs

to be checked, and perhaps first-hand empirical research needs to be conducted with current and recent American, Russian, and other astronauts on the appropriateness or lack of appropriateness of this assumption.

21. The design of Martian greenhouses, or biotrons, needs more careful study, including a more careful determination of how much space is required for production, not just research, for various crew sizes.

22. The implications of noise and vibration in a tight environment needs more careful design study.

23. Various notions of regolith containment systems need to be investigated more fully. It may well be that as the Martian soil does not have much strength, the lateral loads put on a canopy structure from the severe Martian winds may make this type of regolith containment system inappropriate.

24. Research needs to be done profiling the personality characteristics of astronauts likely to go to Mars (e.g., possibly a variation of an environmental response inventory with characterization of environmental dispositions), and then base design decisions on these profiles and preferences.

25. While we have begun some work developing habitability requirements for long-duration missions (this report as well as Moore et al., 1992), the first missions will be 14 to 42 day missions to the Moon, which will more than likely be a test-bed for future Martian exploration and habitation. Habitability requirements for 14 to 42 day lunar missions need to be investigated and articulated. A most interesting issue here, suggested to us by a NASA-JSC reviewer at the American Society of Civil Engineers Space 92 meeting, would be to investigate, first, the quantitative space demands and then the qualitative habitability requirements for short-duration missions, and how they would change for increasing numbers of crew members and for increasing mission durations. One part of this would be the definition of usable space (e.g., the tables in NASA-STD-3000 on usable volumes), and how it should vary with crew composition, mission profiles, and mission durations. Similarly would be the analysis of usable to gross space, and usable to surface area (i.e., correlated to mass at lift-off), which analysis we have begun to do (Moore & Rebholz, 1992), but needs to be taken much further.

A fundamental dilemma underlies all of this needed research and design investigation. First is the advisability of thoroughly investigating a narrow range of issues (human factors/environment-behavior issues) versus a more comprehensive analysis of habitability and construction technology, for instance, or simultaneous consideration of two or three different prototypes, the latter allowing the exploration of the possibility of major changes during the life of the base, and the possibility of taking concept deigns into further design development before capitalizing on certain alternatives while abandoning others. Another way to put it is to ask is it more important at this stage of Martian design exploration to "design society" or to focus on research and the solution of manageable, knowable issues?