PAX PERMANENT MARTIAN BASE
Space Architecture for the First Human Habitation on Mars

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PAX PERMANENT MARTIAN BASE:

Space Architecture for the First Human Habitation on Mars

Janis Huebner-Moths, Joseph P. Fieber, Patrick J. Rebholz & Kerry L. Paruleski (edited by Gary T. Moore).

ABSTRACT

America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative (the "Synthesis Report," sometimes called the Stafford Report after its astronaut chair, published in 1991) recommended that NASA explore what it called four "architectures," i.e., four different scenarios for habitation on Mars. The Advanced Design Program in Space Architecture at the University of Wisconsin-Milwaukee supported this report and two of its scenarios--"Architecture 1" and "Architecture 4"--during the spring of 1992. This report investigates the implications of different mission scenarios, the Martian environment, supporting technologies, and especially human factors and environment-behavior considerations for the design of the first permanent Martian base. The report is comprised of sections on mission analysis, implications of the Martian atmosphere and geologic environment, development of habitability design requirements based on environment-behavior and human factors research, and a full design proposed (concept design and design development) for the first permanent Martian base and habitat. The design is presented in terms of a base site plan, master plan based on a Mars direct scenario phased through IOC, and design development details of a complete Martian habitat for 18 crew members including all laboratory, mission control, and crew support spaces.

OTHER MONOGRAPHS IN THE SPACE ARCHITECTURE MONOGRAPH SERIES

1. *Space Architecture: Lunar Base Scenarios*, by Anthony J. Schnarsky, Edwin G. Cordes, Thomas M. Crabb & Mark K. Jacobs (edited by Edwin G. Cordes, Gary T. Moore & Stephen J. Frahm). ISBN 0-938744-59, R88-1, 1988; pp. vi + 80, illus.; $10.00.

2. *Genesis Lunar Outpost: Program/Requirements Document for an Early Stage Lunar Outpost*, by Dino J. Baschiera & 12 others (edited by Edwin G. Cordes). ISBN 0-938744-61-5, R89-1, 1989; pp. xix + 89, illus; $10.00.

3. *Genesis Lunar Outpost: Criteria and Design*, by Dino J. Baschiera, Joseph P. Fieber, Timothy L. Hansmann, Janis Huebner-Moths & Gary T. Moore (edited by Timothy L. Hansmann & Gary T. Moore). ISBN 0-938744-69-0, R90-1, 1990; pp. xii + 107, illus.; $10.00.

4. *Genesis II: Advanced Lunar Outpost*, by Joseph P. Fieber, Janis Huebner-Moths & Kerry L. Paruleski (edited by Gary T. Moore). ISBN 0-938744-74-7, R91-2, 1991; pp. xvi + 72, illus.; $10.00.

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EXECUTIVE SUMMARY

America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative (Stafford, 1991; called the "Synthesis Report") recommended that NASA explore what it called four "architectures," i.e., four different scenarios for habitation on Mars.

The Advanced Design Program in Space Architecture at the University of Wisconsin- Milwaukee supported this report and two of its scenarios--"Architecture 1" and "Architecture 4"--during the spring of 1992. This Space Architecture Design Group investigated the implications of different mission scenarios, the Martian environment, supporting technologies, and especially human factors and environment-behavior considerations for the design of the first permanent Martian base.

The following report is comprised of sections on mission analysis, implications of the Martian atmosphere and geologic environment, development of habitability design requirements based on environment-behavior and human factors research, and a full design (concept design and design development) for a first permanent Martian base and habitat. The design is presented in terms of a base site plan, master plan based on the Zubrin "Mars direct" scenario phased through IOC, and design development details of a complete Martian habitat for 18 crew members including all laboratory, mission control, and crew support spaces.

Our thinking, based on an integration of the Synthesis Report and a document from the Exploration Program Office (Wheeler, 1992), suggested the likelihood of the following four mission scenarios: (1) *precursor telerobotic missions* around 1998, (2) *expeditionary landings* around 2005 to 2014 on the order of 500 days total trip time with a stay of 30 to 100 days, (3) longer duration missions on the order of 1,000 days with a typical stay time of 500 to 600 days between 2007 and 2016 to establish *human-tended outposts*, and (4) long-duration missions to establish the initial operating configuration of the first *permanent base* (IOC) between 2009 and 2022. There are significant environment-behavior issues of habitation to be explored and solved in a long-duration permanent Martian base. The focus, therefore, of our current research and design work--and this report, the fifth in the Space Architecture Monograph Series--has been on the environment-behavior determinants of a long-duration *permanent* base.

Our work built off what the Synthesis Report referred to as the Mars "Waypoint" (by which is meant Mars planetary activities for human exploration of Mars and the Solar System, i.e., as a waypoint to later exploration into the Solar System). We accepted the Synthesis Report recommendations of a crew size of 6 crew members for the initial human-tended outpost and the ExPO recommendation of a crew size of 18 for the permanent IOC base. The base is designed assuming a mostly closed-loop life support system (closed except for food, which will be produced on an experimental basis in a pair of biotrons or Martian greenhouses) and remote automatic emplacement, checkout, and verification of the habitat and life support system.

The Mars waypoint assumes significant transfer of learning from orbital and lunar facilities including evaluation of lunar habitats. Our previous work in the USRA Advanced Design Program was instructive. An early phase of our Martian work was an analysis and critique of the five lunar habitats[1] designed by the Space Architecture Design Group since 1989--especially the two habitats taken into design development--for positive lessons to be transferred to the design of the first Martian habitat. Additional issues considered in this report include the following: mission scenario analysis; implications of the Martian atmosphere and geologic environment; changeability, replaceability, and expandability; supporting technologies; and especially human factors and environment-behavior considerations and design requirements for permanent Martian bases and habitats.

Until recently, human and environment-behavior considerations were not viewed as significantly important elements for successful extraterrestrial exploration. Instead, science and engineering were paramount in the eyes of the designers. "There is now an increased awareness on the part of planners that design does affect behavior" (Fisher, Bell, & Baum, 1978). By studying the effects of human

[1] This critique was presented at the American Institute for Aeronautics and Astronautics Aerospace Design Conference, Irvine, California, February 1992 (Moore & Rebholz, 1992) and at the Environmental Design Research Association 22nd Annual Conference, Boulder, Colorado (by the student TAs). A set of resulting design requirements for human habitation of extraterrestrial planets was presented at the American Society of Civil Engineers' Space 92 Conference, Denver, Colorado, May 1992, and published in their proceedings (Moore, Paruleski, Huebner-Moths, Fieber, & Rebholz, 1992).

behavior in isolated and confined environments and then creating design requirements, it is expected that human factors can have a profound impact on the success of extraterrestrial space exploration.

A permanent Martian base will provide for a multi-national, multi-racial, mixed-gender crew for stay times as long as two years. The base will include mission related facilities such as research labs, mission operations workstations, airlock and dust-off chamber, storage for logistics, and life-support system. It will also contain crew-support facilities such as crew quarters, individual and group passive recreation areas, an active exercise facility, wardroom for eating or teleconferencing and meetings, hygiene facilities, health maintenance facility, as well as special places for privacy and psychological retreat.

Emphasis in our work and in this report is placed, therefore, on human factors and environment-behavior requirements that impact on habitability for long-duration habitation. A full range of issues must be investigated, from pragmatic issues of productivity and functionality to more abstract issues of imagery and symbolism. Considerations included but were not limited to anthropometric effects of 1/3rd gravity, safety, astronaut satisfaction and productivity, minimizing or alleviating stress, social interaction and privacy, orientation and wayfinding, perceptual variety, efficiency, functional convenience, and place and identity--the quality of "home."

A modular space frame construction system will provide the protective shelter for the habitat itself, called Pax (for the international Peace Settlement, opposite of the Latin name of the planet, Mars, the God of War), situated at the middle of a north-south axis to the base as a whole. This framing system will combine open square and triangular geometries to produce a roof and column support system. The proposed frame system is a kit of components, redundant in size and shape, that will allow the astronauts relative ease of construction. The system will consist of a structural space frame, column support system, textile regolith containment and radiation shielding system, and Martian regolith.

The habitat, or central portion of Pax, will be constructed in several stages. Construction can commence when two rigid modules and six crew members are on site, and their equipment, rovers, and logistics are in place. Additional modules and their crew will arrive, bringing the full compliment of rigid modules to four, and the number of crew members to twelve.

It is proposed that the final habitat, at IOC, will be comprised of five operational modules, each two floors in height: a 9-m hard-module entry module for dust-off, suit stowage and maintenance, and full recreation and exercise center in the lower level; two 12-m inflatable modules, one for laboratories and mission command and the other for crew quarters and the crew support facility; and two additional 9-m hard modules serving as two Martian greenhouses. The last hard module, part of the initial deployment, will be transferred elsewhere on the Martian surface as a hazardous laboratory.

Design development of all the interior habitat spaces--laboratories, mission control spaces, greenhouses, and all crew quarters and support spaces--makes up the majority of this report.

In conclusion, several critical design features of Pax are summarized, together with major strengths and limitations of this design and directions for future research and design development.

PREFACE AND ACKNOWLEDGEMENTS

Faculty and students of the University of Wisconsin-Milwaukee School of Architecture and Urban Planning (UW-Milwaukee) have been actively involved in the research, analysis, and design of extraterrestrial environments since 1987. In 1987 the School began working with the Astronautics Corporation of America, a worldwide aeronautics and aerospace company headquartered in Milwaukee, to define space design issues and criteria. In the fall of 1987, the Department of Architecture offered its first studio in "Space Architecture: Lunar Base Scenarios." The studio resulted in the first of our Space Architecture Monograph Series (Schnarsky, Cordes, Crabb & Jacobs, 1988). The School's Center for Architecture and Urban Planning Research (CAUPR) hosted a series of lectures and workshops by leading members of the aerospace industry and nationally recognized experts, made slide and video presentations at national meetings including the 3rd through the 8th Annual Summer Conferences of the Universities Space Research Association and wrote a series of articles about space research and design (e.g., Schnarsky, 1988).

In 1989 CAUPR was awarded a $115,000, three-year grant from NASA/Universities Space Research Association (NASA/USRA) to conduct an Advanced Design Program in Space Architecture. Created as a result of that grant, the Space Architecture Design Group has been responsible for research and technical papers, lectures, talks, and exhibits at local, state, and national conferences, and has received six research and design awards (for a complete listing of available publications, please see Appendix B). We have subsequently been awarded a minimum three-year sustaining grant from USRA for the 1992-95 period.

A selected group of 29 environment-behavior and human factors issues formed the basis for the Martian base design for 1991-1992. The issues selected have their origins in previous design work and research of lunar bases completed by the Space Architecture Design Group. This report summarizes those issues, discusses the design criteria, and presents a design proposal, named *Pax*, based upon accumulated research and design trade studies.

The Space Architecture Design Group would like to express appreciation for the continued support, encouragement, and opportunities the Advanced Design Program (ADP) has provided. We thank NASA and USRA for sponsoring the project, and Vicki Johnson, ADP Director, Barbara Rumbaugh, ADP Administrator, and their staff, for their continued support, and our growing array of Mentors and colleagues at NASA Johnson Space Center, including John Connolly, Kriss Kennedy, Wendell Mendell, Deborah Neubek, and Michael Roberts, for their advise and insights. Our thanks also to Brent Hellickson, Mark Galertner, and Cheri Morrow of the University of Colorado, Michael Pogue of Johnson Engineering, and Marc Cohen of NASA-Ames Research Center, whose critiques of our lunar work very much influenced the current work. We would like to thank the following for critical feedback and suggestions during the project:

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1. OBJECTIVES

In 1991, the National Space Council published *America at the Threshold: Report of the Synthesis Group on America's Space Exploration Initiative* (Stafford, 1991; referred to as the "Synthesis Report"). That report recommended that NASA explore what it called four "architectures," four different scenarios for habitation on Mars based on lunar exploration and habitation.

For the spring of 1992, the Advanced Design Program in Space Architecture at UW-Milwaukee supported that report and its four scenarios, specifically "Architecture 1" and "Architecture 4." The purpose of this project was to research design, and offer a proposal to NASA for a first Martian permanent base and habitat.

Rather than responding to all the issues that ultimately would have to be considered in the design of a mature Martian base, and based on a self-critique of our last two years' work and very helpful suggestions from colleagues around the country, we decided to focus on human/environmental considerations of Martian base design. Three other sets of issues were investigated to less depth. The objectives, therefore, were to investigate and design in response to the following:

- Mars mission scenarios
- Mars environment
- human factors and environment-behavior considerations
- changeability, replaceability, and expandability

1.1 MARS MISSION SCENARIO

A Mars mission scenario outlines the activities that will occur in getting to Mars, and what will be done there. Scenarios are divided into four phases of development, beginning with precursors and continuing to a permanent Martian base. The objectives in this portion of the report will be to outline and then integrate different scenarios for getting to and staying on Mars.

1.2 MARS ENVIRONMENT

The Martian environment will have a great impact on the design of any habitat, its infrastructure, and the activities that occur in and around it. The "environment" includes factors such as atmospheric considerations, radiation, altitude, soil composition and temperature.

Key environmental issues that will determine the location and character of a Martian base include the presence of water, distance from the origin of dust storms, elevation, geologic features, and surface conditions. All of these will impact the safety of the base and crew and the possibilities of scientific gain from the mission.

1.3 HUMAN FACTORS AND ENVIRONMENT-BEHAVIOR CONSIDERATIONS

Until recently, human and environment-behavior considerations have not been viewed as significantly important elements for successful extraterrestrial exploration. Science and engineering were paramount in the eyes of designers. "There is now an increased awareness on the part of planners that design does affect behavior" (Fisher, Bell, & Baum, 1978). By studying the effects of human behavior in isolated and confined environments and then creating design requirements, it is expected that human factors can have a profound impact on the success of extraterrestrial exploration.

A permanent Martian base will provide for a multi-national, multi-racial, mixed-gender crew for stay times as long as two years. The base will include mission related facilities such as research laboratories, mission operations workstations, airlock and dust-off chamber, storage for logistics, and life-support system. It will also contain crew-support facilities such as crew quarters, individual and group passive recreation areas, an active exercise facility, wardroom for eating, teleconferencing and meetings, hygiene facilities, and a health maintenance facility, as well as special places for privacy and psychological retreat.

Emphasis in our work and in this report is placed on human factors and environment-behavior (HF/EB) requirements that impact on habitability for long-duration habitation. A full range of issues will be investigated, from pragmatic issues of productivity and functionality to more abstract issues of imagery and symbolism. Considerations included but were not limited to anthropometric effects of 1/3rd gravity, safety, astronaut satisfaction and productivity, minimizing or alleviating stress, social interaction and privacy, orientation and wayfinding, perceptual variety, efficiency, functional convenience, and place and identity--the quality of "home."

Though Martian bases have not been explored in any detail to date, a number of lunar base designs have appeared in technical publications (Alred, 1989; Capps & Moore, 1990; Graf, 1988; Lin, Senseney, Arp, & Lindbergh, 1988; Moore, Baschiera, Fieber, & Moths, 1990; Moore et al., 1991; Namba, Yoshida, Matsumoto, Sugihara, & Kai, 1988; Nowak, Sadeh, & Janakus, 1992; Richter, Drake, Kumar, & Anderson, 1990; Thangavelu, 1991; Vanderbilt, Criswell, & Sadeh, 1988). The vast majority of these have been driven by mass efficiency and cost containment, adaptation of current technology, or structural considerations, not by detailed analyses of human factors/environment-behavior considerations. Yet, as Clearwater and Harrison (1990; cited in Cohen & Brody, 1991) point out, the temptation to trade cost or structural efficiency for habitability would be a major mistake. Substantial concern has been expressed about the biological needs of astronauts, including radiation and reduced-gravitational exposure (e.g., Nicogossian & Parker, 1982). In contrast, relatively little research and design consideration has been given to psychological and social adjustment to space. It is becoming increasingly acknowledged, however, that psychological and social factors are important determinants of the success or failure of extraterrestrial missions (Connors, Harrison, & Akin, 1985).

Our research since 1989, and our continued approach as explored in the this project, has investigated the effect of elevating human factors and environment-behavior criteria in extraterrestrial habitat design (Moore, 1990; Moore et al., 1990, 1991; Moore & Huebner-Moths, 1991; Moore & Rebholz, 1992; Moore, Paruleski, Huebner-Moths, Rebholz, & Fieber, 1992).

A sizable amount of research has been published, conducted, or supported by NASA documenting important findings on habitability design from the human factors, psychological, sociological, and environment-behavior points of view (e.g., Connors et al., 1985; Clearwater, 1985, 1987; Clearwater & Harrison, 1990; M. Cohen, 1990; Cohen & Brody, 1991; Cordes & Moore, 1990; Harrison, Caldwell, & Struthers, 1988; Harrison, Sommer, Struthers, & Hoyt, 1988; Hewes, Spady, & Harris, 1966; Moore, 1990; Stuster, 1986). It is not the purpose of this report to present additional empirical findings, nor to review and criticize the literature to date. A primary purpose, however, is to begin the process of extracting design-relevant requirements from this literature and show their impact on Martian base design.

1.4 CHANGEABILITY, REPLACEABILITY, AND EXPANDABILITY

Changeability, modularity, replaceability, and expandability are crucial factors in the design of a Martian or any other extraterrestrial base. Modularity and replaceability not only allow ease of construction, but can contribute to the ability to easily adapt the base to changing functions over time. If the reorganization of spaces is make easy, expansion of the base becomes simpler. Allowing the crew to change the space around them will create an environment that is comfortable and may contribute to lessened stress and increased productivity. Including these factors in the design of any base and habitat will assure needed flexibility that will positively influence both the form and the function of the mission.

2. PROCEDURE

The Synthesis Report presented two mission durations for Mars exploration: long-duration missions on the order of 1,000 days with a typical stay time on Mars of approximately 500 days (1-1/3rd years, 16-17 months), and short-duration missions on the order of 500 days with a 30 to 100 day stay on Mars (1-3 months). Our thinking lead us to believe that there were significant architectural, habitation, and environment-behavior issues to be explored and resolved in a long-duration permanent Martian habitat that would contain research work stations and crew living quarters. Reviewing other published mission scenarios (Stafford, 1991; Weaver, 1992; Zubrin, Baker & Gwynne, 1991) also lead us to believe that an initial short-duration outpost will quickly be followed by one or more exploratory long-duration outposts, which in turn will be followed by a permanent long-term base. The focus of our work for 1992, therefore, was on a long-duration permanent base.

Our work built off what the Synthesis Report referred to as the Mars "Waypoint" (by which is meant Mars planetary activities for human exploration of Mars, i.e., as a waypoint to later exploration into the Solar System). Phasing the development of a permanent base, we accepted the Synthesis Report recommendations of a crew size of 6 crew members for an initial human-tended outpost for change-out durations of 500 to 600 days on the Martian surface. The first permanent base, termed *initial operational configuration* (IOC), would be accomplished by repeating the mission via a revisit of a previously explored site, emplacement of one additional 6-person outpost, and then development of a permanent base for long-duration missions with stays on the order of 500 to 600 days or longer, and this time for multiples of 6 crew members, likely a full crew of 18 crew members.

The Mars waypoint assumes significant transfer of learning from orbital and lunar facilities including utilization of lunar in-situ resources and evaluation of lunar habitats. Our work in Years 1 and 2 of the USRA Advanced Design Program is thus very instructive. An early phase of our Martian work was an analysis and critique of the five former lunar habitats-- especially the two alternatives taken into detailed schematic design--for positive and negative lessons to be transferred to the design of a Martian habitat. The Synthesis Report recommended that the Mars habitat would be tested as a prototype on the Moon. As our previous work started with the Moon (see the four previous monographs in this series, listed in Appendix B), we expanded from our lunar knowledge base and lunar habitat design experience to generate alternatives for Martian habitation.

Thus, in the spring of 1992, the Space Architecture Design Studio designed a permanent, long-duration base for the surface of Mars. Subsequently named *Pax* (for the international Peace Settlement, opposite of the Latin name of the planet, *Mars*, the God of War), this first Martian permanent base will be capable of providing housing, research space, mission control space, and all amenities for 18 astronauts to live on Mars for durations up to two years.

The work was accomplished in an overlapping sequence of eight principle phases, as shown in the time line of Figure 2-1.

2.1 ORGANIZATION/MISSION SCENARIO

Analysis of alternative mission scenarios. As there are significant differences in the literature (Stafford, 1991; Weaver, 1992; Zubrin, et al., 1991), we elected to develop an integration of the commonalties between the three most prominently discussed mission scenarios (2 weeks-- January 6-21, 1992).

2.2 BASE DESIGN RESEARCH

Detailed scenario presentation followed by background research and development of design requirements on overall base design. A range of base design issues were explored (e.g., implications of the Mars environment) relevant to site selection, size and character of the site, site design, master plan, and sequencing of phases to IOC and NOC. Other issues were explored relevant to overall configuration of the site plan (siting of the habitat, solar array field, methane production facility, wind power facility, launch and landing facility, vehicle storage and maintenance facility, nuclear power plan, and transportation infrastructure; 3 weeks--January 23-February 11).

2.3 CONCEPT DESIGN EXPLORATION

Schematic design studies to develop and explore different base layout master and site planning concepts. The implications of four alternative concept designs for the base as a whole were explored, analyzed, and then compared at an internal preliminary design review (PDR--January 30):

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

From the late-January PDR, considerable advantages were found for surface construction with a combination of hard module and inflatable structures (2-1/2 weeks-- January 24-February 11).

2.4 HABITAT DESIGN RESEARCH AND REQUIREMENTS

Accomplished in two parts:

- literature research on the full range of human factors and environment- behavior considerations in habitat design, including but not limited to crew quarters, crew support facility, mission operations, research workstations, biosphere, wardroom, recreation spaces, hygiene facility, and research laboratories;
- development of design requirements based on accumulated research (3 weeks-- February 4-20).

2.5 HABITAT SCHEMATIC DESIGN

Schematic designs developed for each space (laboratories, crew quarters, etc.) in response to the design requirements. Design directions and objectives were established for the complete schematic design of each activity space, the habitat as a whole, and the base site and master plan. Design attention was paid, however, to the habitat interior design in order to respond most directly to the human factors and environment-behavior requirements. Following an internal PDR (March 3), a formal intermediate design review (IDR) was conducted (April 3) to review the results of individual schematic designs and set priorities for the continuing work. Special guest reviewers from the UW-Milwaukee Department of Architecture, from the local profession, and from NASA- Johnson Space Center offered critical comments and recommendations for continued design development (7 weeks--February 13-April 3).

2.6 INTERIOR DESIGN DEVELOPMENT

Design development of all interior spaces, refinement of design details, response to raised criticisms, and beginning of integration across the habitat as a whole. The layout of the base site and master plan were refined and solidified during this time. The overall conceptual design for the habitat as a whole, in response to a set of environment-behavior derived design principles, was integrated at this time. The final designs for each module and their subspaces was refined and consolidated. A not-quite-final design review (NQFDR, April 16) was conducted of the design development to identify areas needing fine-tuning (e.g., materials handling within the laboratories) and issues of integration across the habitat or base as a whole (e.g., lighting, color and material selection and coordination; 6 weeks--March 5-April 16).

2.7 DESIGN INTEGRATION AND PRESENTATION

In response to this final, internal self-evaluation, final design development and design integration occurred. The presentation of the results of the project--in mid-fidelity models for each floor of each module with lighting, colors, and textures, a mid-fidelity model of the habitat and regolith-containment space- frame structure, and drawings of site selection, site plan, and construction sequence to IOC and NOC--was developed. Slides were taken of all models and drawings, and of diagrams to explain the environment-behavior bases of habitat and base design (3 weeks--April 16- May 7).

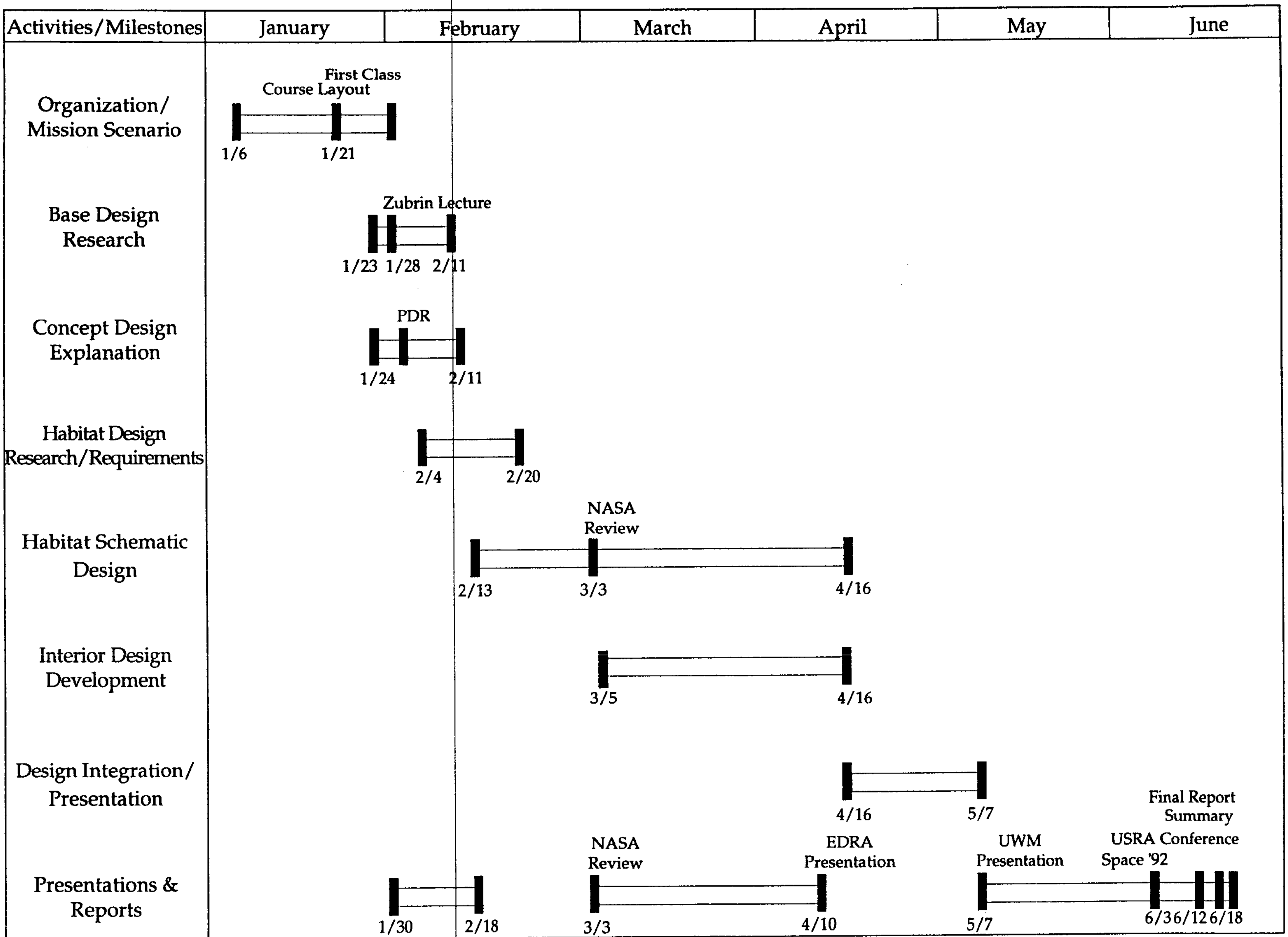

Figure 2-1. The 1992 timeline.

2.8 PRESENTATIONS AND REPORTS

Preliminary reports were written during the project and were reviewed at the NASA PDR and other times. The final product is a slide presentation based on photographs of large take-apart models, together with this final report. The project was and will be reviewed on several occasions in different forums: final internal design review at UW-Milwaukee School of Architecture and Urban Planning, invited presentation at the American Society of Civil Engineers Space 92 Conference in Denver and at the Annual NASA/USRA Summer Conference in Washington, D.C., and exhibition at the Wisconsin Space Conference.