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GENESIS LUNAR OUTPOST: AN EVOLUTIONARY LUNAR HABITAT

N91-18158

UNIVERSITY OF WISCONSIN-MILWAUKEE

Students at the University of Wisconsin-Milwaukee Department of Architecture undertook a series of studies of lunar habitats during the 1989-90 academic year. Undergraduate students from architecture and mechanical and structural engineering with previous backgrounds also in interior design, biology, and construction technology were involved in a seminar in the fall semester followed by a design studio in the spring. The studies resulted in three design alternatives for lunar habitation, and an integrated design for a early stage Lunar Outpost.

EARLY STAGE LUNAR OUTPOST

On the 20th anniversary of "One giant leap for mankind," President Bush announced the goal of landing people on the Moon by 2005, and this time to stay. Project *Genesis* is proposed as the first early stage, permanently occupied habitat on the Moon.

Research, design, and development of Project *Genesis* was initiated in 1989 by the University of Wisconsin-Milwaukee (UWM) Center for Architecture and Urban Planning Research and Department of Architecture in cooperation with the College of Engineering and Applied Science. UWM/Architecture is one of only 3 architecture schools in the 44-university NASA/USRA University Advanced Design Program. The program stresses the systems approach to design in which the class works together on a major "real world" project. The objective this year was to design a lunar outpost for the year 2005 based on environment-behavior, architectural, and engineering design concepts.

Genesis is proposed as an evolutionary, long-term testbed for all materials, processes, and development strategies to be employed in a mature lunar colony for the next 20 years, and as a testbed for all processes to be employed in the exploration and settlement of Mars.

Following guidelines provided by aerospace engineers and scientists at NASA's Johnson Space Center (NASA/JSC) and its prime contractors, the UWM Space Architecture Design Group designed *Genesis* for a full-time crew of 8 to 12 persons on rotations of 6 to 9 months with a maximum duration of 20 months. Gender, nationality, and ethnicity are expected to vary as the consortium of world aerospace partners all become involved in free-flowing scientific communication.

Five mission objectives were identified for Project *Genesis*: (1) lunar surface mining and production analysis; (2) lunar construction technology and materials testbed; (3) closed ecological life-support system (CELSS) test facility; (4) lunar farside observatory; and (5) human factors and environment-behavior research facility.

The first crewed mission to establish the outpost, which is expected to land on the Moon in 2005, 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 extra vehicular activities (EVA) involved in base construction. A pressurized construction module will be the first order of business, followed by the evolutionary development of the rest of *Genesis*. Once all systems, subsystems, and backups have been verified, and the initial operation configuration (IOC) has been put in place, crew change-outs will occur every 9 months to a year as the astronauts and their partners perform research and manufacturing operations.

PROJECT GOALS

This year's project had three goals:

1. Design solutions. To develop creative yet realistic architectural and engineering solutions to space design issues in response to human factors and environment-behavior issues, safety, energy, construction technology, and the utilization of natural resources.

2. Curriculum development and pedagogy. To enhance, further develop, and maintain courses and studios in the area of space architecture and related subjects in the School of Architecture and Urban Planning in conjunction with the College of Engineering and Applied Science at the University of Wisconsin-Milwaukee, and also to offer the design student the opportunity to become well versed in space and high technology.

3. Useful information. To produce information and design solutions useful to the aerospace community, NASA, its prime contractors and subcontractors, and NASA/USRA schools on long-duration habitation design, and to publish this information and disseminate it in a manner that makes is accessible and timely to these communities.

LUNAR BASE MISSION OVERVIEW

A lunar outpost has eight major objectives to satisfy[1,2]:

1. Located at an Earth-facing equatorial location.
2. Constructed of lightweight, durable materials that require little EVA time.
3. Contained within the next generation of Earth-lunar transport systems: (a) U.S. space transport shuttle system, (b) heavy-lift launch vehicle such as the autonomous Shuttle C with cargo capacity of 69,000 kg (150,000 lb) and cargo bay 25 m × 4.5 m diameter (82 × 15 ft), (c) low-Earth-orbit Space

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Station *Freedom* (SSF) and associated platforms, and (d) the planned cislunar transport system consisting of an orbital transfer vehicle (OTV) and a separate reusable lunar lander.

4. Capable of housing 8-12 astronauts of different nationalities, genders, and specialties for periods up to 20 months with a normal change-out of 6-9 months.

5. Provision for all life-support systems including (a) human factors, (b) health and safety, (c) environment-behavior issues, (d) habitability of crew areas, crew support, operations of base, and design for productivity, and (e) Controlled Ecological Life-Support Systems (CELSS) and Environmentally Controlled Life-Support Systems (ECLSS).

6. Integration of advanced technologies: (a) space construction technology, (b) advanced systems of energy use and energy conservation, and (c) advanced mechanical systems including power, thermal, air movement, and hydraulic systems.

7. Understanding and response to the physics, geology, and natural environment of the Moon, lunar resource utilization, and appropriate "urban" design to retain the natural qualities of the Moon.

8. Support for five main mission research 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 farside observatory; and (e) human factors and environment-behavior research facility including ongoing post-occupancy evaluations (POEs) of *Genesis* itself.

DESIGN METHODOLOGY

To achieve these goals, the project team proceeded in three phases:

1. Fall semester seminar. The project began with a fall semester seminar (Architecture 392/792). Twelve students from architecture, interior design, mechanical and structural engineering, and liberal arts/pre-architecture had a series of lectures, extensive readings, and simple sketch designs to learn the material needed to design a lunar habitat. The seminar was under the leadership of Edwin Cordes, a recent graduate of the UWM M.Arch. program and of the International Space University in Strasbourg, France, and Dr. Gary Moore, a research architect and environmental psychologist, the overall project director. The teaching assistant was Mr. Timothy Hansmann, who had been a NASA/USRA intern at JSC. The product was a programming/requirements document[1].

2. Spring design studio: Preliminary design on three design alternatives. A space architecture design studio (Architecture 690) was conducted in the spring semester of 1990. Eleven students, most of whom had been in the fall seminar, were drawn from architecture, interior design, and mechanical and structural engineering. Issues included anthropometrics, human factors, health and safety, psychological and social issues, habitability, energy systems, construction technology, internal and external base operations, and base master planning and phasing. After preliminary exploration of different subsystems of the base (research module, manufacturing areas, habitat module, base planning and layout), three alternative designs were explored in detail and presented at a preliminary design review (PDR) in February 1990 attended by representatives of NASA/JSC, USRA, industry, and academia. Each team was made up of architects and engineers with specialties in environment-behavior studies, interior design, structural or mechanical engineering, and construction technology. This division—vertically by subsystem and horizontally by specialty—insured that each subsystem responded to all design factors and that all subsystems would contribute to an integrated solution.

The product was a set of design drawings and presentation boards, together with a slide presentation. It was presented at several regional and national meetings and received a special student design award from the Environmental Design Research Association at its 21st annual conference.

3. Spring design studio: Design development of final integrated design solution. The design concepts and ideas selected at the PDR were further developed. A number of technical issues needed further research, analysis, and design exploration: materials, joining systems, hatches and gaskets, structural system, deployment systems, and regolith containment systems. Each was explored in depth by one or two members of the team with critical input from our NASA/JSC consultants and industry representatives. The project team was subdivided into teams for the further exploration and design development of parts of the overall *Genesis* Lunar Outpost. The three teams were site and master planning, interior configuration, and construction technology.

Three extra-credit students served as team leaders for the design teams; all are now working for NASA or NASA contractors. The product was a set of design development drawings and slide presentation that was presented at the NASA/USRA 6th Annual Advanced Design Program Summer Conference, NASA/Lewis Research Center, and elsewhere in this country and overseas.

THREE DESIGN ALTERNATIVES

As a first design phase, three design alternatives were explored in detail based on differing sets of engineering and architectural assumptions: (1) Space Station *Freedom* (SSF) rigid space structures using clusters of space station-sized pressure vessels, aluminum alloy domes, and interconnect nodes; (2) underground architecture using the natural lunar craters and lava tubes; and (3) inflatables using a laminated Kevlar bladder with a space frame structure.

In each design alternative, separate modules were designed for laboratory and habitation functions. The entire facility was designed to be buried under a sufficient amount of lunar regolith (0.5 to 1.5 m) for proper radiation protection and thermal control.

Concerns of the design teams included provision of public and private spaces for all functions, design for 1/6 gravity of the Moon, systems for multiple uses to conserve space and weight, accessibility to all areas and components, graphic coding to allow ease of identification by crewmembers, and interior configuration, which includes provisions for life support and power supply systems. The laboratory area includes workstations for eight crewmembers, an exercise facility, a limited hygiene facility, a system for holding a variety of experiments, command and control center, and a storage system for consumables, excess equipment, and personal items. The habitation area includes sleeping and personal areas for the eight crewmembers, hygiene facilities for full body and hand cleansing, meal preparation area, dining area with facilities for teleconferences and meetings, crew health care and emergency medical facility, and storage system for food, medical supplies, and personal items.

Prefabricated Rigid Construction

The first design alternative focused on the use of SSF-type hard modules with connectors and EVA chambers (see Fig. 1). The floor plan has a central command center flanked by science and medical facilities, domestic management, central large domed research and teleconferencing workstations, and crew quarters. Each of the larger modules was designed to fit in a standard space shuttle cargo bay, and would be fully outfitted prior to liftoff.

This alternative would develop through a series of phases (see Fig. 2) with each specified in terms of the number of flights with crew and logistics payloads to construct each phase up to IOC. Phases A, B, and C are the three subphases of

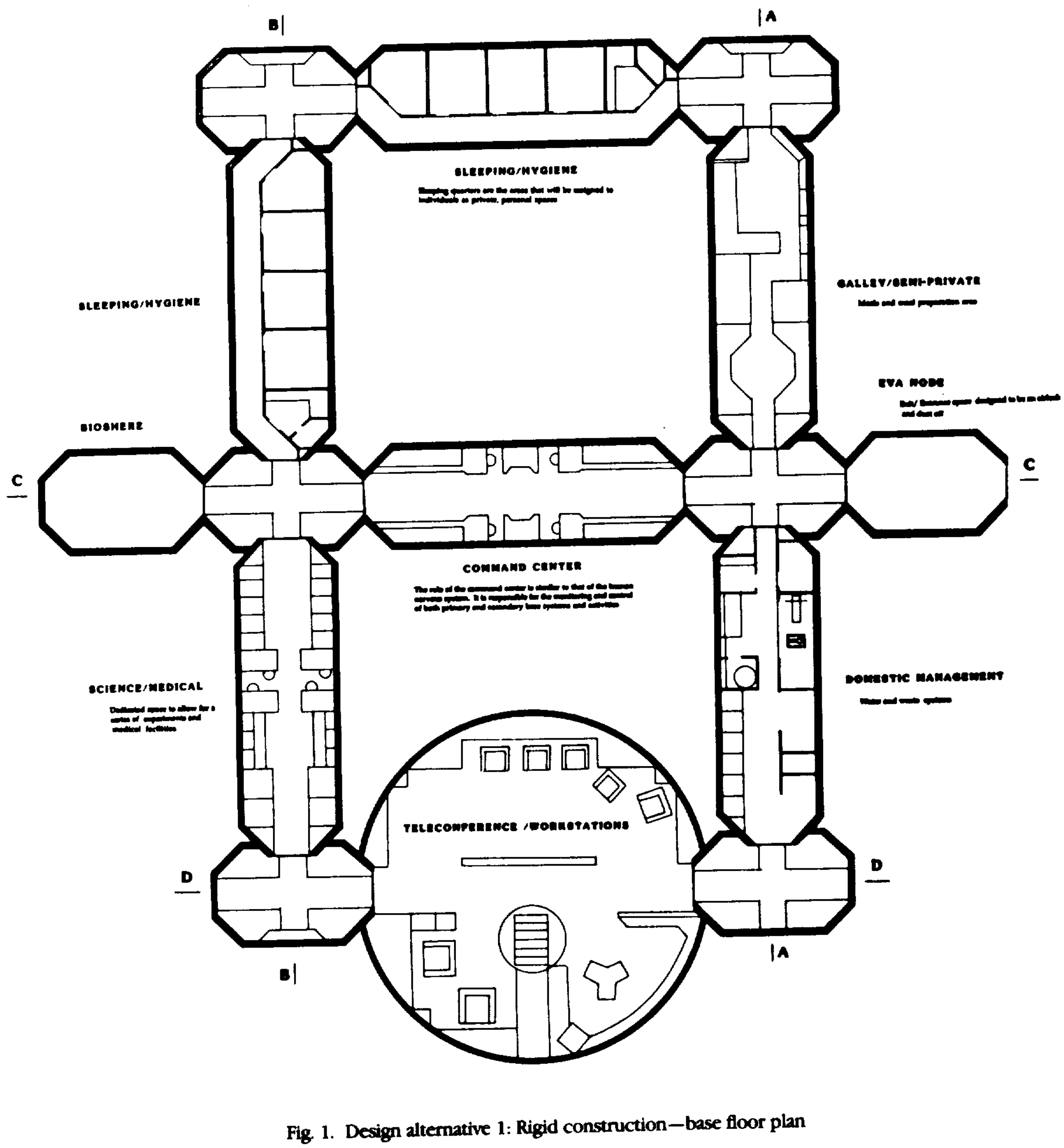

Fig. 1. Design alternative 1: Rigid construction—base floor plan

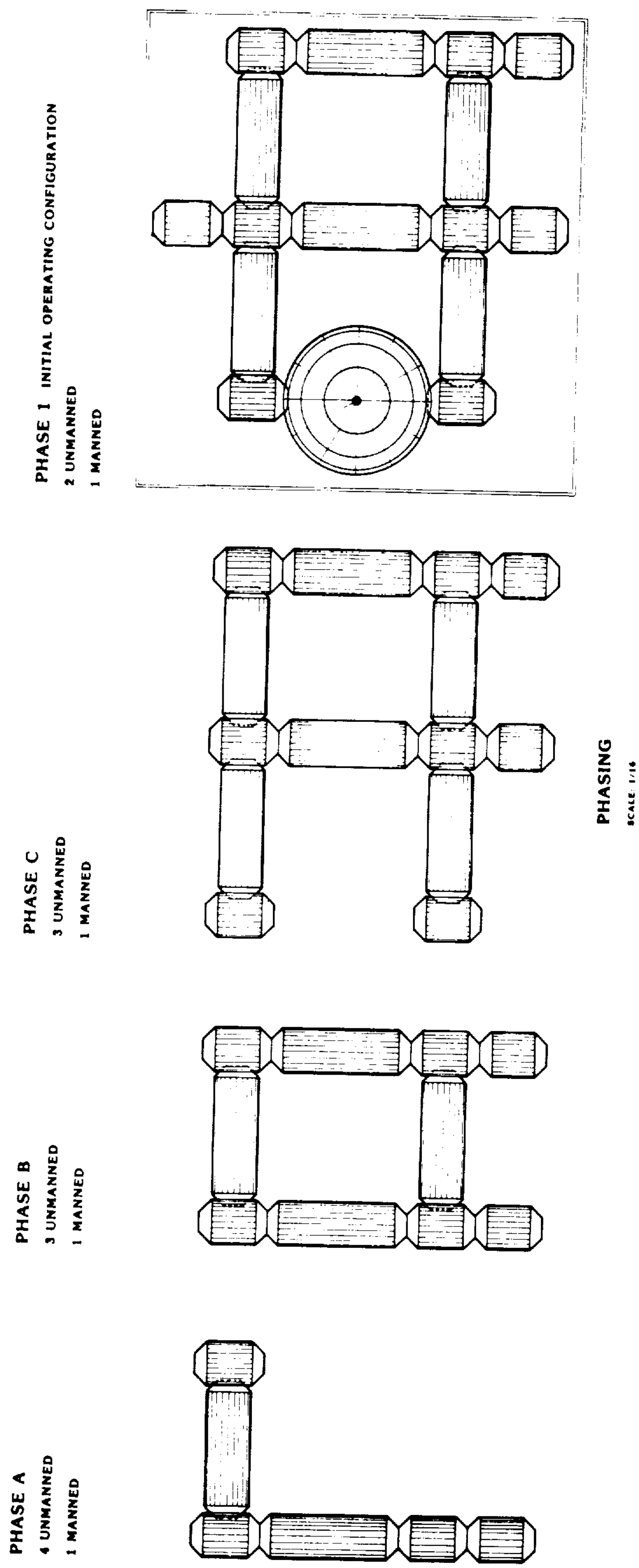

Fig. 2. Initial three subphases leading to IOC

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Phase 1 IOC. The IOC involves a dome habitat center constructed from prefabricated Earth-based construction technology (aluminum sheets, self-rigidizing foam, etc.).

Lunar Craters and Lava Tubes

The second design alternative explored the possibilities of using lunar craters and associated lava tube systems. The design uses a descending lava tube opening (see Fig. 3) with a command center inside the upper entrance of the lava tube. The walls are formed from a rigidizing foam wall system. As the lava tube continues its steep descent, an electromagnetic elevator system would be installed.

The large, natural, open volume of the lava tube can be converted into a two-story habitat with crew quarters, laundry, meal preparation area, biosphere, conference and library area, laboratory, exercise area, and ball court (see Fig. 4).

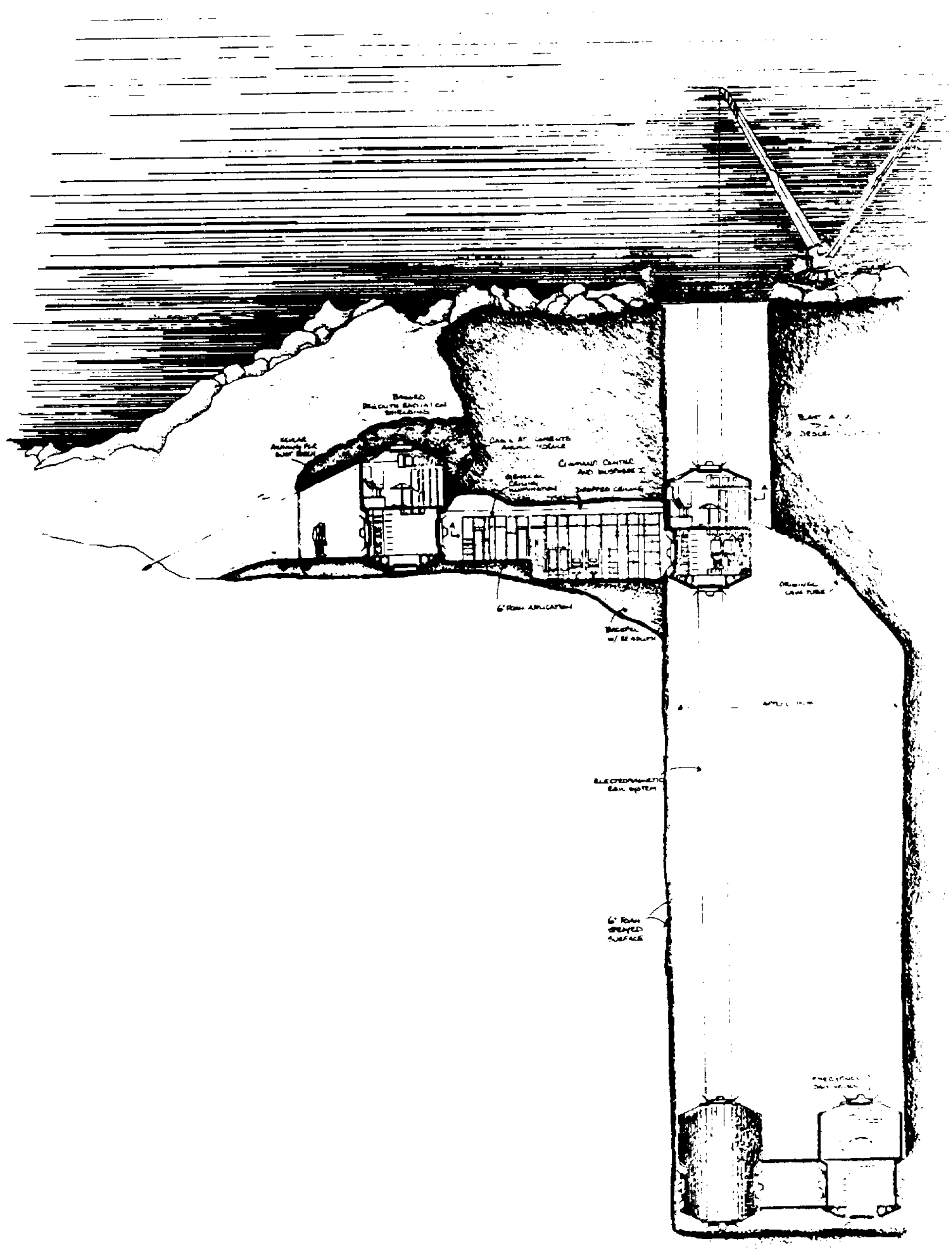

Fig. 3. Design alternative 2: Lava tube construction—entrance to the lava tube from a lunar crater, command center on the surface level, wall section, and electromagnetic elevator

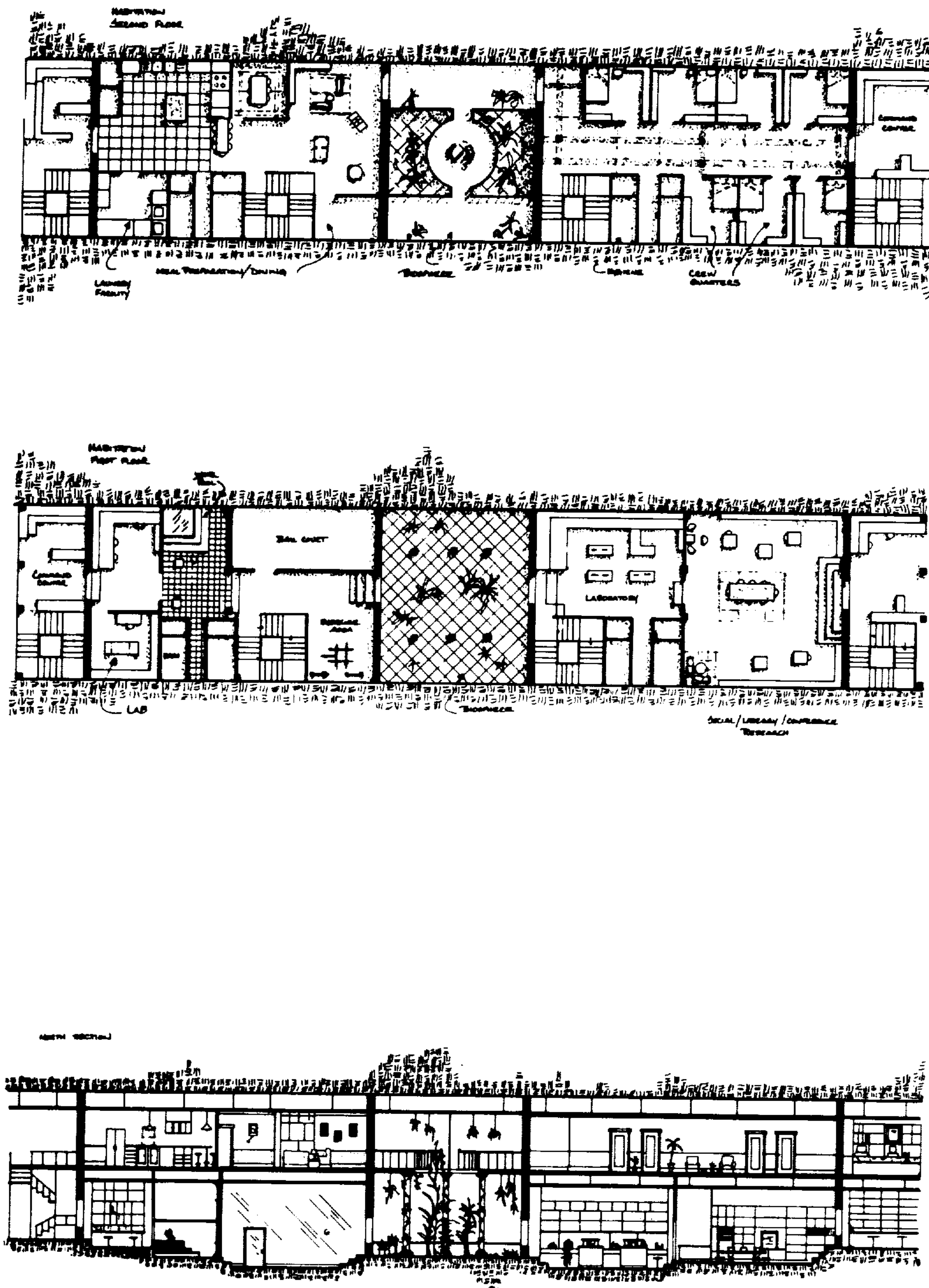

Fig. 4. Lower level floor plan and section of the lava tube design alternative. The two ends of this plan and section connect with the two lower ends of the elevator tubes

Inflatable Structures

The third design alternative explored the use of inflatables as the primary means of developing a lunar habitat. This scheme also explored site layout and the qualities of "urban design" as well as phasing and deployment of inflatables (see Fig. 5 and 6).

FINAL INTEGRATIVE DESIGN SOLUTION

From the three design alternatives evolved an elaborate but efficient lunar outpost. The final design recommendation consists of standard space station modules, nodes, and inflatables sited near lunar lava tubes. The layout reflects an organizational idea or geometry that allows the base to be understood functionally as well as used efficiently.

Master Plan

The following is a list of master plan components for the proposed base:

1. ***HLLV (Heavy Lift Launch Vehicle) Base Operations Module.*** This module will encase base operations and support functions.
2. ***Inflatable Habitation Dome #1.*** This structure will house the crew support and related activities.
3. ***Inflatable Mission Operations Dome #2.*** This structure will house mission operations and support functions.
4. ***Inflatable Biosphere Dome #3.*** This dome will have multiple functions—a biosphere for natural vegetation, entry and gathering place, and storage area.
5. ***Standard Crew Support Module #1.*** This module will contain additional crew support and hygiene facilities.
6. ***Standard Exercise/Health Maintenance Module #2.*** This module will house all exercise and health maintenance equipment for the entire base.
7. ***Standard Mission Operations Modules #3 and 4.*** These modules will contain additional mission operations, research workstations, and support functions.
8. ***Logistics Module.*** This module supports supply and resupply functions for the crew and base.
9. ***Three EVA (Extra Vehicular Activity) Modules.*** These modules will house activities pertaining to safety, EVA, and observations.
10. ***Three Cupolas.*** These spaces will be used to provide a view to the lunar environment.
11. ***Launch and Landing Facilities.*** These will include remote landing areas with lander servicing equipment and crew/payload transfer systems.
12. ***Base Garage Areas.*** These will be large nonpressurized hangars with pressurized areas for repairs accessible to all zones until each has its own limited facility.

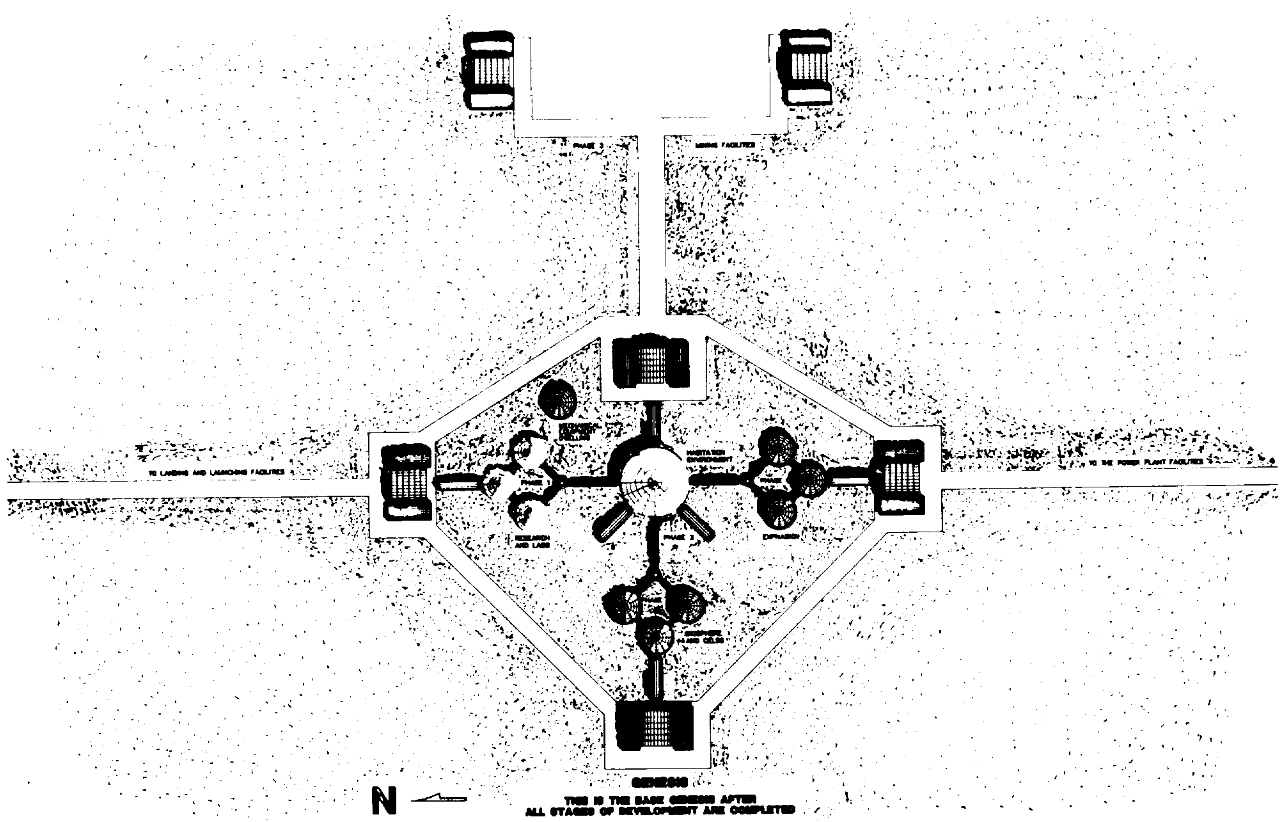

Fig. 5. Design alternative 3: Inflatables—site configuration of an inflatable lunar outpost (north is to the left)

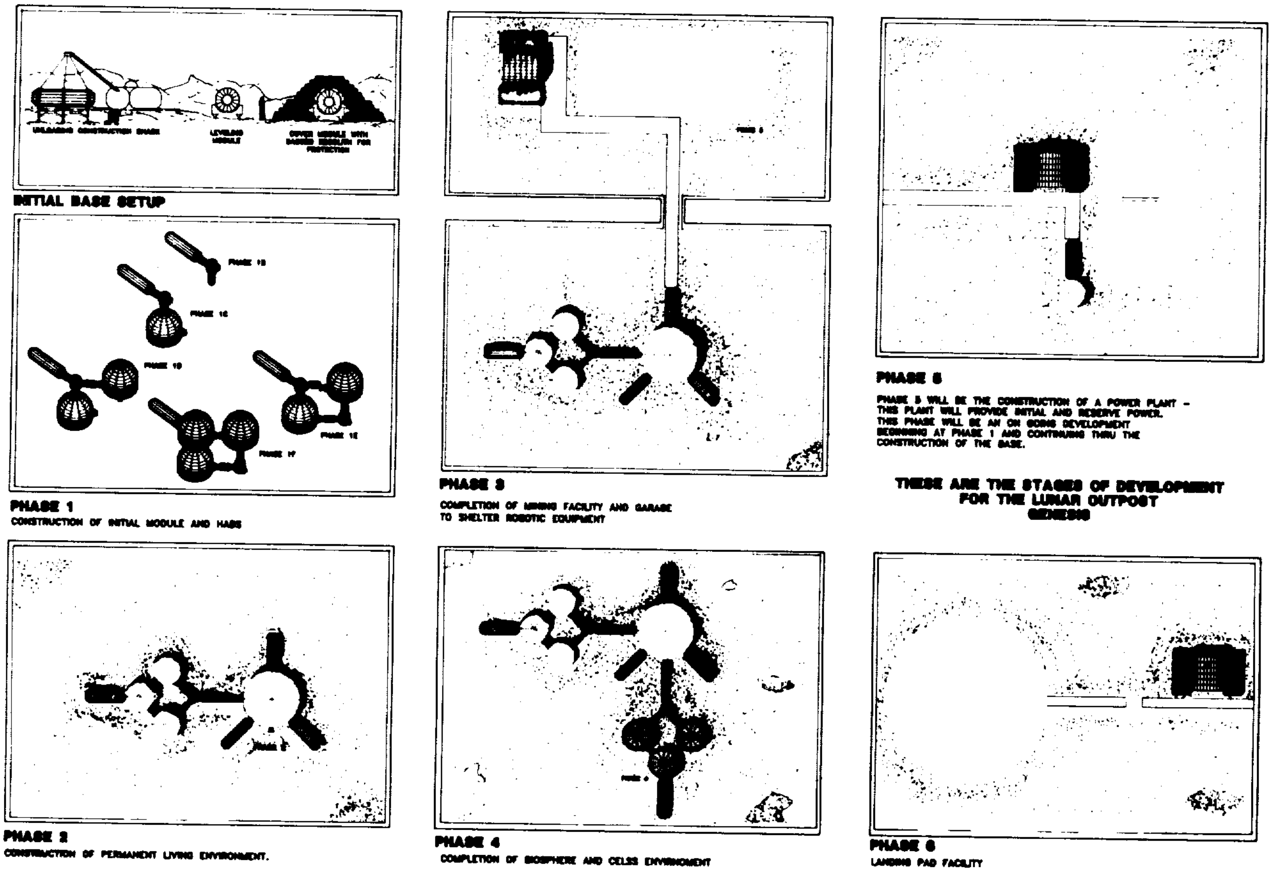

Fig. 6. Phased development of the inflatable site from initial base setup through Phase 1 IOC

13. Transportation Systems. These will provide surface transportation to travel to the more distant base elements as well as transferring payloads or crew.

14. Surface Mining and Production Analysis Operations. Mining and refinement of metals, isotopes (helium-3), lunar oxygen, and other materials.

15. Construction Technology Testbed and Telerobotic Research Laboratories. These will support high-technology construction methods and construction of robotic systems.

16. Power Plant. This will consist of a number of redundant systems including solar array fields, an SP-100 and 550 nuclear power facility, and fuel cells.

Site Plan and Base Layout

The lunar outpost consists of four major areas (see Fig. 7). The first is the centrally located habitat/research area. The second is the permanent power facility located to the north (left, in Fig. 7). The third is the mining and production facility located to the west. The fourth area is dedicated to the launch and landing facility positioned to the south.

The power plant is approximately 1 km to the north of the habitat. It consists of a small nuclear power generator (SP-100) that will be employed in the middle phases of the base development, and a more permanent nuclear facility (550) that will be set into place at IOC. These facilities are either placed in a crater or surrounded by a lunar berm to provide protection from any leakage of radiation.

The mining and production plant is also located just over 1 km from the habitat to provide safety from dust or objects that may be ejected into the atmosphere. An area of 92 m × 92 m × 2 m has been projected for an annual mining expedition. In this area, the production of lunar oxygen and other chemicals will be produced to provide *Genesis* with the means of becoming self-sufficient.

There will be two types of launch and landing facilities. The first will be temporary sites to provide ease of construction. These sites will be 250-400 m away from the base location. The second type of facilities will be the permanent launch and landing pads. These sites will be located no less than 3 and preferably about 5 km from the base. These pads will be located in close proximity to those areas of the base most frequently served, i.e., logistics and storage areas. The orientation of the base on the lunar surface was determined by the link it has with Earth. The lunar landers will descend east-west from lunar orbit and must have a clear path to the pads. By having the major axis north-south (perpendicular to the lander orbit) and placing the pads to the south, no base component will be endangered if a lander overshoots its objective.

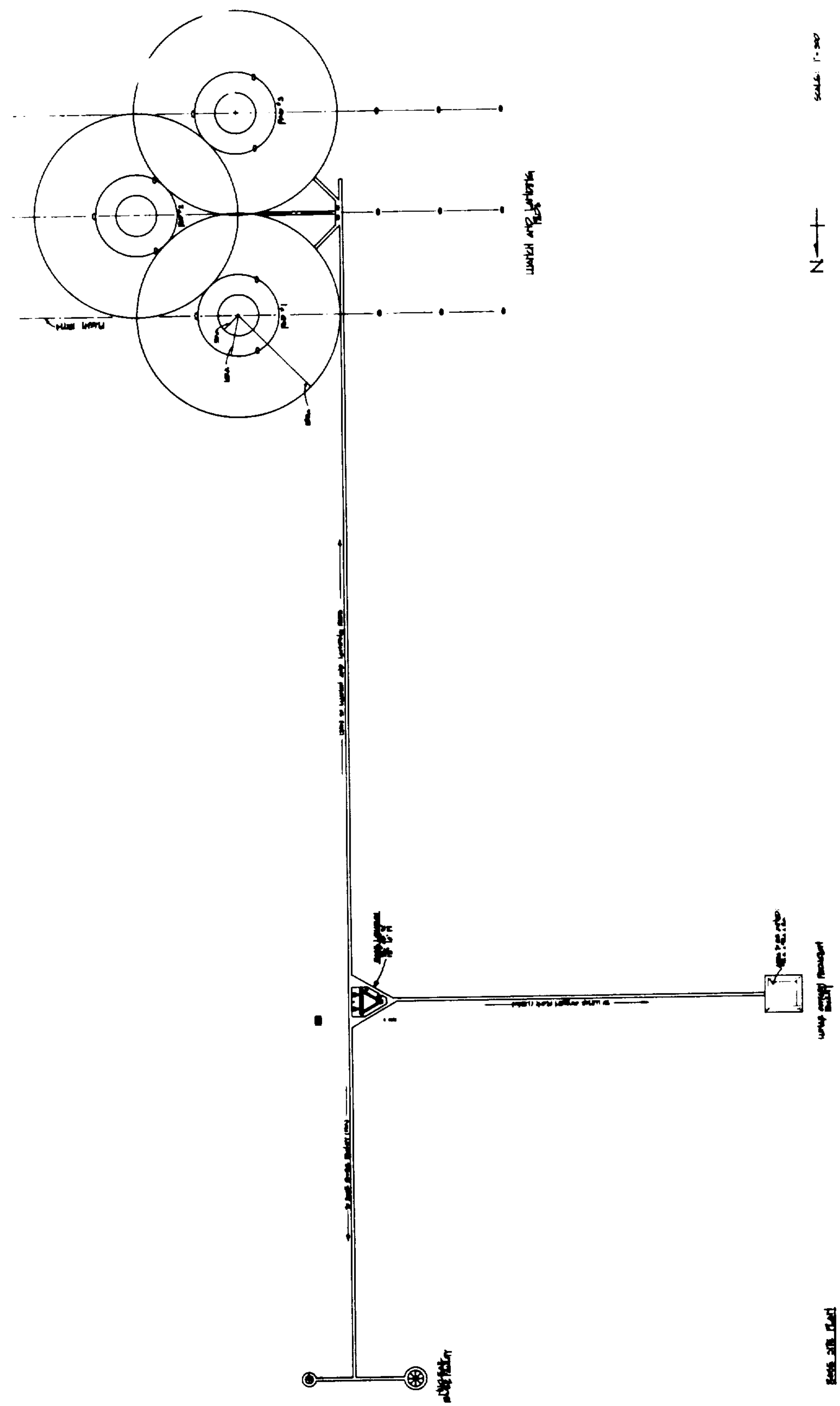

Fig. 7. *Genesis* Site Plan

A roadway system will be developed for each phase of the base's development[2]. Organized roadways between all segments of the base will allow efficient transportation of materials and crew while also giving the base some structure.

Interior Configuration

The interior configuration of the *Genesis* provides space for base operations (command center, communications center), mission operations (workstations for the five research functions), and the crew habitat (crew quarters, recreation, etc.). Key design issues included habitability, anthropometrics, health and safety, psychological and social needs, crew support systems, construction technology, appropriate lighting, and possibilities for expansion. These were organized under four main categories, with four criteria for each (Table 1).

Table 1. Key Design Issues and Evaluation Criteria

Design Issue Categories	Evaluation Criteria
Habitability	Reliability
Safety	Resilience
Constructability	Efficiency
Expandability	Transportability

In Phase 1 (see Fig. 8), the HLLV Base Operations Module is put in place as a command center. The lower level is used for crew support for four people and would consist of a galley, dining area, group recreation area, medical and exercise facilities, and personal quarters for two crewmembers. The other crew quarters remain in the assembly vehicle.

Phase 2 (Fig. 9) provides for the expansion of base and mission operations. The upper level of the HLLV Base Operations Module remains as originally constructed, but the crew quarters would be shifted into the Inflatable Habitation Dome #1 and associated Crew Support Module #1. The lower level of the HLLV Mission Operations Module would be refitted with operations workstations necessary for base expansion. Inflatable Mission Operations Dome #2 would also be built and fitted during Phase 2 so that about 50% of total research functions could be operational by the end of Phase 2.

Phase 3 (Fig. 10) has added full-scale exercise and health maintenance facilities in Standard Module #2, and expands mission research operations with the addition of Standard Mission Operations Modules #3 and 4. Each is located in proximity to the domes that are the center of research and habitation functions. A temporary flexible connector would connect the entire base into a complete base by the end of Phase 3.

The full IOC (Fig. 11) is realized in Phase 4 by the addition of the multifunctioning Inflatable Biosphere Dome #3 that functions as the major and symbolic entry to *Genesis*, as a place of psychological retreat, and (on the lower level) for storage. The permanent location for the logistics module is now moved near the entry/storage area.

The outpost is covered with 0.5 m of lunar regolith for radiation and thermal control.

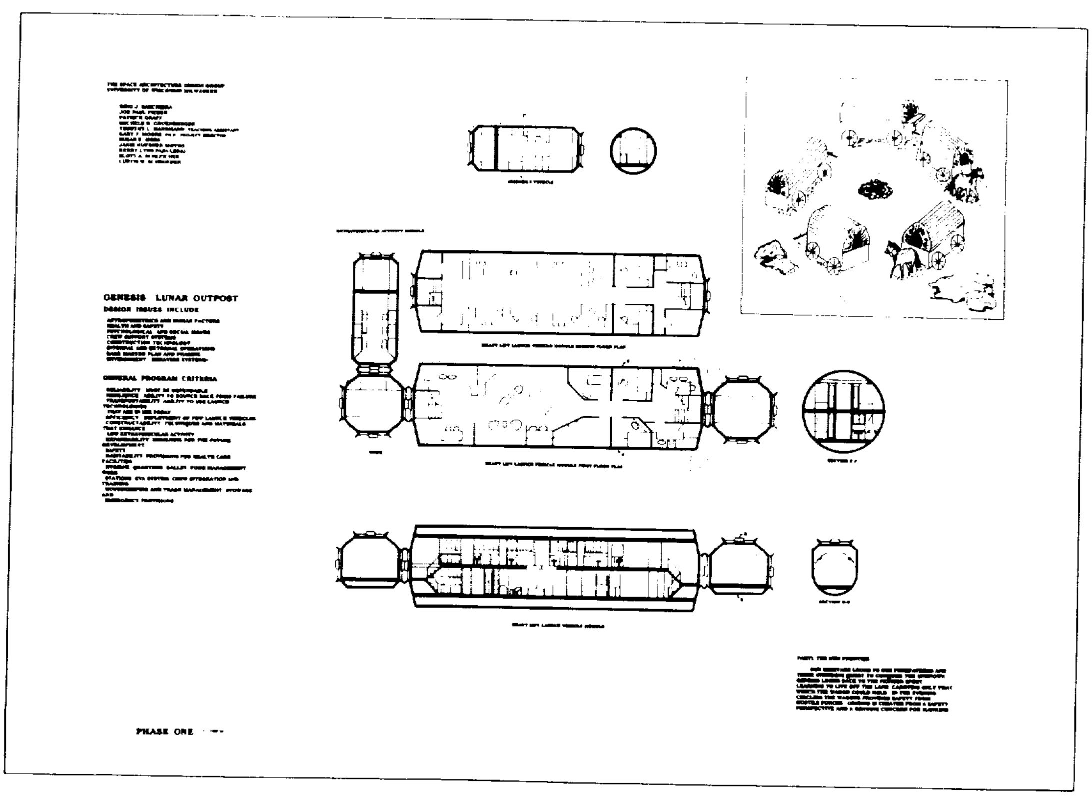

Fig. 8. Phasing of Project *Genesis*: Phase 1 Emplacement

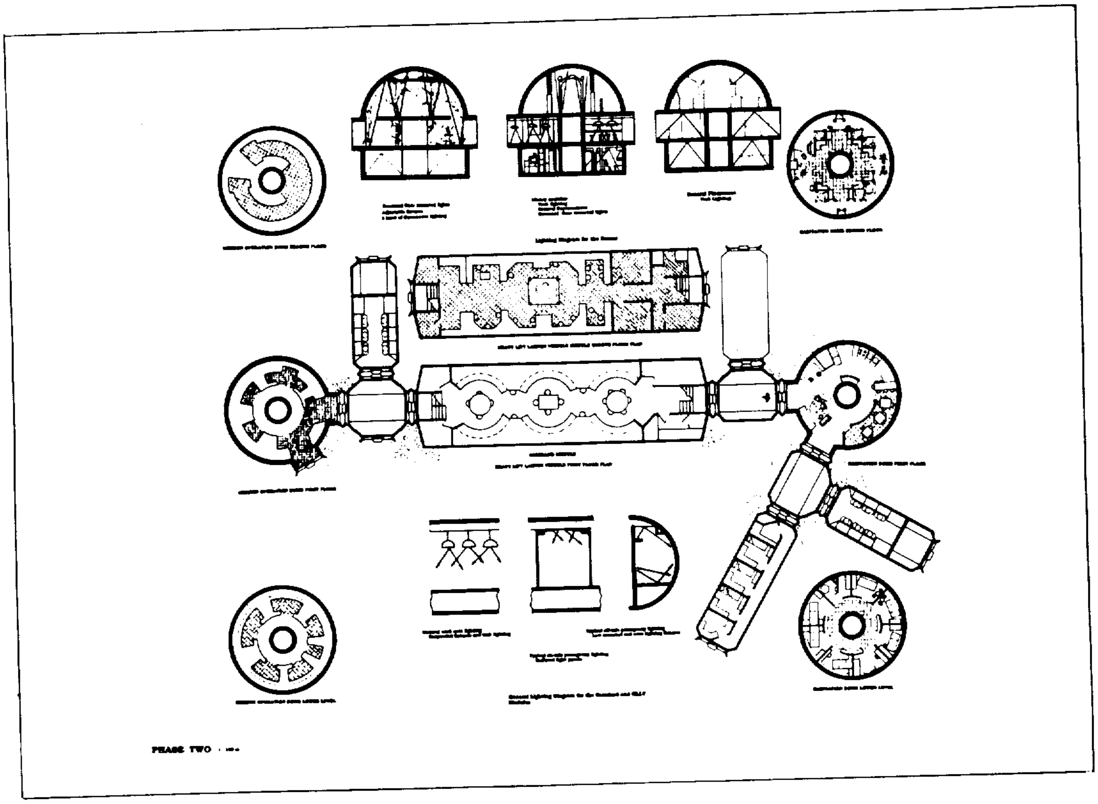

Fig. 9. Phase 2 Integration

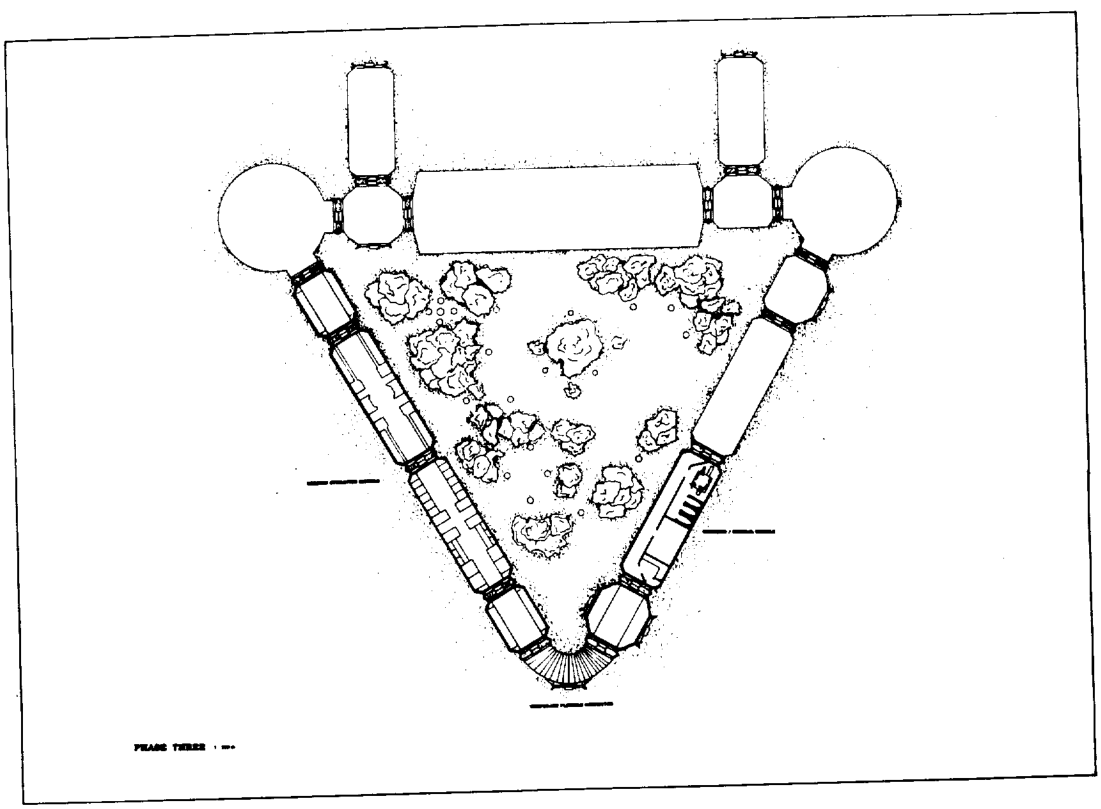

Fig. 10. Phase 3 Completion

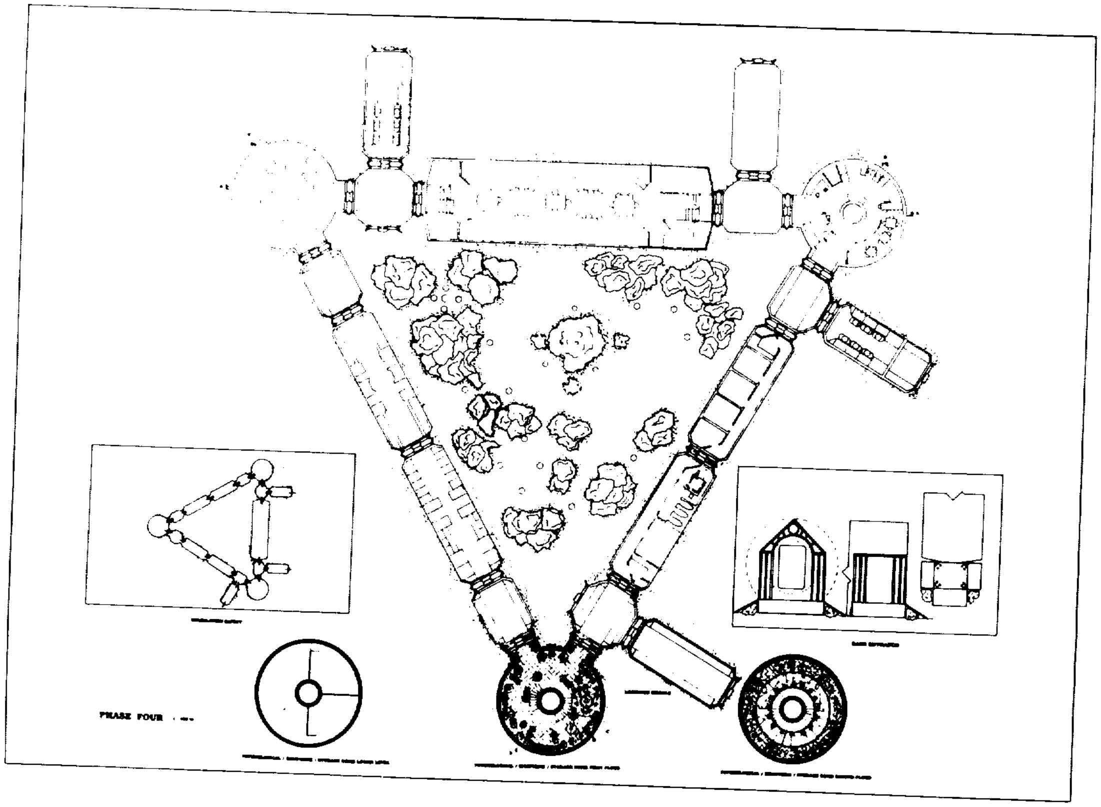

Fig. 11. Complete Initial Operating Configuration (IOC)

Construction Technology

A series of technological issues were addressed by the project team in the design. Chief among these were materials, structural systems, means of deployment and construction, attachment rings, and regolith shielding and containment(2).

The two types of modules to be employed are the HLLV module (27.4 m × 7.6 m diameter) and a standard SSF-type module (13.4 m × 2.4 m diameter). The materials of both modules consist of two layers of aluminum enclosing a layer of insulation making a wall thickness of 11 cm. The major difference between the SSF modules and the module designed here is the creation of an airlock opening in the end of the module that accommodates full-sized (1.3 m × 2.1 m) uninhibited walk-through. The modules will be outfitted on Earth, and will employ a rack system to allow components to be easily interchanged or replaced.

The domes will be a half-sphere on top of a cylinder. They will be foam-filled, rib-rigidized, air-supported, single membrane inflatables approximately 10 m in diameter and 10 m at the center (see Fig. 12). The material is proposed to be a laminate membrane composed of Beta cloth (a durability material) for the outermost layer; Kevlar, the main strength material, woven with Spectra to aid in flexibility; Mylar, to provide an air-tight barrier; and Nomex, the innermost material, to protect against fire hazards (Fig. 13).

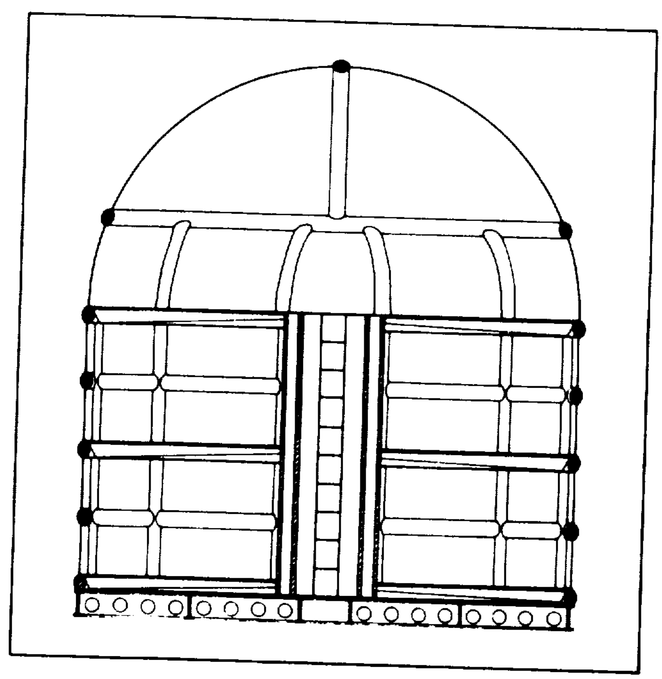

Fig. 12. Section of a foam-filled, rib-rigidized, air-supported, laminate-membrane inflatable

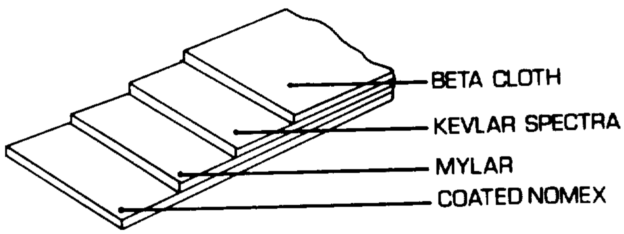

Fig. 13. Inflatable Material Laminate

A rigid platform will spread the weight of the structure over the subregolith and stabilize and level the structures. The foundation will be composed of auger-type bits telerobotically threaded into the regolith. The framework for the base of the inflatable is a lightweight space frame truss (see Fig. 14). The truss radiates outward from a central ring and can fold together for launch and deployment. The truss will be made of aluminum plates and welded channels. The flat surface that covers the truss is made of pie-shaped aluminum panels.

The inflatable membrane will be continuous except for two airlock openings. These openings will be sealed so the entire structure becomes a pressure vessel in which air will be placed at 10855 mbar. The inside of the membrane will be lined with ribs formed by chemically welding the same material to the membrane so a grid is formed. The inside of the ribs will be lined with the two components of the foam, and separated by a form of resin-gel. When the inflatable is ready for deployment, the ribs will be opened to a vacuum, the gel will evacuate, and the components will interact to form a rigid foam. Expanding these ribs will lift the membrane into its approximate form.

The proposed method for attaching a hard module to an inflatable is by using a sandwiched metal ring that will be attached to the inflatable on Earth. The inflatable will be constructed with the necessary opening left in the membrane. The membrane will have a bead formed at the point where the rib fits into the ring. This bead will be sandwiched between the two metal pieces when they are joined to form an airtight seal.

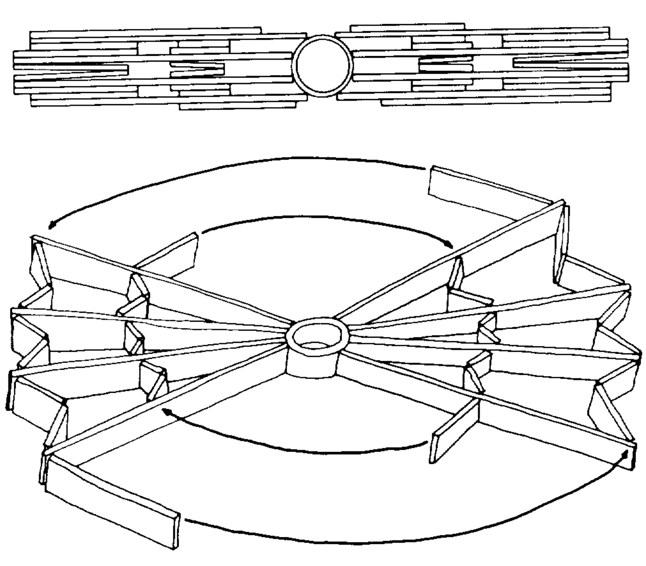

Fig. 14. Lightweight Deployable Space Frame Truss

Regolith shielding will be needed for protection against radiation, micrometeoroid impacts, and thermal regulation. The thickness required has been calculated to be approximately 50 cm. The regolith shielding will be in the form of Beta cloth bags filled with regolith and stacked upon the structures. A specially designed machine will gather regolith, bag it, and transfer these bags to a conveyor that will lift the bags into position (see Fig. 15), thus completing the construction of Project *Genesis* Lunar Outpost.

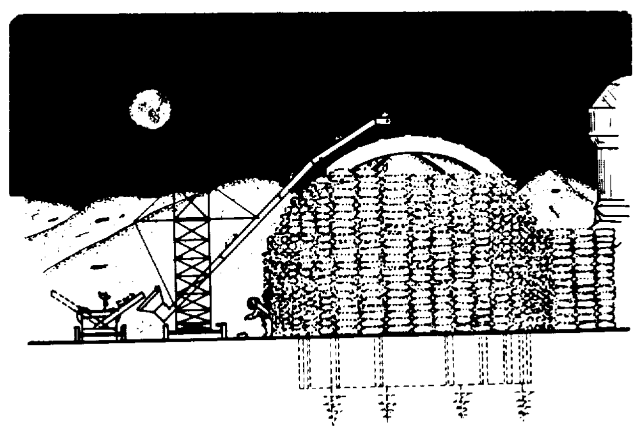

Fig. 15. Concept drawing for lunar regolith bagging and assembly procedure

FUTURE CONSIDERATIONS

There is considerable work still to be done to better understand and design the first lunar habitat. Among the most central issues that need consideration are the following:

1. Comparative, in-depth study of the lunar (versus martian) environment with special attention to atmosphere, radiation levels, solar flares, *in-situ* materials, topography, power sources, temperature extremes, etc.
2. Basic research on long-term effects of reduced gravity and design studies on different approaches to 1/6 gravity.
3. Mass calculations, studies of ways to reduce mass, and rough order-of-magnitude cost estimates.
4. Analysis of total number of flights based on minimum mass calculations.
5. Space allocation study including human factors analysis of the minimum space required for different habitation and research functions.
6. Detailed trade studies of different areas of the lunar habitat, e.g., the health maintenance facility, exercise facility, crew quarters, air locks, and workstation rack designs. Design development studies of these different areas including through study perspectives and/or models.

7. Replacement studies of how to replace/renovate/expand parts of the habitat.

8. Comparative analysis and extraction of design-relevant findings and implications from previous space experience, analogous situations, and simulations, e.g., *Mir* and *Skylab*, Antarctica and Navy submarines, and *Tektite*, respectively.

9. In-depth mechanical study including more careful radiator study to remove body and machinery heat from under the regolith.

10. Studies of different ways of getting natural light into a regolith-covered lunar habitat without admitting gamma ray particles, including but not limited to partially covered cupolas, flexible light pipes, periscopes, etc.

11. Precise regolith depth studies to protect lunar habitats from radiation and micrometeoroids.

12. Habitability study of the short- and long-term effects of underground environments and windowless environments.

13. Design studies of regolith containment systems, second-generation regolith bagging machines, and processes (including sequences) of habitat construction.

14. Structural calculations for all structural members including but not limited to the structure of lunar inflatable domes.

15. Study of various construction techniques for lunar application including, but not limited to, prefabricated modules, rigid structures, inflatables, and *in-situ* resource utilization.

16. Study of materials for lunar habitat application, especially elastomers and thin films, e.g., Kevlars, Mylars, Spectra, Nomex, aluminums, titaniums, rigidizing foams, and *in-situ* resource utilization of lunar regolith.

These studies will be conducted in subsequent years under USRA and (hopefully) other funding. They will be of two basic types: research and analysis studies, and design and development studies. The results will be reported in future reports and papers.

ACKNOWLEDGMENTS

Designs and illustrations by the Space Architecture Design Group: Dino J. Baschiera, Joe Paul Fieber, Patrick Groff, Michele Gruenberger, Susan E. Moss, Janis Huebner Moths, Kerry Lynn Paruleski, Scott A. Schleicher, and Curtis W. Schroeder; Teaching Assistant Timothy Hansmann. Paper compiled and written by Gary T. Moore, Faculty Advisor, with Dino Baschiera, Joe Fieber, and Janis Moths. This project was supported by an Advanced Design Program grant from NASA/Universities Space Research Association. This paper is a summary of a larger document, *Genesis Lunar Outpost: Criteria and Design* (Hansmann and Moore, 1990) available from the authors. Our thanks to James Burke, NASA/Jet Propulsion Laboratory, and Stephen Paddack, NASA/Goddard Space Flight Center for critical comments.

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