

---

## 6 / LUNAR CONSTRUCTION

**T**HE FIRST HABITATS, LABORATORIES, and industrial plants to go to the lunar surface undoubtedly will be prefabricated and self-contained to the greatest extent possible. Masses and volumes will be constrained by the capabilities of the transportation network to the Moon. Current working concepts are very similar to the engineering sketches in 1971; *i.e.*, space station modules are placed on the surface and buried for protection from the galactic radiation flux. The base is expanded through the addition of more modules to an interconnected network.

For early engineering studies, emplacement of a fully configured module creates a realistic scenario for modeling transportation, surface operations, power, and other requirements. As a lunar surface facility evolves beyond an outpost or camp, expansion of operational capability must be weaned from dependence on expensive transportation from Earth. Large enclosed volumes will be needed for maintaining equipment, housing increasingly complex scientific apparatus, and providing comfortable living and working environments. Innovative architectural approaches using locally derived building materials and available tools will mark the beginning of true lunar habitation.

The space program has left behind the “man in a can” approach as human factors engineering has become an ever larger activity. Sophisticated computer-aided design is utilized in planning the interiors of habitation modules and laboratories in the LEO space station. As the durations of manned missions lengthen, the crew can no longer be expected to “adjust” to the situation. Psychological well-being and crew comfort become important components of productivity.

Although the design of a work station in space today embraces many more elements than the interior of a Mercury capsule, the human factors engineer still must operate within the constraints a prefabricated volume imported in the payload bay of the space shuttle. On a planetary surface, the presence of local resources enlarges the options for design. The human factors designer begins to assume a more familiar persona, that of an architect.

LUNAR BASES AND SPACE ACTIVITIES OF THE 21ST CENTURY (1985)

The environmental constraints and the available construction materials on the Moon will lead eventually to a lunar architectural style as recognizable as Gothic or Neoclassical. Land's paper presents an architect's eye view of lunar structures and speculates what types will be appropriate for lunar conditions. Kaplicky and Nixon concentrate on providing shielded volumes quickly and simply for protection of pressurized structures.

Lin notes that the abundance of calcium oxide in lunar minerals raises the possibility of concrete as a local construction material. If oxygen is produced on the Moon as a propellant for the Space Transportation System, then sufficient water should be available to combine with lunar-derived cement and regolith aggregate. Young discusses the versatility of concrete and cementitious material in a variety of structural contexts and identifies research needed to characterize lunar cement chemistry. Hörz reviews the possibility of using naturally occurring geologic structures for habitation.

The first humans to live and work on the Moon will be supported by an advanced technology. Yet, the basic incompatibility of human physiology with the environment will limit the flexibility of response to challenges of everyday existence. Our tools will be very sophisticated, but our actual resources will be limited initially. In many ways, the development of a lunar economic and social infrastructure will require the kind of adaptability and innovation seen in successful enterprises in the Third World. For this reason, Khalili's perspective on lunar architecture provides an interesting and thought-provoking contrast to "orthodox" scenarios.

The final two papers in the section touch on aspects of engineering and planning that are ubiquitous on Earth but badly neglected so far in lunar studies. The collection of data relevant to civil engineering was only an ancillary activity in the Apollo scientific investigations. As Johnson and Leonard demonstrate, a large body of lunar environmental data must be accumulated to properly design future lunar structures. As construction and habitation expand, the effects of human activity will impact the lunar environment. Briggs reviews some issues to be considered.

# LUNAR BASE DESIGN

**Peter Land**

*Illinois Institute of Technology, College of Architecture, Planning and Design, Chicago, IL 60616*

---

A successful lunar base operation must have appropriately designed structures to house and facilitate the performance of its functions and personnel and to respond to the very special problems of the irradiated, near vacuum lunar environment. This paper on lunar base design proposes the concept of a radiation shield with pressurized enclosures underneath. It examines a range of factors related to base planning, including shielding considerations. Several ways of designing and building shields are described in detail, and the form and location of pressurized enclosures outlined. The paper also enumerates the related areas of needed research, development, and testing work upon which further progress will depend.

## INTRODUCTION

Various impressions of extensive future "lunar cities" and base complexes have recently been proposed and illustrated. By terrestrial standards, most anticipate a large building operation, considerable quantities and weights of building materials, fairly heavy plant and equipment, and a sizable labor force. In view of the high cost of transport and the unknown performance of building materials and structures in the irradiated vacuum lunar environment as well as other factors, a different strategy is proposed.

An approach for the post-camp phase base is advocated that proceeds from particulars to generalities. Starting from a small building of simple configuration, it expands to testing and evaluation of materials and structural concepts. With this experience the base grows in stages to a larger installation, becoming more self-sufficient and using more lunar resources. An incremental approach contrasts with some earlier proposals that show sizable and finite arrays of structures built in one operation. It is doubtful that a large base is initially required or could even be built, and its design would probably be out of date before completion.

It is important to take time now to plan a long-range physical development strategy for the lunar base. This will guide the design thinking and be reflected in the initial shape of the complex. An evolutionary approach will probably generate a linear layout for the base, reflecting incremental growth, transportation, solar orientation, and excavation factors. The overall success of the lunar base operation will very much depend upon the building(s) and the structure(s) that will house a wide range of functions and processes.

## LUNAR BASE CONCEPT

First generation structures of the post-camp stage would consist of two independent parts: pressurized enclosures under radiation shielding canopies. The size and shape of the enclosures will be determined by the dimensions of the operations they accommodate.

The height and extent of the shielding canopies will be influenced by the building system. Canopies will be heavy and, ultimately, made almost entirely from lunar resources. The pneumatic structures forming pressurized enclosures will be lightweight and packable into small volumes for transport and terrestrial manufacture.

In this concept, one main radiation shield consists of lunar regolith spread over a supporting structure and raised above the lunar surface. The shield can be expanded at the perimeter on one or more sides, where and when needed. Structurally independent pressurized enclosures of the required shape and volume are erected under the shield. Part or all of the shielded space can be pressurized. Different heights can be obtained under the shield by dropping the floor level, where required, by excavating with drag-line technique. Equipment such as antennae, heat exchangers, telescopes, *etc.*, can be mounted over the shield or conveniently placed in an equipment "park" on one side. This concept of the base aims at simplicity in general configuration, building technology, erection, and expansion. It reduces the chance of failure in building or maintenance and minimizes the need for heavy equipment in construction.

The design concept of a lunar base will be influenced by many factors, but two are of particular importance: cosmic radiation and maximum use of lunar materials. Data on radiation levels at the lunar surface indicate that 1.5–2.0 m of regolith would be required to provide shielding of sufficient density to block radiation to acceptable levels, such as dosages encountered by terrestrial x-ray workers. With this thickness of shielding, regolith on supporting structures is a viable concept for the base.

All lunar operations will, as far as possible, be carried out under the shield(s). Under the shield will be either a pressurized "shirtsleeve" or a non-pressurized "suited" environment. Servicing and assembly of large pieces of equipment would not necessarily require a pressurized environment but could be done under the shield, where operators would have radiation protection and would be suited for pressurization only.

## **RADIATION AND SHIELDING CONCEPT**

These design proposals for radiation shields with structures supporting regolith are based upon generally accepted data for radiation levels and regolith density for shielding. However, fresh data (See R. Silberberg *et al.*, this volume) indicate that initial estimates of the regolith thickness for radiation protection may be too low. In particular, the hazard from secondary neutrons, generated within the shielding material by cosmic rays must be carefully evaluated. Additionally, "storm cellars" with very thick overburdens must be constructed for safe haven during occasional solar flares. If a great increase in regolith thickness were required from these considerations, the concept of supporting structure might become uneconomic and the greater thickness would be more economically provided by tunnels or caverns. Therefore, radiation levels and regolith density are pivotal questions affecting lunar base design.

## **RADIATION AND BASE LAYOUT**

A range of tasks must be carried out by unshielded workers on the lunar surface. The duration of these activities for each person will be severely limited by radiation exposure,

measured as accumulated dosage over a period of time. This will consist of high intensity, unshielded lunar surface exposure together with some very low intensity radiation under the shield. To maximize the permissible time that a person can work unprotected on the lunar surface, or indeed at the lunar base itself, radiation dosage, when not actually engaged on surface operations, must be minimized.

This will affect the design of the base in two ways. First, all parts of the base should be consolidated under one shield, as far as is practical. In this way, no unnecessary radiation dosage will be accumulated by personnel in moving between different installations and parts of the base, as would be the case with a fragmented based layout. Second, the effectiveness of the shielding should be maximized. Some parts of the base must be separated from the main installation for operational and safety reasons; connecting links must be shielded in those cases. Since the radiation flux is isotropic, the edges of the shield must also be protected by regolith mass to screen out horizontal infiltration. Entrances should be labyrinthine, with overlapping screen walls to effectively block radiation.

Several options are viable for the design of the shield support structure and are described as follows. The first bays of the support structure would need to be erected quickly to give a radiation-free work area; therefore, they would probably utilize entirely terrestrially manufactured components.

## BASE STRUCTURES

### Flat Shield, Pressurized Enclosures Beneath (Figs. 1,2)

The structure supporting the regolith consists of floors resting on deep lattice girders connected to columns and erected in sections. The bay dimension of the structure and

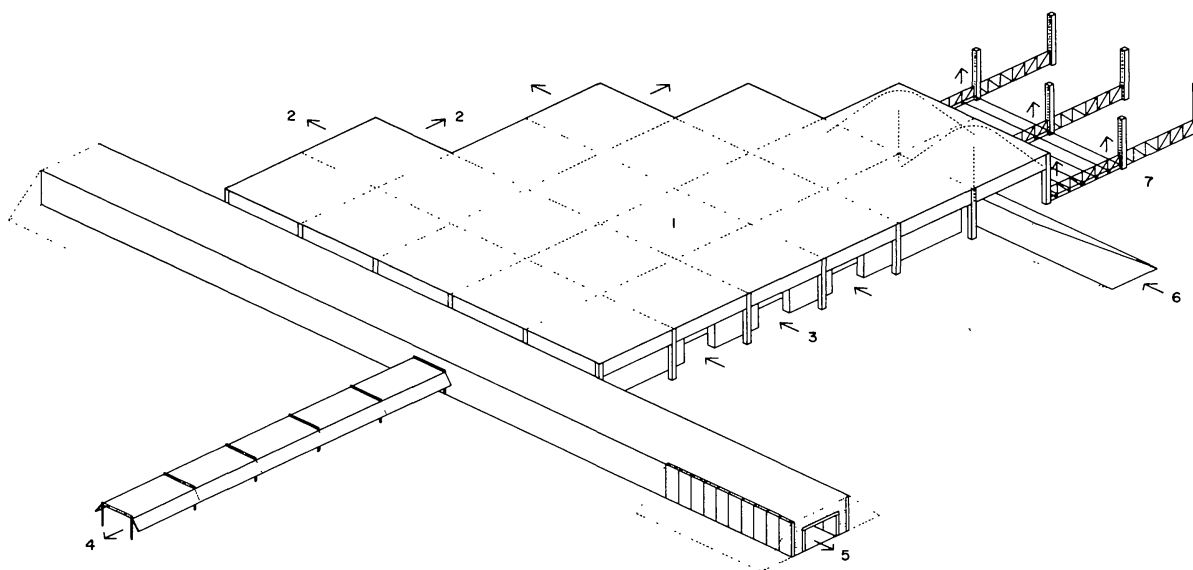


Figure 1. BASE CONCEPT I. Flat shield raised in sections, pressurized enclosures beneath. Overall view of base. (1) Regolith shielding. (2) Perimeter expansion. (3) Base entry through overlapping radiation barrier walls, from lunar surface equipment and installations "park." (4) Solar shaded links to other parts of base. (5) Shielded links to other parts of base. (6) Ramp access to lower levels. (7) Initial erection sequence.

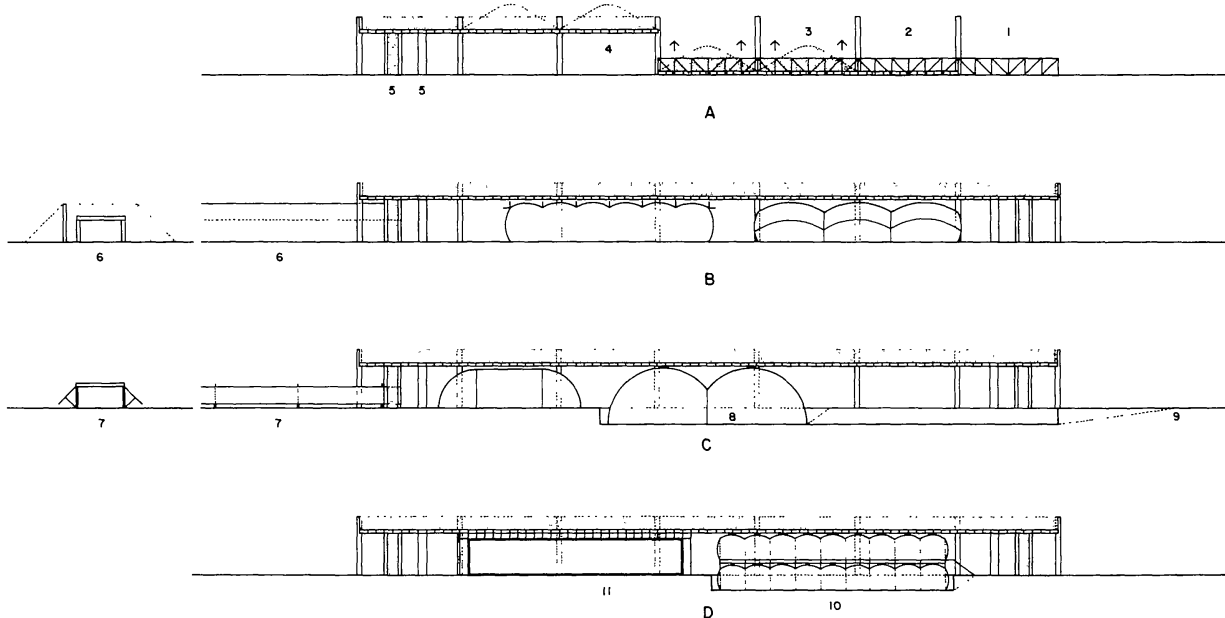


Figure 2. BASE CONCEPT I (see Fig. 1). Section A showing erection sequence. (1) Aluminum lattice girders and columns in place. (2) Prestressed floors, employing moulded regolith components, attached at ends to girders. (3) Floor loaded with regolith raised by jacks up column guides. (4) Regolith leveled off. Sections B-D show range of pressurized enclosures shapes and types for different uses under shield. (5) Entry through overlapping radiation barrier walls. (6) Shielded link to other parts of base. Bermed or with walled sides. (7) Solar shaded link to other parts of base. (8) Large pressurized enclosures for big equipment maintenance. (9) Ramp access to lower levels. (10) Small pressurized enclosures for agriculture, etc. (11) Pressurized enclosure (to be developed later) using impervious membranes applied to interior surface of rectangular enclosure. Extra top and side reinforced panels to resist outward thrust of pressure.

spacing of the columns will be influenced by the functions of the base and the pressurized envelopes underneath. Column spacing could be close on one axis, perpendicular to the floor span, and wide on the other, or it could be equally spaced on both axes. Flexibility in column spacing and relatively large spans are feasible. Because of the  $1/6$  gravity environment, the dead load of dry regolith is not high, and the lattice girders can be very deep in the thickness of the regolith.

The bays of this shield support structure would be raised by pneumatic jacks to the required level, at which point the ends of the beams would be permanently connected to the columns. The regolith overburden could be loaded either before erection of the structure or after. Placing regolith at ground level mainly involves pushing operations, with some leveling needed after the platforms are raised. Placing regolith on elevated floors requires lifting and reaching operations that require more energy and equipment.

*Prestressed floors.* The floors would consist of moulded regolith components, prestressed from end to end with stranded fibre-glass tendons by using small, portable hand jacks. Components would be assembled flat on a leveled lunar surface, with tendons inserted and prestressed to form narrow floor sections. All sections would be connected at their ends to the transverse girders.

*Folded aluminum floors.* Here, the floors use all aluminum lightweight components. Folded aluminum sheet material with a deep section for high strength/weight ratio can be fabricated with a profile to permit "nesting" for transportation. The maximum length of components is determined by payload bay space dimensions of the transport vehicle. This floor system of terrestrial manufacture would be used for the initial sections of the shield. Later, with a production plant installed, moulded regolith components would be produced for the floors.

*Pneumatic component floors.* These would employ inflatable beams, which have been successfully used for bridges in military application to carry trucks and tanks over gullies and craters. They consist of large-diameter inflated long tubes, smaller cross tubes, etc., with an aluminum deck over all. This floor system of terrestrial manufacture would also be used for initial sections of the shield.

### **Low Arch Shield, Pressurized Enclosures Beneath (Figs. 3,4)**

If the structure supporting the regolith is a low arch working in compression with no tensile stresses, then no reinforcement is required. Components of such an arch can be made of moulded regolith, assembled over a movable pneumatic support form. The arches are assembled in sections, each the width of the form, embracing several rings of components. After one section is in place and covered with regolith, the form is partially deflated and moved forward to assemble a new arch section.

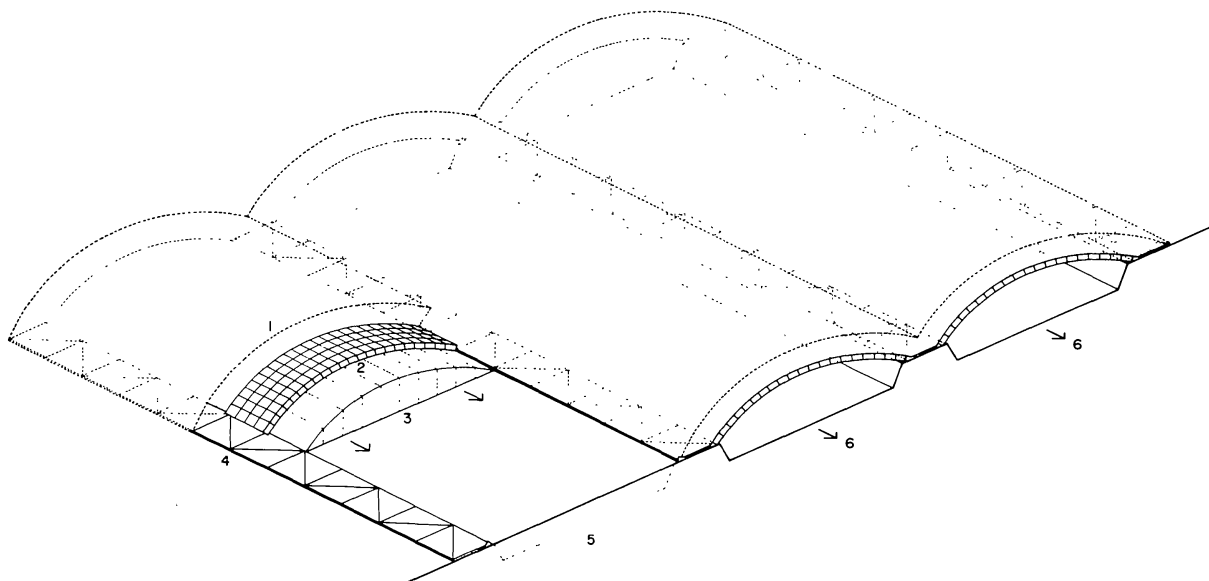


Figure 3. BASE CONCEPT II. Low arch shield using moulded regolith components assembled over temporary, movable pneumatic support form, pressurized enclosures beneath. General view of base. (1) Regolith shielding. (2) Interlocking, moulded regolith arch components. All components identical dimensions. (3) Movable pneumatic form supporting arch assembly. (4) Aluminum lattice girders to accommodate outward thrust of arches. Girders assembled flat on surface with short components and anchored to surface with vertical pins or connected with transverse cables at convenient, widely space intervals. (5) Height increased where required by excavation. (6) Expansion.

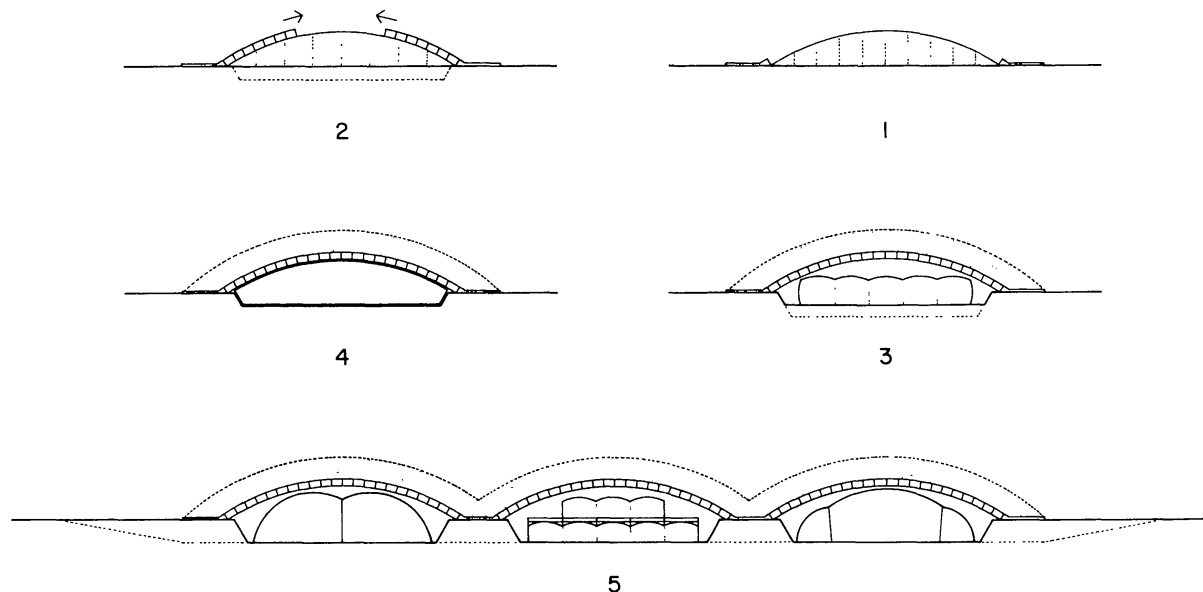


Figure 4. BASE CONCEPT II. (See Fig. 3). (1) Inflated arch support form. (2) Interlocking, moulded regolith arch components laid over inflated form. (3) Regolith pushed over arch, pneumatic support form removed, excavated underneath where required by dragline scoop and pressurized enclosures erected. (4) Alternative pressurized enclosure using hermetic membrane applied to inner surface of shield. (5) Interconnected arch shields with range of pressurized enclosures.

The thrust of the arch is horizontal and is accommodated by two aluminum lattice girders conveniently assembled from short sections flat on a level surface, one on each side of the arch. The girders are anchored by pins driven into the lunar surface or by transverse connecting cables. All the girders are conveniently deep, and cables can be widely spaced. As in the first concept, initial sections of the arch can be quickly assembled using terrestrially manufactured components to provide immediate radiation protection. These components could be of folded aluminum or plastic with a profile that permits "nesting" for compact and economic transportation.

The weight and size of the prestressed floors and compression arch shield structures using moulded regolith components will be determined by the lifting capacity of one or two persons or equipment, as well as the moulding technique. The design of the components will employ a thin-rib, deep-section configuration to maximize stiffness and minimize weight. Components will be interlocking both transversely and longitudinally and self-aligning under stress. They will be manufactured in a lunar plant from presorted regolith, formed accurately to the required configuration through moulding, either by firing to the necessary temperature for sintering and surface sealing using a direct solar or electrical furnace, or by using a double-mix epoxy or portland-type cement to bond regolith aggregates.

#### Low Arch Shield with Pneumatic Support Structure (Fig. 5)

In this concept, a pneumatic structure permanently supports the regolith. The deflated structure is laid on a leveled surface, regolith is pushed over, and the structure is inflated.



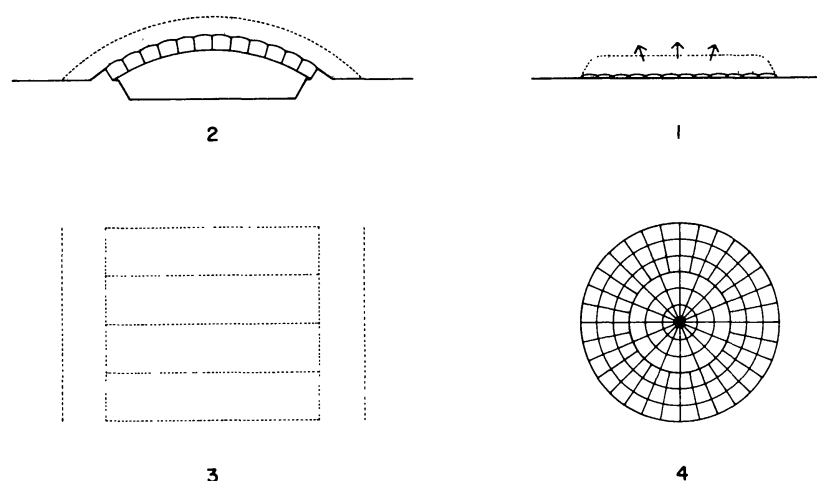


Figure 5. BASE CONCEPT III. Low arch shield with pneumatic support structure. Deflated pneumatic hybrid structure flat on ground, regolith pushed over. (2) Structure inflated, raising the regolith, afterwards evened out or thickened where necessary. (3) Plan showing the concept applied in sections for a continuous low arch shield. (4) Plan showing concept applied in a low, domed shield.

The raised regolith is evened out afterward or thickened where necessary. The upper surface of the structure is ribbed to anchor into the regolith. This concept can be applied in sections to form a continuous low arch or a single domed structure.

## ARCHED AND DOMED SHIELD SUPPORT STRUCTURES

Arches or domes must be fairly flat since regolith cannot be placed on curved sides that rise too vertically. The dome form can be erected without supporting formwork for most, but not all, of its height, if the courses are raised equally all around the perimeter. However, this dome form must be almost a hemisphere with steep sides that are difficult to cover and that have excessive middle height, making it inconvenient to use. Another considerable disadvantage of the dome is that many components (a dome will have thousands) will have different dimensions, greatly complicating component moulding. In contrast, the low arch form would have only slightly inclined sides, so that regolith can be easily pushed over it, and all building components are dimensionally identical. Also, the arch form can be very conveniently expanded lengthwise.

## PRESSURIZED ENCLOSURES AND PNEUMATIC STRUCTURES

Pneumatic structures under shielding canopies can be of three types: air supported, air inflated, and hybrid. Each would need to be evaluated for lunar application. The *air-supported* structure has one structural membrane supported by the push of internal pressure. The *air-inflated* structure has beams, columns, and arches that are independently pressurized and that support membranes between them. The two concepts are combined in *hybrid* structures making this type particularly attractive for lunar applications. Cable mesh containment technique gives the advantage of special shaping and additional membrane support for accommodating higher stresses in the lunar vacuum environment. Rigid elements could be incorporated in the membranes to obtain stiffening, flattening, curving, sealing, mounting, etc.

Pneumatic structures have good potential for lunar application in combination with shielding canopies, especially for the initial building thrust after the post-camp stage.

They are small in volume and light in weight, can be formed in a wide range of shapes, and can provide environments at a range of pressures. A great deal of design work and technical experience covering work done over more than 40 years is available in this specialized technology area. Since about 1950, thousands of small and large structures have been erected in many countries for many uses. Recent advances in flexible plastic material with very high strength/weight ratios make pneumatic structures particularly attractive for lunar application under radiation shielding.

## **SUNKEN AND BERMED STRUCTURES**

These could accommodate smaller spans and spaces of the lunar base. To avoid the need for a heavy conventional excavator, lightweight equipment must be fully evaluated, particularly dragline techniques. In a lunar application a dragline would consist of continuous cables with attached scoops running over one motorized and one free vertical capstan. The dragline would run continuously with minimum attendance to excavate trenches of any depth or width. Shielding platforms of any of the types discussed would be erected in the trenches and the loose regolith pushed over to the required thickness. Pneumatic structures would afterwards be inflated beneath the platforms. The use of dragline technique would suggest a linear base arrangement, and the powered capstan could afterward be used as a transportation spine and system.

Each of these concepts has merits and weak points. The design that combines regolith directly on a pneumatic support structure has the disadvantage that if a reduction in pressure is experienced, the shield will drop and crush the contents underneath. There is the risk of failure in the other proposals, but independent, pressurized enclosures may protect their contents and support a failed shield.

## **SOLAR SHADING CANOPIES**

Canopies are proposed to create partial or complete shade over walkways or vehicular driveways linking different parts of the base that for safety or functional reasons must be separated from the main base shield. A horizontal canopy would give total shade at lunar noon. Temperature in the canopy shade would depend upon the width of the canopy, since radiative thermal transfer or conduction via the ground will occur at the edges. Solar shade with low temperature means that personnel moving under the canopies by walking or vehicle need not be suited for cooling, but only for pressure.

Canopies might be perforated with small holes to permit the passage of some light as a fine pattern. This would slightly raise the temperature of any intercepting surface, the intensity depending upon the size of the perforations in the canopy.

The feasibility of lightweight, portable or mobile shading canopies must be studied. These could be placed on the lunar surface where and as required: for servicing the plant, vehicles, mining operations, construction, *etc.* Personnel working on these tasks could possibly have more freedom of movement and greater work range and duration with lighter suits.

## **SERVICE STATIONS**

The distance a person can travel will be limited by radiation exposure time on the lunar surface. Any long distance travel by relatively slow moving vehicles is difficult to envisage. To undertake long distance movement, shielded service stations must be built at strategic spacing for radiation-free resting and sleeping environments, supplies, servicing, *etc.* They would also offer emergency shelter at the time of increased radiation that comes with solar flares, generally predictable in advance, for persons some distance from the main base. Ideally, surface vehicles for long distance travel must be developed with radiation shielding.

## **SOLAR ORIENTATION**

This might be a very important determinant in the layout of the base, or parts of it. As the sunsets and sunrises are relatively long and low-angled, energy build-up on vertical or steeply inclined surfaces might be considerable; this problem should be studied in base layout and design. Entrances and external operational edges of the complex should be orientated away from the sun to minimize temperatures at these points. Also, vertical surfaces, perhaps in combination with horizontal ones, could be developed to provide shade where needed.

## **INTERIOR ENVIRONMENT**

The psychology of interior space and treatment in sealed environments is an important aspect of the base design. The mental stability and vitality of base inhabitants is an essential factor and will be influenced by interior design. Experience from sealed environments, such as in submarines, some industrial complexes, tunnels, *etc.*, must be fully evaluated for possible application in the lunar context.

## **RESEARCH AREAS**

If the lunar base is to be on line by 1995, research and development must be initiated in the near future. The main technology and engineering issues generated by the base concepts and for which terrestrial based testing, development, and research work must be done include the following:

1. Regolith should be tested for moulding building components using heat, sintering, and sealing. Lunar-based experiments are needed for a simple solar furnace.
2. Regolith moulding using bonding agents and cementitious materials such as portland cements and double mix epoxies needs testing in terrestrially based vacuum experiments.
3. Regolith potential for glass and ceramic building materials should be determined. Increased strength of materials in an anhydrous lunar environment should be evaluated.

4. Degradation of materials in a lunar environment should be studied, especially in such materials as plastic, including Kevlar, Teflon, and adhesives, and in metals, in particular, aluminum variants. There is a need for radiation/vacuum exposure experiments.

5. Physical movement of materials following wide diurnal temperature changes should be tested, as should regolithic ceramic-based components, plastics, *etc.*

6. The shape and size of components for compression arch shields and their assembly should be modeled and tested, along with interlocking joints and component profiles.

7. The shape and size of components for prestressed flat shields and their assembly should be modeled and tested.

8. Pneumatic, pressurized envelopes in a wide range of shapes and sizes using Kevlar, Teflon, and steel cable materials should be tested. Net as a structural element, containing and shaping an internal pressure membrane, could be researched. A technique for generating a range of shapes should be developed.

9. The initial stage of the base and community layout should be planned for expansion. Options should be diagrammed and analyzed.

10. The influence of transportation on community layout should be studied, with emphasis on a linear transport route for moving people and goods, shielded or unshielded, pressurized or not. Connections to other parts of the base could be diagrammed and options analyzed.

11. The influence of solar orientation on community layout should be tested with models and a solar simulator. Glare and thermal gain must be minimized.

12. Shaded canopies linking separate parts of the base should be modeled and tested with a solar simulator. Both vertical and horizontal shades should be studied; perforated shades should also be studied.

13. Trenching methods for excavation should be studied using dragline techniques: a rotating cable with scoops travelling around two or more surface capstans. Its influence on base layout and possible later use for transport should be considered.

14. Inside/outside air-lock/valve design for equipment and vehicles as well as individuals should be researched with attention to physical convenience, dust filtration, pressure leaks, and various sizes.

15. The psychological aspects of interior design should be studied, since emotional stability can be influenced by human-related dimensions, color, textures, *etc.*

## **FORM AND FUNCTION IN LUNAR BASE DEVELOPMENT**

Functional considerations will determine the width, height, span, and areas of the various functional components of the lunar base (which need to be more precisely defined). As yet, we do not have specifications and dimensions for the range of anticipated base functions. A small base planning group should be formed to work in close collaboration with all specialized areas of the lunar base group to determine the dimensional characteristics of the base functions with their environmental and servicing needs. The functional inventory will influence the base design, but the ultimate design will also be affected by the building system and shape(s) decided upon.

As far as can be estimated, some large-span enclosures will be needed for the servicing and/or assembly of large pieces of equipment, including lunar surface and spacecraft, telescopes, *etc.* However, the major part of the base could probably be interconnected spaces of fairly small dimensions that would still be much larger than camp stage modules and more economic to erect and maintain. Therefore, both large- and small-area units must be considered.

Although the post-camp stage objective is ultimately to develop an entirely lunar-based construction capability, this would be difficult in the beginning. Structures for radiation shielding will use lunar regolith, but pressurization will generate tensile forces that cannot be handled by first generation regolith processing, such as the fabrication of relatively simple ceramic/glass block components. Nevertheless, structures with floor areas larger than those provided inside imported camp stage modules must be erected as soon as possible.

At a later phase in the evolution of the lunar base, shielding and pressurization might be combined in structures entirely fabricated from regolith. However, this would occur after the base has a fairly large combined floor area to house the necessary plant with workshop capability. A second generation building system combining pressurization with shielding, using regolith in a rigid system, must be able to accommodate tensile stresses generated by pressurization and temperature movement. Speculation on second generation structures suggests a flat or almost flat upper surface to support regolith shielding. Curved forms can better handle pressurization, but loose regolith cannot be heaped onto the steeply inclined surfaces of some curved forms. Outer skirt walls under flat or arched shields must be able to accommodate tensile stresses resulting from the outward push of pressurization. The way this will be done depends upon the manner in which the regolith is used. Skirt wall panels using interlocking ceramic components can be prestressed vertically; panels using cements or epoxies as bonding agents with regolith aggregates could also employ short filament glass fibres for reinforcement within the mix. Sealing between panels could be provided by adhesive tapes applied internally and kept in position by outward pressure.

As mentioned at the beginning of this paper, impressions of some lunar bases presented over the past few years suggest enormous technical problems. The designs and options presented by this author indeed reveal technical unknowns. However, the required information and solutions can be obtained through research and development, some main areas of which have been outlined. These indicate that an integrated program of planning, research, and design can lead to the building of a lunar base within an optimum time frame.

# **A SURFACE-ASSEMBLED SUPERSTRUCTURE ENVELOPE SYSTEM TO SUPPORT REGOLITH MASS- SHIELDING FOR AN INITIAL-OPERATIONAL- CAPABILITY LUNAR BASE**

**Jan Kaplicky and David Nixon**

***Future Systems Consultants, 1103 South Hudson Avenue, Los Angeles, CA 90019***

---

The early deployment of a lunar base in the form of a manned research outpost and habitat could be aided by potential savings of time and money achieved through the use of direct derivatives of module types being developed for the space station. These would be grouped as a complex at lunar surface level. To achieve solar flare radiation protection, the complex would require shielding, which could be provided by an elevated superstructure envelope that would support the required depth of regolith mass. This preliminary design concept examines a typical configuration for a simple and economical superstructure envelope as a prelude to detailed investigations into different design options, their characteristics, and performance criteria.

## **PURPOSE**

The deployment and occupation of a manned lunar base following selection of a suitable lunar surface location may well be the next logical step beyond the space station in terms of both scientific research and space commercialization. The chances of an early manned presence on the lunar surface might be improved if the extensive technology developed for the space station could also be used to develop an Initial-Operational Capability (IOC) lunar base in advance of permanent and fully manned facilities. Such a base may be operated initially as a Phase II facility, gradually evolving into a Phase III facility (Duke *et al.*, 1985). One area where direct transfer of technology is possible is in the provision of crew living quarters and working facilities. The design of these could be based on the habitation, logistics, and laboratory modules developed for the space station with modifications for lunar surface application, including fitting out for one-sixth gravity operation. This approach could save considerable time and money, allowing attention and funding to be focused on the development of an Earth-to-Moon space transportation system that will be needed for advanced base construction, manning, and operation.

## **DESIGN CONCEPT**

A program for a lunar base, which might initially aim to provide a research outpost and living habitat for up to six persons, might take the form of surface deployment and linkage of a series of modules grouped into a complex. This complex would comprise

habitation, logistics, and laboratory modules derived from the three generic types being developed for the IOC space station in 1993. A pressurized construction workshop module and unpressurized pilot oxygen production plant module would also be required.

A major obstacle to the utilization of space station modules for an early base appears to be the difficulty of providing rapid and permanent protection against solar flare radiation and mini/micrometeoroid impact if the modules are deployed on the surface. The concept of protecting modules by burying them beneath 2 m of lunar regolith would not be feasible, since the superimposed loading of regolith on outer module surfaces would be likely to reach figures in excess of  $5000 \text{ N/m}^2$  (taking into account regolith volume weight in one-sixth lunar gravity and minimum 2 m depth of material required).

This figure would almost certainly be incompatible with the proposed thin, pressure-hull construction of the space station common module identified in the Space Station Reference Configuration Description issued by NASA (Space Station Program Office, 1984). Were it to be possible, once buried, module exteriors would be inaccessible for inspection and maintenance. Base complex reconfiguration and modification—which might involve module, utility, or environmental control, and life-support system repositioning, repair, or upgrading—would also become extremely difficult.

To solve these problems and avoid the need for extensive or deep excavations, it would be possible to develop a simple, manually deployable, superstructure envelope to enclose the module complex at lunar surface level and provide the necessary shielding by means of a “stand-off” layer of regolith deposited over the upper surface of the envelope. This would provide full protection to modules and any external environmental control and life-support system equipment while leaving space around the modules clear for access, circulation, or additional growth. Such an envelope system could be manufactured from a standardized and simplified “kit-of-parts” and transported to the lunar location in stowed form by an Earth-to-Moon transportation system for on-site construction by mission specialists.

Several design configurations for an envelope of this type are possible. This outline design concept describes a typical configuration based on a simple, rectangular plan capable of providing protection for six modules, each nominally 10 m in length and 4.5 m in diameter. The concept is schematic and is intended as a prelude to detailed investigations into complex grouping alternatives, structural design, load characteristics, and material properties.

## STRUCTURE AND MATERIALS

The overall envelope is configured as a shallow, flat-topped mound of loose regolith supported by a continuous tension membrane connected to a regular grid of telescopic columns and tapered beams beneath. The column and beam grid delineates the volume occupied by the module group. Physical access would be provided at both ends, which would be left open with suitable allowance for protective overhangs. Beams and columns would be based on an orthogonal grid of structural bays of  $5 \times 2 \text{ m}$ -size each with the 5-m beam span straddling the girth of the modules, and with an internal clear height

of 5 m. A series of high-tensile, fine-mesh membranes would be stretched between the beams to provide support for the regolith mass above, with mesh bays experiencing controlled convex billowing under load. The mesh would be made of woven graphite fiber, sized to allow deposit of approximately 1 mm regolith grain-size upwards. Regolith would be deposited over the previously erected envelope by a manually remote-controlled mobile conveyer system designed to deliver loosely compacted material on a bay-by-bay basis.

Vertical columns and angled beams would be fabricated from advanced composites, which would be derived from graphite/epoxy or similar technology developed for the space station's deployable truss structure. Each column would be connected to a circular footpad to spread the superimposed load over the ground surface, estimated to be in the region of 55,000 N compressive load per column, assuming a  $5 \times 2$  m clear bay size (the minimum feasible bay size that would work with module complex group dimensions). Columns would be designed as telescopic tubes to facilitate low preassembly of all beams to columns at node points and mesh membrane captive attachment to all beam edges. With main beams spanning 5 m in a lateral direction (side-to-side), short 2-m length struts would be needed to provide support to the frames at right-angles to the beam lines in a longitudinal direction (end-to-end). These would typically be spaced at 2.5-m intervals. Cross-bracing would also be required to provide longitudinal stiffening.

Assuming that a Lunar Base IOC would require the provision of shielding for up to six modules (together with access, circulation, and some exterior-mounted environmental control and life-support system equipment), the total plan area of the envelope would amount to approximately 546 m<sup>2</sup>. This plan assumes that the minimum feasible protected area comprises a rectangular plan of 26 m end-to-end and about 21 m side-to-side, allowing the emplacement of two rows of three modules each, with modules located side-to-side and pointing in the longitudinal direction toward the open ends of the envelopes, as shown in Figure 1. This configuration would require a basic component schedule that would include 56 telescopic columns, 84 footpads, 70 main beams, 143 lateral struts, and 65 woven mesh membrane panels. Preliminary (and very approximate) estimates suggest a diameter of about 125–150 mm for the outermost tube of the telescopic columns,  $300 \times 75$  mm describing the mean section profile of main beams, 75 mm diameter struts and cross-braces, and 500–750 mm diameter footpads. The actual footpad diameter would be determined by the ground-bearing strength condition in the selected location; it is based on the assumption that loosely compacted surface regolith would be removed to expose densely compacted material capable of achieving a reasonable bearing pressure.

## **MANUFACTURE, TRANSIT, AND ASSEMBLY**

The manufacture and evaluation of the superstructure envelope system would take place in a 1 g environment on Earth, destined for a one-sixth g environment on the Moon. This would enable the system to be fully preassembled and load-tested in a simulated lunar setting using a dry sand-based aggregate mix to represent the lunar regolith shielding.



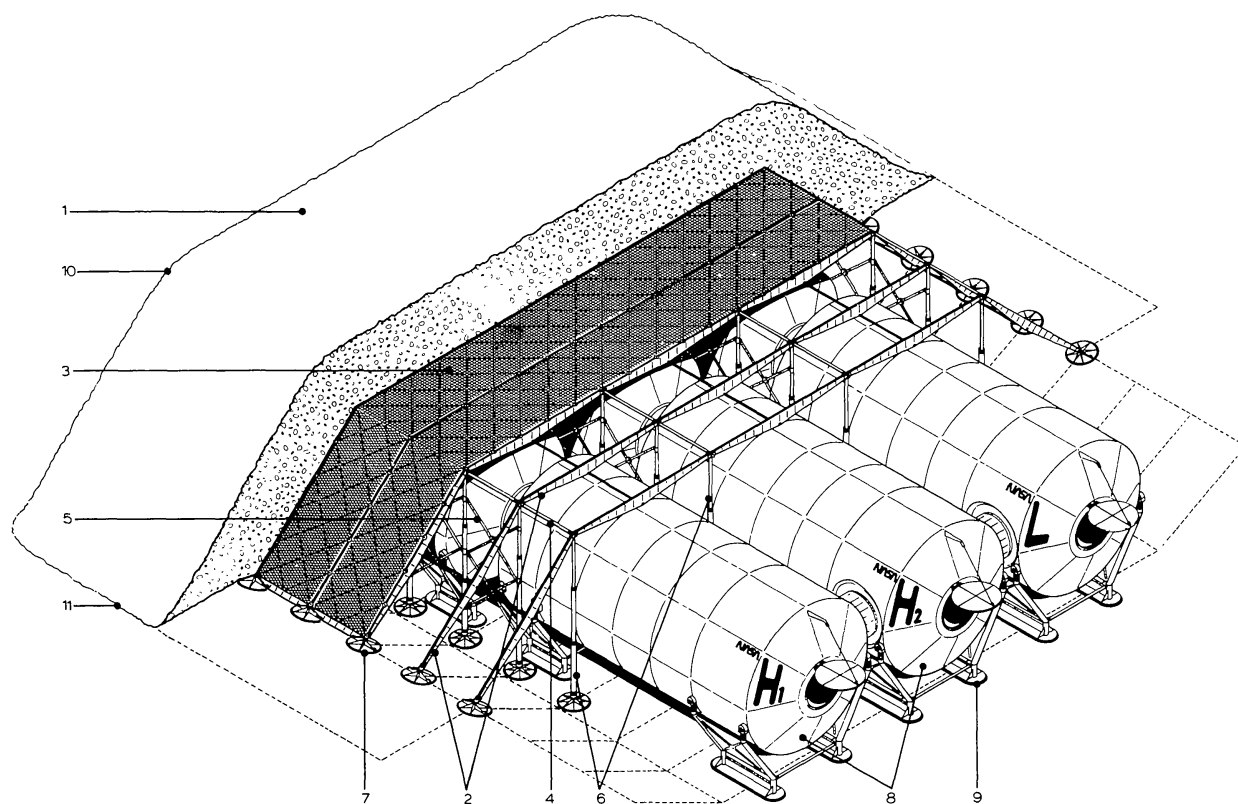


Figure 1. Cutaway illustration of superstructure envelope system: 1—regolith mass shielding; 2—main tapered beams; 3—graphite fiber mesh; 4—longitudinal struts; 5—longitudinal bracing; 6—telescopic tubular columns; 7—circular footpads; 8—linked habitat/laboratory/workshop modules; 9—module ground support cradles; 10—crest of slope; 11—base of slope.

As with the Apollo missions, it would be possible to test most lunar surface operations in a terrestrial environment beforehand. This would apply to the entire construction sequence of the envelope system: unpacking, layout, assembly, hoisting, leveling, tie-down, regolith deposition, and possibly even module insertion and interconnection.

The fully stowed envelope system, complete with tools and accessories, would be delivered to low-Earth orbit by the shuttle, with transit from low-Earth orbit to lunar surface by means of an Earth-to-Moon transportation system. Preliminary outline estimates of material/component weights indicate that the complete system would amount to 5000–7500 kg launch weight and be capable of being stowed in a volume equivalent to a cylinder measuring 5.5 m long by 2.5 m in diameter, thus enabling its conveyance in a single mission. Another mission would convey a lunar tractor (or similar vehicle), which would be required to move the lunar base modules from their soft-landed locations to the selected lunar base site, as well as the mechanical conveyer system required to transfer surface regolith from the lunar base environs to the upper surface of the envelope canopy. As with the proposed space station assembly, each manned module would require a single dedicated mission.

Once all equipment were brought to the lunar base location, the superstructure envelope would be erected in a predetermined sequence by a team of mission specialists. This would proceed after loose surface regolith clearance and excavation. All beams, struts, columns, and footpads would first be assembled at "shoulder" level (*i.e.*, at the height determined by the top of the outermost telescopic column tube prior to extension), followed by attachment of the mesh membrane panels. Each structural bay would then be raised to the correct height, working from one end of the envelope to the other, using manually operated screws and crank handles. After leveling, tightening, and anchoring down, regolith deposition would be carried out, and the superstructure envelope would be ready for module insertion, interconnection, and subsequent lunar base operation.

### CONTINUATION OF RESEARCH

Essentially, the concept outlined in this paper represents a simple "elevated-bunker" approach to providing mass shielding for a lunar research outpost and habitat, as shown in Figure 2. Several design variations are possible, depending on module complex grouping, local ground conditions, and logistics considerations.

The central point, however, is that a system of this type could provide a rapid and efficient means of surface protection for an early manned presence and is therefore well

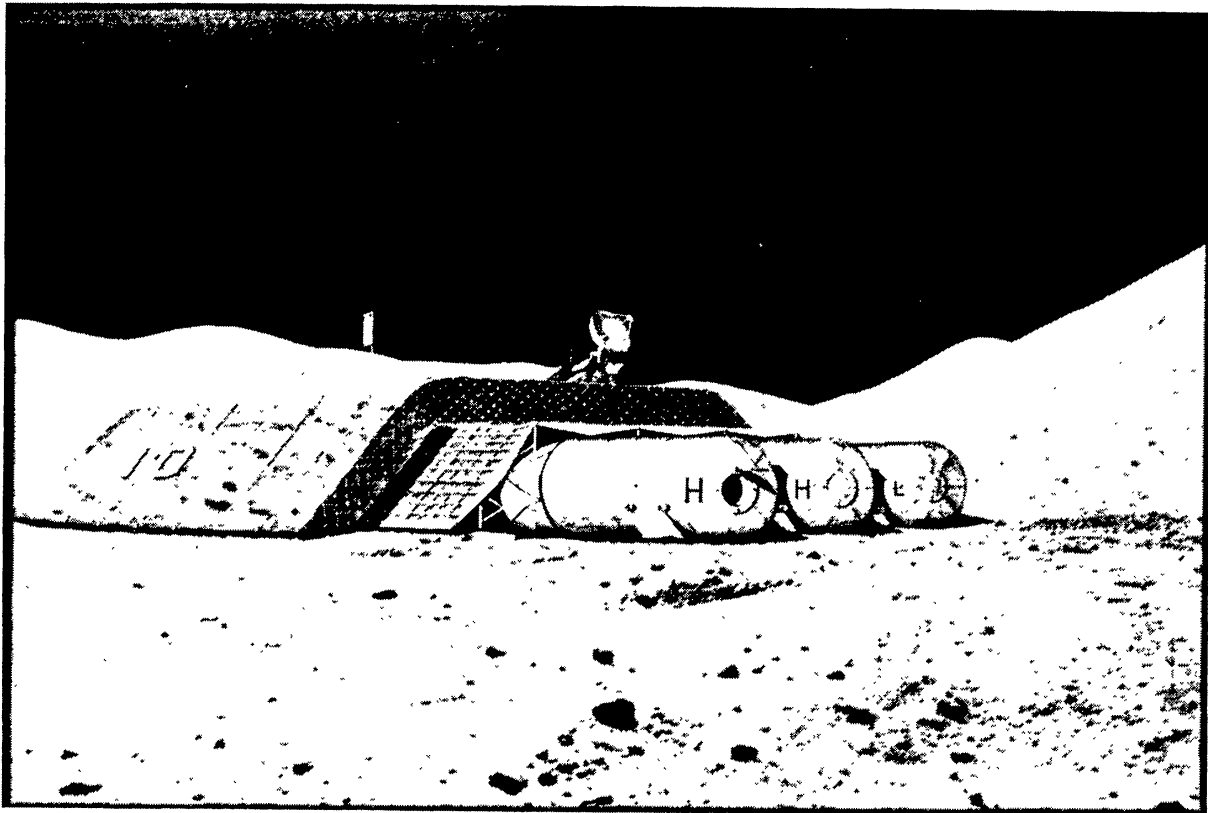


Figure 2. View of the lunar base from the surface, showing system construction.

worth further investigation. Although the use of modified space station modules may be the most logical and economical solution to providing habitable facilities, an elevated envelope system of the type discussed in this paper could be applicable to other lunar base habitat options, including an advanced lunar base community covering a large surface area. These reasons clearly point to the need for further research on the design concept. In the future, the authors plan to address the following issues in particular. (1) Investigation of the range of static and dynamic (seismic/impact) loads to which the structural system would be subject, based on known lunar regolith mass properties. (2) Analysis of the range of forces and stresses imposed on all structural members comprising the system, in accordance with preliminary element and component detailed design and physical material properties. (3) Organization of data generated in (1) and (2) into a representative criteria set that could form guidelines for a preliminary lunar structural design code. (4) Detailed investigation into activities and phasing implicit in the entire logistics sequence including, in serial order, the following: system prototyping, manufacture, testing and simulation, stowage, Earth-to-Moon transportation, lunar surface retrieval, unpacking and layout, low-assembly, hoisting, leveling and tightening, anchoring and tie down, and, finally, regolith deposition.

## REFERENCES

- Duke M. B., Mendell W. W., and Roberts B. B. (1985) Towards a lunar base programme. *Space Policy*, 1, 49-61.
- Space Station Program Office (1984) *Space Station Reference Configuration Description*. JSC 19989, NASA/Johnson Space Center, Houston. 798 pp.

# CONCRETE FOR LUNAR BASE CONSTRUCTION

**T. D. Lin**

***Construction Technology Laboratories, The Portland Cement Association,  
5420 Old Orchard Road, Skokie, IL 60077***

---

Prior to the establishment of lunar scientific and industrial projects envisioned by the National Aeronautics and Space Administration, suitably shielded structures to house facilities and personnel must be built on the Moon. One potential material for the construction is concrete. Concrete is a versatile building material, capable of withstanding the effects of extreme temperatures, solar wind, radiation, cosmic rays, and micrometeorites. This paper examines data published by NASA on lunar soils and rocks for use as concrete aggregates and as possible raw materials for producing cement and water, and investigates the technical and economic feasibility of constructing self-growth lunar bases. A hypothetical 3-story, cylindrical concrete building with a diameter of 210 ft (64 m) was analyzed for conditions of a vacuum environment, lunar gravity, lunar temperature variations, and 1 atmosphere internal pressure. The advantages of concrete lunar bases are subsequently discussed.

## INTRODUCTION

A project proposed within the National Aeronautics and Space Administration to build permanent lunar bases after the turn of the century has drawn tremendous interest from scientific and engineering communities across the nation. Lunar bases will enable mankind to extend civilization from Earth to the Moon. Ample solar energy, low gravitational force, and abundant minerals on the Moon will provide excellent conditions for the development of scientific and industrial space activities. Prior to the establishment of these activities, suitably shielded lunar structures must be built to house facilities and to protect personnel from the effects of solar wind, radiation, cosmic rays, and micrometeorites.

As a material capable of withstanding these effects, concrete is proposed for construction and can be produced largely from lunar materials. This discussion covers the process of making cement from lunar material, concrete mixing in a lunar environment, physical properties of concrete at lunar surface temperatures, and structural design suitable to lunar conditions.

## CEMENTITIOUS MATERIALS

Cements used in construction on Earth are made basically with raw materials such as limestone, clay, and iron ore. A burning process transforms the raw materials into primarily calcium-silicate pebbles called clinker. The clinker is then ground into micron-sized particles known as cement. A wide variety of cements are used in construction. The chemical compositions of these cements can be quite diverse, but by far the greatest amount of concrete used today is made with portland cements. A typical portland cement

(Mindess and Young, 1981) consists of about 65% calcium oxide (CaO), 23% silica (SiO<sub>2</sub>), 4% alumina (Al<sub>2</sub>O<sub>3</sub>), and small percentages of other inorganic compounds. Among these constituents, calcium oxide is the most important in the cement manufacture.

Other types of cements produced with lower calcium oxide content are available, e.g., slag cement, expansive cement, alumina cement, and low calcium silicate cement. High alumina cement has 36% calcium oxide while low calcium silicate cement has only 30% (Takashima and Amano, 1960). Theoretically, a cementitious material can be made with any proportion of CaO:SiO<sub>2</sub>:Al<sub>2</sub>O<sub>3</sub> that falls within the calcium-silica-alumina phase diagram.

## LUNAR MATERIALS

Information from Apollo lunar soils and rocks indicates that most lunar materials consist of sufficient amounts of silicate, alumina, and calcium oxide for possible production of cementitious material. Table 1 shows the chemical compositions of some selected lunar samples (Morris, 1983; Ryder and Norman, 1980; Fruland, 1981). It appears that the content of calcium oxide in lunar material is relatively low in comparison with other major cement ingredients; our discussion, therefore, will center around the calcium oxides.

Table 1. Chemical Compositions of Selected Lunar Samples

Element	<i>Major Elements, wt %</i>				
	Mare Soil (10002)	Highland Soil (67700)	Basalt Rock (60335)	Anorthosite Rock (60015)	Glass (60095)
SiO <sub>2</sub>	42.16	44.77	46.00	44.00	44.87
Al <sub>2</sub> O <sub>3</sub>	13.60	28.48	24.90	36.00	25.48
CaO	11.94	16.87	14.30	19.00	14.52
FeO	15.34	4.17	4.70	0.35	5.75
MgO	7.76	4.92	8.10	0.30	8.11
TiO <sub>2</sub>	7.75	0.44	0.61	0.02	0.51
Cr <sub>2</sub> O <sub>3</sub>	0.30	0.00	0.13	0.01	0.14
MnO	0.20	0.06	0.07	0.01	0.07
Na <sub>2</sub> O	0.47	0.52	0.57	0.04	0.28

A review of available literature on Apollo lunar samples reveals that a typical mare soil has a CaO content of nearly 12% by weight, highland soil 17%, basalt rocks 14%, and anorthosite rocks, a calcium-rich plagioclase in the feldspar group, almost 19%. A rock type with 19% CaO content is a good candidate for lunar cement production. Lunar sample 60015, a coherent, shock-melted anorthosite rock, is an example. The rock is approximately 12 × 10 × 10 cm and is largely coated with a vesicular glass up to 1 cm thick, as shown in Fig. 1. The glass layer has been interpreted as a quenched liquid derived from melting the surface layer of the anorthosite rock. Quenched glass generally is an amorphous substance and represents a potential cementitious material if ground to fine particle size.



*Figure 1. Pristine cataclastic anorthosite glass-coated sample 60015.*

Glasses are common in lunar soils. Table 2 shows the averaged glass contents in lunar samples brought back by the Apollo missions. Note that samples taken from Shorty Crater rims have glass content as high as 92.3%. The chemical compositions of glass could possibly be similar to glass sample 60095 shown in Table 1.

Table 2. Average Glass Content of Lunar Samples

Mission	Average Glass Content, %
Apollo 11	6.6
Apollo 12	18.0
Apollo 14	12.2
Apollo 15	29.4
Apollo 16	10.6
Apollo 17	31.1

## PROCESS METHODS

Figure 2 shows condensation temperatures of various elements in basalt rocks (Wood, 1975). Interestingly, all cementitious elements including Ca, Al, Si, Mg, and Fe have condensation temperatures about 1400 K, at least 200° higher than those of non-cementitious elements. This unique physical property may enable us to separate cementitious elements from non-cementitious ones in the process of cement manufacture.

However, a temperature of 3000 K or higher will be needed for the elemental evaporation in the process. This may cause some degree of difficulty in finding suitable material for containment use.

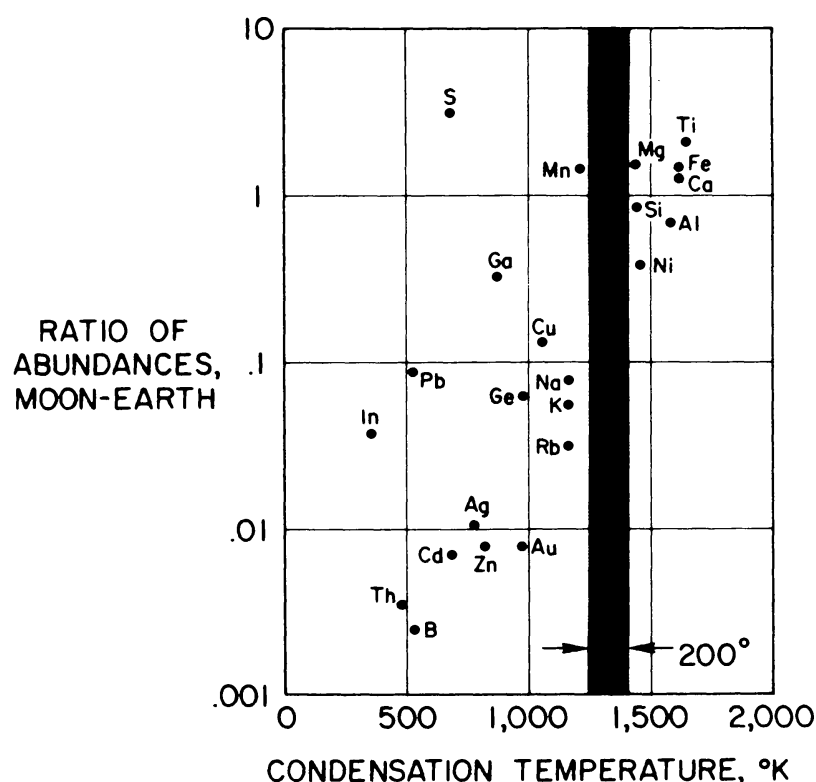


Figure 2. Condensation temperature of basalt minerals.

Figure 3 shows residual fractions of multicomponent melt consisting of FeO, MgO, SiO<sub>2</sub>, and Al<sub>2</sub>O<sub>3</sub> of solar elemental abundances during the evaporation process at temperatures up to 2000°C (Hashimoto, 1983). The complete evaporation of FeO in Stage I may be utilized for metallic iron beneficiation. The remaining residues in Stage IV have high concentrations of CaO and Al<sub>2</sub>O<sub>3</sub> and a small amount of SiO<sub>2</sub>. Calculated CaO:Al<sub>2</sub>O<sub>3</sub>:SiO<sub>2</sub> proportions of the combined residues at lines A and B of Fig. 3 fall in the stoichiometric range of commercial high alumina cement (Lea, 1971).

## AGGREGATES

Aggregates generally occupy about 75% by weight of the concrete and greatly influence concrete properties. Aggregates, according to American Standard for Testing and Materials (ASTM), are not generally classified by mineralogy. The simplest and most useful classification is based on specific gravity. Lunar soils and rocks all have specific gravities higher than 2.6 and are believed to be quality material for aggregate use. To produce concrete on the Moon, lunar rocks can be crushed to suitable coarse aggregate size, and the abundant lunar soils can be sieved to good gradation of fine aggregates.

Glassy soils used as aggregates may develop alkali-aggregate reactions that could cause the concrete to crack or spall. The lunar materials have never been exposed to oxygen and water, and the chemical and physical stability of these materials when exposed to water are not yet fully known. Research on lunar soil for possible aggregate application is indeed important.

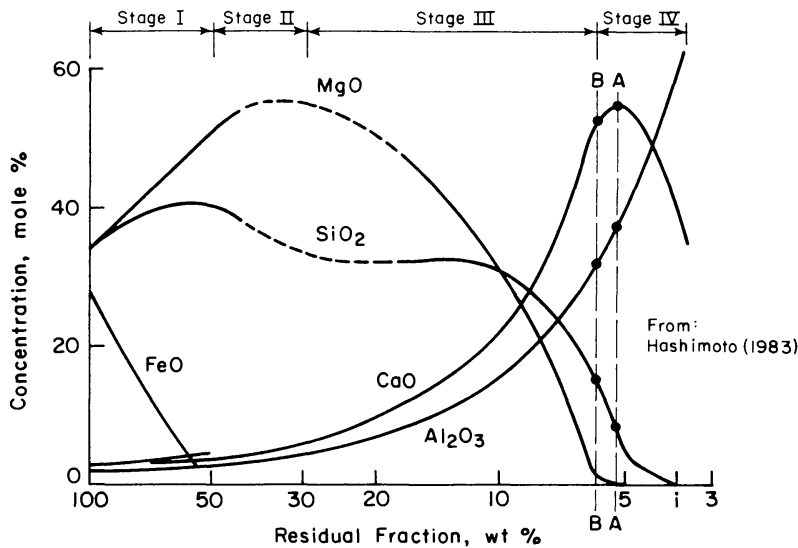
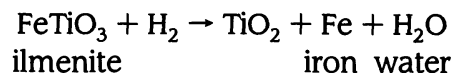


Figure 3. Change of composition of residual molten oxide material as a charge is vaporized away into a vacuum, at 2073 K.

CHEMICAL COMPOSITION, WEIGHT PERCENT			
Compound	Solar Elemental Abundances		Alumina Cement
	@ A-A	@ B-B	
CaO	42.7	40.0	36-42
Al <sub>2</sub> O <sub>3</sub>	52.3	48.8	36-51
SiO <sub>2</sub>	5.0	11.0	4-9

## WATER PRODUCTION

There have been studies on oxygen and metal production using lunar materials. Proposed methods include an alkali-hydroxide-based scheme (Cutler, 1984), hydrogen reduction of ilmenite (Agosto, 1984), and others. The ilmenite reduction reaction yields iron and water.



Hydrogen is not readily available on the Moon and may have to be imported from Earth. The terrestrial hydrogen can be transported in the form of liquid hydrogen (H<sub>2</sub>), methane (CH<sub>4</sub>), or ammonia (NH<sub>3</sub>) (Friedlander, 1984). In considering the need for carbon and nitrogen for life support and the higher boiling points of methane at -322°F (-161°C) and ammonia at -91°F (-33°C) than liquid hydrogen at -426°F (-252°C), it may be more advantageous to import methane and ammonia to the Moon rather than liquid hydrogen.



## REINFORCED CONCRETE

Concrete is basically a mixture of two components: aggregate and cement paste. The paste, comprised of cement and water, binds the aggregate into a rock-like mass as it hardens.

The flexural strength of plain concrete is generally low, about one-tenth of its compressive strength. However, concrete reinforced with either steel or glass fibers has increased flexural strength, strain energy capacity, and ductility. Test data reveal that concrete reinforced with 4% by weight of steel fibers possesses nearly twice the flexural strength of plain concrete (Hanna, 1977). These fibers act as crack arresters, that is, the fibers restrict the growth of microcracks in concrete.

## STRUCTURAL DESIGN

Design of structures for a lunar base differs from design of structures on Earth. First, there are no wind and earthquake loads on the Moon. Second, the lower lunar gravity, one-sixth that of Earth, could permit an increase in the span length of a flexural member to 2.4 times, based on the flexural theory of a simply supported beam.

Figure 4 shows a proposed three-level concrete structure with a diameter of 210 ft (64 m). The structure is assumed to be subjected to 1 atmosphere pressure inside

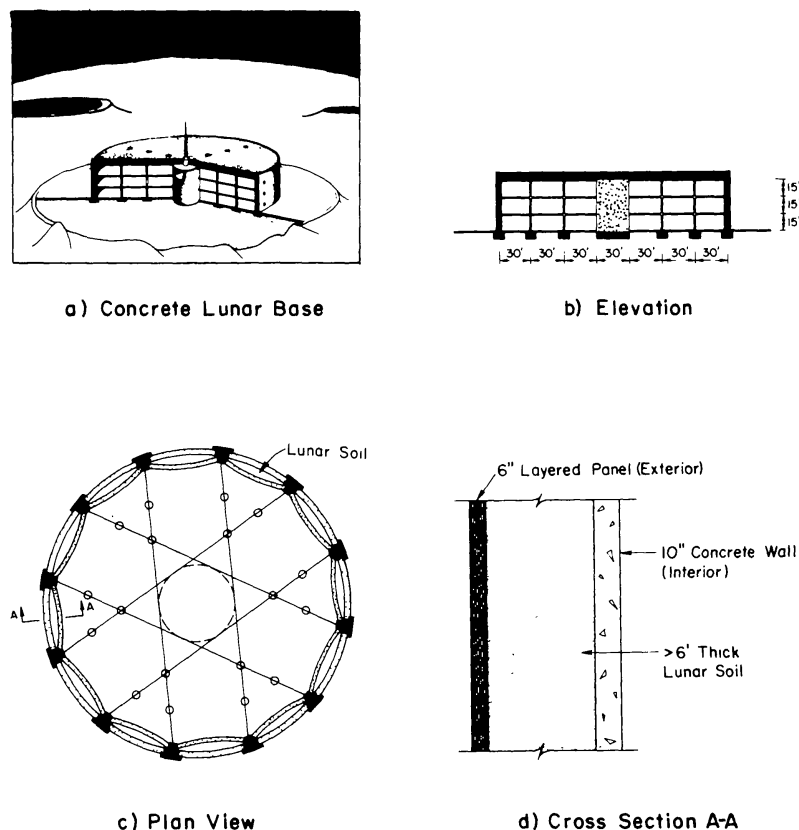


Figure 4. Proposed three-level concrete lunar base.

and vacuum outside. The cylindrical tank at the center of the system serves as a safety shelter for inhabitants in case the system suffers damage or air leak. It could also serve as a "storm cellar" during solar flares. The roof will be covered with lunar soil of suitable thickness 6–18 ft (2–6 m) (Arnold and Duke, 1978) to protect personnel and facilities from harmful effects of cosmic radiation.

Plain concrete is normally weak in tension but strong in compression. Conceivably, the major demand on the structural system will be the high tensile stresses in the wall resulting from the internal pressure. To solve the problem, use of circular panels facing outward and supported by columns will change the tension into compression (Fig. 4c). Steel tendons can then be used to secure the columns into position. For effective use, these tendons could be placed around the cylindrical tank, stressed to provide hoop forces on the tank, and then anchored to columns at the opposite side. The 6-inch-thick (15 cm) layered panels at external faces of the wall (Fig. 4d) are non-load-bearing units. They are used to contain the soil between the internal and external panels. A layered system that is free to expand can minimize the thermal stresses due to extreme temperature changes on the Moon.

The proposed concrete lunar base structure has 90,000 ft<sup>2</sup> (8,360 m<sup>2</sup>) of usable area. Approximately 250 tons of steel and 12,200 tons of concrete would be needed for the construction. That much concrete requires approximately 1,500 tons of cement and 490 tons of water. All these materials can be obtained on the Moon except hydrogen. The needed hydrogen from Earth is about 55 tons.

## ADVANTAGES OF A CONCRETE LUNAR BASE

Concrete lunar bases offer the following advantages:

1. *Economic.* Table 3 compares energy requirements for four major construction materials (Mindess and Young, 1981). To produce 1 m<sup>3</sup> of aluminum alloy requires 360 GJ energy; 1 m<sup>3</sup> of mild steel requires 300 GJ; 1 m<sup>3</sup> of glass requires 50 GJ; and 1 m<sup>3</sup> of concrete requires 4 GJ. The energy ratio between aluminum alloy and concrete is 90:1. Less energy requirement in the production can be translated into lower cost.

Table 3. Typical Properties of Construction Materials

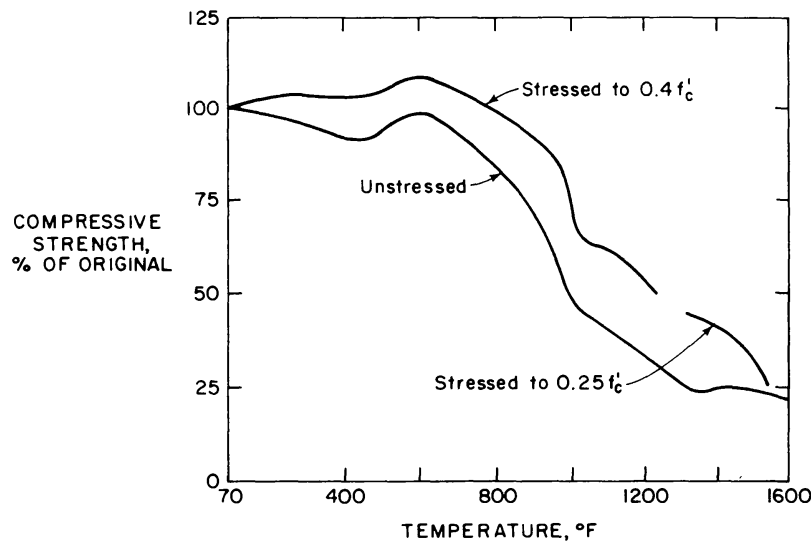
Materials	$\alpha$ (10 <sup>-6</sup> /°C)	k (W/m K)	$E_{\text{rq}}$ (GJ/m <sup>3</sup> )
Aluminum Alloy	23	125	360
Mild Steel	12	50	300
Glass	6	3	50
Concrete	10	3	3.4 (4.0)*

\*H<sub>2</sub>O is made from ilmenite.

2. *Compartmentalization.* One major advantage of concrete is that it can be cast into any monolithic configuration. A lunar structure could be compartmentalized to prevent catastrophic destruction in case of any local damage.

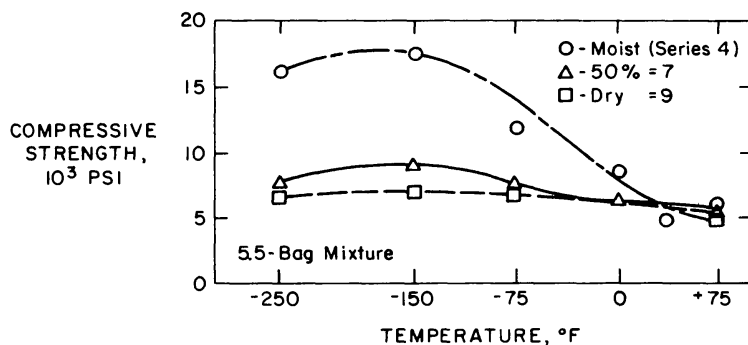
3. *Concrete Strength.* Lunar surface temperature may vary from  $-250^{\circ}\text{F}$  ( $-150^{\circ}\text{C}$ ) in the dark to  $+250^{\circ}\text{F}$  ( $120^{\circ}\text{C}$ ) facing the sun. Figure 5 shows that the strength of heated concrete is practically unaffected by  $250^{\circ}\text{F}$  ( $120^{\circ}\text{C}$ ) (Abrams, 1973). Concrete maintained at 75% relative humidity and temperature of  $-150^{\circ}\text{F}$  ( $-100^{\circ}\text{C}$ ) increases in strength two and one-half times that of concrete maintained at room temperature, and two times at  $-250^{\circ}\text{F}$  ( $-150^{\circ}\text{C}$ ). Concrete that has 0% relative humidity neither gains nor loses the strength in the course of the cooling period, down to  $-250^{\circ}\text{F}$  ( $-150^{\circ}\text{C}$ ) (Montage and Lentz, 1962).

4. *Heat Resistance.* Concrete is thermally stable up to  $1100^{\circ}\text{F}$  ( $600^{\circ}\text{C}$ ). The low thermal conductivity as shown in Table 3 and high specific heat make concrete an excellent heat resistant construction material.



a) High Temperature Effect

Figure 5. Effect of temperature on compressive strength of siliceous aggregate concrete.



b) Low Temperature Effect

5. *Radiation Shielding.* Most radiation energy will be converted into heat energy in the course of attenuation in an exposed body. In general, a hardened concrete consists of 95% aggregate and cement and 5% water by weight. Both aggregate and cement are non-metallic and inorganic, and are excellent materials for absorbing gamma-ray energy. Water is the best substance for absorbing neutron energy (U. S. Scientific Laboratory, 1950).

6. *Abrasion Resistance.* Micrometeorites can strike the Moon with relative speeds up to 25 miles/s (40 km/s). These microparticles may abrade the surface of the lunar structures. Concrete possesses high abrasion resistance, which increases proportionally with concrete strength.

7. *Effect of Vacuum.* Exposed to the lunar environment, the free moisture in concrete may eventually evaporate, but the chemically bonded water will not. Again, Fig. 5 shows that the loss of free moisture, which generally takes place around 212°F (100°C) has no adverse effect on concrete strength.

A pressurized concrete structure may not be completely airtight. To solve this problem, an epoxy coating, or another sealant that hardens without oxidation, can be applied on the internal surface.

## CONCLUSION

Reinforced concrete has many material and structural merits for the proposed lunar base construction. The attractiveness of this proposal lies in the fact that most of the components of the concrete can be produced simply from lunar materials. The scenario for the self-growth lunar base is as follows:

1. *Materials:* Cement could be obtained by high-temperature processing of lunar rocks. Aggregates would be obtained by physical processing of lunar rocks and soils. Lunar ilmenite would be heated with terrestrial hydrogen to form water, while the residual iron could be processed into fibers, wire, and bars for reinforcement.

2. *Concrete:* Casting and curing chambers for concrete could be developed from empty shuttle fuel tanks. Temperature and humidity control, as well as controlled drying and recycling of excess water, are vital parameters because water is an expensive commodity in space.

3. *Construction:* The evaluation of the most suitable structural design must include considerations of constructability. It is possible to optimize the concrete properties in order to achieve the most suitable design, both for ease of construction and for maintenance-free service.

Conceivably, concrete lunar bases will be essential facilities for the scientific and industrial developments on the Moon. Perhaps concrete will provide the ultimate solution to the colonization of outer space. The task of constructing lunar bases is a great challenge to scientists and engineers in this fascinating space age.

## REFERENCES

- Abrams M. S. (1973) *Compressive Strength of Concrete at Temperatures to 1600°F*. RD016.01T. Portland Cement Association, Skokie, IL. 11 pp.
- Agosto W. N. (1984) Electrostatic concentration of lunar soil ilmenite on vacuum ambient (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 24. NASA/Johnson Space Center.
- Arnold J. R. and Duke M. B. (editors) (1977) *Summer Workshop on Near-Earth Resources*. NASA Conf. Public. 2031. NASA, Washington. 95 pp.
- Cutler A. H. (1984) An alkali hydroxide based scheme for lunar oxygen production (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 21. NASA/Johnson Space Center, Houston.
- Friedlander H. N. (1984) An analysis of alternate hydrogen sources for lunar manufacture (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 28. NASA/Johnson Space Center, Houston.
- Frulan R. M. (1981) *Introduction to the Core Samples from the Apollo 16 Landing Site*. NASA Curatorial Branch Public. 58. NASA/Johnson Space Center, Houston. 45 pp.
- Frulan R. M. (1982) *Catalog of the Apollo 16 Lunar Core 60009/60010*. NASA Lunar Curatorial Branch Public. 61. NASA/Johnson Space Center, Houston. 155 pp.
- Hanna A. N. (1977) *Steel Fiber Reinforced Concrete Properties and Resurfacing Applications*. RD049.01P, Portland Cement Association, Skokie, IL. 16 pp.
- Hashimoto A. (1983) Evaporation metamorphism in the early solar nebula—Evaporation experiments on the melt FeO-MgO-SiO<sub>2</sub>-CaO-Al<sub>2</sub>O<sub>3</sub> and chemical fractionations of primitive materials. *Geochem. J.*, 17, 111.
- Lea F. M. (1971) *The Chemistry of Cement and Concrete*. Chemical Publishing, New York. 497 pp.
- Mindess S. and Young J. F. (1981) *Concrete*. Prentice-Hall, New York. 671 pp.
- Monfore G. E. and Lentz A. E. (1962) *Physical Properties of Concrete at Very Low Temperatures*. RD 145. Portland Cement Association, Skokie, IL. 39 pp.
- Morris R. V. (1983) *Handbook of Lunar Soils*. NASA Planetary Materials Branch Public. 67. NASA/Johnson Space Center, Houston. 914 pp.
- Ryder G. and Norman M. D. (1980) *Catalog of Apollo 16 Rocks*. NASA Curatorial Branch Public. 52. NASA/Johnson Space Center, Houston. 1144 pp.
- Takashima S. and Amano F. (1960) Some studies on lower calcium silicates in portland cement. *Reviews of 74th General Meeting of Cement Association of Japan*. Yogyo Cement Co., Osaka. 44 pp.
- U. S. Scientific Laboratory (1950) *The Effects of Atomic Weapons*. Combat Forces Press, Washington. 730 pp.
- Wood J. A. (1975) The Moon. *Sci. Amer.*, 233, 93–102.

# CONCRETE AND OTHER CEMENT-BASED COMPOSITES FOR LUNAR BASE CONSTRUCTION

J. Francis Young

*Departments of Civil Engineering and Ceramic Engineering, University of Illinois at Urbana-Champaign, 208 N. Romine, Urbana, IL 61801*

The use of concrete and other materials based on a cementitious matrix is evaluated for the construction of a manned space station on the Moon. Consideration is given to the most recent developments in the science and technology of cementitious materials and the feasibility of *in situ* construction using lunar materials. It is concluded that concrete construction on the Moon should be technically feasible.

## INTRODUCTION

Recently it has been suggested (Lin, 1984) that concrete could be successfully used in the construction of a lunar base. This exotic use for such a mundane material seems at first sight impracticable. We associate concrete with massive structures involving the use of structural elements with large cross-sections that require large volumes of concrete. When we look at typical concrete properties (Table 1) we are still more convinced of the inappropriateness of concrete on the Moon. It is relatively weak, even in compression, and also fails in a brittle manner, so that tensile steel is required as reinforcement. It suffers from dimensional instabilities and various durability problems, as any highway traveller can testify.

The wide popularity of concrete, however, indicates that it has important advantages that outweigh the problems cited above. A major advantage is versatility. Concrete can be cast in almost any shape imaginable: witness the famous Sidney Opera House in Australia, or the Bahai temple now under construction in India (Anonymous, 1984). Furthermore, by a suitable choice of constituent materials and their proportions, concrete can be manufactured to exact and unique specifications for any given application. Another dominant advantage is economy: large masses of concrete can be produced cheaply

Table 1. Typical Properties of Conventional Concrete.

	Normal Strength	High Strength
Compressive Strength	5000psi (35MPa)	12,000psi (85MPa)
Flexural Strength	800psi (6MPa)	1300psi (9MPa)
Tensile Strength	500psi (3.5MPa)	800psi (6MPa)
Modulus of Elasticity	$4 \times 10^6$ psi (28GPa)	$5 \times 10^6$ (35GPa)
Strain at Failure	0.002	0.003
Drying Shrinkage	0.05–0.1%	0.05–0.1%

because concrete is made from inexpensive ingredients obtained primarily from local sources. This was one of the major assumptions of Lin's (1984) proposal: that concrete can probably be made from lunar materials, thereby avoiding the costly alternative of transporting construction materials from Earth.

Economy is relative, however. If large quantities of concrete are required, the costs of mining, processing, and fabrication on the Moon may exceed the costs of ferrying lightweight prefabricated components made from steel or plastics from Earth. Continuing developments in concrete technology have led to high strength concrete two to three times stronger than conventional concrete. Such concretes can be used to produce structures of lower mass, and they also have better overall performance, since strength is an indicator of the quality of the concrete. Concrete with 14,000 psi (100 MPa) compressive strength can now be produced under field conditions (Burge, 1983; Radjy and Loeland, 1985), while special cementitious systems have been developed whose strengths are at least double the above figure (Hirsch *et al.*, 1983; Young, 1985). Since these materials do not use large-sized aggregates (particulate fillers) they cannot be considered concretes in the conventional sense, so I refer to them as cement-based materials. They not only have the potential to make a large impact on the economics of future lunar construction, but are also likely to be more suitable for the lunar environment.

Lunar base construction is an interesting materials problem for which there are several possible solutions. Lin (1984) sought to highlight the potential for concrete-based lunar structures, and in this paper I will examine the feasibility of his approach in light of the most recent developments of cement-based systems. I will be concerned only with the materials aspects; further development of structural designs is a separate problem whose solution depends on the decisions made with regard to a set of optimum material properties.

## NEW CEMENT-BASED MATERIALS

Dr. Lin's structural design, while quite an elegant solution to the problem, assumes conventional concrete properties; he is considering a brittle material with only modest strength (up to 10,000 psi [70 MPa] in compression). His preliminary design called for 10-in thick precast sections, which represents quite a large mass in the lunar structure. Although transportation from Earth is eliminated by using lunar resources wherever possible, it must be assumed that mining and processing will still be expensive. Thus, reduction in mass would be desirable, but is possible only with a greater improvement in concrete performance.

As mentioned above, high performance cement-based composites have been developed during the last few years and are now entering the market place. These composites are attaining compressive strengths in the range of 30,000–40,000 psi (200–300 MPa), and, when reinforced with fibers, they can exhibit good ductility. Two distinct approaches have been taken, leading to MDF and DSP cements, as described below. Further evaluation of their properties and improved versions of these materials can be anticipated over the next few years.

Table 2. Typical Mechanical Properties of High Performance Cement-Based Materials.

	MDF Cement Paste	DSP Cement Paste
Compressive Strength, MPa	300	250
Flexural Strength, MPa	150	4
Modulus of Elasticity, GPa	50	40
Strain at Failure	—	0.003
Fracture Energy, J/m <sup>2</sup>	200	40
Critical Stress Intensity Factor, Mpa.m <sup>1/2</sup>	3	0.3

MDF (Macro-Defect-Free) cements were developed and named by Birchall and co-workers (Birchall *et al.*, 1982; Birchall, 1983; Alford and Birchall, 1985; Kendall *et al.*, 1983; Kendall and Birchall, 1985). The approach is to apply new processing techniques to the creation of the paste (cement + water) that forms the binding matrix in the composite. A water-soluble polymer is added as a processing aid, and only small quantities of water are used. The Earth-dry formulation is mixed under high shear, during which the polymer prevents excessive entrapment of air by cavitation and provides cohesiveness and plasticity. The blended dough can now be roll-mixed (calendered) to eliminate residual entrapped air bubbles (the macro-defects). The plastic dough is readily molded into the desired shapes by extrusion, pressing, or other conventional plastics processing operation. The material is moist-cured at 80°C followed by air drying; a combination of cement hydration and polymer dehydration during this regime densifies the matrix. The properties of MDF pastes are impressive, as can be seen in Table 2, although as yet we do not fully understand the fundamentals of the material. The ratio of compressive strength to flexural strengths strongly suggests that the polymer is not simply a processing aid, but is actively contributing to the engineering properties. Portland cement has been successfully replaced by calcium aluminate cement (which actually appears to perform better).

DSP cements, which were conceived by Bache (1981), represent a quite different approach, since they were designed to be castable, like concrete. This is done by control of the particle size distribution of the cement to minimize the void space between cement grains, which must be filled with water to make the system castable. As in the case of the MDF systems, the idea is to minimize the amount of water used in order to minimize the porosity of the final product, since material properties are always very strongly porosity dependent. Bache added a very finely divided silica (particle size 0.1  $\mu\text{m}$ ), a by-product of silicon and silicon alloy production, to Portland cement in order to provide the void-filling capabilities. This material has the added advantage of reacting chemically with the cement paste to become an integral part of the cementitious matrix. A dispersing surfactant is also necessary to achieve castability. Later approaches to the DSP concept have used more than one addition for particle size control (Roy *et al.*, 1985; Wise *et al.*, 1985). The properties of DSP materials are comparable to MDF pastes (see typical



values in Table 2) except that they are much more brittle due to the absence of a polymer phase. DSP cements can also be formulated with calcium aluminate cements.

The structures of the paste matrix formed by both systems are quite similar at the micron level. Residual unhydrated grains of cement act as a "micro-aggregate" embedded in a matrix of hydration (reaction) products. The unhydrated cement makes up quite a large volume fraction of the paste, in contrast to cement paste in conventional concrete. We do not yet know the implications of this observation with regard to service performance. Fibers or fillers can be added to either matrix to achieve desired properties, such as ductility, abrasion resistance, *etc.*

These new materials are beginning to be used commercially as useful substitutes for metals or reinforced plastics. MDF composites can be drilled, tapped, or machined. They have been used (Alford and Birchall, 1985) in turntables and speaker cabinets for stereo systems, since the polymer imparts good acoustic properties. They are also being considered for ballistic protection and electromagnetic radiation screening. DSP composites are being used for press tools and molds in the aerospace and automotive industries (Wise *et al.*, 1985) where they replace metals and for machinery parts where abrasion resistance is of prime concern (Hjorth, 1983, 1984). DSP-based molds have been successfully used in vacuum forming (Wise *et al.*, 1985). Such molds have been found to have lower vacuum leak rates than the aluminum molds that they replace.

It is clear from the above discussion that these advanced materials have the potential to provide structures of low mass (reduced cross-sections) to act as an air-tight radiation shield and with sufficient ductility and abrasion resistance to resist meteorite impacts. However, at present little is known about the long-term properties of these materials: their response to large temperature fluctuations, strong drying, impact loadings, fatigue, prolonged vacuum, *etc.* An extensive evaluation program will be necessary to obtain this kind of information, although no doubt it will be gradually developed. Studies will need to be made on a variety of composites made with different combinations of cements, aggregates, and fibers.

## LUNAR PRODUCTION OF MATERIALS

The potential for utilizing lunar resources for the constituents of cement-based composites is an attractive scenario. However, the manufacture of cement, which is a crucial step, will not be a straightforward problem. Both Portland cement and calcium aluminate cement contain over 60 wt % of CaO, whereas lunar rocks and soils are relatively low in CaO (<20 wt %). Limestones do not occur on the Moon. It is possible that a CaO enrichment scheme could be developed using differential vaporization (Agosto, 1984), but the economics may be prohibitive. Perhaps digestion by molten alkali hydroxides to break down minerals into their oxides (Cutler, 1984) might be feasible.

However, one should not be constrained by conventional cement chemistry. One could attempt to manipulate the existing chemical composition to provide a reactive material by fusion-recrystallization processes. Perhaps reactive glasses with a reactive solution, such as carbonic acid (Young *et al.*, 1974) or a polyelectrolyte (Wilson, 1978,

1979) could be used, either of which can initiate very rapid reactions. Development of a suitable cementitious system may require some innovative approaches but should not be an insurmountable problem. It remains to be seen to what extent the strategies of the DSP and MDF systems could be successfully implemented if a new cement chemistry is adopted.

The question of suitable aggregates is much less critical. Processed Moon rocks should be satisfactory provided they are not excessively weak and there is a reasonable thermal match with the cementitious matrix. This is necessary to avoid the creation of internal stresses that could cause internal microcracking and loss of properties (e.g., vacuum tightness, abrasion resistance, etc.). Lack of moisture eliminates most durability problems encountered with aggregates on Earth, such as alkali-aggregate reactions or freeze-thaw distress. Whether lunar soil can be successfully used as aggregate will depend primarily on its fineness and particle characteristics. Since weathering does not occur, clay minerals should be absent, helping to reduce the potential water demand. It may be possible to use lunar soil as a densifying fraction in a DSP-type formulation.

Inorganic fibers—rock wool or glass, for example—could probably be made *in situ*, as could steel fibers using iron extracted from rocks. It might be economical to bring lightweight organic fibers (polypropylene, Kevlar, or carbon) from Earth, since the weight fractions needed to enhance ductility and resistance to cracking are quite low. Similarly organic compounds used in small quantities as processing aids might also be brought to the Moon economically.

The final ingredient is water, which must either be shipped in from Earth or synthesized on the Moon. It will therefore be a scarce and expensive commodity. This is an advantage technically, in that the manufacture of high performance concrete (or other cement-based composites) will now become the most attractive choice economically because less water would be used. One needs to carefully examine alternate hardening strategies that might not use water as the sole reactant, such as carbonation curing (Young *et al.*, 1974; Goodbrake *et al.*, 1979). Carbon dioxide could be obtained from the organic refuse of human activity. The actual water needed could be less than one quarter of that used in conventional concrete, especially if the water removed during drying is collected and recycled. Terrestrial hydrogen burnt in oxygen extracted from Moon rocks (Friedlander, 1984) is the most likely source of water, although it may be possible to obtain some hydrogen on the Moon (Carter, 1984).

## FABRICATION OF CONCRETE

Concrete will have to be formed into precast elements under controlled conditions of humidity and temperature. This is, of course, the key to the hardening process, as well as to maintaining the high level of quality control that will be essential. The "curing" process will involve not only promoting the chemical reactions required for strength development, but also subsequent drying to equilibrium with the lunar atmosphere. This involves much stronger drying than is normally encountered on Earth, but laboratory studies tell us what to expect. Drying shrinkage will be about 2–3 times the usual values

and, unless developed very slowly, will cause cracking. Controlled drying may well be the most crucial part of the whole “curing” process and may dictate the choice of hardening strategies. Use of heat and concomitant carbonation would not only increase the rate of strength development, but would also provide a more dimensionally stable material.

## CONCLUDING REMARKS

The goal of making concrete on the Moon is an intriguing challenge, one that can almost certainly be met technically. Concrete is truly a versatile material: when the tight economic restraints of terrestrial construction are removed, it will be possible to take advantage of methods and strategies that most engineers are not yet aware of. The basic principles that would guide development are well established, although considerable research and development will still be needed to generate the necessary specific information.

## REFERENCES

- Agosto W. N. (1984) Lunar cement formulations (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 81. NASA/Johnson Space Center, Houston.
- Alford N. M. and Birchall J. D. (1985) The properties and potential applications of Macro-Defect-Free cement. In *Very High Strength Cement-Based Materials, Mater. Res. Soc. Symp. Proc.*, 42, pp. 265–276. Materials Research Society, Pittsburgh. In press.
- Anonymous (1985) Temple for Bahai faith uses God's blueprints. *Eng. News Rec.*, 213, 34–35.
- Bache H. H. (1981) Densified cement/ultrafine particle based materials. *Papers Presented to the 2nd Intl. Conf. on Superplasticizers in Concrete*. Aalborg Portland, Aalborg, Denmark. 36 pp.
- Birchall J. D. (1983) Cement in the context of an energy expensive future. *Phil. Trans. Roy. Soc. Lond.*, A310, 31–42.
- Birchall J. D., Howard A. J., and Kendall K. (1982) Strong cements. *Proc. Brit. Ceram. Soc.*, 32, 25–32.
- Burge T. A. (1983) 14,000 psi in 24 hours. *Concr. Intern.*, 7, 39–40.
- Carter J. L. (1984) Lunar regolith fines: A source of hydrogen (water) (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 27, NASA/Johnson Space Center, Houston.
- Cutler A. H. (1984) An alkali hydroxide based scheme for lunar oxygen production (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 21. NASA/Johnson Space Center, Houston.
- Friedlander H. N. (1984) An analysis of alternate hydrogen sources for lunar manufacture (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 28. NASA/Johnson Space Center, Houston.
- Goodbrake C. J., Young J. F., and Berger R. L. (1979) Reactions of hydraulic calcium silicates with carbon dioxide and water. *J. Am. Ceram. Soc.*, 62, 488–491.
- Hirsch P., Birchall J. D., Double D. D., Kelly A., Moir G. K., and Pomeroy C. D. (editors) (1983) *Technology in the 1990s: Developments in Hydraulic Cements*. The Royal Society, London. 207 pp.
- Hjorth L. (1983) Development and application of high-density cement-based materials. *Phil. Trans. Roy. Soc. Lond.*, A310, 167–173.
- Hjorth L. (1984) Silica fumes as additions to concrete. In *Characterization and Performance Prediction of Cement and Concrete* (J. F. Young, ed.), pp. 165–175. Engineering Foundation, New York.
- Kendall K., Howard A. J., and Birchall J. D. (1983) The relationship between porosity, microstructure, and strength, and the approach to advanced cement-based materials. *Phil. Trans. Roy. Soc. Lond.*, A310, 139–154.

- Kendall K. and Birchall J. D. (1985) Porosity and its relationship to the strength of hydraulic cement pastes. In *Very High Strength Cement-Based Materials, Mater. Res. Soc. Symp. Proc.*, 42., pp. 143–148. Materials Research Society, Pittsburgh.
- Lin T. D. (1984) Concrete structures for lunar base construction (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 79. NASA/Johnson Space Center, Houston.
- Radjy F. F. and Loeland K. E. (1985) Microsilica concrete: A technological breakthrough commercialized. In *Very High Strength Cement-Based Materials, Mater. Res. Soc. Symp. Proc.*, 42., pp. 305–312. Materials Research Society, Pittsburgh.
- Roy D. M., Nakagawa Z., Scheetz B. E., and White E. L. (1985) Optimized high strength mortar: Effects of particle packing and interface bonding. In *Very High Strength Cement Based Materials, Mater. Res. Soc. Symp. Proc.*, 42., pp. 133–142. Materials Research Society, Pittsburgh.
- Wilson A. D. (1978) The chemistry of dental cements. *Chem. Soc. Revs.*, 7, 265–296.
- Wilson A. D. (1979) Glass ionomer cements—ceramic polymers. *Cements Res. Progr.*, 1984, 279–310.
- Wise S., Satkowski J. A., Scheetz B., Rizer J. M., MacKenzie M. L., and Double D. D. (1985) The development of a high strength cementitious molding/tooling material. In *Very High Strength Cement-Based Materials, Mater. Res. Soc. Symp. Proc.*, 42., pp. 253–263. Materials Research Society, Pittsburgh.
- Young J. F., Berger R. L., and Breese J. (1974) Accelerated curing of compacted calcium silicate mortars on exposure to CO<sub>2</sub>. *J. Amer. Ceram. Soc.*, 57, 394–397.
- Young J. F. (editor) (1985) *Very High Strength Cement-Based Materials. Mater. Res. Soc. Symp. Proc.*, 42., Materials Research Society, Pittsburgh. 317 pp.

## **MAGMA, CERAMIC, AND FUSED ADOBE STRUCTURES GENERATED *IN SITU***

**E. Nader Khalili**

***Southern California Institute of Architecture, 1800 Berkeley Street, Santa Monica, CA, 90404***

---

The accumulated human knowledge of “universal elements” can be integrated with space-age technology to serve human needs on Earth; its timeless materials and timeless principles can also help achieve humanity’s quest beyond this planet. Two such areas of knowledge are in earth architecture and in ceramics, which could be the basis for a breakthrough—in scales, forms, and functions—in low gravity fields and anhydrous-vacuum conditions. With the added missing link of the element of fire (heat), traditional earthen forms can be generated on other celestial bodies, such as the Moon and Mars, in the form of magma structure, ceramic structure, and fused adobe structure. Ceramic modules can also be generated *in situ* in space by utilizing lunar or meteoritic resources.

### **TIMELESS MATERIALS—TIMELESS PRINCIPLES**

The traditional techniques of building without centering, *i.e.*, leaning-arches, corbelling, and dry-packing can have greater applications in lower gravity fields, as well as higher material strength, than in the restricted conditions of these techniques’ terrestrial origins. At the same time, the “high-tech” heat-obtaining skills of solar heat, plasma, microwave, and melting penetrators can provide ceramic-earth shelters and appropriate technology for both developed and underdeveloped nations. Through understanding and utilizing the principles of “Yekta-i-Arkan”—unity of elements—integration of tradition and technology in harmony with the laws of nature is possible at many levels of microcosm and macrocosm.

### **MAGMA STRUCTURE**

Lunar base structures can be generated and cast, based on the natural space formations created by magma-lava flow such as tubes and voids. By utilizing existing lunar contours or by forming mounds of lunar soil to desired interior spaces, structures can be cast *in situ* with the generated magma. Either way, the upper layers of the mounds and the apex, consisting of unprocessed lunar resources, can generate magma flow with focused sunlight (Criswell, 1976).

Ceramic-glass (Grodzka, 1976) and/or other lunar fluxes may be added to the main composite for lowering the melting temperature. Basalt melting point, 900° to 1200°C, can be lowered to glass composites’ melting point with added lunar flux. As the molten composite flows with the low gravity crawl, the lava crust can be formed in spiral, circular, or multi-patterned rib troughs on the mound. A controlled flowing magma can cast single- or double-curvature monolithic shell structures. The underlying loose soil mound can

then be excavated and packed over the monolithic shell for radiation/thermal/impact shielding (Carrier, 1976). Since high depth of necessary soil coverage over the structure is detrimental to both architectural flexibility and harmonious interaction of inner and outer space environments, the variable magma viscosity can be utilized to reduce the estimated 2-m thickness (Land, 1984) of the packed soil protections depending on material composites and attained temperature degree/time parameters.

The viscosity of the generated magma and the packed regolith can counterbalance internal atmospheric pressure, and the semi-glazed interior can provide an airtight membrane. The pliability of the magma medium can present new dimensions in the creation of sculptured interiors for the ultimate functional utilization of the generated spaces. It also offers an aesthetic dimension, since the molded forms conform to human generic non-angular tendencies. The organic material of magma and the possibilities for ceramic glazing of the interior will open a new era in integration of the arts to scales unattainable for humans under the limits of terrestrial conditions.

Magma materials, basaltic in particular, have produced agricultural soils and with suitable atmospheric conditions have proved to produce vegetation. Plant successions have taken place in magma-lava metamorphosis in terrestrial lava tubes and voids. Many examples of flora can be seen in old lava beds of the volcanic regions of the world. Similar conditions will be present in lunar magma structures when the temperature-moisture ambient exists for a life-supporting environment. Thus, common spaces of lunar bases could be designated as mini-agricultural zones that could both generate suitable atmosphere to sustain human life and provide supplemental nutrition resources.

Natural lava structures, such as Craters of the Moon National Monument, can provide case studies in the design development stages. Research is needed to determine material composites, magma crust formation patterns, and span limitations.

## **PREFABRICATED MAGMA MEMBERS**

Conventional structures can be built with magma in lunar base complexes by prefabricating structural members. Beams, columns, panels, and connections can be prefabricated with generated magma composed of unprocessed lunar resources fused with solar heat. Magma-lava solidified structural members can be reinforced with fibers or reinforcing mesh produced from lunar resources. The precast panels and members can be post-tensioned by tendons or fused with spot mortar composed of similar magma materials. Precast magma and ceramic members can be shaped to fit desired forms and functions. Lunar soil troughs and fused regolith layer form work can be utilized for casting systems.

## **CERAMIC STRUCTURE**

The use of shielding ceramic tiles on the space shuttle points to the potential of ceramic materials for lunar and space applications. Ceramic structures of limited spans can be cast *in situ* on lunar sites; they can also be generated in space. On lunar sites,

a centrifugally gyrating platform—a giant potter's wheel—featuring adjustable rims with high flanges can be utilized for the dynamic casting of ceramic and stoneware structures. A mass of lunar resources can be “thrown” in the stationary center zone of the platform and melted by focused sunlight to flow to the periphery rotating zone and cast desired shapes. Known lunar resources can also be spun on the same platform to create tensile fiber; by integrating the two operations, monolithic ceramic structures with tensile fiber reinforcing layers can be generated. Double-shell ceramic structures sandwiched with space and/or packed with insulating materials can provide radiation, thermal, and impact shielding. Such units can be used singularly for lunar camps or combined around a common hub and/or spine to form a lunar base complex.

The centrifugal platform system with its adjustable rim flanges can be utilized for lunar base infrastructure parts: pipes, ducts, and tunnel rings. Prefabricated sections for utility sheds can also be formed in single- or double-shell modules.

In space, a centrifugally gyrating platform moving in three dimensions can create more variations of ceramic structured modules than is possible in terrestrial or gravity fields. Attached to a space station, the gyrating platform can generate ceramic modules *in situ*. The resources for ceramic structures can either be of lunar or martian origin or, in space, from captured meteoroids.

## FUSED ADOBE STRUCTURE

Lunar base structures can be constructed *in situ* utilizing lunar adobe blocks produced from unprocessed lunar soil or the by-products of industrial mining operations. Lunar adobe blocks can be formed by the fusion of lunar resources with solar heat. It is anticipated that vacuum conditions and the essentially zero-moisture content of lunar soils should significantly reduce thermal diffusivity (Rowley, 1984). Lunar adobe blocks can be used to build structures without form work, employing the earth-architecture techniques of dry-packing, corbelling, and leaning-arches (Khalili, 1986). The low gravity field and vacuum conditions, which allow for a smaller angle of repose and enhance lunar soil cohesion (Blacic, 1984), will give greater opportunity, in the case of the leaning-arch technique, for larger spans and shallower vaults and domes. The same advantages will cause the soil-packed covering to follow desirable contours for more flexible interaction of interior and exterior space and solar orientation. Fused spot-mortar or lunar dust sprayed at fusion point temperature can be used to bond the blocks in medium and large span structures. Arches, domes, vaults, and apses can be constructed to fit the contours of the moonscape; these curved surfaces can create sun and shade zones that are functionally desirable.

For functional or aesthetic reasons, total or partial interior ceramic glazing of lunar adobe structures can be done with lunar resources containing glass (Heiken, 1976) and other fluxes by solar heat fusion or plasma technology. The difficulty of mechanical separation of lunar dust can be solved by the bulk use of the soil at its powder stage, involving pre-heating the dust and guniting it on the structure at the point of fusion.

The techniques of earth-architecture and the human skills that have evolved to deal with natural materials and to meet the historic challenges of harsh environments and terrestrial gravity can put future men and women in direct touch with the lunar world. Discovering suitable dimensions of blocks, techniques of construction, and appropriate material composites while developing their own sense of unity with the lunar entity can be the start of human independence from Mother Earth, creating shelters in the heavens. The organic growth of lunar architecture, with its own materials and equilibrium of elements, can be used to initiate an indigenous and ecologically balanced human environment without damaging the heavenly body.

On Earth, one of the main tasks of architects, engineers, and builders has historically been nothing but winning the fight against gravity; now and in the future, the chance for victory on the Moon will be six times as great as it has been here on Earth.

### **INITIAL IN SITU CONSTRUCTION**

Locating a lunar lava tube may well be one of the first stages of setting up a lunar base site. Lava tubes can provide the most expedient and economical way of starting an indigenous lunar architecture. Terrestrial lava tubes are the best design model for exploring the development of appropriate life-supporting environments in lunar lava tubes. Either at the initial stage or in the following phases of lunar base construction, locating and utilizing lava tubes can be of great value.

An immediate construction system for the lunar base, after the initial camp setup, can utilize unprocessed lunar resources in a non-mechanized construction system. This system uses existing rocks of different sizes and dry-pack techniques. The low gravity field and higher rock fracture strength give added advantages for larger spans of corbelling and leaning-arch earth-structure systems. Meteoroid and/or indigenous rock structures covered with lunar soil for radiation and thermal shielding can provide immediate, non-life-supporting shelters. Structures built with the same techniques can be fitted with an airtight fabric mesh for human habitation (Blacic, 1984).

### **PAVING AND LUNAR DUST STABILIZATION**

The lunar soil, with a particle size of about 70 microns, which adheres to everything and churns up with vehicular traffic, needs to be stabilized (Carrier and Mitchell, 1976). Fusion of the top layers of lunar soil with focused sunlight can form a magma-lava crust to arrest unstable lunar dust. Spacecraft landing pads, vehicular traffic roads, and pedestrian walkways can be paved with solar heat by on-spot fusion of the top layers, penetrating to desirable depth. Unprocessed lunar soil can be fused by solar energy via a manual or automatic and remote control "paving" vehicle. Inappropriate regolith areas can be topped with a layer of appropriate lunar soil before its fusion. For low temperature fusion, lunar fluxes can be sprayed on top of the soil prior to introducing solar heat. Paving surfaces of heavier traffic areas can be constructed from composites fused to ceramic and stoneware consistency with desired colors and textures.



As a general rule, it is the use of the universal principles of the terrestrial element of fire (heat)—the solar rays—that must be thought of at the forefront of mediums and materials for planetary base design and construction. Adhering to the philosophy of the use of local resources, human skills, and solar energy, we can achieve our quests on the Moon, Mars, and beyond.

We must learn from the accumulated human knowledge of earth-architecture, which has sheltered humans in the harshest conditions. Each person going to the Moon, regardless of his or her work, must be aware of these fundamental principles and techniques to participate in creating an indigenous architecture to form their communities, not only because of economic benefit but also because of spiritual reward. As an old Persian saying goes, "Every man and woman is born a doctor and a builder—to heal and shelter himself."

*Acknowledgments.* The Geltaftan Group, consisting of of Manouchehr Sedehi, Mahmoud Hejazi, Ezzatollah Salmanzadeh, Ali Gourang, Ostad Asghar, and A. A. Khorramshahi, supported my work in earth-and-fire developments. Eyal Perchik, Alessandra Runyon, Tsosie Tsinhnahjinnie, Steven Haines, Ellwood Pickering II, Barclay Totten, students at the Southern California Institute of Architecture, have helped advance my research work.

## **REFERENCES**

- Blacic J. D. (1984) Structural properties of lunar rock materials under anhydrous, hard vacuum conditions (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 76. NASA/Johnson Space Center, Houston.
- Carrier W. D. III and Mitchell J. K. (1976) Geotechnical engineering on the Moon (abstract). In *Lunar Science VII, Special Session Abstracts*, pp. 92–95. Lunar Science Institute, Houston.
- Criswell D. R. (editor) (1976) *Lunar Science VII, Special Session Abstracts (on Lunar Utilization)*, pp. iii–vi. Lunar Science Institute, Houston.
- Grodzka P. (1976) Processing lunar soil for structural materials (abstract). In *Lunar Science VII, Special Session Abstracts*, pp. 114–115. Lunar Science Institute, Houston.
- Heiken G. (1976) The regolith as a source of materials (abstract). In *Lunar Science VII, Special Session Abstracts*, pp. 48–52. Lunar Science Institute, Houston.
- Khalili E. N. (1986) *Ceramic Houses*. Harper and Row, San Francisco. In press.
- Land P. (1984) Lunar base design (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 102. NASA/Johnson Space Center, Houston.
- Rowley J. C. (1984) In-situ rock melting applied to lunar base construction and for exploration drilling and coring on the moon (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 77. NASA/Johnson Space Center, Houston.

# **LAVA TUBES: POTENTIAL SHELTERS FOR HABITATS**

**Friedrich Hörz**

***Experimental Planetology Branch, SN4, NASA/Johnson Space Center, Houston, TX 77058***

---

Natural caverns occur on the Moon in the form of "lava tubes," which are the drained conduits of underground lava rivers. The inside dimensions of these tubes measure tens to hundreds of meters, and their roofs are expected to be thicker than 10 meters. Consequently, lava tube interiors offer an environment that is naturally protected from the hazards of radiation and meteorite impact. Further, constant, relatively benign temperatures of  $-20^{\circ}\text{C}$  prevail. These are extremely favorable environmental conditions for human activities and industrial operations. Significant operational, technological, and economical benefits might result if a lunar base were constructed inside a lava tube.

## **INTRODUCTION**

This paper addresses the existence of natural caverns on the Moon in the form of "lava tubes," and it suggests that they could provide long-term shelter for human habitats and industrial operations.

The origin of lava tubes is genetically related to the formation of "sinuous rilles," which represent flow channels of molten lava. Such channels generally form at high extrusion rates of low viscosity magmas. Sinuous rilles are abundantly observed on lunar basalt surfaces (e.g., Oberbeck *et al.*, 1969, 1971; Greeley 1971, 1972; Cruikshank and Wood, 1972; Head, 1976). The distribution of sinuous rilles on the lunar front side was mapped by Guest and Murray (1976).

Lava tubes are well known from basaltic volcanic terranes on Earth (Ollier and Brown, 1975; Greeley, 1971, 1972, 1975; Cruikshank and Wood, 1972; Hulme, 1973; Peterson and Swanson, 1974). A number of processes may contribute to their formation: (1) radiative cooling may cause surface crystallization and crusting-over of the liquid lava. (2) Commonly, such relatively thin crusts break apart and collapse because the melt below continues to flow. Solid but relatively hot chunks of this crust will raft on the lava river and may coalesce into larger and larger aggregates until a solid roof forms. (3) Radiative cooling takes place at the sides of such lava flows, leading to crusting and aggregation of solids and ultimately to the buildup of pronounced levees, which in turn increase channelled melt flow. Additional aggregation from these levees, aided by spattering of lava splashes, can lead to the formation of solid roofs.

Commonly, low viscosity magmas are also very hot. Hulme (1973) and Peterson and Swanson (1974) present field observations that lava tube cross sections may be modified and enlarged by thermal erosion, *i.e.*, by remelting of the tube's ceiling, walls, and floor.

Typical heights and widths of terrestrial lava tubes are generally measured in a few meters; cross-sectional dimensions in excess of 10 m are rare. The length of lava tubes on Earth may reach 10 to 20 km, but most lava tubes are only 1–2 km long. Greeley (1975) points out that the frequency of such underground lava conduits on Earth may have been underestimated in the past and that they are indeed relatively common around terrestrial shield volcanoes such as those in Hawaii.

## LUNAR LAVA TUBES

High extrusion rates and extremely low viscosities characterize lunar basaltic volcanism (Moore and Schaber, 1975), conditions very conducive to the formation of lava channels and tubes. Open channels in the form of sinuous rilles are very abundant on lunar basalt surfaces. Their widths and depths are typically hundreds of meters, and they are commonly a few tens of kilometers long. They are, thus, much larger than their terrestrial analogs (e.g., Oberbeck *et al.*, 1969, 1971). Indeed many of the above studies address the problem of how to properly scale the dimensions of terrestrial lava channels and tubes to their much larger counterparts on the Moon. Hulme (1973) argues for increased turbulence and increased thermal erosion during lunar basalt flow. In detail, the highly meandering nature of many lunar rilles is also not observed to the same degree in terrestrial analogs. Increased meandering is probably best explained by reduced gravity and extremely shallow flow gradients.

In contrast to numerous open flow channels in the form of sinuous rilles, bona fide lava tubes are rarely observed on the Moon; they could indeed be rare geologic features. On the other hand, they are subsurface and will therefore generally not show up in lunar surface imagery. The only lava tubes that can be recognized from lunar surface photos are those that have partially collapsed roofs. Thus, little can be surmised about the absolute frequency and global distribution of lunar lava tubes. They may well be more common than can be demonstrated at present. The important point and the crux of this paper is, however, that they do exist on the Moon.

Figure 1 shows a lava tube with large segments of collapsed roof. A modest topographic ridge forms the crest of the tube as pointed out by Oberbeck *et al.* (1969). The elongated depressions must be caved-in portions of this ridge system. Their elongated plane view and the lack of any raised rims distinguishes these depressions from circular impact craters. Note also the highly braided nature of the elongated depressions, in stark contrast to the random distribution of circular impact features dotting the surroundings. This observation in particular lends additional credence to the interpretation that the entire linear feature is a partially collapsed lava tube. Figure 2 represents another feature interpreted by Cruikshank and Wood (1972) as a partially collapsed lava tube. This tube seems to be unusually straight. The width of the open rille is approximately 200 m, and the uncollapsed roof segments are a few hundred meters long. Note the size of impact craters that were suffered by the seemingly intact roof segments.

What do we know about the roof thicknesses of lunar lava tubes, and are these roofs sufficiently massive and structurally stable to provide long-term shelter against

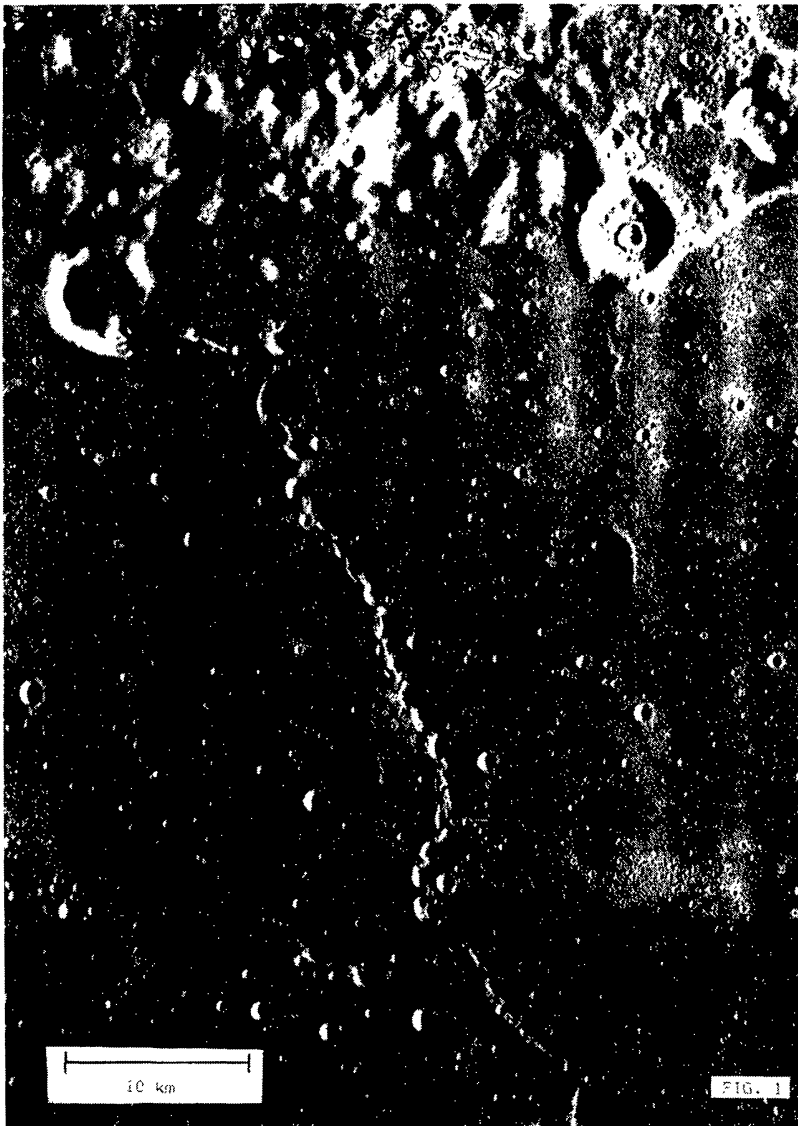
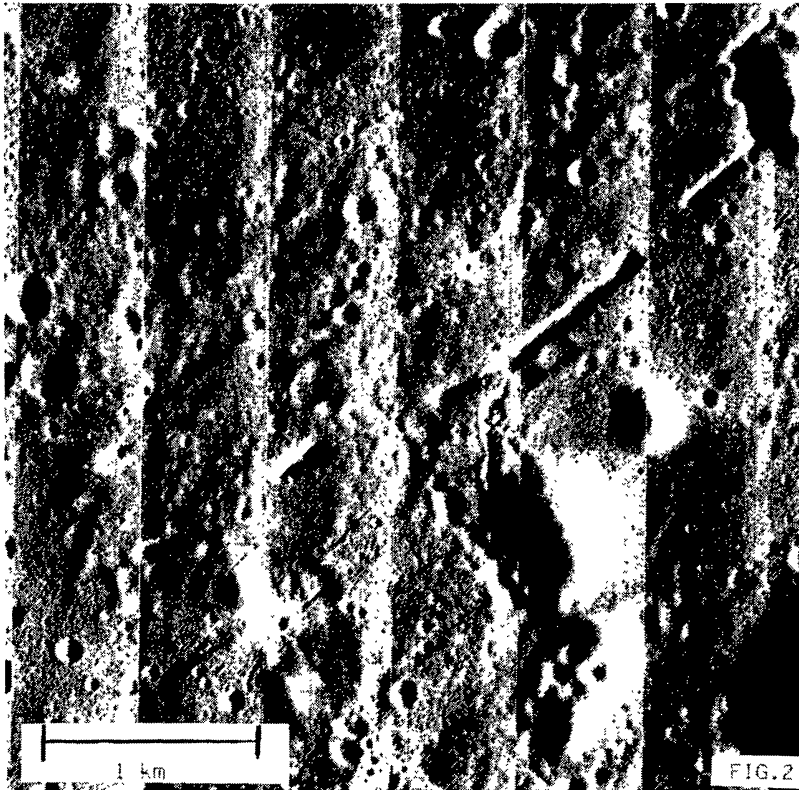


Figure 1. One of the most prominent lunar lava tubes, first described in detail by Oberbeck *et al.* (1969). The lava tube is approximately 40 km long and up to 500 m wide. Note that some sections of the roof are uncollapsed and that the tube continues underground toward the south (at bottom of picture). Also, note that slopes leading into the rille may be of different steepness; the flatter ones might be negotiated with ease. Uncollapsed sections of the tube are on the order of a few hundred meters long, particularly in the northern part. Dimensionally, these lava tubes would be more than adequate to serve as receptacles for modular habitats and a variety of machinery. Note that this lava tube happens to be within a few kilometers of a highland contact, and it is not inconceivable that access to different raw materials may be possible from a single lava tube (Lunar Orbiter 5, frame 182. Northern Oceanus Procellarum).

radiation and meteoroid bombardment? According to Oberbeck *et al.* (1969), the ratio of roof thickness ( $T_R$ ) of terrestrial lava tubes relative to typical dimensions of tube cross sections ( $T_C$ ) ranges from 0.25 to 0.125. Oberbeck *et al.* (1969) also use simple structural beam modeling to calculate that basalt “bridges” spanning a few hundred meters are possible on the Moon provided they are at least 40–60 m thick. These estimates happen to agree with the terrestrial  $T_R/T_C$  ratios. Importantly, these estimates are also in good agreement with the following observations: uncollapsed roofs of lava tubes display impact craters a few tens of meters across (see Fig. 2), occasionally as large as 100 m. The diameter/depth ratio of small lunar craters is approximately 4 to 5 (Pike, 1977). Thus, crater excavation depths approaching 20 m can be demonstrated. Using ballistic penetration mechanics (e.g., Gehring, 1970) and associated spallation processes at the rear surface (the roof's ceiling) of a slab-like impact target, one can estimate conservatively that the



*Figure 2. Lunar lava rille with uncollapsed roof sections that measure hundreds of meters. Note that mountains are close by which certainly differ in chemistry and mineralogy from the relatively flat basalt surfaces. This rille was extensively described by Cruikshank and Wood (1972) (Lunar Orbiter 5, frame M-191).*

roof thickness must be at least two times larger than any crater depth; otherwise complete penetration of the slab (roof) would have occurred. Following these arguments, the maximum crater sustained by an uncollapsed roof yields a minimum measure of roof thickness. The thicknesses of some lunar lava tube roofs are thus a few tens of meters. In principle, the minimum roof thickness of specific lava tubes could be assessed using the above crater-geometry relationships.

While impact craters indicate that initial roof thickness must have been substantial, the cratering process has also contributed to the erosion and structural weakening of such natural basalt bridges. Judging from the thickness of lunar soils on representative basalt surfaces, the uppermost 5–10 m of solid bedrock (lava tube roofs) are totally comminuted into fine-grained lunar soil. Penetrative cracks associated with this average regolith depth are a factor of 3–5 deeper on the basis of seismically disturbed areas below terrestrial craters (Pohl *et al.*, 1977). Importantly, the above-mentioned spallation process occurs at the tube's ceiling even for impact events that are not penetrative; *i.e.*, it occurs as long as the stress amplitude of an impact-triggered shock wave exceeds the basalt's tensile strength (*e.g.*, Hörz and Schaal, 1981). This spallation-induced thinning and weakening is of more concern for the structural integrity of a given roof than surficial erosion. A few relatively large craters (>50 m) may have done more structural damage than the cumulative effects of many <20-m-diameter craters. Because meteorite impact is a stochastic process, it is difficult to predict the structural integrity and exact thickness of a lava tube roof with great precision. Nevertheless, rough estimates can be made via

photogeologic techniques related to crater geometry as outlined above. An obvious strategy would be to select roofs or roof segments that have suffered relatively small cratering events only. Such segments are clearly safer than areas close to, if not directly below, a relatively large impact crater.

What do we know about cross-sectional dimensions of lunar lava tubes, and how do their interiors look? As indicated above, the linear dimensions of sinuous rilles and lava tubes are significantly larger on the Moon than on Earth; collapsed portions of some lunar lava tubes indicate correspondingly large tube interiors (see Figs. 1, 2). There is little doubt that lunar lava tubes have large enough cross sections to house most any habitat. Restrictions and enlargements of cross sections occur in terrestrial lava tubes, but on relatively modest scales. The surface relief of terrestrial lava tube interiors can be highly variable, ranging from relatively smooth to very rough and knobby. However, this variability occurs on relief scales that are extremely small compared to cross-sectional dimensions. We can only assume that lunar lava tubes display similar relief. In addition, the above-mentioned spallation products will have accumulated on the floor; they may possibly make initial trafficability cumbersome until removed or leveled (using readily available lunar soil as fill).

## **LUNAR BASE INSIDE A LAVA TUBE**

Based on the foregoing, it appears that natural caverns of suitable sizes to house an entire lunar base exist on the Moon. Roof thicknesses in excess of 10 m will provide safe and long-term shelter against radiation and meteorite collisions. Creation of similarly shielded environments will constitute a significant and costly effort for any lunar base located at or close to the lunar surface. Substantial operational advantages for a lava tube scenario emerge as outlined below.

The primary suggestion advocated by this report is to use lava tubes merely as receptacles for prefabricated, modular habitats, either imported from Earth (initially?) or fabricated from lunar resources, if not in place (at later stages?). We do not suggest that the lava tube itself may be suitably modified to serve as the primary habitat. There are too many uncertainties related to detailed geometry of the cross section and to the surface roughness of the walls and floors. Indeed, lava tube interiors may be too large, at least initially. Furthermore, penetrative cracks in the roof may exist, which would make it extremely difficult, if not impractical, to render the enclosed volume airtight. Modest site preparation inside the lava tube would consist of leveling the floor with lunar soil, an earth-moving operation similar in scale to site preparation on the surface. The lava tube would then be ready to act as a receptacle for self-enclosed habitats as well as for a large number of industrial operations, all safely protected from radiation and meteorite impact.

The primary advantage of housing the lunar base in a naturally sheltered environment is the potential to use extremely lightweight construction materials. None of the components would have to support any shielding mass whatsoever. Indeed, many components, such as a habitat shell, would not even have to support much of their own weight because

they could be supported from the walls and ceilings of the lava tube. Habitats could even be inflatable, supported by air pressure only. In any case, construction and selection of materials would be entirely dictated by expected wear and tear. Widespread use of thin foil materials (metals, plastics?) is possible not only for the habitat itself, but also for a variety of ducts, storage tanks, *etc.* Any lunar base will include a variety of machinery located outside the man-rated, shirt-sleeve environment. Some of this gear will have to be protected against meteorite impact (e.g., all life-support systems). Much of this equipment will also have to be visited occasionally by crews for monitoring, maintenance, and repair. Inside a lava tube, the layout of this equipment could resemble that of terrestrial operations with all components freely exposed and easily accessed for inspection and repair. This seems particularly convenient for a variety of duct work, pipes, valves, storage tanks, *etc.*, used to transfer gases and liquids. It is also possible to house some machinery inside lightweight shells to create an optimum environment for its operation (e.g., bio-processing plant). Such lightweight shells and habitats are easily connected with each other, providing great flexibility for expansion of the lunar base as well as for specific environmental engineering inside individual enclosures and compartments. In summary, numerous structural and operational advantages would present themselves if a lunar base could be designed and constructed without continuous concern for the hazards of radiation and meteorite impact.

Lava tube interiors offer additional environmental differences compared to the lunar surface. These differences may be beneficial for a number of engineering tasks and operational aspects. Being underground and some tens of meters removed from the lunar surface, there is a relatively constant-temperature environment (estimated at  $-20^{\circ}\text{C}$ ; Mendell, personal communication, 1985). This contrasts with the diurnal temperature cycle of  $-180^{\circ}$  to  $+100^{\circ}\text{C}$  at the surface. Temperature management inside a lava tube appears significantly easier than at the surface, where complex thermal insulation and control systems appear unavoidable. Also, the selection of materials functioning properly over a wide range of temperatures is severely limited at the surface; in contrast, a wide range of common materials may be used at the more benign and constant temperatures prevailing inside a lava tube. Furthermore, inside a lava tube, all equipment is well shielded from IR and UV radiation. Materials (e.g., certain plastics) that otherwise deteriorate if exposed to this radiation could be used indiscriminately inside a lava tube. In short, additional environmental differences of a subsurface location may allow widespread use of common materials that may not be suitable for use on the lunar surface.

Some additional advantages for siting a lunar base inside a lava tube come to mind. The front and rear entrances of the tube may be sealed off rather readily to keep a relatively dust-free environment for all operations; loose dust may be a nuisance for a fair number of operations on the surface. It is also possible to conceive of lightweight, highly flexible suits for crews venturing outside the man-rated habitats but remaining inside the tube; neither thermal insulation nor meteorite impact is of great concern for such suits. Heavy, vibrating machinery may be solidly anchored to firm bedrock (a rarity on the lunar surface). The lava tube may serve as convenient "hangar" or "garage" for all kinds of equipment that have low duty cycles and that must be kept in a protected environment.

A major operational drawback in utilizing lava tubes may be their difficult accessibility. Negotiation of perhaps steep slopes and the climbing in and out of a local "hole" appears cumbersome, possibly impractical. Relatively shallow sinuous rilles, somewhat flattened by impact craters, exist however. Also, the Apollo 15 crew visited the edge of Hadley rille and felt that their Lunar Rover could have negotiated the slopes of this rille (Irwin, personal communication, 1985).

Location of a lunar base at the bottom of a hole seems not very economical from an energy point of view, because mass will have to be lowered and especially raised when needed on the lunar surface and when being readied for export to LEO or GEO. These energy considerations are, however, a matter of degree, because most large-scale industrial operations rely heavily on gravity for material transport. Some modest elevation difference between the source of lunar raw materials and the processing plant is desirable even for such simple operations as sieving and magnetic separation. For this reason, a lunar base may be more functional if located at the base of some slope. Why not a sinuous rille/lava tube where chutes or pipes may be laid out such that they terminate inside the lava tube at exactly that station where the high-graded raw materials are needed?

The most serious drawback in the utilization of lava tubes relates, however, to the present status of lunar surface exploration. Only a few lava tubes are recognized. High resolution photography of the entire lunar globe is needed to improve the inventory of lunar lava tubes and to determine their spatial distribution. Detailed imagery appears at present to be the only means for an improved understanding of their dimensions, roof thicknesses, and global distribution. Furthermore, lava tubes are viable candidates for shelters only if desired raw materials are close by. The distribution of specific lunar resources is also largely unknown at present. It appears prudent to further explore the lunar surface and its resources via remote sensing from polar orbit. Lava tubes are viable candidates to house a lunar base if basaltic raw materials are desired. Lava tubes are, however, not excluded if non-basaltic resources were the ultimate choice. As illustrated in Figs. 1 and 2, lava tubes occur within kilometers of non-mare terrains with lithologies that differ substantially from the surrounding basalts.

## CONCLUSIONS

Establishment of a lunar base, its construction, its layout, its diverse functions, and its ultimate location will be the compromise result of numerous scientific, technical, and economic considerations. Some of these considerations may be incompatible with housing a lunar base inside a lava tube. The simple purpose of this contribution is to remind everybody that natural caverns exist on the Moon. They provide a natural environment that is protected from meteorite impact, shelters against radiation, and is at a constant, relatively benign temperature. Such a natural environment allows widespread use of lightweight construction materials, great flexibility in the choice of such materials, and it results in improved operational capabilities. If a lunar base were emplaced on the lunar surface, a qualitatively similar environment would have to be engineered with great complexity and cost.



## REFERENCES

- Cruikshank D. P. and Wood C. A. (1972) Lunar rilles and Hawaiian volcanic features: Possible analogues. *Moon*, 3, 412-447.
- Gehring J. W., Jr. (1970) Engineering considerations in hypervelocity impact. In *High Velocity Impact Phenomena*, (R. Kinslow, ed.), pp. 463-514. Academic Press, New York.
- Greeley R. (1971) Observations of actively forming lava tubes and associated structures, Hawaii. *Mod. Geol.*, 2, 207-223.
- Greeley R. (1972) Additional observations of actively forming lava tubes and associated structures, Hawaii. *Mod. Geol.*, 3, 157-160.
- Greeley R. (1975) The significance of lava tubes and channels in comparative planetology (abstract). In *Papers Presented to the Conference on Origins of Mare Basalts*, pp. 55-55. Lunar Science Institute, Houston.
- Guest J. E. and Murray J. B. (1976) Volcanic features of the nearside equatorial lunar maria. *J. Geol. Soc. London*, 132, 252-258.
- Head J. W. (1976) Lunar volcanism in space and time. *Rev. Geophys. Space Phys.*, 14, 265-300.
- Hörz F. and Schaal R. B. (1981) Asteroidal agglutinate formation and implications for asteroidal surfaces. *Icarus*, 46, 337-353.
- Hulme G. (1973) Turbulent lava flows and the formation of lunar sinuous rilles. *Mod. Geol.*, 4, 107-117.
- Moore H. J. and Schaber G. G. (1975) An estimate of the yield strength of the Imbrian flows. *Proc. Lunar Planet. Sci. Conf. 6th*, pp. 101-118.
- Oberbeck V. R., Quaide W. L., and Greeley R. (1969) On the origin of lunar sinuous rilles. *Mod. Geol.*, 1, 75-80.
- Oberbeck V. R., Greeley R., Morgan R. B., and Lovas M. J. (1971) *Lunar Rilles—A Catalog and Method of Classification*. NASA TM X-62,088, 83 pp.
- Ollier C. D. and Brown M. C. (1965) Lava tubes of Victoria. *Bull. Volcan.* 25, 215-229.
- Peterson D. W. and Swanson D. A. (1974) Observed formation of lava tubes. *Speleology*, 2, 209.
- Pike R. J. (1976) Crater dimensions from Apollo data and supplemental sources. *Moon*, 12, 463-477.
- Pohl J., Stöffler D., Gall H., and Ernstson K. (1977) The Ries impact crater. In *Impact and Explosion Cratering* (Roddy D. J., Pepin R. O., and Merrill R. B., eds.), pp. 343-404. Pergamon Press, New York.

# DESIGN OF LUNAR-BASED FACILITIES: THE CHALLENGE OF A LUNAR OBSERVATORY

**Stewart W. Johnson**

*The BDM Corporation, 1801 Randolph Road, S. E., Albuquerque, NM 87106*

**Ray S. Leonard**

*The Zia Company, P.O. Box 1539, Los Alamos, NM 87544*

---

This paper focuses on the development process and systems engineering needed to emplace and support an astronomical observatory on the Moon. Factors taken into account are the types of observations to be accomplished, the structures and systems needed to support and to protect the elements of the observatories associated with the science mission, the interaction of the lunar regolith with the structures and foundations, and maintenance requirements. The requirements for advanced scientific research can be met with an appropriate mix of automation, robotics, and suited astronaut intervention. It is suggested that a time-phased, multidisciplinary approach be initiated to determine the observations to be made, the best sites for use, and the technical requirements, as well as to resolve critical technical issues relating to the planning, design, development, and placement of the observatory. Fourteen critical issues related to the development of observatory facilities are listed and discussed. These critical issues will be sharpened in the future as operational requirements become clearer. In the final analysis, the design and development strategy must flow down from requirements. Cost and risk must be elements in the decision process. The question is posed as to how the technologies of the Hubble Space Telescope, the Space Infrared Telescope Facility, and the Gamma Ray Observatory may be adapted to a lunar setting.

## SCOPE AND APPROACH

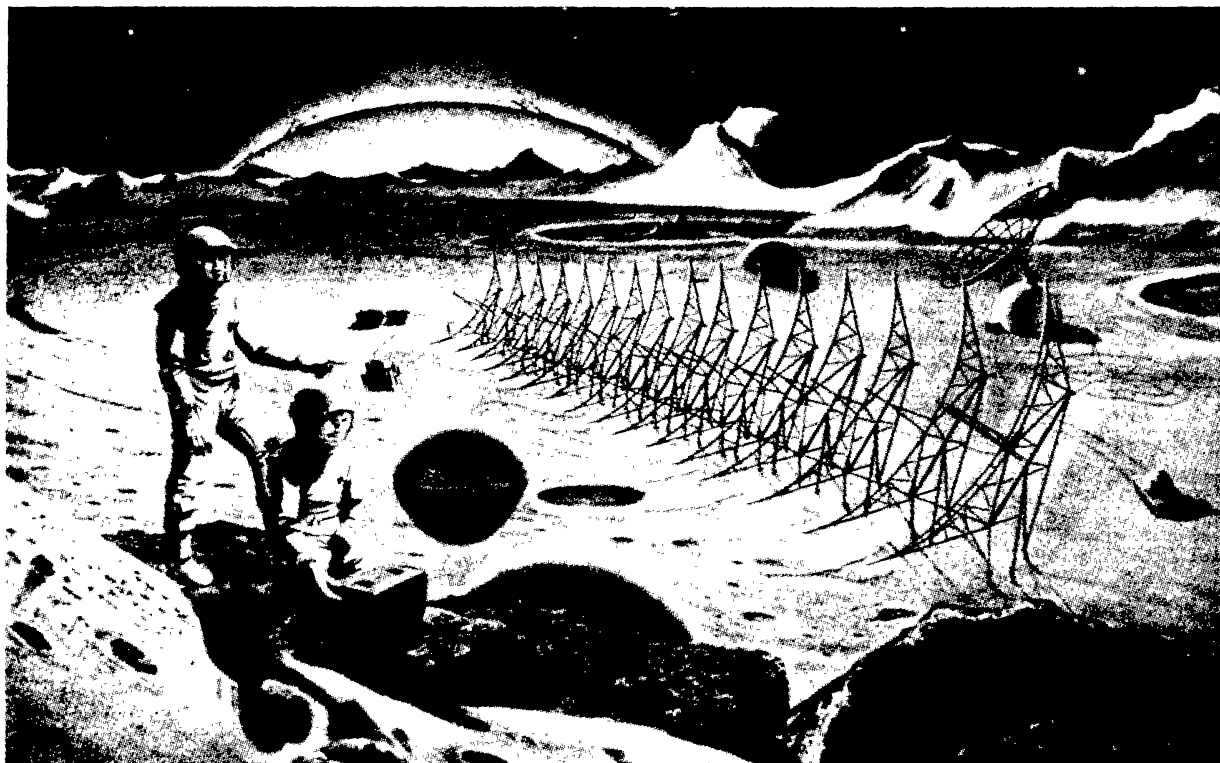
An astronomical observatory on the Moon offers the potential advantages of emplacement on a stable platform in an environment unencumbered by atmospheric obscurations. A radio astronomy observatory on the farside of the Moon would avoid much of the electromagnetic "noise" associated with man's terrestrial activities. The long lunar night would provide extended periods for dark sky observation (Johnson and Leonard, 1984; *Astronomy and Astrophysics for the 1980s*, 1982). The approach in this paper is to focus on the development process and systems engineering needed to emplace and support an astronomical observatory on the Moon.

## SOME HIGHLIGHTS OF PAST EFFORTS RELATING TO OBSERVATORIES IN SPACE

The idea of a telescope in space was mentioned in 1923, when H. Oberth, a German rocket pioneer, suggested an orbital telescope (Longair and Warner, 1979). He realized

the advantage of observations in space where stars do not twinkle and where there is negligible absorption in the ultraviolet and infrared. Since the launch of Sputnik in 1957, in a period of less than 30 years, many significant contributions to astronomy have been made by use of orbiting instrumentation. There were OAO, SAS-I (Uhuru), Ariel, ANS, Copernicus Orbiting Observatory, Skylab, OSO-7, Solar Max, Explorer, IMP, and others that added to our scientific understanding and to our experience in space operations. The recent Infrared Astronomy Satellite (IRAS) was an enormous success in opening new vistas in the solar system and the universe. The Einstein Observatory (HEAO2) in 1979 probed x-ray sources. Currently under development are the Hubble Space Telescope (ST) and the Gamma Ray Observatory (GRO). Further in the future are the Space Infrared Facility (SIRTF), which will be a free flyer, and the Advanced X-Ray Astronomy Facility (AXAF), which will continue work done by the Einstein Observatory mission of 1979. The ST, the GRO, AXAF, and SIRTF are complementary in that they span a range of wavelengths. Each of these instruments is built upon earlier successful orbiting observatories that led to enticing discoveries and suggested improvements in sensors and instrumentation.

Establishment of scientific requirements and development of conceptual designs for a space-based telescope is a lengthy and iterative process. The Space Telescope was first proposed in the early 1960s at a summer study (Longair and Warner, 1979). Meetings



*Figure 1. Radio astronomy from the Moon has three advantages over terrestrial observation: man-made, terrestrial-originating background noise is avoided (particularly on the farside); there is less gravitational pull to cause distortions in the structures; and there is a slower period of rotation relative to objects being observed (from Malina, 1969).*

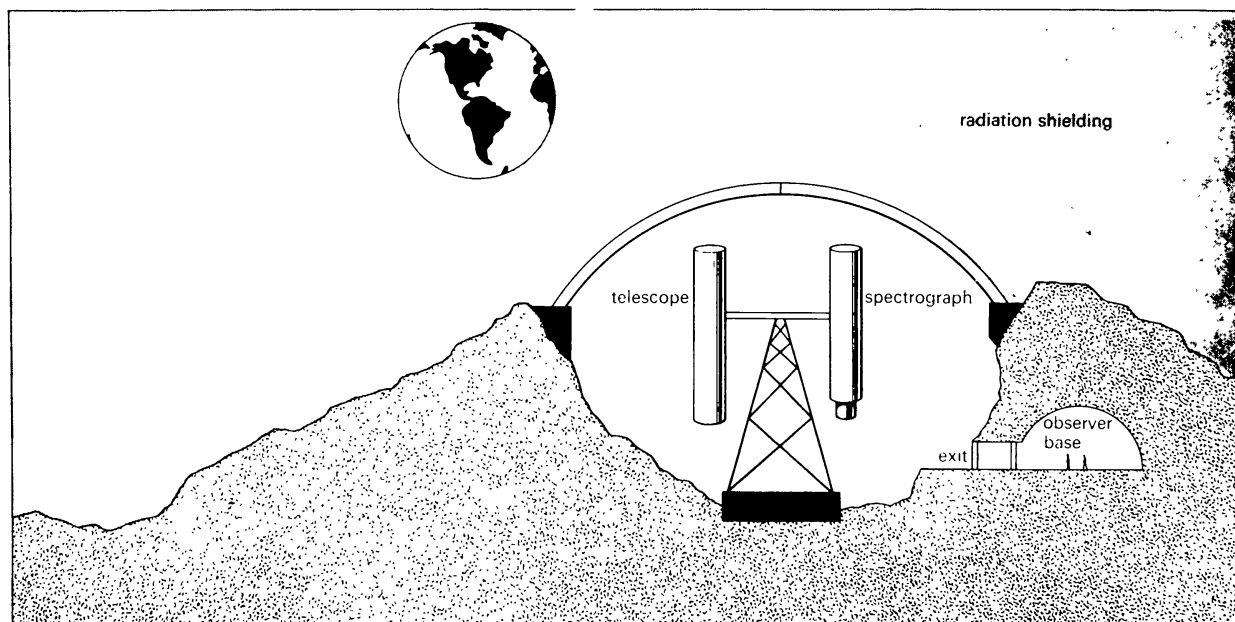


Figure 2. The Lunar International Symposium (LIL) of 1965 suggested this semi-permanent observatory in a small lunar crater. Radiation shielding lids of expanded foam materials are shown (Malina, 1969).

in 1967 and 1968 by an NAS *ad hoc* committee discussed how a space telescope could be used. A 1974 AIAA Symposium led to additional discussion of space telescope use. The NASA Space Telescope project was initiated by an advanced study (Phase A) activity in 1971 and 1972. During 1973–1976, Phase B scientific definition studies were carried out. Final design and development (Phases C and D) began in 1977, the year that Congress approved a 2.4-m space telescope. Launch of this Hubble Space Telescope is anticipated in 1986 or 1987. The telescope is to be maintained and refurbished in orbit at 2- or 3-year intervals and may be returned to Earth for major refurbishment at 5-year intervals. The operational life of the system may be 15 years. Might a similar instrument someday be located on the Moon?

Discussions of the scientific and engineering challenges facing a lunar surface telescope began over 20 years ago. In 1964, a Lunar International Laboratory (LIL) panel anticipated that a manned, permanent research center would begin operations on the Moon sometime in the period 1975–1985. At the International Academy of Astronautics Lunar International Laboratory Project Symposium in Athens in 1965, it was noted (Malina, 1969) that the Moon “represents...an ideal place to site an observatory for both optical and radio telescopes (p. 109).” Figures 1–3 illustrate concepts for lunar observatories suggested at the LIL Symposium (Malina, 1969).

The report of the astronomy working group (Hess, 1967) listed necessary measurements to be made on the Moon before the establishment of a lunar astronomical base. Designs of observatories for the Moon (e.g., for those illustrated in Figs. 1–3) will require extensive data on the lunar environment. The environmental characteristics (Table 1) to be determined at selected lunar sites may influence site selection. Sites suggested include the crater

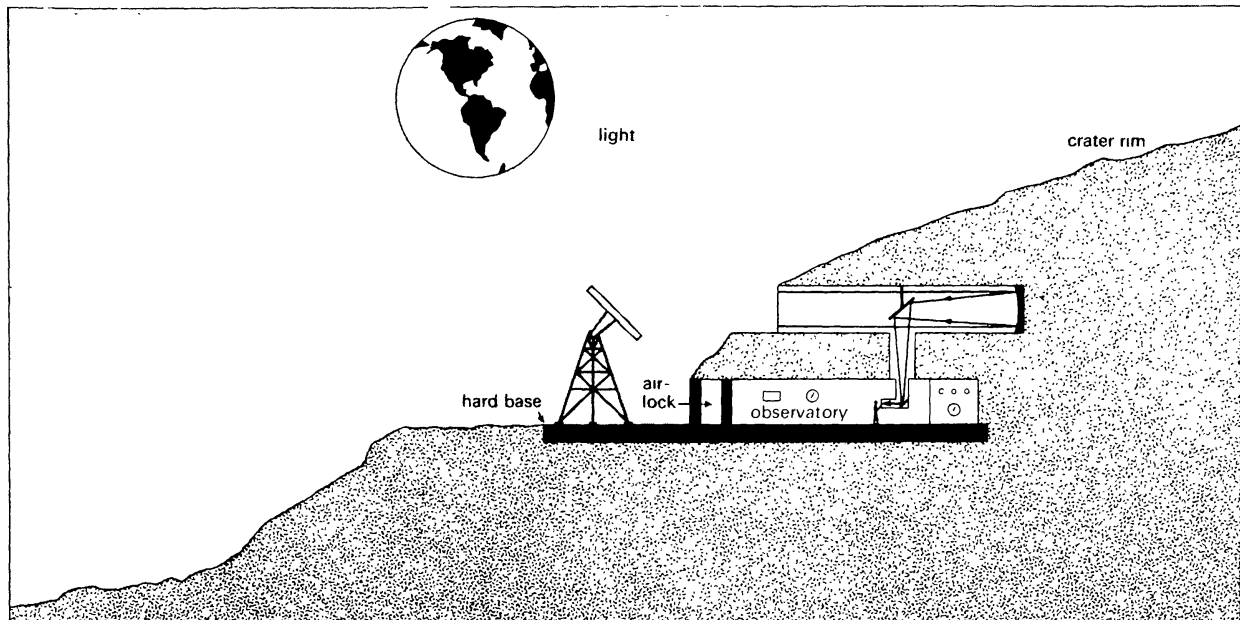


Figure 3. This fixed-based observatory was also proposed at LIL such that sensitive equipment could be protected by a considerable thickness of lunar soil and rock (Malina, 1969).

Grimaldi because of its location near the equator and near the limb. Another option is a site slightly south of the equatorial plane to provide access to the Magellanic Clouds. The very large telescope was suggested at a site on the farside of the Moon to avoid earthlight.

A MIMOSA (1967) Program III that was to commence in 1971 and extend until 1988 involved 1-meter optical telescopes set up at the south pole and the center of the farside to evaluate the potential of lunar-based astronomy. A 12-man permanent

Table 1. Characteristics to be Determined at Selected Sites\*

1. Micrometeoroid environment
2. Radio frequency noise levels
3. Surface impedance and conductivity
4. Density and extent of lunar ionosphere (if it exists)
5. X-ray and  $\gamma$ -ray intensities, including zenith-angle distribution of intensities
6. Soil mechanics such as bearing strength and stability, depth profiles of temperature, seismic activity, and ionizing radiation
7. Thermal effects on astronomical instrumentation
8. Contaminants such as dust, spacecraft outgassing, spacecraft radio frequency interference, and astronaut seismic noises
9. Deterioration of precision optical surfaces
10. Evaporation rates for optical coatings

\*from Report of Astronomy Working Group (Hess, 1967)

base in the crater Grimaldi was to use an array of radio, optical, and x-ray telescopes. MIMOSA was based on an upgraded Saturn V launch rate of three to four per year through the 1970s and six per year in the 1980s.

Successful operation of astronomical observatories on the Moon will necessitate the meeting of many stringent requirements for materials, structures, and controls. New proposals for observatories are arising in the scientific community. Some innovative concepts in interferometry (Burke, 1984) require precise knowledge of interactions between array elements, support structures, and the lunar regolith. Other, more traditional installations may require protected, pressurized environments. Each observatory instrument complex, from the simplest to the most elaborate, presents a challenge to soil mechanics, foundation engineering, structural material selection and design, and construction planning.

## SOIL MECHANICS AND FOUNDATION ENGINEERING

Johnson *et al.* (1971) used Surveyor and Apollo mission results in an investigation of the lunar regolith as a site for an astronomical observatory. A telescope system was postulated involving a large reflector, and foundations were designed for cases of a deep regolith and a shallow regolith. It was noted that the lunar soil is fine-grained, relatively dense, and weakly cohesive. More information is needed on the lunar environment, including thermal cycling and behavior of the surface under dynamic loads. Previously, Johnson (1964) considered criteria for lunar base structures, taking into account gravitational, vacuum, and other effects.

There are known to be significant variations in the lunar soil both laterally and with depth as revealed by trenching and core tubes (Johnson and Carrier, 1971; Carrier *et al.*, 1972). In emplacing an observatory on the Moon, it will be necessary to have knowledge of soil and rock profiles and engineering properties at depth and to monitor soil and foundation behavior during observatory placement. The regolith may vary in thickness from 1–15 m and be underlain by perhaps jointed or fractured rock. It may be feasible to compact or stabilize the regolith. The wide range in lunar temperatures implies a thermal cycling (and expansion and contraction) of the regolith, suggesting that foundations should be placed below the depth of thermal cycling. Both total and differential settlements are to be controlled appropriately.

## DESIGN AND CONSTRUCTION ALTERNATIVES

A variety of materials offers promise for use at a lunar observatory. The materials range from aluminum, graphite epoxy, and metal matrix composites to castings from lunar rock. The choice of materials will depend on progress in the development of the technology of the base and where the observatory will be sited. Early facilities and those away from the main base will probably be fabricated on Earth. Sensitive components will be shielded by burial in the lunar regolith. Air-inflated structures offer the possibility of providing mobile repair hangars that could be used at remote observatory sites.

If robots and automated construction equipment are to be used, consideration will have to be given to a myriad of design details. For example, connections and hookups

(e.g., for fluids) must take a positive connection with little adjustment required. Semi-autonomous construction equipment offers the possibility of providing tremendous cost savings in building and maintaining a lunar observatory. Developments on Earth are already validating concepts of semi-autonomous telecommanded systems of construction and exploratory vehicles and equipment for use in hazardous environments and in military contexts.

## **RELATIONSHIPS BETWEEN REQUIREMENTS AND CRITICAL ISSUES**

An observatory on the Moon will be established to meet a set of pre-determined requirements. Requirements related to what missions it will perform (e.g., radio astronomy, optical astronomy, x-ray astronomy, and gamma-ray astronomy), how to perform these missions (e.g., mass and configuration on the Moon, energy needs, and shielding), and how well (resolution, available viewing time, data rate to Earth, etc.). From the requirements will flow a set of critical issues to be resolved. There will be an interplay between requirements and critical issues and technology development programs. Requirements will probably not be fixed until there is a definition of transport and logistics capabilities (mass transportable to the Moon) and the incremental costs to establish a type of observatory on the Moon.

Many critical issues must be resolved before an observatory can be established on the Moon. Some of the issues can be enumerated as follows.

(1) What is the operational role of the lunar astronomical observatory relative to in-orbit and Earth-based observatories? Various options are to be considered for prioritization of viewing and technical oversight management.

(2) What collectors and sensors are to be placed at the sites, and what is the desired time-phasing of placement? Can derivatives of ST, AXAF, SIRTF, GRO, and other systems be used to reduce development time and cost?

(3) What site or sites are to be used? What is the relationship of sensor or astronomical discipline to site, and how can a range of sites be utilized and developed in an optimal time-phasing to achieve scientific returns and be compatible with the lunar base infrastructure?

(4) What information is needed on potential sites, and how are the sites to be surveyed and screened (e.g., for soil profiles and other properties)? Sites need proximity to support but distance from detrimental effects of mining and launch operations.

(5) How is the interface between observatory systems and the lunar regolith to be addressed (e.g., selection of foundation elements to be used on the Moon)? Thermal profiles, conductance, impedance, presence of hot spots, and regolith strength and deformation characteristics need to be evaluated.

(6) How are sites to be preserved for the operational life of observatory systems (e.g., leveling, excavation, dust mitigation, and pollutant control)? Some effort is suggested to establish protected areas for astronomy and to monitor site environments.

(7) How are required positioning tolerances to be met and controlled? Burke (1984) comments that for an optical interferometric array on the Moon, element position and orientation would be controlled to 100 Å in 20 km. What would be the trade-off between structural and foundation precision placement and position holding by closed loop automatic control?

(8) What materials should be used in support structures considering the lunar environment with its radiation, thermal cycling, vacuum, and meteoroid impacts? Are materials such as the metal matrix composites (with low coefficients of thermal expansion) required or are aluminum alloys feasible with appropriate control loops? The composite materials can be tailored to meet coefficient of thermal expansion and stiffness needs. Should structural elements formed from lunar soil be developed and used?

(9) How should logistics and construction needs be met with the appropriate mix of automation, robotics, vehicles, and suited man activity? Cost studies and evaluation of operational risks are needed to establish a desirable mix.

(10) Communications, data storage, and data transfer questions relative to the lunar base, lunar orbit, Earth orbit, and Earth's surface need to be investigated.

(11) System monitoring, protection, maintenance, upgrading, and refurbishment requirements need to be identified, and capabilities need to be planned and built into the system. Experience in Earth orbit should be helpful, particularly if derivatives of Earth-orbiting systems may be used.

(12) What separation distance restrictions are desirable in relation to other lunar activities anticipated such as the logistics base, mining and resources recovery, spaceport launches and landings, and habitat operation? A logical means of setting separation distances needs to be developed.

(13) Shielding for personnel and equipment against the radiation environment of space needs to be addressed. In the design of the observatory facilities, charged particles from the solar wind, solar cosmic rays, and high-energy galactic cosmic rays from outside the solar system will be of concern (Smith and West, 1983), as well as products of the interaction of primaries with shielding materials. Gammas and neutrons originating from power sources may also be present. In space, the proton dosage during a solar flare may be potentially lethal (Benton, 1984). Protection in "storm shelters" with heavy shielding is suggested. Microprocessors such as those used in experiments and life support equipment will have to be protected.

(14) Support requirements such as power, cooling, heating, and associated expendables need to be addressed. Included are cryogenics for cooling detector arrays and possibly advanced refrigeration (cryocooler) capabilities.

## **SYSTEM MODELING AND OPTIMIZATION**

Resolution of these critical issues will be assisted by system models developed to facilitate the evaluation of various options before construction or fabrication of hardware. Analytical models may be constructed of flow of fluids, rate of heat rejection, power



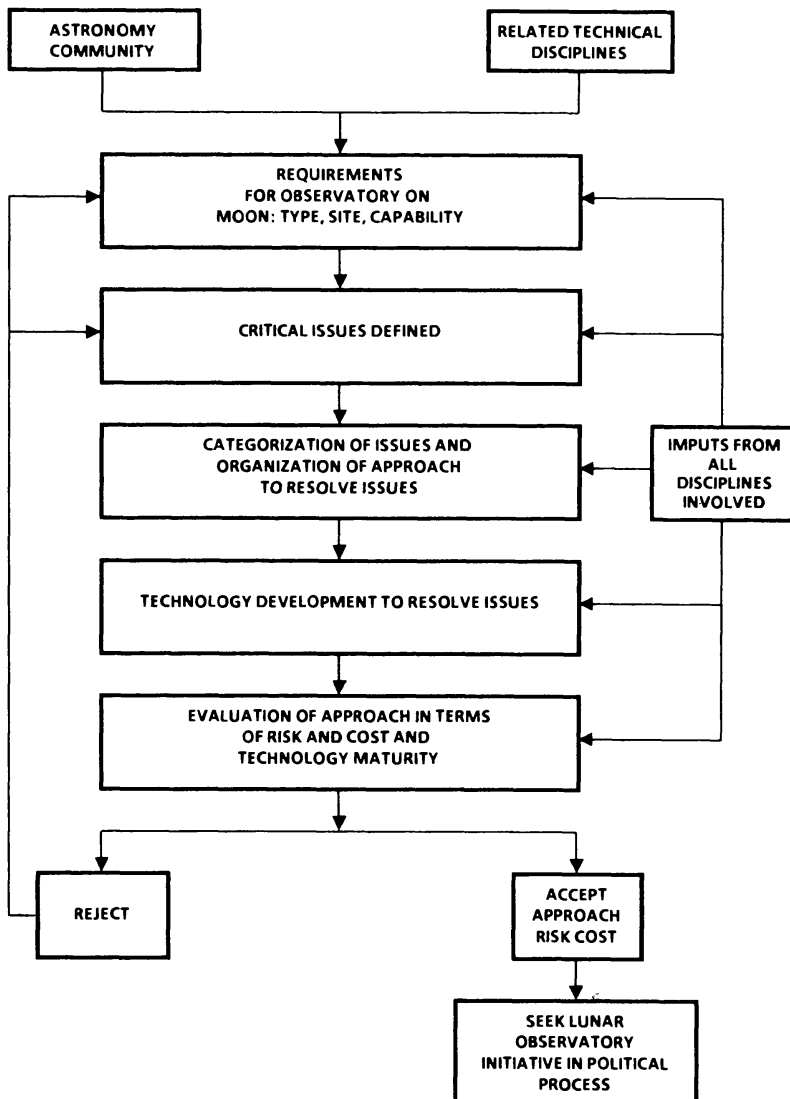


Figure 4. Illustrated are the generation of requirements for the observatory, the definition of critical issues, and how technology programs relate to ultimate decisions after risks and cost are taken into account.

consumption, process flow and performance, and costs. An important model from the standpoint of selecting alternatives is a life cycle cost (LCC) model. It is proposed that one of the first tasks of a lunar observatory working group should be the development of models complete with weighting factors for the various components and systems. Models will assist in calculating the effects of requirements (e.g., resolving power and data handling) on the cost of the observatory. In operations research, many techniques for formalizing the decision process have been developed. Some attributes that might be considered in formalized models to assist in the decision process are refurbishment requirements, power (quantity and quality) for experiments, lighting, heating, ventilation, air conditioning, environmental control, utilities (water, cryogenics, sewage, gas, and air), and thermal control. Models will also assist in trade-offs on structural requirements such as stiffness, natural frequency, thermal stability, precision of erection or alignment, damping, and passive and active control. Results of trade-off studies can be fed back into LCC

models. Approaches to optimizing solutions of complex multi-attribute problems (Edwards, 1977) will be applied.

## THE FUTURE EFFORT

The pathway to success in the development of a lunar astronomical observatory involves an early start and a multidisciplinary approach to state requirements and to clarify and resolve critical issues. Cost models based on life cycle cost and systems engineering methods will assist in planning and implementing a phased development of a lunar astronomical observatory. Mathematical modeling of the observatory system and its operation will help clarify critical issues and suggest improved approaches. Developmental programs will be initiated to resolve these issues and to reduce the risks involved in placing an observatory on the Moon. Figure 4 portrays a process whereby inputs from the multidisciplinary community are used to derive requirements. Perhaps the observatory will be an international facility built with inputs from many nations. If that is to be the case, then the breadth of input could be great and financial backing will be increased. Once it is determined what capabilities are desired and some allotted mass of equipment is known, issues will be defined. Technology programs will be developed to resolve the issues and to build and test the system.

*Acknowledgments.* The authors acknowledge the support of the BDM Corporation and the Zia Company in the preparation of this paper.

## REFERENCES

- Astronomy and Astrophysics for the 1980s (1982) *Vol. 1, Report of the Astronomy Survey Committee of the Assembly of Mathematical and Physical Sciences*, pp. 165–166, National Research Council, National Academy Press, Washington, D.C.
- Benton E. V., Almasi J., Cassou R., Frank A., Henke R. P., Rowe V., Parnell T. A., and Schopper E. (1984) Radiation measurements aboard Spacelab 1. *Science*, 225, 224–228.
- Burke B. F. (1984) Astronomical interferometry on the Moon (abstract). A Paper Presented at the Symposium on Lunar Bases and Space Activities of the 21st Century, NASA/Johnson Space Center, Houston.
- Carrier W. D., III, Johnson S. W., Carrasco L. H., and Schmidt R. (1972) Core sample depth relationships: Apollo 14 and 15. *Geochim. Cosmochim. Acta*, 3, 3213–3221.
- Edwards W. (1977) How to use multiattribute utility measurement for social decisionmaking. In *Systems Engineering: Methodology and Applications* (A. Sage, ed.), pp. 206–220. IEEE Press, New York.
- Hess W. N. (editor) (1967) *Summer Study of Lunar Science and Exploration*. Report of Astronomy Working Group, pp. 369–390. NASA SP-157.
- Johnson S. W. (1964) *Criteria for the Design of Structures for a Permanent Lunar Base*. Ph.D. Thesis, University of Illinois, Urbana, IL. 177 pp.
- Johnson S. W. and Carrier W. D., III (1971) Lunar soil mechanics. *The Military Engineer*, 63, 324–328.
- Johnson S. W. and Leonard R. S. (1984) Lunar-based platforms for an astronomical observatory. In *Proceedings of National Symposium and Workshop on Optical Platforms* (C. L. Wyman, ed.), pp. 147–158, volume 493. Society of Photo-Optical Instrumentation Engineers, Bellingham, Washington.
- Johnson S. W., Rohloff K. J., Whitmire J. N., Pyrz A. P., Ullrich G. W., and Lee D. G. (1971) The lunar regolith as a site for an astronomical observatory. In *Proceedings of the Ninth International Symposium on Space Technology and Science* (M. Uemura, ed.), pp. 1059–1076. AGNE Publishing, Inc., Tokyo.

## 422 / Lunar Construction

- Longair M. S. and Warner J. W. (editors) (1979) *Scientific Research with the Space Telescope*. International Astronomical Union Colloquium, no. 54, Princeton, New Jersey. 327 pp.
- Malina F. J. (1969) The lunar laboratory. *Sci. J.* (Special Issue: Man on the Moon), 5, 108–113.
- MIMOSA (1967) *Study of Mission Modes and System Analysis for Lunar Exploration, Final Report, Recommended Lunar Exploration Plan*, volume III. LMSC-A847942, Lockheed Missiles and Space Company, Sunnyvale, CA. 154 pp.
- Smith R. E. and West G. S. (compilers) (1983) *Space and Planetary Environment Criteria: Guidelines for Use in Space Vehicle Development*. NASA TM-82478. 191 pp.

# ENVIRONMENTAL CONSIDERATIONS AND WASTE PLANNING ON THE LUNAR SURFACE

Randall Briggs and Albert Sacco Jr.<sup>1</sup>

*Worcester Polytechnic Institute, 166 South Street, Shrewsbury, MA 01545*

<sup>1</sup>*Chemical Engineering, Worcester Polytechnic Institute, advisor*

---

Lunar operations in the near future will pose waste management judgments. Final decisions must be established to maintain a high degree of operational efficiency within technological and economical limits. The purpose of this study is to identify environmental considerations arising from a lunar manufacturing facility. Certain assumptions guide the setup and operation of the lunar base presented. The author does not suggest that such assumptions will become reality but, instead, presents an outline of a base that appears promising at the present time. The goal of this paper is to promote conversation and thought towards fundamental decisions that will need to be made before the building of lunar facilities begins. The following assumptions were taken: (1) the base will be manned by a crew of 15 workers; (2) the primary function of the base will be the extraction of oxygen from ilmenite ( $\text{FeTiO}_3$ ) via a hydrogen reduction process; (3) nuclear power will form the central power supply on the surface; (4) a semi-closed life support system will be employed with the total resupply of food coming from Earth.

Many questions still exist as to what will be done with much of the refuse brought about by man's existence on the lunar surface. What will become of spent nuclear reactors? Will carbon and phosphate salts from man's waste be stored for later use? Will chemical transportation create a significant lunar atmosphere? These are some of the myriad of questions that confront planners of the lunar base. In order to achieve the best possible results from the operation, questions like these will soon have to be addressed.

## INTRODUCTION

If NASA's tentative schedule is to be kept and the lunar facility is to be implemented before 2010, it is not too soon to begin contemplating the impact of man and his activities on the lunar surface and to discuss ways in which his presence and activities will not limit his possibilities in more distant times. A principal goal of any project such as the proposed lunar facility is to grant the most alternatives, economically and technically feasible at the time, to future planners. The paper identifies several wastes that promulgate future operational choices and several that limit more distant activities.

Table 1 presents a rough estimate of the oxygen needs that NASA might typically require at the time oxygen production begins on the lunar surface (oxygen needs and trip parameters were developed through personal communication with B. Roberts and W. Richards of the Johnson Space Center, 1984). A typical lunar oxygen mission can return a net amount of liquid oxygen (LOX) to low Earth orbit (LEO) totaling 54,400 kg (assuming an aerobrake weight that is 14.5% of entry weight, an overall trip  $I_{sp}$  of 480 s, and an OTV and lunar lander oxygen to fuel ratio of 7:1; mass payback ratio

Table 1. Typical Oxygen Needs of NASA in LEO as Lunar Facility Becomes Operational (Yearly)

Mission from LEO	LOX per Mission (kg)	Total Missions	Total LOX (kg)
Lunar	77,200	4	309,000
Manned Geosynchronous	38,000	4	152,000
Other	—	—	91,000
Total:			552,000

is 2.6). The production rate on the surface to get this amount of LOX to LEO is approximately 200,000 kg. The other 146,000 kg of LOX is used in the transport of cargo to LEO. This brings the lunar oxygen production rate to 200,000/54,400 or 3.7 kg LOX produced on the lunar surface per kg LOX free in LEO.

Referring to Table 1, a total of 552,000 kg LOX will be needed in LEO. Therefore the lunar oxygen production rate is set at 3.7 by 552,000, or  $2.1 \times 10^6$  kg LOX per year.

## MINING, BENEFICIATION, AND THE HYDROGEN REDUCTION OF ILMENITE

The reduction of ilmenite with hydrogen holds much promise for the production of oxygen on the lunar surface for several reasons. (1) The process employs only one significant chemical equation,  $\text{FeTiO}_3 + \text{H}_2 \rightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O}$ . The water vapor is electrolyzed back to hydrogen, to be recycled, and oxygen. (2) The lunar maria is known to be 10% or more, by weight, ilmenite. (3) Beneficiation, with an electrostatic separator, is relatively easy and yields material of high purity for further processing.

Beginning with the production rate of  $2.1 \times 10^6$  kg LOX and working under the assumptions of (a) 90–100% conversion in the reaction above, (b) lunar soil consisting of 10–12% ilmenite, (c) soil density of 1,800 kg/m<sup>3</sup>, and (d) no significant loss in the beneficiation process, the following approximate values are arrived at: 20,000 tons  $\text{FeTiO}_3$  mined/year,  $1.1 \times 10^5$  m<sup>3</sup> bulk soil mined/year, and 18,000 tons  $\text{FeTiO}_2$  generated/year.

## LIFE SUPPORT

It is possible that the permanently manned outposts in space, at least initially, will have a life support system that is semi-closed (Spurlock and Modell, 1979). To achieve a greater payback from the lunar operation, components of water and air must be recycled to limit resupply transportation costs. The initial facility, however, may not be capable of supplying its own foodstuffs. The total resupply of food from Earth is therefore assumed.

Table 2. Basic Requirements and Waste Generation for a Lunar Crew of 15\*

Requirements	Per Man, Daily (kg)	Total for Crew (kg)
Metabolic oxygen	0.9	13.5
Drinking water	3.6	54.0
Hygiene water	5.4	81.0
Food	0.6	9.0
<i>Waste Production</i>		
Carbon dioxide	1.0	15.0
Water vapor	2.5	37.4
Urine	1.5	22.5
Feces	0.16	2.4
Metabolic heat	12,660 kJ	189,900 kJ

\*Sharpe (1969), p. 107.

Table 2 lists the material that a life support system must be capable of handling. Figure 1 displays the various units in a feasible life support system.

Central to the support system is the oxidation water reclamation unit. For many years, Robert Jagow has studied the wet oxidation process of waste recycle as it exists in industry and in its application to various other environments (Jagow, 1972, 1975). From this process, Jagow has shown that wash water, human waste, and trash can be oxidized at elevated temperatures and pressures to produce water, carbon dioxide, and a cake of phosphates and sodium salts. The water may be recycled for direct human use, and the carbon dioxide could be converted to oxygen and carbon. From Table 2, the carbon dioxide from respiration from the 15-member crew will be about 15.0 kg/day. About 1500 kg of pure carbon will be produced yearly.

## POWER

A dependable, constantly operative power supply will be needed on the lunar surface. Survival will be dependent upon a few kilowatts of power to clean the air of the workers, regenerate the oxygen, and recycle the water. At the same time, large amounts of energy must be produced to accommodate the taxes imposed by the processing facilities. Nuclear power holds a promising key to these lunar needs.

Nuclear power is attractive for several reasons. Proposed units are easy to maintain and operate. It is anticipated that the unit can be dropped into place, started, and left alone until its productive life is over. Nuclear power units have a high energy density. Nuclear power is also capable of producing large amounts of both thermal and electrical energy—five to twenty watts thermal to every one watt electrically produced (French, personal communication, 1984).

Nuclear power units now in study under the program name SP-100 are being adapted to the zero-g environment. These reactors will have a lifetime of seven to ten years

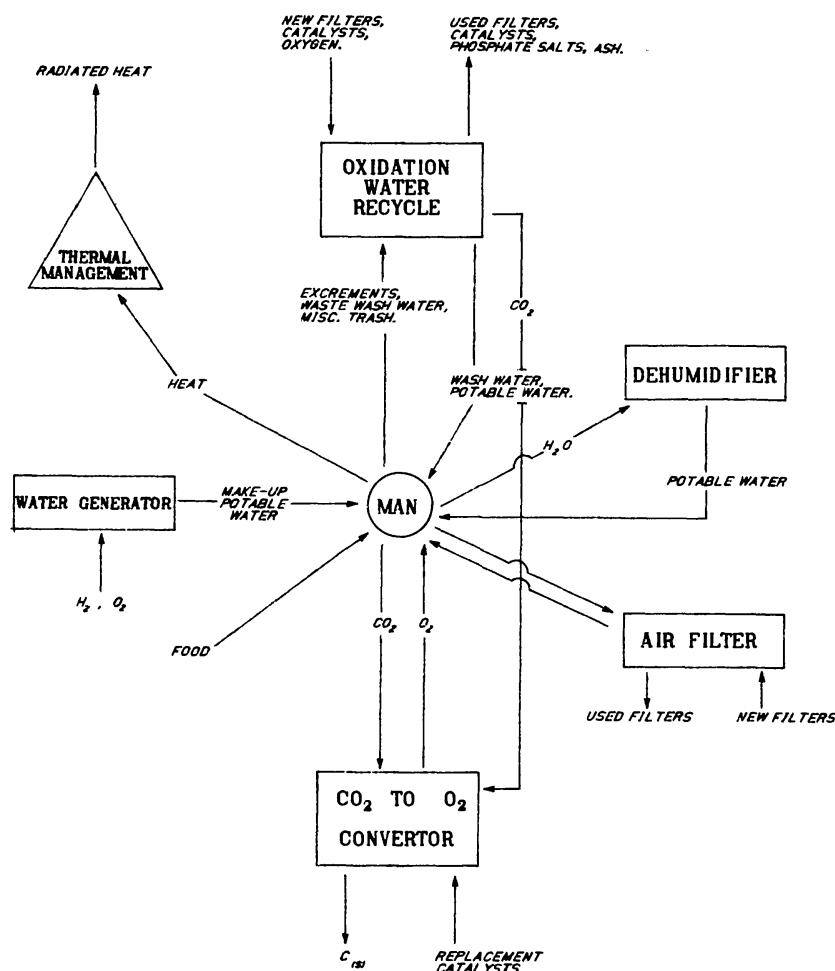


Figure 1. A feasible semi-closed life support system.

and will be capable of generating between 100 to 400 kW of electrical power. It has been proposed to conform such units to the lunar environment, employing native soil for shielding purposes (French, 1984).

## TRANSPORTATION

Transport of man and materials to low lunar orbit (LLO) will conveniently be adapted from geosynchronous transport now being drawn up by NASA. Heavy lift vehicles (HLV) and the space shuttle will bring material to LEO, and orbital transfer vehicles (OTV) will travel to LLO, transferring the payload to lunar descent vehicles.

Initially it is conceivable that the lunar descent vehicles will be disposable. Until the production of oxygen begins, there will be no need to bring substantial material off the surface and, further, no ability to fuel vehicles after descent. Upon the production of oxygen, however, a great desire will arise to make these lunar surface transports reusable. Many flights will be needed to transport oxygen off the lunar surface for the trip back to LEO. If such flights were made with disposable transportation, operation costs would reduce the operation's payback.

NASA has estimated the total base mass to be approximately 181,500 kg at the time of oxygen production. Lunar descent platforms, each having a mass of 4,900 kg, have been estimated to be capable of transporting approximately 18,800 kg of cargo (Richards, personal communication, 1984). Thus, to transport the initial base to the Moon,  $181,500/18,800$  or about ten trips need to be made. This leaves  $10 \times 4,900$  kg or 49,000 kg of scrap material on the lunar surface.

## POTENTIALS AND PROBLEMS

Discussion of potentials to increase future operational alternatives and identification of problems that may arise from man's existence on the Moon can proceed from the general outline of the major components of the lunar base given above.

If man is to become self-sufficient on the lunar surface, the groundwork must be laid to close his life support system. Man must eventually develop food production on the lunar surface and cut the "umbilical cord" that will tie him to Mother Earth.

Current work, under the program name Controlled Ecological Life Support System (CELSS), is proceeding to achieve this goal. An experimental bio-regenerative life support system is being considered for attachment to the Space Station in 1998. It is possible that a similar system could be landed on the lunar surface. In this event, advantages exist to aid in the success of this project and reduce the economical cost incurred.

As discussed above, the life support system generates carbon from the conversion of carbon dioxide to oxygen and filters phosphate salts from the water reclamation unit. This material need not be deemed waste, since such rare and life-required elements could be employed in a pilot agricultural facility. It seems logical that these elements from the support system should be stored for later use. It has also been proposed that parts of the discarded transport platforms (up to 40%) be made of similar rare lunar materials (Babb *et al.*, 1984). In this manner, what might previously be considered waste could be used to the advantage of man.

Nuclear power units have potential additional use. This opportunity arises from the large quantity of thermal energy that reactors generate. This excess heat can be radiated into space, if desired, and be considered waste. If, however, processing facilities such as the hydrogen reduction process are developed in a way as to be receptive to this alternative energy source, waste can again be used to the advantage of the base.

Several waste problems still remain unanswered. Will those operating the lunar base consider it economically feasible to refill the mining pits previously excavated? Many now working on this subject seem to believe that the idea of a moral duty to leave the Moon as it has been for eons is sheer "lunacy." However, Williams *et al.* (1979, p. 283) stated, "Although conveniently located craters can be refilled with wastes initially, back filling the mine site is the only feasible long term solution." Backfilling here would include the ilmenite-poor soil (90% of that is mined) and the reduced ilmenite,  $\text{FeTiO}_2$ , from the reactor.

What will become of the spent nuclear reactors? If those under design in the SP-100 program are to be employed, the energy rating of 100 kW and the high demands of the lunar facility will necessitate several reactors. To reduce the cost of transport,



it has been proposed to strip the reactor of its shielding and, in its stead, employ native soil. This requires that the surrounding area be off-limits to personnel and overhead flights (French, 1984). The reactors will provide their services for about ten years, at which point they will be shut down. Two options exist at that time. One choice is to dig up the reactors and refuel them or move them to a different locality. This procedure, however, will require a strong surface infrastructure capable of safely handling such a technically difficult task; perhaps not developed fully enough for several decades after the initial setup. The second option is then forced upon the lunar base—to leave the reactors buried. Since the prospect of tens of discarded nuclear reactors will face the lunar facilities after several years of operation, the need of strict reactor management will arise to avoid limiting future operational plans. If not, the prospect of scattered sites, each being off-limits to lunar activities, will confront more distant lunar workers.

Will chemical transportation cause an impact in the formation of a restrictive lunar atmosphere? It has long been realized that the farside of the Moon provides astronomers the perfect locality for an observation post; the existence of a distinct lunar atmosphere will limit the options of these astronomers. It has been estimated that a long-lived atmosphere (with a life of several hundred years) could be created on the Moon with a mass of  $10^8$  kg or equivalently if an amount on the order of 60–100 kg/s entered for an extended period of time (Vondrak, 1974).

Calculations can be made for the scenario presented here. For each lunar descent and ascent a total of 98,000 kg exhaust vapor is formed (Richards, personal communication, 1984). Since each trip to the lunar surface returns 54,400 kg LOX to LEO, and a total of 552,000 kg of LOX is to be returned to LEO, about 11 trips must be made in the course of a year. In one year, then, 11 by 98,000 kg or  $1 \times 10^6$  kg of vapor enter the lunar atmosphere. This is on the order of 0.01 kg/s.

One may conclude that although a long-lived atmosphere will not be developed in this case, a finite cover can be formed and may pose astronomical limitations. Further, if oxygen requirements increase in time and more flights on and off of the lunar surface occur, while some alternative form of transportation (e.g., a mass driver) is not employed, the formation of a substantial lunar atmosphere is not out of the question.

What are the legal responsibilities of NASA and the United States when constructing and operating the base? In 1967, President Lyndon Johnson ratified the "Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies," and pledged to abide by certain guidelines in outer space. The following passages are from this treaty.

*Art. I, para. 1*

*"The exploration and use of outer space, including the moon. . . shall be carried out for the benefit and in the interest of all countries, irrespective of their degree of economic or scientific development, and shall be the province of all mankind."*

*Art. IX, para. 1*

*"State parties to the treaty. . . shall conduct all their activities in outer space, including the moon. . . with due regard to the corresponding interest of all other State Parties to the treaty. State*

*Parties. . . . shall pursue the studies of outer space, including the moon. . . and conduct exploration of them so as to avoid their harmful contamination.*

*A State Party to the treaty which has reason to believe an activity or experiment planned by another state party in outer space, including the moon. . . . would cause potentially harmful interference with activities in the peaceful exploration and use of outer space. . . . may request consultation concerning the activity or experiment."*

If NASA intends to operate processing facilities on the lunar surface, it must not alter the existing environment. If this is not done, it will surely elicit a response from other signatory nations. Intentions of operations and their impact must, in accordance with the treaty, be available to these nations. Therefore, NASA's lunar facilities must not cause other State Parties to question the environmental impact of base activities.

Many prospective lunar activities at this time have unanswered questions and pose many waste management problems. These problems arise from units and procedures that appear at this point promising to be included at the initial lunar base. The opportunity exists for several of the wastes to be utilized by the crew to increase opportunities and decrease cost of operation in the lunar environment. Table 3 summarizes the environmental considerations identified by this study. Questions and opportunities that are open to base planners must be addressed soon to deal with these waste problems and provide the maximum future operational options. It is not too soon to begin to address the impact of man and his activities on the lunar surface.

Table 3. Summary of Environmental Considerations Arising from Proposed Lunar Operations and Facilities

Waste Origin	Environmental Consideration	Potential Benefit
Transportation Hardware	Use of disposable descent platforms for pre-oxygen production transportation places hundreds of tons of scrap material scattered in the base vicinity.	Building platforms of materials beneficial to man on the Moon allows him to accumulate lunar deficient elements.
Chemical Propulsion	Traditional chemical transportation used at projected levels could lead to experimental and operational limitations.	None.
Life Support System (LSS)	Man's life processes produce bio-wastes. Most material is recycled; however initial LSS is not closed, giving rise to phosphate and carbon residue.	Life support residue is rare to the Moon. These materials can be utilized at a later time for lunar agriculture.
Nuclear Power	Reactors stripped of man-made shielding must employ native soil to limit radiation. Surrounding area will be restricted to personnel and overhead flights.	Thermal energy produced by reactors can be used in material processing.
Mining and Processing	Strip mining of topsoil produces large pits and piles on the surface. Unprocessed material is rejected by processing facilities.	None.

*Acknowledgments.* This presentation was made possible by Worcester Polytechnic Institute, being adapted from a project under the guidance of Dr. Albert Sacco, Chemical Engineering.

## REFERENCES

- Babb G. R., Davis H. P., Phillips D. C., Stump M. R. (1984) Impact of lunar and planetary missions on the Space Station (abstract). In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 53. NASA/Johnson Space Center, Houston.
- French J. R. (1984) Nuclear powerplants for lunar bases. In *Papers Presented to the Symposium on Lunar Bases and Space Activities of the 21st Century*, p. 116. NASA/Johnson Space Center, Houston.
- Jagow R. B. (1972) Design and development of a prototype wet oxidation system for the reclamation of water and the disposition of waste residues onboard space vehicles. NASI-9183, Lockheed, Sunnyvale, CA. 146 pp.
- Jagow R. B. (1975) A study to evaluate the feasibility of wet oxidation for shipboard waste water treatment application. DOT-CG-23034-A, Lockheed, Sunnyvale, CA. 189 pp.
- Sharpe M. R. (1969) *Living in Space*. Doubleday, Garden City, NY. 192 pp.
- Spurlock J. and Modell M. (1979) Systems engineering overview for regenerative life-support systems applicable to space habitats. In *Space Resources and Space Settlements* (J. Billingham, W. Gilbreath, B. O'Leary, and B. Gosset, eds.) pp. 1-11. NASA SP-428, NASA, Washington, DC.
- Vondrak R. R. (1974) Creation of an artificial atmosphere on the Moon. *Nature*, 248, 657-659.
- Bunch T. E., William R. J., McKay D. S., and Giles D. (1979) Mining and beneficiation of lunar ores. In *Space Resources and Space Settlements* (J. Billingham, W. Gilbreath, B. O'Leary, and B. Gosset, eds.), pp. 275-288. NASA SP-428, NASA, Washington, DC.

(This Page Intentionally Left Blank)

