6 / LUNAR CONSTRUCTION

The 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 of 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.
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, Khalil'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.

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LUNAR BASE DESIGN

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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 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 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 dragline 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 “shirt sleeve” or a non-pressurized “suite” 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 overburden can 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 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 terrestrial 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

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**Figure 1. BASE CONCEPT 1.** Flat shield raised in sections, pressurized enclosures beneath. Overall view of base (1) Regolith shielding (2) Perimeter expansion (3) Base-enclosed area shaded. Overlapping radiation barrier walls, from lunar surface equipment and installations “park.” (4) Solar shaded links to other parts of base. (5) Shaded links to other parts of base. (6) Ramp access to lower levels. (7) Initial erection sequence.
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.
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 framework 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, but would be minor. 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 terrestrial 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

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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 N/m² (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 × 2 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, line-mesh membranes would be stretched between the beams to provide support for the regolith mass above, with mesh bays experiencing controlled convex bulging 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 conveyor 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 × 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-preamendment 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 m². 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 replacement 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 × 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 footprint 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.
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

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**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 6000-7500 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.

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