

Engineering, Design and Construction of Lunar Bases

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Abstract: How do we begin to expand our civilization to the Moon? What are the technical issues that infrastructural engineers, in particular, must address? This paper has the goal of introducing this fascinating area of structural mechanics, design, and construction. Published work of the past several decades about lunar bases is summarized. Additional emphasis is placed on issues related to regolith mechanics and robotic construction. Although many hundreds of papers have been written on these subjects, and only a few tens of these have been referred to here, it is believed that a representative view has been created. This summary includes environmental issues, a classification of structural types being considered for the Moon, and some possible usage of in situ resources for lunar construction. An appendix provides, in tabular form, an overview of structural types and their lunar applications and technology drivers.

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Introduction

Concepts for lunar base structures have been proposed since long before the dawn of the space age. We will abstract suggestions generated during the past quarter century, as these are likely to form the pool from which eventual lunar base designs will evolve. Also, one concept will be suggested that has particularly attractive qualifications for the surface lunar base. Significant studies have been made since the days of the Apollo program, when it appeared likely that the Moon would become a second home to humans. For an early example of the gearing up of R&D efforts, see the Army Corps of Engineers study (Department of the Army 1963) (note the date of this report!). During the decade between the late 1980s to mid-1990s, these studies intensified, both within NASA and outside the government in industry and academe. The following references are representative: Benaroya and Ettouney (1989, 1990), Benaroya (1993a, 1995), Duke and Benaroya (1993), Ettouney and Benaroya (1992), Galloway and Lokaj (1994, 1998), Johnson and Wetzel (1998, 1990a), and Johnson (1996), Mendell (1985), Sadeh et al. (1992). Numerous other references discuss science on the Moon, the economics of lunar development, and human physiology in space and on planetary bodies. An equally large literature exists about related policy issues. These topics are outside the scope of this paper.

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Unfortunately, by the mid-1990s, the political climate turned against a return to the Moon to stay and began to look at Mars as the “appropriate” destination, essentially skipping the Moon. The debate between “Moon First” and “Mars Direct” continues, although it is clear that the latter will do no more for the expansion of civilization into the solar system than did the Apollo program. It is also clear that we do not have the technology and experience to send people to Mars for an extended stay. Physiological and reliability issues are yet unresolved for a trip to Mars; the Moon is our best first goal.

The emphasis below is on structures for human habitation, a technically challenging fraction of the total number of structures likely to comprise the lunar facility. The test for any proposed lunar base structure is how it meets certain basic as well as special requirements. On the lunar surface, numerous constraints, different from those for terrestrial structures, must be satisfied by all designs. A number of structural types have been proposed for lunar base structures. These include concrete structures, metal frame structures, pneumatic construction, and hybrid structures. In addition, options exist for subsurface architectures and the use of natural features such as lava tubes. Each of these approaches can in principle satisfy the various and numerous constraints, but differently.

A post-Apollo evaluation of the need for a lunar base has been made (Lowman 1985) with the following reasons given for such a base:

- Advancing lunar science and astronomy;
- Stimulus to space technology and test bed for technologies required to place humans on Mars and beyond;
- Utilization of lunar resources;
- Establishment of U.S. presence;
- Stimulation of interest of young Americans in science and engineering; and
- Beginning of long-range program to ensure survival of species.

The potential for an astronomical observatory on the Moon is very great, and it could be serviced periodically in a reasonable fashion from a lunar base. Several bold proposals for astronomy

from the Moon have been made (Burns et al. 1990). Nearly all of these proposals involve use of advanced materials and structural concepts to erect large long-life astronomy facilities on the Moon. These facilities will challenge structural designers, constructors, and logistics planners in the 21st century (Johnson 1989; Johnson et al. 1990). One example is a 16 m diameter reflector with its supporting structure and foundation currently being investigated by NASA and several consortia.

Selection of the proper site for a lunar astronomical facility, for example, involves many difficult decisions. Scientific advantages of a polar location for a lunar base (Burke 1985) are that half the sky is continuously visible for astronomy from each pole and that cryogenic instruments can readily be operated there due to the fact that there are shaded regions in perpetual darkness. Disadvantages arise from the fact that the sun will essentially trace the horizon, leaving the outside workspace in extreme contrast, and will pose practical problems regarding solar power and communications with Earth; relays will be required.

Environment

The problem of designing a structure to build on the lunar surface is a difficult one, discussed here in a necessarily cursory way. Many issues are not discussed, but will need to be tackled eventually. Some important topics not discussed here, but necessary in a detailed study, include the following:

- Relationships between severe lunar temperature cycles and structural and material fatigue, a problem for exposed structures;
- Structural sensitivity to temperature differentials between different sections of the same component;
- Very-low-temperature effects and the possibility of brittle fractures;
- Outgassing for exposed steels and other effects of high vacuum on steel, alloys, and advanced materials;
- Factors of safety, originally developed to account for uncertainties in the Earth design and construction process, undoubtedly need adjustment for the lunar environment, either up or down, depending on one's perspective and tolerance for risk;
- Reliability (and risk) must be major components of lunar structures, just as they are of significant Earth structures (Benaroya 1994);
- Dead/live loads under lunar gravity;
- Buckling, stiffening, and bracing requirements for lunar structures, which will be internally pressurized; and
- Consideration of new failure modes such as those due to high-velocity micrometeorite impacts.

In a light, flexible structural system in low gravity, light structural members (for example, composite cylinders that have a wall thickness of only a few $1/1,000^{\text{th}}$ of an inch) are sometimes designed to limit their load-carrying capacity by buckling when that limit is met. In turn, the load would have to be redistributed to other, less-loaded structural members. Such an approach offers possibilities for inflatable and other lunar surface structures where it would be simpler and less costly to include limit-state and sacrificial structural elements. Some of these discussions are under way (Benaroya and Ettouney 1992a,b), in particular regarding the design process for an extraterrestrial structure.

Our purpose in this paper is to discuss the technical issues and provide some historical context. Important issues such as financing the return to the Moon, enhancing human physiological understanding, and many others are beyond the scope here. The

focus for us, again, is to provide the reader with a brief glimpse of the structural and structural-related engineering issues for human habitation on the Moon.

Important components in a design process are the creation of a detailed design and prototyping. For a structure in the lunar environment, such building and realistic testing cannot be performed on the Earth or even in orbit. It is not currently possible, for example, to experimentally assess the effect of suspended (due to $1/6 g$) lunar regolith lunar soil fines on lunar machinery. Apollo experience may be extrapolated, but only to a boundary beyond which new information is necessary.

Another crucial aspect of a lunar structural design involves an evaluation of the total life cycle that is, taking a system from conception through retirement and disposition, or the recycling of the system and its components. Many factors affecting system life cannot be predicted due to the nature of the lunar environment and the inability to realistically assess the system before it is built and utilized.

Finally, it appears that concurrent engineering will be a byword for lunar structural analysis, design, and erection. Concurrent engineering simultaneously considers system design, manufacturing, and construction, moving major items in the cycle to as early a stage as possible in order to anticipate potential problems. Here, another dimension is added to this definition. Given the extreme nature of the environment contemplated for the structure, concurrency must imply flexibility of design and construction. Parallelism in the design space must be maintained so that at each juncture alternate solutions exist that will permit continuation of construction, even in the face of completely unanticipated difficulties. This factor needs to be further addressed and its implications clearly explored. A discussion of lunar design codes has already started (Benaroya and Ettouney 1992a,b).

Loading, Environment, and Regolith Mechanics

Any lunar structure will be designed for and built with the following prime considerations:

- *Safety and reliability:* Human safety and the minimization of risk to "acceptable" levels are always at the top of the list of considerations for any engineering project. The Moon offers new challenges to the engineering designer. Minimization of risk implies in particular structural redundancy and, when all else fails, easy escape for the inhabitants. The key word is "acceptable," a subjective consideration deeply rooted in economic considerations. What is an acceptable level of safety and reliability for a lunar site, one that must be considered highly hazardous? Such questions go beyond engineering considerations and must include policy considerations: Can we afford to fail?
- *1/6 g gravity:* A structure will have, in gross terms, six times the weight-bearing capacity on the Moon as on the Earth; or, to support a certain loading condition, one-sixth the load-bearing strength is required on the Moon as on the Earth. In order to maximize the utility of concepts developed for lunar structural design, mass rather than weight-based criteria should be the approach of lunar structural engineers. All of NASA's calculations have been done in kg_{force} rather than newtons. Calculations are always without the gravity component; use kilogram feet per square centimeter as pressure, for example.

In the area of foundation design, most classical analytical approaches are based on the limit-state condition, in which the design is based on the limit of loading on a wall or footing at the

point when a total collapse occurs—that is, the plastic limit. Since many of the structures on the Moon require accurate pointing capabilities for astronomy, communication, and so on, a settlement-based design method would be more useful. Chua et al. (1990) propose a nonlinear hyperbolic stress-strain model that can be used for the lunar regolith in a finite-element analysis. The paper also shows how the finite-element method can be used to predict settlement of the railway under a support point of a large telescope. Chua et al. (1992) show how a large deformation-capable finite-element program can be used to predict the load-displacement characteristics of a circular spud-can footing, which was designed to support a large lunar optical telescope.

A note against assuming that less gravity means a footing can support more load: if soil can be assumed to be linearly elastic, then the elastic modulus is not affected by gravity. However, the load-bearing capacity of a real soil depends on the confining stress around it. If the soil surrounding the point of interest were heavier because of larger gravity, the confining stress would be higher and the soil at the point of interest could support a higher load without collapsing.

The area of lunar soil (regolith) mechanics was exhaustively explored in the 1970s. Much of the work was approached from interpretation based on classical soil mechanics. Newer work and development of nonlinear stress-strain models to describe the mechanics of the lunar regolith can be found in Johnson et al. (1995b) and Johnson and Chua (1993). Chua et al. (1994) show how structure-regolith simulations can be done using the finite-element approach.

- *Internal air pressurization:* The lunar structure is in fact a life-supporting closed environment. It will be a pressurized enclosed volume with an internal pressure of nearly 15 psi. The enclosure structure must contain this pressure and must be designed to be “fail-safe” against catastrophic and other decompression caused by accidental and natural impacts.
- *Shielding:* A prime consideration in the design is that the structure be able to shield against the types of hazards found on the lunar surface: continuous solar/cosmic radiation, meteorite impacts, and extreme variations in temperature and radiation. In the likely situation that a layer of regolith (lunar soil) is placed atop the structure for shielding, the added weight would partially (in the range of 10–20%) balance the forces on the structure caused by internal pressurization mentioned above.

Shielding against micrometeorite impacts is done by providing dense and heavy materials, in this case compacted regolith, to absorb the kinetic energy. Lunar rocks would be more effective than regolith because the rocks have fracture toughness, but may be more difficult to obtain and much more difficult to place atop surface structures.

Much effort in this country has been devoted to determining the damage effects on human beings and electronics resulting from nuclear weapon detonation, and little is being done to determine long-term, sustained low-level radiation effects such as those that would be encountered on the Moon. According to Silberberg et al. (1985), during the times of low solar activity, the annual dose-equivalent for humans on the exposed lunar surface may be about 30 rem (radiation equivalent man), and the dose-equivalent over an 11 year solar cycle is about 1,000 rem, with most of the particles arriving in one or two gigantic flares lasting 1 to 2 days. It appears that at least 2.5 m of regolith cover would be required to keep the annual dose of radiation at 5 rem, which is the allowable level for radiation workers (0.5 rem for the general public). A shallower cover may be inadequate to protect against the primary radiation, and a thicker cover may cause the second-

ary radiation (which consists of electrons and other radiation as a result of the primary radiation hitting atoms along its path).

In recent years, there has been a move away from silicon-and germanium-based electronic components toward the use of gallium arsenide. Lower current and voltage demand and miniaturization of electronic components and machines would make devices more radiation hardened.

Radiation transport codes can be used to simulate cosmic radiation effects, which is not possible in the laboratory. One such code that has been found to be effective is LAHET (Prael et al. 1990), developed at the Los Alamos National Laboratory.

- *Vacuum:* A hard vacuum surrounds the Moon that will preclude the use of certain materials that might not be chemically or molecularly stable under such conditions. This is an issue for research.

Construction in a vacuum has several problems. One would be the possibility of outgassing of oil, vapors, and lubricants from pneumatic systems. Hydraulic systems are not used in space for this reason. The outgassing is detrimental to astronomical mirrors, solar panels, and any other moving machine parts because these structures tend to cause dust particles to form pods. For more discussion of construction challenges in the extraterrestrial environment, see Chua and Johnson (1991). Another problem is that surface-to-surface contact becomes much more abrasive in the absence of an air layer. The increase in dynamic friction would cause fusion at the interfaces, for example, a drill bit fusing with the lunar rock. This is of course aggravated by the fact that the vacuum is a bad conductor of heat. The increase in abrasiveness at interfaces also increases wear and tear on any moving parts, such as railways and wheels.

Blasting in a vacuum is another interesting problem to consider. When the explosive in a blast hole is fired, it is transformed into a gas, the pressure of which may sometimes exceed 100,000 terrestrial atmospheres. How this would affect the area around the blast on the Moon and the impact of ejecta resulting from the blast is difficult to predict. Keeping in mind that a particle set in motion by the firing of a rocket from a lander could theoretically travel halfway around the Moon, the effects of surface blasting on the Moon would be something to be concerned about. Discussion of the tests involving explosives that were performed on the Moon can be found in Watson (1988). Joachim (1988) discussed different candidate explosives for extraterrestrial use, and the Air Force Institute of Technology (Johnson et al. 1969) studied cratering at various gravities and/or in vacuum. Bernold (1991) presented experimental evidence from a study of blasting to loosen regolith for excavation.

- *Dust:* The lunar surface has a layer of fine particles that are easily disturbed and placed into suspension. These particles cling to all surfaces and pose serious challenges for the utility of construction equipment, air locks, and all exposed surfaces (Slane 1994).

Lunar dust consists of pulverized regolith and appears to be charged. The charge may be from the fractured crystalline structure of the material or may be of a surficial nature, for example, charged particles from the solar wind attaching themselves to the dust particles. Criswell (1972) reported that the dust particles levitated at the lunar terminator (line between lunar day and lunar night) and that this may be due to a change in polarity of the surficial materials. Johnson et al. (1995a) discuss the issue of lunar dust and its effects on operations on the Moon. Haljian (1964) and Seiheimer and Johnson (1969) studied the adhesive characteristics of regolith dust.

- *Ease of construction:* The remoteness of the lunar site, in conjunction with the high costs associated with launches from Earth, suggests that lunar structures be designed for ease of construction so that the extravehicular activity of the astronaut construction team is minimized. Construction components must be practical and, in a sense, modular in order to minimize local fabrication for initial structural outposts.

Chua et al. (1993) discuss guidelines and the developmental process for lunar-based structures. They present the governing criteria and also general misconceptions in designing space structures. For example, a device that is simple and conventional looking and has no moving parts is preferred over one that involves multiple degrees of freedom in an exotic configuration involving a yet-to-develop artificial intelligence control, if the former meets the functional requirements. Other misconceptions are that constructing on the Moon is simply a scaling of the effects of similar operations on Earth, and that theoretical predictive tools, especially those performed with computers, can accurately predict events. It is also a misconception that astronauts would have to work around the structure, rather than that, the structure would be designed as to make construction easy for the astronauts.

- *Use of local materials:* This is to be viewed as extremely important in the long-term view of extraterrestrial habitation, but feasibility will have to wait until a minimal presence has been established on the Moon. Initial lunar structures will be transported for the most part in components from the Earth (Fig. 1).

The use of local resources, normally referred to as ISRU (in situ resource utilization), is a topic that has been studied, more intensely now than ever, because of the possibility of actually establishing a human presence on the Moon, near-earth orbit, and Mars. Discussions are found in Johnson and Chua (1992) and Casanova and Aulesa (2000).

Possible Structural Concepts

Various concepts have been proposed for lunar structures. In order to assess the overall efficiency of individual concepts, decision science and operations research tools have been proposed, used (Benaroya and Ettouney 1989), and demonstrated (Benaroya and Ettouney 1990). Along these lines, various concepts are compared (Richter and Drake 1990) using a points system for an extraterrestrial building system, including pneumatic, framed/rigid foam, prefabricated, and hybrid (inflatable/rigid) concepts.

In a very early lunar structural design study, Johnson (1964) presented the then-available information with the goal of furthering the development of criteria for the design of permanent lunar structures. In this work, the lunar environment is detailed, lunar soil from the perspective of foundation design is discussed, and excavation concepts are reviewed. An excellent review of the evolution of concepts for lunar bases up through the mid-1980s is available (Johnson and Leonard 1985), as is a review of more recent work on lunar bases (Johnson and Wetzel 1990b). Surface and subsurface concepts for lunar bases are surveyed (Hypes and Wright 1990) with a recommendation that preliminary designs be considered that focus on specific applications. America's future on the Moon is outlined as supporting scientific research, exploiting lunar resources for use in building a space infrastructure, and attaining self-sufficiency in the lunar environment as a first step in planetary settlement. The complexities and costs of building such a base will depend on the mission or missions for which such a base is to be built.

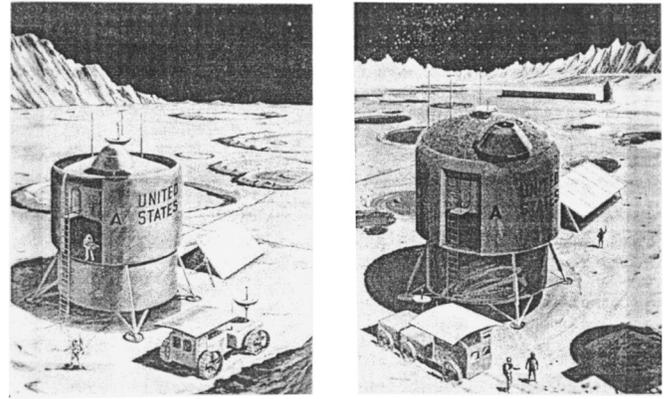


Fig. 1. Two versions of LESA modules emplaced on Moon by Boeing in 1963 [reprinted with permission from Lowman (1985, p. 37)]

A complete Earth-Moon infrastructure (Griffin 1990) uses proven technologies and the National Space Transportation System for early development of a lunar outpost (Fig. 2). Transfer vehicles and surface systems are developed so that the payload bay of the Space Shuttle can be utilized in transport. The lunar outpost structural scheme separates radiation protection from module support, allowing easy access, installation, and removal of elements attached to the shuttle trusses.

Several types of structures have been proposed for lunar outposts. A preliminary design of a permanently manned lunar surface research base has been briefly studied by Hoffman and Niehoff (1985), with criteria for the base design to include scientific objectives as well as the transportation requirements to establish and support its continued operations.

Inflatables

A pillow-shaped structure proposed by Vanderbilt et al. (1988) as a possible concept for a permanent lunar base (Fig. 3) consists of quilted inflatable pressurized tensile structures using fiber composites. Shielding is provided by an overburden of regolith, with accommodation for sunlight ingress. These studies of the inflatable concept are continued by Nowak et al. (1990) with consideration of the foundation problem and additional reliability concerns and analysis (Nowak et al. 1992). This concept is a significant departure from numerous other inflatable concepts in that it shows an alternative to spheroidal inflatables and optimizes volume for habitation. Inflatable structural concepts for a lunar base are proposed (Broad 1989) as a means to simplify and speed

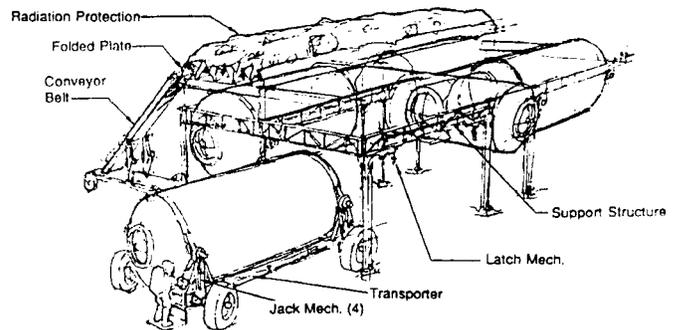


Fig. 2. Modules for lunar base [reprinted with permission by ASCE from Griffin (1990, p. 397)]

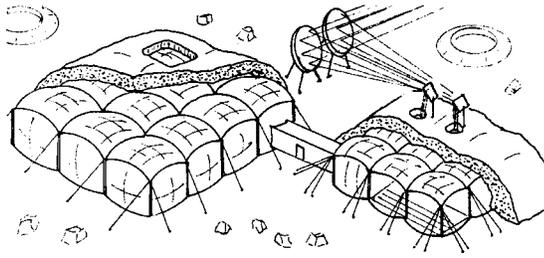


Fig. 3. Inflatable structure [reprinted with permission by ASCE from Vanderbilt et al. (1988, p. 353)]

up the process while lessening the costs. The inflatable structure is suggested as a generic test-bed structure for a variety of application needs for the Moon (Sadeh and Criswell 1994). Design criteria are also put forward (Criswell et al. 1996).

Another pressurized membrane structure, proposed by Chow and Lin (1988, 1989) for a permanent lunar base, is constructed of a double-skin membrane filled with structural foam. A pressurized torus-shaped substructure provides edge support, and shielding is provided by an overburden of regolith. Briefly, the construction procedure requires shaping the ground and spreading the uninflated structure upon it, after which the torus-shaped substructure is pressurized. Structural foam is then injected into the inflatable component, and the internal compartment is pressurized. The bottoms of both inflated structures are filled with compacted soil to provide stability and a flat interior floor surface. Backfilling is a difficult operation to carry out through an airlock. It will, of course, be crucial to ensure that the interior is dust-free (Fig. 4).

A detailed architectural master plan is also proposed for a horizontal inflatable habitat (Kennedy 1992). Finite-element simulations of inflatable structures are needed because it is very difficult to reproduce a hard vacuum and low-gravity condition on Earth. The finite-element modeling would have to be large-deformation capable and have membrane elements (which are essentially beam elements that are without bending stiffness) and axial tensile stiffness, but not axial compression stiffness. The program should also ideally be able to model regolith-structure interaction. GEOT2D (Chua et al. 1994) is a program that has the capabilities needed to simulate inflatable structure-regolith interaction.

Erectables

An expandable platform suggested by Mangan (1988) as a structure on the Moon consists of various geometrically configured 3D trussed octet or space frame elements used both as building blocks and as a platform for expansion of the structure. Examples of the shapes to be used include tetrahedral, hexahedral, octahedral, and so on. This effort is primarily qualitative.

A concept proposed by King et al. (1989) would use the liquid oxygen tank portions of the Space Shuttle external tank assembly for a basic lunar habitat. The modifications of the tank, to take place in low Earth orbit, will include the installation of living quarters, instrumentation, air locks, life-support systems, and environmental control systems. The habitat is then transported to the Moon for a soft landing. This idea, if proven economically feasible, may provide the most politically palatable path to the lunar surface, with the added advantage that many of the necessary technologies already exist and only need resurrection (similar to Fig. 2).

A semiquantitative approach to lunar base structures provided by Kelso et al. (1988) gives some attention to economic consid-

erations, and the structural concepts included could be developed in the future. A modular approach to lunar base design and construction is suggested by Schroeder et al. (1994b) as a flexible approach to developing a variety of structures for the lunar surface. In a related vein, a membrane structure is suggested for an open structure that may be used for assembly on the lunar surface by Schroeder et al. (1994a). A tensile-integrity structure has been suggested as a possible concept for larger surface structures by Benaroya (1993b) (Fig. 4).

Concrete and Lunar Materials

A structural analysis and preliminary design of a precast, prestressed concrete lunar base is reported by Lin et al. (1989). In order to maintain structural integrity, and thus air tightness, when differential settlement is possible, a floating foundation is proposed. All materials for such a lunar concrete structure, except possibly hydrogen for the making of water, may be derivable from lunar resources. Horiguchi et al. (1998) study simulated lunar cement.

The use of unprocessed or minimally processed lunar materials for base structures, as well as for shielding, may be made possible (Khalili 1989) by adopting and extending terrestrial techniques developed in antiquity for harsh environments. A variety of materials and techniques discussed are candidates for unpressurized applications.

The use of indigenous materials is considered by Happel (1992a,b) for the design of a tied-arch structure. The study is extensive and detailed and also includes an exposition on lunar materials.

Construction of layered embankments using regolith and filmy materials (geotextiles) is viewed as an option using robotic construction (Okumura et al. 1994), as are fabric-confined soil structures (Harrison 1992).

In order to avoid the difficulties of mixing concrete on the lunar surface due to lack of water, Gracia and Casanova (1998) have suggested examining use of sulfur concrete because sulfur is readily available on the Moon.

Lava Tubes

Ideas regarding the utility of constructing the first outposts under the lunar surface have been proposed. A preliminary assessment is provided by Daga et al. (1990) of a lunar outpost situated in a lava tube. They conclude that an architectural solution is needed to the problems surrounding the development of a lunar outpost, but that lunar surface structures are not the best approach. Rather subselene development offers real evolutionary potential for settlement.

In another structural approach, fused regolith structures are suggested by Clifton (1990) and Crockett et al. (1994). In this case, the structures are small and many and reside on the surface. A prime advantage offered for planning numerous smaller structures is safety and reliability. The premise of this work is to use the sun's energy to fuse regolith into components.

Construction in New Environment

Site plans (Sherwood 1990) and surface system architectures (Pieniasek and Toups 1990) are forcefully presented as being fundamental to any development of structural concepts. One of the challenges to the extraterrestrial structures community is that of construction. Lunar construction techniques have differences

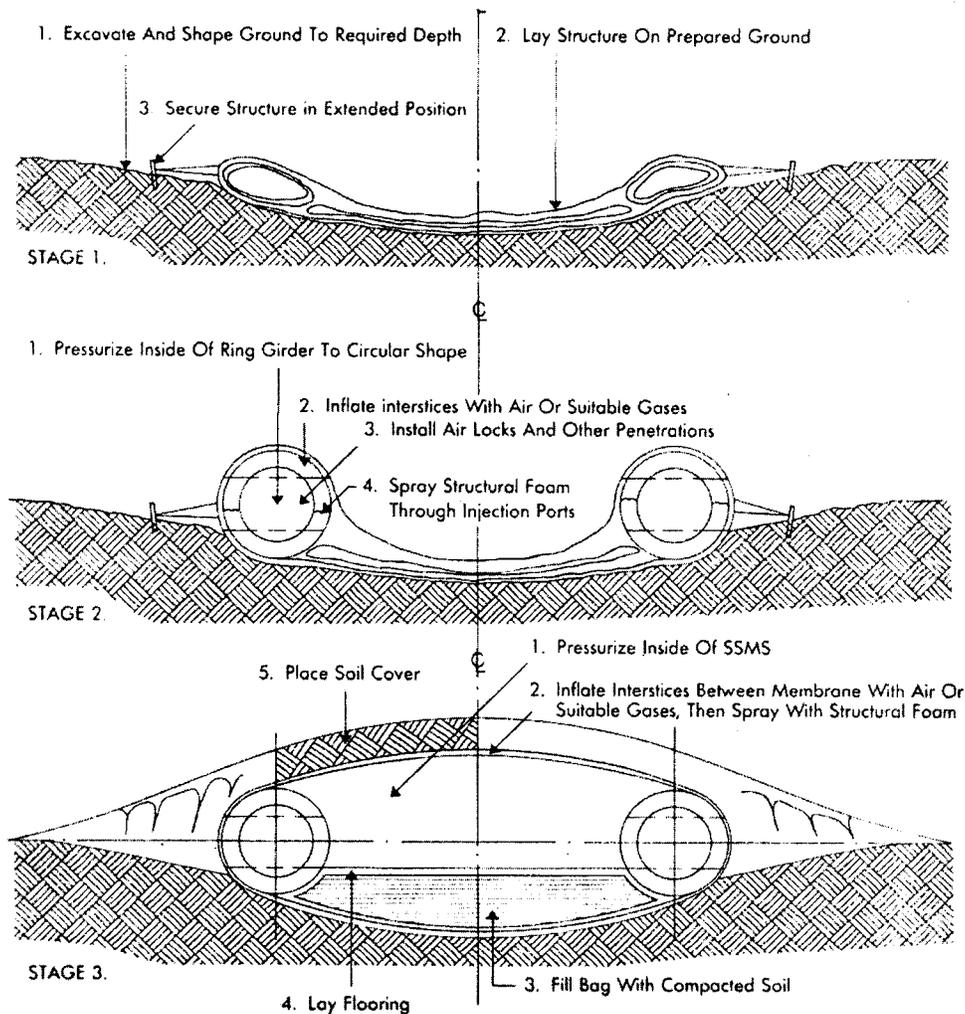


Fig. 4. Inflatable membrane structure—construction sequence [reprinted with permission by ASCE from Chow and Lin (1988, p. 372)]

from those on Earth; for example, the construction team will likely operate in pressure suits, motion is dominated by $1/6 g$, solar and cosmic radiation are not shielded by an Earth-type atmosphere, and suspended dust exists in the construction site. Toups (1990) assesses various construction techniques for the classes of structures and their respective materials.

Structural and architectural designs along with manufacturing plants and construction methods are discussed by Namba et al. (1988b) for a habitable structure on the Moon using concrete modules. The module can be disassembled into frame and panels.

A qualitative study by Drake and Richter (1990) is made of the design and construction of a lunar outpost assembly facility. Such a facility would be used to construct structures too large for transport to the Moon in one piece. The assembly facility would also be used to support operation and maintenance operations during the functional life of the lunar outpost. A series of trade studies is suggested on the construction of such an assembly facility.

Construction of a lunar base will at least partially rest on the capabilities of the Army Corps of Engineers. Preparations that are now under way are outlined by Simmerer (1988) and challenges discussed by Sargent and Hampson (1996).

All the above are contingent on the “practical” aspects of building structures on the Moon. These aspects include the sort of machinery needed to move equipment and astronauts about the surface; the methods needed to construct in $1/6 g$ with an ex-

remely fine regolith dust working its way into every interface and opening; and the determination of the appropriate layout of structures considering human safety and operations needs. Using harsh Earth environments such as the Antarctic as test beds for extra-terrestrial operations is advocated by Bell and Neubek (1990).

The performance of materials and equipment used for lunar construction needs to be examined in terms of the many constraints discussed so far. Structures that are unsuitable for Earth construction may be adequate for the reduced-gravity lunar environment (Chow and Lin 1989). Several research efforts have been directed to producing construction materials, such as cement, concrete, and sulfur-based materials, from the elements available on the Moon (Lin 1987; Agosto et al. 1988; Leonard and Johnson 1988; Namba et al. 1988a; Yong and Berger 1988; Strenski et al. 1990).

The appendix to this paper provides a long list of structures that require a study not only of the materials that could be used for construction, but also of the necessary tools/equipment, methods of operation/control, and most importantly, how to construct structures with and within the lunar environment (that is regolith, vacuum, $1/6 g$). Because most of the construction methods developed since the beginning of mankind are adapted to fit and take advantage of terrestrial environments (that is, soil characteristics, atmosphere with oxygen, and $1 g$ gravity), technologies that are common on Earth either will not work on the Moon or are too

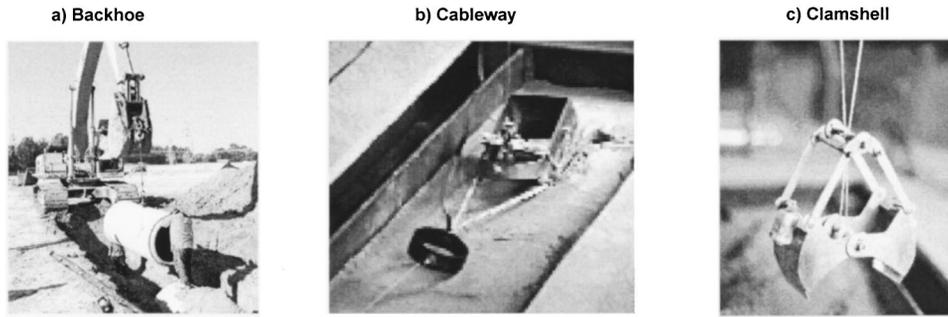


Fig. 5. Common “Earth” excavators that depend on gravity

costly or inefficient. The following sections will address some of the unique problems and circumstances that we face.

Creating Base Infrastructure

The availability of an adequate infrastructure is key to the survival and growth of any society. “In all human societies, the quality of life depends first on the physical infrastructure that provides the basic necessities such as shelter, water, waste disposal, and transportation,” wrote Grigg (1988.) Today, and especially for the lunar base, we have to add communication and power as part of the physical infrastructure. All of these constructed facilities have one issue in common, namely the interaction with lunar surface materials: (1) rocks; (2) regolith; and (3) breccias. Lunar soil, referred to as regolith, differs from soil on Earth in several respects that are significant for construction. While the soil that establishes the top layers (10–20 cm) is loose and “powdery,” easily observable in Apollo movies, the regolith reaches the relative density of 90–100% below 30 cm. The grain size distribution of a common regolith, as well as its high density below the top layers, is hardly found in the terrestrial environment. This creates unique problems for excavating, trenching, backfilling, and compacting the soil (Goodings et al. 1992). These operations, however, are needed to create (1) building foundations; (2) roadbeds; (3) launch pads; (4) buried utilities (power, communication); (5) shelters and covers; (6) open-pit mining; and (7) underground storage facilities.

Excavating “Hard” Lunar Soil

Bernold (1991) reported about efforts to study the unique problems related to digging and trenching on the Moon. All the common excavation technologies used on Earth depend on the effect

of gravitational acceleration that turns mass into forces that are needed to cut, scoop, and move soil (Fig. 5).

Because of the drastically reduced gravity, transporting the masses and material to the lunar surface would be prohibitively expensive. Dick et al. (1992) presented the result of experimental work to study an alternative to traditional excavation of soil, namely the use of explosives to loosen the dense soil so it can be excavated with a limited amount of force. Fig. 6 presents images of the effect of a small amount of explosives on lunar simulants.

Fig. 6(a) shows the direction and position of ejecta clumps 43.16 and 52.24 ms after detonation, while Fig. 6(b) presents an overview and 6(c) a cross section of the crater created by a small amount of explosives. Although the ejection of regolith would not be acceptable on the lunar surface, since the resulting dust would travel far, research showed that explosives buried deep enough would not create craters but loosen the soil very effectively. In fact, Fig. 5(b) demonstrates how a lightweight bucket pulled by a cable was slicing into the lunar soil simulant that had been loosened in this manner. Furthermore, the sensor-equipped lightweight backhoe excavator required a drastic reduction of energy to dig the loosened soil (Lin et al. 1994).

Building Transportation Infrastructure

The creation of durable roads without using asphalt or concrete as a top requires the planning/cutting of the existing surface and the compaction of fill material. The main objectives of the road base and road surface are to distribute the point loads under the wheels/tracks to the maximum allowable bearing capacity, to provide stable traction resistance for the needed rim pulls (force at the rim of the wheel to allow motion) and breaking forces, and for abrasion resistance. Earthbound equipment that achieves these objectives depends on a large mass, gravitational force, and a

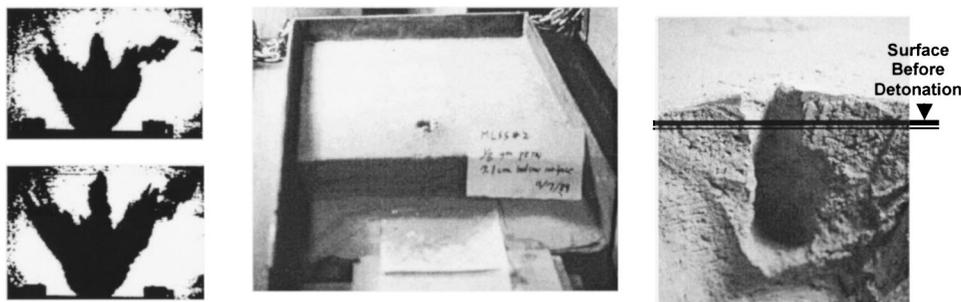


Fig. 6. Effect of buried explosive charges on lunar soil simulants: (a) ejecta milliseconds after detonation; (b) effect of 1/8 g PETN buried at 7.1 cm; and (c) detonation chamber, chimney, and crater after removal of loose soil

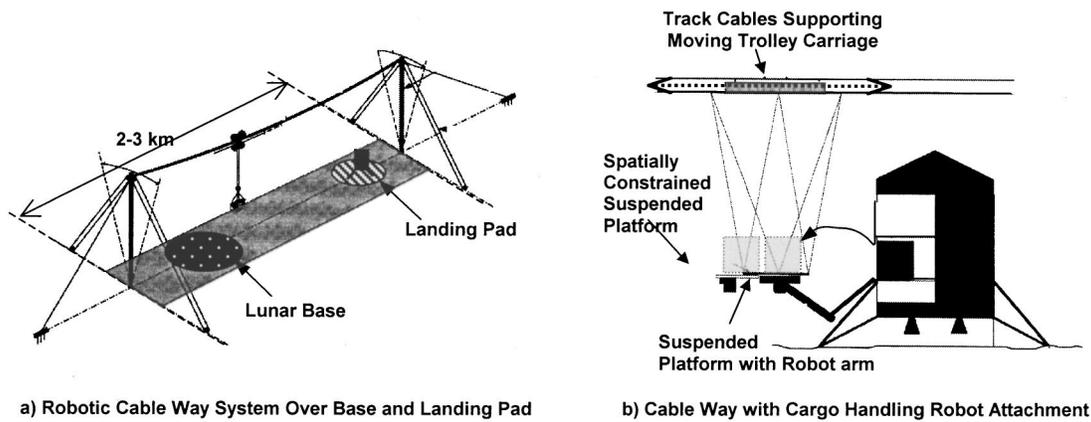


Fig. 7. Robotic transportation system for lunar base

sufficient power source. It is obvious that the size of each would make it cost-prohibitive to deploy on the Moon, even if the power source were switched from diesel engines to electric. In addition, Bernold (1994b) showed that the compaction of lunar soil necessary for creating a stable roadbase would create unique problems. Preliminary research data indicated that the normal size distribution of soil particles would make it impossible to achieve needed density and strength using common methods of static or vibratory compaction.

However, reducing the percentage of fines present in the regolith can increase the compacted strength of the dry and mainly cohesionless lunar soil. In addition, the surface has to be covered with larger-size stones that have to be crushed from rock, requiring additional equipment such as rock-drill and pyrotechnic equipment, loaders, rock crushers, vibrating screens, and conveyor feeders. It is apparent that the construction of trafficable and stable roads and/or pads on the Moon will require many different machines capable of pushing, loading, cutting, sizing, and compacting regolith as well as the crushing, transportation, spreading, and compaction of rock. The use of multipurpose equipment will certainly be desirable but, on the other hand, slow the operation. If one wants to rely on "Earth-proven" technologies, significant disadvantages will have to be overcome. The most significant handicap is the large reduction of gravitational acceleration that is the basis for the efficient operation of terrestrial roadbuilding equipment.

As an alternative to wheel-or water-based transportation, Bernold (1994a) proposed a cable-based transportation system: "Lunar tramway systems can take advantage of the reduced gravity, which permits building wider spans and/or using smaller cable diameter for lifting and transporting heavy loads. The use of luffing masts and a unique semistable rigging platform provide many opportunities for reaching wide areas on the lunar surface and performing various tasks needed for handling material, construction, servicing and maintaining facilities needed on a lunar base." Fig. 7 presents the basic elements of a cable-based transportation system that could cover large areas.

As depicted in Fig. 7, the track cables are attached to two (or more) masts, thus being able to span long distances (for example, 3,000 m) because the lower gravity reduces not only the weight of the load to 1/6, but also the weight of the cable itself, leading to much smaller cable deflections than on Earth. Two electrowinches and cables at each mast provide the mechanism for luffing (side-ways rotation around its base socket) the track cables. As indicated in Fig. 7(a), the luffing mechanism adds a significant capa-

bility in that it allows the transportation system to cover a rectangular area. In addition, the mast and cables can be lowered all the way to the ground during the final landing approach of a cargo ship. Fig. 7(b) presents the concept of a trolley-carriage that is being moved along the track by a haul cable. Attached to the carriage are either three or six lift cables that can be individually operated with winches. By combining these cable-based mechanisms, a spatially controlled platform can be established (Richter et al. 1998). While the system can be used to unload a lunar lander, it can also support construction and mining operations. Fig. 8 portrays a platform attachment capable of (1) excavating trenches to bury cables and pipes; (2) removing rock boulders; (3) collecting rocks for the crusher; (4) deploying soil or rock drills; and (5) mining open pits for processing.

As shown in Fig. 8, the same spatially constrained platform supporting a cargo-handling robot can be reconfigured to carry a shovel excavator capable of loading regolith and rock boulders into a pan mounted on top of the platform. For other operations, such as trenching, the same robot arm could reconfigure itself to work as a backhoe, drill boom, or other desirable end-effectors.

A major problem that needs to be considered in the design of robotic systems for construction is the question of control. The complexities of working in a totally new environment will make it impossible to have the lunar construction equipment operate autonomously. Kemurdjian and Khakhanov (2000) discuss several specific aspects of the problem. These include the effects of low gravity on traction, the amount of power to be consumed, and

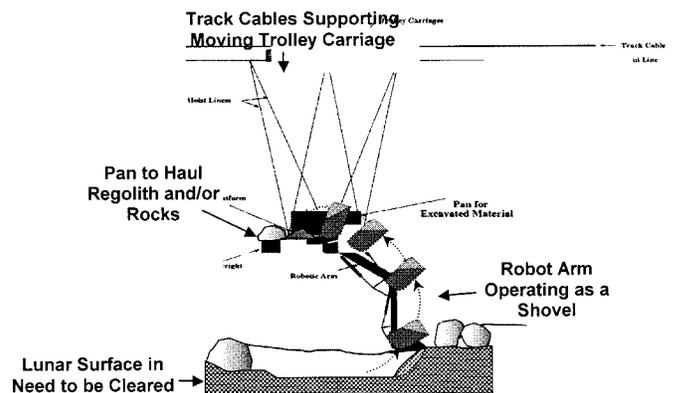


Fig. 8. Cable-based robot shovel excavator at work

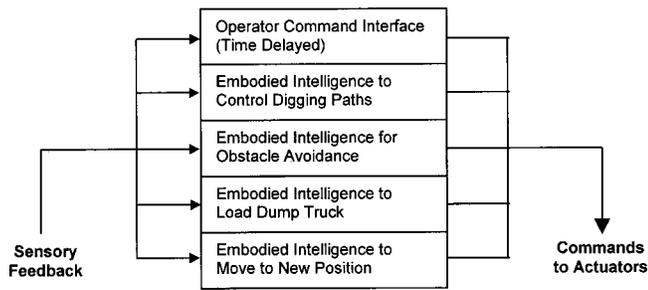


Fig. 9. Layered control architecture for Earth-based teleoperation of lunar equipment

most importantly, the dynamics of such vehicles. At the same time, the problems associated with exposing astronauts to long prolonged extravehicular activities (EVA) and the cost of deploying human operators on the lunar surface make it unlikely that each piece of equipment will be steered by an operator who rides on it.

Robotic Control of Construction Equipment

One of the main problems in robotic control of equipment is the time that signals need to travel through vacuum, atmosphere, or fiber-optic or other communication lines. The time it takes a signal to travel through a network is commonly referred to as latency. Nelson et al. (1998) report about their work on the issue of latency: “Teleoperation is commonly used in the remote control of terrestrial mining equipment. Teleoperating mining equipment on the Moon from the Earth is attractive but involves a transmission loop time delay of 4 to 10 s. A human operator can handle time delays of about 1 second in simple teleoperation applications.” A variety of control schemes that help alleviate the problems caused by excessive signal delays have been developed. They range from teleautonomous, to predictive teleoperation, to semiautonomous operation (Conway et al. 1990). In this context, one effort by researchers is to equip mobile computerized equipment with the robustness and intelligence to react to the dynamics of the environment. To do this, it is critical “to build complete agents which operate in dynamic environments using real-time sensors. Internal world models which are complete representations of the external environment, besides being impossible to obtain, are not at all necessary for agents to act in a competent manner” (Brooks 1986, 1990). Since work in construction always requires moving within, and interacting with, a complex environment while handling messy materials that have to be joined, layered on top, inserted, and so on, a distributed intelligence embodied in the site equipment and sensors and communicating via networks may serve as a uniquely qualified approach to creating a semiautonomous fleet of equipment.

Fig. 9 presents a partial model of layered control architecture for a teleoperated backhoe operation that integrates human control with intelligent control modules that work in parallel rather than in sequence. The layered control architecture for robotic excavation was first proposed by Huang and Bernold (1993, 1994). The key feature of this approach is the distribution of the control task to the most efficient module.

Issue of Water on Moon

In a recent development, it appears that there may be water-ice in some craters near the poles of the Moon. It was suggested that

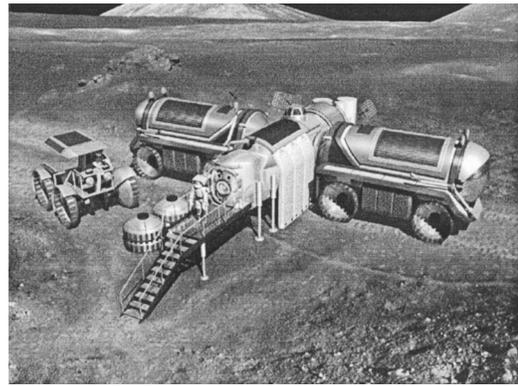


Fig. 10. Lunar habitat assembled out of components delivered by automated cargo flights. Pressurized rovers, logistics modules, and spacesuit maintenance and storage module combine to provide living and working quarters for crew (NASA/JSC image #S93-45585).

water-laden comets and asteroids may have deposited the water. If water does exist in those craters, it was conjectured by Chua and Johnson (1998) that the moisture distribution may consist of water-ice mixing with the regolith to saturation or near saturation, and reducing outward according to the matric suction pressure (which is influenced by the particle size distribution). Since the gravitation potential is relatively small compared to the matric suction potential, the water would have been drawn laterally or even upwards over some distance. (Note: Since the regolith has no clays, unlike Earth, there would not be an osmotic suction component to influence moisture migration.) The extent of this unsaturated zone is primarily influenced by how fast the water vapor condensed at the bottom of the crater, which have temperatures as low as -230°C . The Lunar Prospector Mission team indicated that the moisture content in the regolith at the bottom of the crater might be between 0.3 and 1%.

Issue of using Geosynthetics in Extraterrestrial Environment

Some recent papers suggested using geosynthetics as soil reinforcement to construct earth structures such as berms, walls, and slopes. Several problems have to be considered in order for this to be a reality.

- Plastic materials are susceptible to degradation when subjected to radiation;
- The glass transition temperature of many if not all of the geosynthetics used on Earth is well above the cold temperatures encountered on candidate sites, including that on the Moon, which would make the plastics brittle, thus rendering them useless as reinforcing elements; and
- There is little experience on how geosynthetics fare in a hard vacuum and respond to the relatively more abrasive regolith.

Conclusion

We have presented a summary of current thinking regarding some of the issues surrounding the engineering and construction of structures for long-term lunar human habitation. We close here with a NASA vision of how a lunar base may look (Fig. 10).

Acknowledgments

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Appendix: Building Systems

Types of Applications

Habitats

- People (living and working)
- Agriculture
- Airlocks: ingress/egress
- Temporary storm shelters for emergencies and radiation
- Open volumes

Storage Facilities/Shelters

- Cryogenic (fuels and science)
- Hazardous materials
- General supplies
- Surface equipment storage
- Servicing and maintenance
- Temporary protective structures

Supporting Infrastructure

- Foundations/roadbeds/launchpads
- Communication towers and antennas
- Waste management/life support
- Power generation, conditioning, and distribution
- Mobile systems
- Industrial processing facilities
- Conduits/pipes

Application Requirements

Habitats

- Pressure containment
- Atmosphere composition/control
- Thermal control (active/passive)
- Acoustic control
- Radiation protection
- Meteoroid protection
- Integrated/natural lighting
- Local waste management/recycling
- Airlocks with scrub areas
- Emergency systems
- Psychological/social factors

Storage Facilities/Shelters

- Refrigeration/insulation/cryogenic systems
- Pressurization/atmospheric control
- Thermal control (active/passive)
- Radiation protection
- Meteoroid protection
- Hazardous material containment
- Maintenance equipment/tools

Supporting Infrastructure

- All of the above
- Regenerative life support (physical/chemical and biological)
- Industrial waste management

Types of Structures

Habitats

- Landed self-contained structures
- Rigid modules (prefabricated/in situ)
- Inflatable modules/membranes (prefabricated/in situ)
- Tunneling/coring
- Exploited caverns

Storage Facilities/Shelters

- Open tensile (tents/awning)
- “Tinker toy”
- Modules (rigid/inflatable)
- Trenches/underground
- Ceramic/masonry (arches/tubes)
- Mobile
- Shells

Supporting Infrastructure

- Slabs (melts/compaction/additives)
- Trusses/frames
- All of the above

Material Considerations

Habitats

- Shelf life/life cycle
- Resistance to space environment (UV/thermal/radiation/abrasion/vacuum)
- Resistance to fatigue (acoustic and machine vibration/pressurization/thermal)
- Resistance to acute stresses (launch loads/pressurization/impact)
- Resistance to penetration (meteoroids/mechanical impacts)
- Biological/chemical inertness
- Reparability (process/materials)

Operational Suitability/Economy

- Availability (lunar/planetary sources)
- Ease of production and use (labor/equipment/power/automation and robotics)
- Versatility (materials and related processes/equipment)
- Radiation/thermal shielding characteristics
- Meteoroid/debris shielding characteristics
- Acoustic properties
- Launch weight/compactability (Earth sources)
- Transmission of visible light
- Pressurization leak resistance (permeability/bonding)
- Thermal and electrical properties (conductivity/specific heat)

Safety

- Process operations (chemical/heat)
- Flammability/smoke/explosive potential
- Outgassing
- Toxicity

Structures Technology Drivers

Mission/Application Influences

- Mission objectives and size
- Specific site—related conditions (resources/terrain features)
- Site preparation requirements (excavation/infrastructure)
- Available equipment/tools (construction/maintenance)
- Surface transportation/infrastructure
- Crew size/specialization
- Available power
- Priority given to use of lunar material and material processing
- Evolutionary growth/reconfiguration requirements
- Resupply versus reuse strategies

General Planning/Design Considerations

- Automation and robotics
- EVA time for assembly
- Ease and safety of assembly (handling/connections)
- Optimization of teleoperated/automated systems
- Influences of reduced gravity (anchorage/excavation/traction)
- Quality control and validation
- Reliability/risk analysis
- Optimization of in situ materials utilization
- Maintenance procedures/requirements
- Cost/availability of materials
- Flexibility for reconfiguration/expansion
- Utility interfaces (lines/structures)
- Emergency procedures/equipment
- Logistics (delivery of equipment/materials)
- Evolutionary system upgrades/changeouts
- Tribology

Requirement Definition/Evaluation

Requirement/Option Studies

- Identify site implications (lunar soil/geologic models)
- Identify mission-driven requirements (function and purpose/staging of structures)
- Identify conceptual options (site preparation/construction)
- Identify evaluation criteria (costs/equipment/labor)
- Identify architectural program (human environmental needs)

Evaluation Studies

- Technology development requirements
- Cost/benefit models (early/long-term)
- System design optimization/analysis

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