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AN OVERVIEW of LUNAR BASE STRUCTURES: PAST and FUTURE*

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ABSTRACT

This paper aims to summarize the evolution of lunar base concepts over the past approximately half-century. We will discuss the various classes of concepts, the lunar environment as it pertains to structural design, construction, and human habitation. Topics introduced are: The Lunar Surface Environment; Lunar Base Concepts During the Apollo Era; More Recent Concepts for Lunar Structures; Futuristic Concepts and Applications.

To understand the various classes of lunar structures for habitation, it is important to explain the key environmental factors that affect human survival on the Moon and affect structural design and construction on the Moon. The key environmental factors are:

(i) the surface is in a hard vacuum, and is thus vulnerable to galactic and solar radiation and to micrometeorites,
(ii) a shirt-sleeve environment requires an internally-pressurized structure,
(iii) suspended fines from the lunar surface can cause severe damage to mechanisms and machines supporting structural operations.

Lunar base structural concepts attempt to address the above issues in various ways. To reduce vulnerability to radiation and micrometeorites, surface structures need to be shielded, with the most popular approach being the placement of about 3 meters of regolith on top of the structure. This approach leads to challenging construction procedures, and also makes ingress and egress difficult. Structure maintenance in the presence of an envelope of regolith remains to be addressed.

Human habitation requires ways to bring outside light and views into the structure, since long-term habitation in windowless spaces is viewed negatively. The internal pressurization turns out to be the controlling design load for a lunar surface structure, even with 3 meters of regolith on the outside. For inflatable structures, of particular concern is the loss of pressurization.

Structural concepts for human habitation on the lunar surface include the "tin can" structure, the inflatable structure, the truss-based structure, the fused-regolith structure, and hybrids. As expected, each class has its advantages and disadvantages. The "tin can" is comparatively easy to build on Earth orbit and transport and land on the Moon, with the disadvantage that it is not easily expandable. A disadvantage of the inflatable concept is the threat of deflation, but an important advantage is that large volumes can be enclosed by the inflatable, and it is easier to transport. The truss-based structure is most similar to Earth structures, and most easily understood in terms of current structural design and construction practice. However, strength requires heavy

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structural members, not likely to be manufactured on the Moon soon.

It is clear that the type of lunar civilization that *can* evolve depends on the infrastructure that we are capable of building.

INTRODUCTION

Concepts for lunar base structures have been proposed since long before the dawn of the space age. This paper 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. Significant studies were 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 [Army 1963]. (Note the date of this report!) During the decade between the late eighties to mid-nineties, these studies intensified, both within NASA and outside the Government in industry and academe. The following references are representative: Benaroya and Ettouney 1989, Benaroya and Ettouney 1990, Benaroya 1993a, Benaroya 1995, Benaroya et al. 2002, Duke and Benaroya 1993, Ettouney and Benaroya 1992, Galloway and Lokaj 1994 and 1998, Johnson and Wetzel 1988, 1990a,c and Johnson 1996, Mendell 1985, Sadeh et al. 1992. A recent review is by Benaroya, Chua and Bernold (2002). 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.

Unfortunately, by the mid-seventies, and again in the mid-nineties, 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 without an extensive and permanent human spaceflight infrastructure, the latter will do no more to 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. Physiology and reliability issues are yet unresolved for a trip to Mars. The Moon is our best first goal. Kraft Ehricke said in 1984: "If God wanted man to go to Mars, he would have given him a moon."

The emphasis here 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 generic structural types are proposed for lunar base structures. These include concrete structures, metal frame structures, pneumatic construction, and hybrid structures. In addition, options may 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.

Lowman [1985] made a post-Apollo evaluation of the need for a lunar base with the following reasons for such a base:

- lunar science and astronomy
- as a stimulus to space technology and as a test bed for the technologies required to place humans on Mars and beyond
- the utilization of lunar resources
- establishment of a U.S. presence
- stimulate interest in young Americans in science and engineering, and

- as the beginning of a long-range program to ensure the survival of the species.

These are all still primary reasons for a return to the Moon.

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 and Wetzel 1990b]. One example is a 16-meter diameter reflector with its supporting structure and foundation investigated by NASA and several consortia.

Selection of the proper site for a lunar astronomical facility, however, involves many difficult decisions. Scientific advantages of a polar location for a lunar base [Burke 1985] are that half the sky be continuously visible for astronomy from each pole and that cryogenic instruments can readily be operated there since there are shaded regions in perpetual darkness. Disadvantages arise also 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. Recently, van Susante [2002] studied the possibility of using the South Pole for an infrared telescope.

The Environment

Important components in a design process are the creation of a detailed design and prototyping process. 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 effects of suspended (due to *one-sixth g*) lunar regolith fines on lunar machinery. Apollo experience may be extrapolated, but only to a point beyond which new information is necessary.

Our focus in this paper is to explore the lunar environment and how this affects possible types of structures considered for the Moon. Other important topics for study, beyond the scope of this paper, are outlined afterwards.

Loading, environment, and regolith mechanics

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

- *safety and reliability*: Human safety and the minimization of risk to "acceptable" levels should always top the list of considerations for any engineering project. Minimization of risk implies in particular structural robustness, redundancy, and when all else fails, easy escape for the inhabitants. The key word is "acceptable." It is 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?* Or better yet, *What kind of failure can we afford or allow?* See Cohen [1996] for a related discussion.
- *1/6-g gravity*: A given 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-based rather than weight-based criteria will drive 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 kgf/cm^2 as pressure, for example.

Analytical foundation design is primarily based on the limit state condition. The design is based on the limit of loading on a wall or footing to 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, etc., 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 predict the load-displacement characteristics of a circular spud-can footing, designed to support a large lunar optical telescope.

Chua also warns 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 a larger gravity, the confining stress would be higher and the soil at the point of interest can support a higher load without collapsing. Soils under reduced gravity may be less consolidated and have less containment.

The area of lunar soil (regolith) mechanics has been 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 appear in Johnson et al. (1995a), Johnson and Chua (1993). Chua et al. (1994) shows how structure-regolith simulations can be done using the finite element approach.

- *internal air pressurization*: The lunar structure implicitly serves as a life-supporting closed environment. It will be a pressurized enclosed volume with an internal pressure of nearly 15psi (103.42kPa)[1]. The enclosure structure must contain this pressure, and designed to be "fail-safe" against catastrophic decompression caused by accidental and natural impacts.
- *shielding*: A prime consideration in the design is that the structure 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 is placed atop the structure for shielding, the added weight would partially balance (in the range of 10-20%) the forces on the structure caused by internal pressurization mentioned above. Criswell et al. (1996) discuss this "balancing" for inflatables.

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

Much effort in this country has determined the damage effects on human beings and electronics resulting from nuclear weapon detonation but little is known about long-term sustained low-level radiation effects such as those encountered on the Moon. According to Silberberg et al. (1985), during the times of low solar activity, the annual

[1] 1 psi =6.89kPa

dose-equivalent on humans on the exposed lunar surface may be about 30 rem (30 centiSv)[2] and the dose-equivalent over an 11-year solar cycle is about 1000 rem (10Sv) with most of the solar proton particles arriving in one or two gigantic flares lasting one to two 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 (5 centiSv), 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 secondary radiation (which consists of electrons and other radiation as a result of the primary radiation hitting atoms along its path).

In recent years, there is a move away from silicon- and germanium-based electronic components towards the use of gallium arsenide. Lower current and voltage demand, and miniaturization of electronic components and machines would make devices more radiation hardened. Four basic ways to harden a device to radiation are with: junction isolation, dielectric isolation, silicon-on-sapphire devices, and silicon-on-insulator devices. All of these methods work on the principle of isolating each device from surrounding components. This eliminates the possibility of latch up and reduces the possibility of a single event upset because charged ions cannot travel as far in the components.

Radiation transport codes can be used to simulate cosmic radiation effects. 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. This vacuum precludes the use of certain materials that may 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 out-gassing of oil, vapors, and lubricants from pneumatic systems. Hydraulic systems using space-rated lubricants are, however, in use today. The out-gassing is detrimental to astronomical mirrors, solar panels, and any other moving machine parts because they tend to cause dust particles to forms pods. 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, for example, railways and wheels.

Blasting in a vacuum is another serious problem to consider. Blasts create a gas, the pressure of which may exceed 100,000 terrestrial atmospheres. It is difficult to predict how this explosion and the resulting ejecta would affect the area around the blast. Keeping in mind that a particle set in motion from the firing of a lander rocket could theoretically travel half way around the Moon, the effects of surface blasting on the Moon must be considered in any construction scenario. Discussion of tests involving explosives performed on the Moon can be found in Watson (1988). Joachim (1988) discussed different candidate explosives for extraterrestrial use. 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 disturbed and placed into suspension easily. These particles cling to all surfaces and pose serious challenges for the

[2] 1 Sievert (Sv) = 100 rem

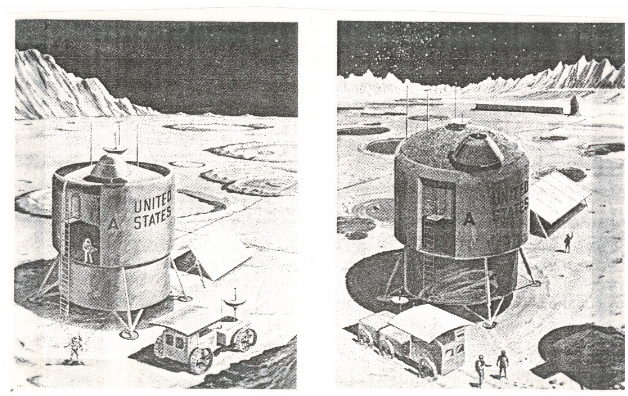
utility of construction equipment, air locks, and all exposed surfaces [Slane 1994].

Lunar dust consists of pulverized regolith and appears to be charged. The charge may come from the fractured crystalline structure of the material or it may be of a surficial nature, for example, charged particles from the solar wind attaching themselves to the dust particles. Criswell reported [1972] that dust particles are levitated at the lunar terminator (line between lunar day and lunar night) and this may be due to a change in polarity of the surficial materials. Johnson et al. (1995b) discussed the issue of lunar dust and its effects on operations on the Moon. Haljian et al. (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 extra-vehicular 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 presented the governing criteria and also general misconceptions in designing space structures. For example, a device that is simple, conventional looking, and has no moving part is preferred over one which involves multiple degrees of freedom in an exotic configuration involving a yet-to-be developed artificial intelligence control if the former meets the functional requirements. Another misconception is 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 designing the structure in such a way as to make construction easy for the astronauts. Cohen and Kennedy (1997) provide a comprehensive discussion of these issues, with a vision of automated delivery and emplacement of habitats and surface facilities.

- *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. See Figure 1.



Two versions of LESA modules emplaced on the Moon by Boeing (1963). [p. 37 Lowman in Mendell, 1985]

Figure 1: Lunar Exploration Systems for Apollo, from Lowman. *Lunar Bases: A Post-Apollo Evaluation*, Lunar Bases and Space Activities of the 21st Century, Proceedings of the Lunar and Planetary Institute, Houston Reproduced by permission of the publisher.

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 human presence on the Moon, on Near-Earth-Orbit [NEO] and Mars. Some of the earlier work is found in Johnson and Chua

(1992). Cohen (2002) states that the predicted water at the lunar poles is less dense and lower grade ore than the residual water in concrete. If concrete existed naturally on the Moon, ISRU proponents would be pushing for the mining of that concrete to recover the water.

Outline of Other Important Considerations

The problem of designing a structure for construction on the lunar surface is a difficult one. Some important topics not discussed in detail in this paper are outline next:

- the relationships between severe lunar temperature cycles and structural and material fatigue, a problem for exposed structures, seals and hatches
- structural sensitivity to temperature differentials between different sections of the same component
- very low-temperature effects and the possibility of brittle fractures
- out-gassing 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 for lunar structures as they are for significant Earth structures [Benaroya 1994]
- dead loads/live loads under lunar gravity
- buckling, stiffening, bracing requirements for lunar structures, which will be internally pressurized
- consideration of new failure modes such as those due to high-velocity micrometeorite impacts, and
- nontechnical but crucial issues such as financing the return to the Moon, and understanding human physiology in space.

In a light flexible structural system in low-gravity, light structural members (e.g., composite cylinders that have wall-thickness of only a few 1/1000ths of an inch) may be designed to limit their load carrying capacity by designing for buckling when that limit is met. In turn, the load is re-distributed 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 have started [Benaroya and Ettouney 1992], in particular regarding the design process for an extraterrestrial structure.

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 helps to ensure that at each juncture alternate solutions exist that will permit the continuation of the 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 1992], and there is a need to study how lunar and Earth codes diverge.

POSSIBLE STRUCTURAL CONCEPTS

In order to assess the overall efficiency of individual lunar structural concepts, decision science and operations research tools are proposed, used [Benaroya and Ettouney 1989] and demonstrated [Benaroya and Ettouney 1990]. Along these lines, Richter and Drake (1990) compared concepts 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 available information with the goal of furthering the development of criteria for the design of permanent lunar structures. Johnson details the lunar environment, discusses lunar soil from the perspective of foundation design, and reviews excavation concepts. A 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 1990c].

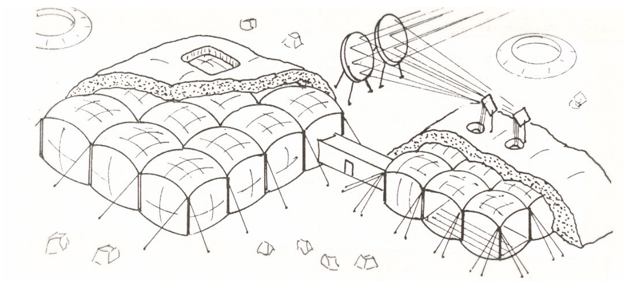
Hypes and Wright (1990) surveyed surface and subsurface concepts for lunar bases with a recommendation that preliminary designs focus on specific applications. America's future on the Moon is outlined as supporting scientific research, exploiting lunar resources for use in building a space infrastructure, and attaining of 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.

Hoffman and Niehoff (1985) used criteria such as scientific objectives and transport requirements in a preliminary design of a permanently manned lunar surface research base.

Inflatables

Vanderbilt et al. (1988) proposed a pillow-shaped structure as a possible concept for a permanent lunar base. The proposed base consists of quilted inflatable pressurized tensile structures using fiber composites. An overburden of regolith provides shielding, with accommodation for sunlight ingress. Nowak et al. (1990) considered the foundation problem and additional reliability concerns and analysis [Nowak et al. 1992]. This concept marks a significant departure from numerous other inflatable concepts in that it shows an alternative to spheroidal inflatables and optimizes volume for habitation. Broad (1989) proposed inflatable structural concepts for a lunar base as a means to simplify and speed up the process while lessening the costs. The inflatable structure can be used as a generic test bed structure for a variety of lunar applications [Sadeh and Criswell 1994]. Design criteria are also put forward [Criswell et al. 1996]. See Figure 2.

Chow and Lin (1988, 1989) proposed a pressurized membrane structure a permanent lunar base. See Figure 3. It is constructed of a double-skin membrane filled with structural foam. A pressurized torus-shaped substructure provides edge support. 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. In a similar vein, Eichold (2000) presented the concept of a lunar base in a crater.



Inflatable structure. [p. 353 Vanderbilt, Criswell, Sadeh in Johnson & Wetzel 1988]

Figure 2: An inflatable structure concept from Vanderbilt et al. *Engineering, Construction, and Operations in Space, Proceedings of the ASCE,* New York, 1988. Reprinted by permission of the publisher, ASCE.

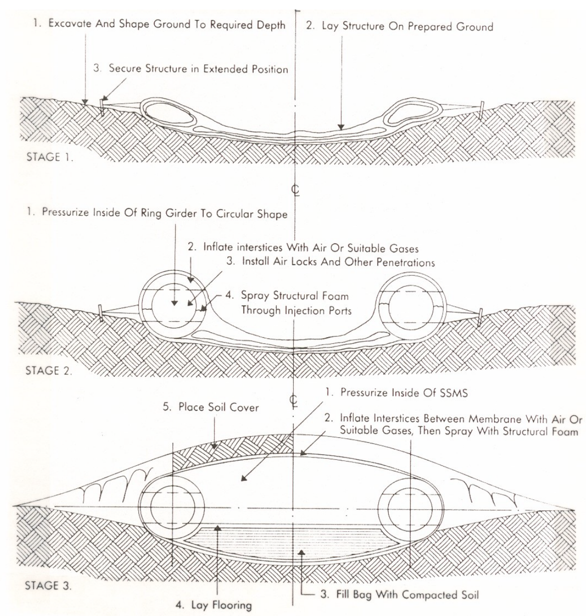
Kennedy (1992) proposed a detailed architectural master plan for a horizontal inflatable habitat .

Finite element simulations of inflatable structures are needed because it is impossible to reproduce a hard vacuum and low gravity condition on Earth. The finite element modeling would be large-deformation capable, have membrane element (which are essentially beam elements without bending) stiffness and axial tensile stiffness but not the axial compression stiffness, since the membrane cannot resist compression. 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.

<u>Erectables</u>

Mangan (1988) proposes an expandable platform structural concept consisting of various geometrically configured three-dimensional trussed octet or space frame elements utilized both as building blocks and as a platform for expansion of the structure. Examples of the shapes used include tetrahedral, hexahedral, and octahedral.

A concept is proposed [King et al. 1989] for using 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 separation from the main external tank structure, 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.



Inflatable membrane structure – construction sequence. [p. 372 Chow & Lin in Johnson & Wetzel 1988]

Figure 3: An inflatable structure concept from Chow and Lin. *Engineering, Construction, and Operations in Space, Proceedings of the ASCE,* New York, 1988. Reprinted by permission of the publisher, ASCE.

A semi-quantitative approach to lunar base structures is provided [Kelso et al. 1988]. Some attention is given to economic considerations and the structural concepts included could be developed in the future.

Schroeder et al. (1994a) propose a modular approach to lunar base design and construction as a flexible approach to developing a variety of structures for the lunar surface. In a related vein, Schroeder et al. (1994b) propose a membrane structure for an open structure that may be utilized for assembly on the lunar surface. A tensile-integrity structure was suggested as a possible concept for larger surface structures [Benaroya 1993b].

Concrete and lunar materials

Lin et al. (1989) provide a structural analysis and preliminary design of a precast, prestressed concrete lunar base. A floating foundation is proposed to maintain structural integrity, and thus air tightness, when differential settlement occurs. All materials for such a lunar concrete structure, except possibly hydrogen for the making of water, may be derivable from lunar resources, however, at very high cost.

Utilizing unprocessed or minimally processed lunar materials for base structures, as well as for shielding, may be possible [Khalili 1989] by adopting and extending terrestrial techniques developed in antiquity for harsh environments. Khalili discusses a variety of materials and techniques that are candidates for unpressurized applications.

Happel (1992a, 1992b) bases his design of a tied-arch structure on indigenous materials. The study is extensive and detailed, and includes an exposition on lunar materials. Construction using layered embankments of regolith and filmy materials (geotextiles) is 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, it has been suggested that a sulfur concrete be examined [Gracia and Casanova 1998]. Sulfur is readily available on the Moon.

Site Planning

Site plans [Sherwood 1990] and surface system architectures [Pieniazek and Toups 1990] are forcefully presented as being fundamental to any development of structural concepts.

SPACE TOURISM

To get a sense of where we might be in 50-100 years, we look to the concepts of the Inston Design Team's concepts for a Lunar Hilton. These concepts were developed under contract with Hilton International, and are reproduced here with permission of Inston. There have been studies of space tourism as the driving force behind a permanent return to the Moon. Collins (2002) is a good place to start.

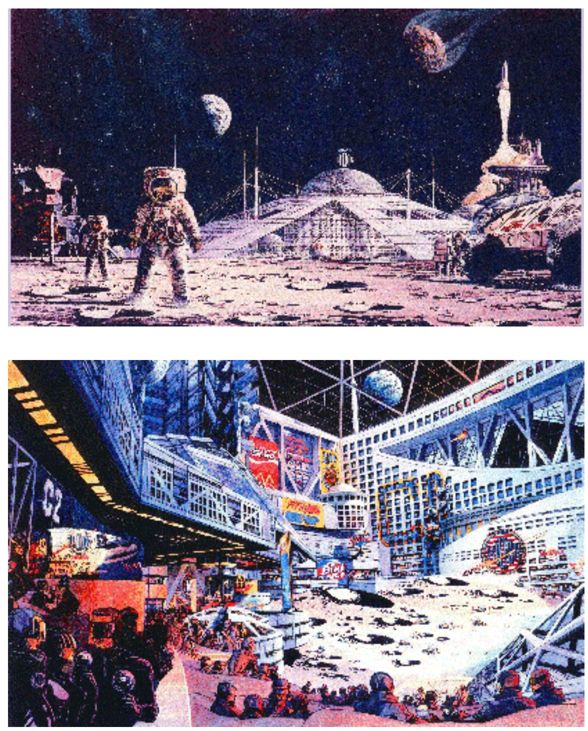


Figure 4: Hilton International concept for lunar hotel and commercial properties. Inston Design Team, with permission.

Construction in a New Environment

One of the challenges to the extraterrestrial structures community is that of construction. Lunar construction techniques have differences from those on Earth, for example, the construction team will likely operate in pressure suits, motion is dominated by *one-sixth g,* solar and cosmic radiation not shielded by an Earth-type atmosphere, and the existence of suspended dust in the construction site. An assessment is provided [Toups 1990] of various construction techniques for the classes of structures and their respective materials. These fall into three categories:

1. methods that require Earth support
2. methods that use natural surface and subsurface features, and
3. techniques that primarily use lunar resources.

Structural and architectural designs, along with manufacturing plants, and construction methods are discussed [Namba et al. 1988a] for a habitable structure on the Moon using concrete modules. The module can be disassembled into frame and panels. The framed and interconnected modular construction permits internal pressurization.

A qualitative study [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 support operation and maintenance operations during the functional life of the lunar outpost.

Construction of a lunar base will at least partially rest on the capabilities of the Army Corps of Engineers. Preparations are outlined [Simmerer 1988] and challenges discussed [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 *one-sixth g* with an extremely 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 extraterrestrial operations is advocated [Bell and Neubek 1988].

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

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

Creating the Base Infrastructure

The availability of an adequate infrastructure and resources are key to the survival and growth of any society. Basic necessities such as shelter, water, waste disposal, and transportation are the foundation of any viable society. Also, 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: rocks, regolith, and breccias. 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 percent below 30 *cm*. The grain size distribution of a common regolith, as well as its high density below the top layers, is rare in the terrestrial environment. This condition 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, 7) and underground storage facilities.

THE ISSUE of WATER on the 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 water/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 outwards according to the matric suction pressure (which is influenced by the particle size distribution and is defined as the pore air pressure minus the pore water pressure). 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^{o}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%.

USING GEOSYNTHETICS in the EXTRATERRESTRIAL ENVIRONMENT

Some recent papers suggested using geosynthetics as soil reinforcement to construct earth structures such as berms, walls, slopes, etc. Chua [in Benaroya et al. 2002] points to several problems that 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 that are encountered on candidate sites including those on the Moon. This would make the plastics brittle thus rendering them useless as reinforcing elements.
- There is little experience on how geosynthetics fare in a hard vacuum and respond to the relatively more abrasive regolith.

CONCLUDING SUMMARY

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. The key lunar environmental facts have been summarized. Key structural types have been studied.

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Appendix: BUILDING SYSTEMS

TYPES of APPLICATIONS

Habitats

- people (living & working)
- agriculture
- airlocks: ingress/egress
- temporary storm shelters for emergencies and radiation
- open volumes

Storage Facilities/Shelters

- cryogenic (fuels & 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 & 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 & material processing
- evolutionary growth/reconfiguration requirements
- resupply versus reuse strategies

General Planning/Design Considerations

- automation & 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 & 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