EVOLVING CONCEPTS OF LUNAR ARCHITECTURE: THE POTENTIAL OF SUBSELENE DEVELOPMENT

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Andrew W. Daga and Meryl A. Daga

Integrated Space Systems Corporation
122 Larchwood Court
Collegeville PA 19426

Wendel R. Wendel

Starnet Structures, Inc.
106 Bell Street
West Babylon NY 11704

In view of the superior environmental and operational conditions that are thought to exist in lava tubes, popular visions of permanent settlements built upon the lunar surface may prove to be entirely romantic. The factors that will ultimately come together to determine the design of a lunar base are complex and interrelated, and they call for a radical architectural solution. Whether lunar surface-deployed superstructures can answer these issues is called into question. One particularly troublesome concern in any lunar base design is the need for vast amounts of space, and the ability of man-made structures to provide such volumes in a reliable pressurized habitat is doubtful. An examination of several key environmental design issues suggests that the alternative mode of subselene development may offer the best opportunity for an enduring and humane settlement.

INTRODUCTION

It has been a very long time since the art and science of architecture has been called upon to contribute fundamentally to the transformation of human civilization. Nevertheless, we can see that humankind's ability to expand civilization to another planet will certainly depend upon our success in contriving a very sophisticated built environment—an architecture that is truly appropriate for the Moon. In seeking this goal, it is conceivable that we may be required to dispense with our terrestrial tradition of "erecting" buildings. Ironically, it may turn out that the profession that contributed to the advancement of civilization by giving humankind an alternative to the cave may call us back to that environment.

The definition of architecture here must be stretched a bit beyond the Vitruvian conception of rigid structure, utility, and aesthetics, for these elements hardly begin to address the complexity of creating a fully integrated biospheric medium. When we consider the subject of building a place for man on the Moon, we must take a radical approach, for there are no applicable earthly precedents to guide us. We must think holistically, in terms of integrated systems, for the problems of lunar habitation are interconnected, and they cannot be considered in isolation. Certainly, we cannot think of architecture merely in terms of structure and function. Given the nature of this extraordinary endeavor, it can be posited that the architect, in the truest definition of his profession, will play a central and critical role in determining the real potential of lunar settlement.

A review of the numerous proposals for lunar base construction and habitation reveals a variety of themes. Looking critically at these, we find many innovative proposals that tend to suffer from their concentration on a very limited set of considerations. There has also been a tendency to rely on preconception, a tendency to extrapolate methodologies developed in previous space missions to the realm of the lunar base. Too often, highly logical designs are nevertheless weakened by a reluctance to consider the more intuitive notions of a designer's mind—a shame at this stage of the discussion. There has been a noticeable deficiency in designs that look beyond the early outpost phases of basing, at the question of how a lunar base may evolve—and at how anticipation of this evolution may guide early base planning. A continuous thread linking most of these proposals is that they have been proposed in the absence of a clearly defined program; however ingenious, they are solutions in search of a problem. To solve the problem of radiation shielding, or of thermal stress, or of atmosphere containment—to solve one problem, or another—is not enough. There has been a lack of comprehensiveness in the consideration of architectural issues, and this is because no one has yet been able to propose a workable architectural program that relates all the various factors that must form the basis of any lunar base design. Until this is accomplished, it will not be possible to evaluate fairly any specific proposal.

This paper is aimed at contributing to the discussion of lunar development by offering to the reader some insight into the range of architectural considerations that must shape this program, and to suggest how differing modes of architectural development are able to respond to a spectrum of factors. In so doing we will attempt to define and formally distinguish between two very different modes of lunar basing, these being the categories of surface-deployed superstructures and subselene adaptational environments. We believe that the alternative mode of subselene development, i.e., the exploitation of natural lunar caverns, may very well yield novel conceptions of the manner in which a lunar base may evolve, and offer a reasonable means of producing a humane lunar settlement.

A Sampling of Critical Architectural Issues

The list of factors that will influence lunar base design is prodigious and spans virtually all fields of human interest. The architecture that we ultimately build, viewed at any stage of evolution, will certainly result as a compromise product reflecting collaboration between many centers of expertise. Matters that seem to go well beyond the purview of architectonic practice will become critical in lunar base design. For many of us, the ability to resist the convention of pursuing narrowly defined technological questions will be an important first compromise.

Another crucial first step will occur when we come to see the architecture of lunar settlement, not in terms of a translation of terratectonic principles, nor in terms of modified off-the-shelf technologies, but rather as a highly specific product of invention. A fitting lunar architecture will require a radical approach, a necessity forced upon us by the distinction of this new planet. We will need to purposefully reconsider the ways we have been conditioned to build on the Earth, and we must be prepared to dispel all preconceptions; we must become preoccupied with novelty. The great promise of this, of course, is not merely implied for architecture on the Moon, but for the quantum improvement of architecture in general.

It should be noted that the most perplexing concerns of lunar base design may relate less to the more widely discussed problems of fractional gravity, radiation flux, and vacuum, and more on the fathomless issues of human behavior and interaction.

With these qualifications in mind, a brief review of several of the more critical architectural considerations is offered.

Lunar Gravity

Of course, one of the most prominent and alien features of the Moon is its fractional gravity, and this will affect the architecture in various ways.

Clearly, structural design will reflect effectively increased load-bearing capacities; however, this must be taken in the context of several interacting factors. For instance, if regolith-mass shielding is to be employed, any inherent load-bearing advantages may be canceled. Although gravitational force will always be a significant factor, even in $1/6\,g$, other factors may govern structural design determinations. Principally, we are thinking about pneumatic forces due to atmosphere containment. Internal air pressure is a variable, and has to be considered a dynamic force. Extreme thermal cycling may force further complication of the structure, thereby reducing the efficiency of spanning systems. The performance of indigenously manufactured structural materials may be compromised by extraordinary design safety factors. Function and safety factors may work to counter any opportunity for material efficiency in spanning members when system redundancy and compartmentalization strategies overrule.

Another effect of reduced gravity concerns anthropometry, space planning, and the dimension of space within a base. The dynamic human dimensional relationship with the built environment is gravity dependent. Intuitive expectations of lunar base spatial requirements can only be modeled hypothetically, and cannot be easily translated from the terrestrial condition. The effect of this problem will contribute to form determination. Also, it seems likely that continued research into this question will result in a modification of present estimations of spatial economy and efficacy.

A third important effect of this issue concerns the health of humans and other animals and plants, and this relates to the largely unknown and potentially deleterious effects of living in a substantially reduced gravitational environment. *Diamandis* (1988) addresses this and points out reasons to doubt that lunar gravity will provide sufficient physiologic stresses over the long term to prevent the same deconditioning that is seen in zero gravity. (Extended stays in zero gravity have led to immunosuppression, muscular atrophy, osteoporosis, cardiovascular deconditioning, and body fluid/metabolite shifts; there is also the strong suggestion that embryogenesis and early development will be adversely affected.) Potentially, these physiologic reactions threaten our ability to adapt permanently to the Moon, and jeopardize as well the option of revisiting Earth. The built environment must be able to accommodate these concerns in several ways. First, a primary method of mitigating physiologic stress will almost certainly depend upon physical exercise, and so the architecture might be designed so as to require the inhabitants to walk long distances between elements of the base. Another means toward the prevention of these physiologic disorders involves the inclusion of some mechanism for providing artificial gravity, as suggested by Diamandis. In both cases, the architecture would need to be capable of providing the requisite spatial volume and three-dimensional sophistication implied by these devices.

Radiation Shielding

It is a well understood fact that the enclosing envelope of any lunar base must be capable of shielding the inhabitants from the intense ionizing radiation that strikes the lunar surface. In the case of surface constructions and modular habitats, it is generally estimated that between 2 and 3.5 m of loosely piled regolith will be required to provide sufficient protection (*Silberberg et al.*, 1985). Considerations of habitat form and exposure are aspects of design that are directly affected by this problem (see *Land*, 1985). Other matters that are called into question include structural complications due to the radiation-shield load; preferences for certain shielding materials (considering the generation of secondary neutrons within the shielding material by cosmic rays, as well as the variable absorptive efficiencies of candidate shield materials); the practicality of fenestration; access to the exterior hull for inspection and repair (see *Kaplicky and Nixon*, 1985); paradoxical limitations on solar access; and the practical considerations of maintenance. The designers of a lunar base are therefore obligated to consider very carefully the ways in which this necessary element will work to shape base architecture.

Atmosphere Containment

The form of a lunar base will be determined by a wide range of factors, but a common denominator in any formula for resolving base morphology will be the restrictions imposed by the physics of atmosphere containment. Without the perfect and reliable confinement of an atmosphere, no lunar base is possible. Having said this, it must also be noted that atmosphere containment cannot be held in isolation as the exclusive determinant of form (as has been a theme in many lunar base proposals). If pressure-vessel physics were to dominate our thinking, we would be limited to the utilization of spheroids and cylinders, and with respect to the many other requirements that must contribute to the definition of base architecture, these forms are fundamentally problematic.

We should realize that the very knowledge of environmental integrity and dependability on the part of the inhabitants will likely become a key to our adaptive ability, and so there is a behavioral component to atmosphere containment. Therefore, while the structure of a lunar base must be designed for fail-safe reliability, there should also be a sufficient level of architectural sophistication to express this strength to the inhabitants.

The enclosure system should be able to withstand accidental and intentional decompression of the structure, and it may be unwise to rely on structural systems that depend upon internal air pressure for support (since their integrity depends upon the integrity of the atmosphere). It is important that any hull-type structure remain accessible for inspection and repair. Also, once established, a lunar base will likely be in a virtually continuous growth mode, so it is important that the structural system be devised so as not to interfere with base expansion and revision.

Very importantly, as a breathable atmosphere represents an absolutely vital resource that, in theory, could become the subject of political influence or the target of sabotage, appropriate safeguards must be considered and eventually integrated into the architecture. (Similar vulnerabilities will exist for water, food, energy, and other vital resources as well.)

Extreme Thermal Stress

Surface temperatures over the lunar diurnal cycle vary over a range of 500°F (260°C). Structural elements that are subject to exposure to this extreme thermal variation, particularly exposed or uninsulated atmosphere-containing superstructures, must be highly elastic in their design. Material fatigue due to thermal cycling may be a problem and could limit the effectiveness of certain materials. Fully sheltered superstructures, with thermal differentials of perhaps 300°F (149°C) will be subject to lesser but still significant extremes. This will constrain the scale of exposed superstructures, as well as the range of geometries that might be available. It will require the use of proven, high-strength materials, which further implies a very high level of architectonic sophistication, construction difficulty, reliance on high-precision components, and the need for redundancy in atmosphere containment systems. If material fatigue is a significant problem, structure lifetime will be adversely affected.

Environmental Ruggedness

Many recent proposals suggest derivative space-station technology (habitat modules) for use as lunar habitats, others suggest pneumatically supported fabric structures, and still others feature large thin-walled aluminum domes. Considering the nature of activities that are postulated for the Moon (mining, industrial manufacturing, chemical production, transportation node, etc.), and considering that this expansion-oriented permanent settlement will be inhabited, not by a highly trained crew, but by a very mixed population of individuals, these proposals seem inadequately rugged. Accidents, abuse, and misuse are certainties within any human-inhabited environment and must be considered in the formulation of any architectural system. The important and early need for a rugged, abusable, "kickable" environment should not remain understated.

Meteoritic Impact Susceptibility

Recent theses on lunar base design have usually considered the effects of micrometeoroidal impacts on structures and equipment (*Johnson and Leonard*, 1985, and others). Certainly, the issue of micrometeoroidal impacts is important in the design of virtually all types of space structures, and it will be a very important concern in lunar base design. The fact that lunar base design must reflect many of the same problems that have typically concerned spacecraft designers is underscored by recent studies that have shown that the lunar-environment dust flux is substantially denser (as much as 10^2) than interplanetary models (*Grün et al.*, 1984). In particular, we must be concerned with the long-term performance of exposed materials, as well as the potential for puncture impacts.

Lunar planners must have special concern, however, for the far more insidious larger meteoritic bodies, for they pose a potentially catastrophic threat to permanent lunar habitats. Macrometeorite impacts do indeed occur on the Moon with sufficient frequency that they pose a real threat to long-term lunar habitation and they must be considered in the planning of any lunar base (Zook, personal communication, 1988). We are concerned here, not with dust, but with multicentimeter metallic projectiles moving at extremely high velocities. We suggest that it is overly simplistic to dismiss this matter on the basis of a statistical supposition. More realistic would be the adoption of a conservative engineering philosophy, where an evaluation of worst-case scenarios would demand that structural designs be devised on the basis of the assumed certainty of various types of collisions and near-collisions. Considering the indeterminate lifetime of lunar base structures, and given the need for the assurance that the inhabitants will demand, this seems a most reasonable approach.

Political Considerations

The political issues that will have an impact on lunar settlement design are perhaps the most difficult to assess and may be the most critical concerns for lunar base planners.

The scope of concerns here is very broad, spanning the intricacies of international relations, nation building, national security, economics, monetary standards, political theory, law, common heritage, and the definition of property on national and individual scales. All these considerations will interactively affect the architecture of lunar settlement. For a broader discussion of the nature of these matters in the context of space and lunar development, the reader is referred to a number of articles, including *Joyner and Schmitt* (1985), *Finney* (1985), *Dula* (1988), *Gabrynowicz* (1991), and *Robinson and White* (1986).

There are a number of political variables that stand out as being determinative of lunar base architecture. First, there is the realization that current international treaty casts doubt on national prerogatives with regard to the construction and property definition of a lunar base. Then there is the question of the predominating politico-economic system philosophy of the nation or nations involved. The governing system, planning philosophy, functional characteristics, and the rate and direction of future growth for the base will all be guided by this issue. Another pivotal planning consideration here is the question of property definition and individual liberty—by which political model will lunar settlement be guided? A related question concerns vital resource authority and distribution, and the problem of delegating authority for the maintenance of essential life-supporting systems (including the architecture itself). Ultimately, redundancy (or decentralization) in vital resource storage and distribution systems may come to parallel the importance of structural system redundancy, but for the purpose of making political control more difficult.

Another concern that should not be overlooked is the ability of architectural systems to respond over time to changing needs and functional requirements, especially as they may be directed by political considerations. Vicissitudes in national and international policy may require unforeseeable changes and constant modification of base facilities. Evolution toward settlement autarky will certainly require a transformable architectural system. Basically, the architecture can either contribute to successful polity, or hinder it, depending on the degree of responsiveness to these changing needs.

There is a potential in the holistic view of architectural planning for providing mechanisms that work to protect pluralistic systems and the rights of the individual. Conversely, a faulty design can be an instrument of control. While these concerns may not be obvious in the early outpost phases of lunar basing, they will surely become mandatory for greater settlements. What must be remembered is that the Moon forces a duty on the architecture for which there is no corresponding terrestrial analog, and that is the obligation of providing essential life-support. In such a role, we can be sure that the architecture will be the subject of political influence.

Behavioral Issues

The interior environment of a lunar base presents myriad psychological and sociological design questions and complications, far too many to list here. It should be noted that although space-environment behavioral problems have been studied at great length at NASA and other agencies, much of this work has focused on considerations that relate to space vehicles, zero-gravity environments, and the social interrelationships of highly trained crew personnel. Much of this work has little or no meaning in a lunar setting, and new research efforts will be needed to properly equip base architects with meaningful insight. Let it suffice to say that the development of any baseline lunar base architectural program will remain incomplete without significant novel research in this area, and that many of the architectural proposals produced to date have originated in the absence of this critical information.

We would like to suggest several areas of behavioral research that will directly affect the architecture of a lunar base, and that require detailed investigation. They include the following:

Spatial volume requirements. To determine the human need for space in the totally confined environment of a lunar base. It is possible that this requirement will be highly determinative of planning strategies, and the need for copious internal volumes may force a reevaluation of current postulations of lunar base size.

Environmentally imposed psychological stress. To anticipate any deleterious psychological reactions or stresses that may result from living with the constant potential for environmental failure; to suggest architectural devices that may ameliorate these apprehensive stresses.

Environmental stimulation and diversity. To further assess the human need for environmental diversification; to suggest sources of environmental stimulation that might supplant missing terrestrial stimuli.

Individual spatial requirements, retreat space, and privacy. To evaluate the essential environmental requirements of the individual within the specific context of lunar settlement; and to do so in the context of such crossover concerns as property definition, political philosophy, and fractional gravity anthropometrics.

Earth-diurnal cycle emulation methodologies. To study methods of recreating various psychological and biological environmental cues based on terrestrial conditioning; to evaluate their effectiveness in the lunar setting; and to suggest possible architectural contributions. Key concerns here are environmental lighting and lighting controls.

Architectural semiotics. To consider evolving concepts of lunar base design that depend upon subliminal suggestion or semiotic message in order to bring about some desired effect. Such devices may be useful in the prevention or moderation of environmentally imposed stress, for example.

Spatial Volume

A misconception, we think, concerning the design of lunar bases, relates to the assumption that spatial volume within a lunar base will be a premium and highly economized amenity. This idea, expressed in so many proposals, seems to be an extension of precedent and practice, and may be due to the fact that, with all previous space missions, large spatial volumes have been achievable only rarely, and then only at great expense. This thinking may also be the product of presumptions about the economic and practical limits of large structures. Of course, a lunar base is essentially a static structure and, as such, it represents a novel mode of space development. While the economics of lunar development will be the subject of continuing study, we should probably take care to avoid any premature conclusions about the cost of large-scale development. In any case, the absolute need for copious internal volumes in a lunar base will inevitably present itself, regardless of economic expectations. It will simply be unfortunate if our lunar ambitions are needlessly restrained.

Simply put, we should expect the architecture of a continuously expanding lunar base to be able to accommodate the spatial needs, whatever they are, of the inhabitants. It should be anticipated that the open volumes of these spaces will be quite large. The need for spatial volume over the long term may be equal to the need for other vital elements of life support, and must be considered a design-driving issue. The need for transition from small-volume early outpost spaces, to large-volume greater settlements may present itself very early in base evolution, and this should be considered in any program evaluation. This is a matter that cannot be overlooked or subordinated.

SUPERSTRUCTURAL AND SUBSELENE MODES

As part of this report, we would like to formally distinguish between two fundamentally different ways of approaching the construction of a lunar base. The responsiveness of each type to critical design issues varies, so the distinction is important.

The category of lunar surface superstructures includes the great majority of lunar base proposals to date. Basically, any erect construction, whether assembled, inflated, or landed, situated on or near the lunar surface, fits this classification. Typically, superstructures rest on a prepared foundation (ideally one anchored to bedrock). Habitable superstructures must provide a structural envelope capable of the reliable containment of an atmosphere. In all cases, it is the structural system that must carry the full range of loads, allowing multiple levels of redundancy and various factors of safety in their design.

Contrasted with this type is the category of subselene development, which involves the environmental adaptation of the lunar subsurface. Within this classification, structural and atmospheric loads may be carried directly by the surrounding rock mantle, with the greatly minimized need for a substantial and sophisticated superstructural enclosure. The direct exploitation of lunar lava tubes (natural caverns) may be considered a particular subtype of subselene development. The use of lava tubes as shelters for superstructural elements (but without closure and pressurization of the tube) can be considered as a hybrid mode of subselene development. A second subclassification might include excavated developments, where self-supporting voids (artificial caverns) are purposefully created. With subselene basing, we distinguish the lunar subsurface as being far more environmentally hospitable to development than is the surface and, therefore, inherently advantageous as a place to put a lunar base.

It may be said that architecture, being a very old profession, tends to enjoy its history and traditions. Certainly, architects enjoy building, and it is understandable that our first visions of lunar basing might demonstrate continuity with the heritage of terrestrial construction. Unfortunately, as we begin to come to grips with the complexities of lunar settlement, predictions of substantial construction and habitation on the lunar surface seem increasingly romantic.

Although detailed evaluations of candidate architectural schemes must await the framework of formal programming, meaningful comparisons of generalized surrface and subsurface basing concepts are possible. The results of our initial studies, which attempt to compare the various attributes of these two modes of development and identify inherent advantages and disadvantages, are shown in Table 1. This study is certainly not conclusive, but it does begin to suggest the applicability of several systems. Even at this stage, however, it seems clear to us that there are deficiencies inherent to all surface habitation schemes, and that the potential of lava-tube-based developments should be investigated further.

Looking at the disadvantages of lunar surface superstructures, it is apparent that there are significant technological issues that will always impose limits on the extent of construction and on other related aspects of architectural design. Even for the smallest surface habitats, the interwoven factors of pressure-vessel physics, thermal stressing of the enclosing skin, radiation shielding, and construction difficulty in a lethal environment present extremely perplexing problems.

The ability to create structures of highly variable morphology is not one of the strengths of this mode of development. The need for morphological complexity, flexibility, and revisability is dictated by functional, behavioral, political, and other considerations, and should not be undermined by inherent structural limitations. Resolving this contradiction will complicate any surface-based design. Further, in order to achieve safe and reliable structures on the surface, additional complication of the structure will be required. Inspection and maintenance needs will add still more complication. The alternative of subselene basing raises the matter of thermodynamic performance, for we must realize that, by comparison, surface structures are inherently poor performers.

As a rule, in order to construct similarly sized environments, with similar safety and performance expectations, we should expect surface-constructed bases to require more sophistication and greater quantities of construction materials. There may also be a need for greater degrees of precision in the manufacture of these materials. Overall surface settlement growth may therefore be inhibited by increased competition for base resources. Considering these limitations, it seems too great a stretch of the imagination to expect a construction sophistication capable of providing the very large internal volumes that are comparable even to small-scale lava tubes. Even if all other problems were to be resolved, failure to accommodate the spatial requirements of the inhabitants would invalidate any exclusive reliance on surface structures.

Finally, with surface-based systems we see many contradictions. For instance, the need for complex architectural form is in opposition to the principles of pressure vessel design, which calls for simplicity; the need for large volumes implies greater hull surface areas, which runs contrary to the issues of radiation shielding, thermal stress, and thermodynamic performance; and the material economy of thin-walled pressure hulls cannot be reconciled with the need for environmental ruggedness and macrometeorite protection.

As we review these issues and contradictions, two strategies of surface construction seem practicable. First, we would expect surface structures to permit an initial and early operational capability on the lunar surface. Early subselene deployment, in the form of lava tubes used as shelter for habitats, may provide an alternative to extensive surface development, and this prospect should be studied actively. However, initial operations from a surface base camp would seem mandatory in light of the need for precursor investigations of lava tubes. In this role for superstructural systems, many of the confounding issues that relate to permanent habitation would not be pertinent, thereby allowing the use of relatively simple structures.

Second, in combination with subselene adaptation, surface constructions will certainly fill many important roles; however, we do not believe these include long-term habitation. Many lunar operations will occur at the surface, requiring both pressurized and nonpressurized facilities. Vestibular surface constructions would be needed for surface access to subselene facilities. Eventually, it may even be desirable for an established subselene base to expand elements of its facilities upward by penetrating the cavern roof.

If surface-constricted superstructures are utilized for long-duration habitation, we may estimate some aspects of their architectural form. In this capacity, those proposals for lunar basing that have indicated a highly compartmentalized bomb-shelter-like environment seem most reasonable. Such an environment would necessarily have few access points, few windows, and be buried under some 7 to 12 ft of regolith. If constructed as a mass structure, possibly in concrete, its walls would probably be quite thick, its spaces forming a chambered matrix. Spatial hierarchy would be based, for a long time, on the distinction between the interior of the base and the inaccessible lunar exterior—there would be no "outside." For all intents and purposes, it would be a man-made cave.

LAVA TUBES

The existence, operational advantages, and favorable environmental conditions of lunar lava tubes were discussed by *Hörz* (1985). Speaking from the perspective of planetary geology, he discussed the theorized origin and formation of lunar lava tubes, and stressed the certainty of their existence. He went on to

TABLE 1. This table summarizes a systems comparison study performed by the authors and identifies the inherent advantages and disadvantages of six generic architectural systems.*

Architectural Systems Comparison

Identification of Inherent Advantages and Disadvantages of Various System Archetypes which are Candidates for Lunar Development

● INHERENT ADVANTAGE ○ POSSIBLE ADVANTAGE ✖ INHERENT DISADVANTAGE ✧ POSSIBLE DISADVANTAGE

	SURFACE				SUBSURFACE	
	HABITAT MODULES S/S-DERIVED OVERCOVERED	THIN SHELL RIGID FRAME OVERCOVERED	MASSIVE SHELL RIGID FRAME OVERCOVERED	SOFT SHELL (INFLATABLE) OVERCOVERED	LAVA TUBE-A (AS SHELTER FOR OTHER STRUCTURES)	LAVA TUBE-B (FULLY ADAPTED HABITAT)
POTENTIAL FOR EOC Does the system have the potential for Early Operational Capability?	●		✧	●	○	✖
SITING LIMITATIONS Does the system inherently limit the site selection process?	●	●	○	●	✖	✖
OVERALL ARCHITECTURAL DESIGN FREEDOM Is the system inherently self-limiting?	✖	✧		✧	○	●
VOLUME-ENVELOPE RELATIONSHIP Does the system offer any inherent advantage or disadvantage with regard to the ratio of constructed envelope to enclosed volume?		✧	✧			●
POTENTIAL FOR PERMANENCE Is there a realistic potential for permanent habitation?	✖		○	✖	○	●
FUNCTIONAL ADAPTABILITY How well will the system adapt to a changing range of functions?	✖	✧	✧	✧	○	●
FENESTRATION Can the system accommodate direct views of the exterior?	●	●	●	○	✖	✖
POTENTIAL FOR VERY LARGE VOLUMES Does system have the capacity to provide copious internal volumes?	✖	✧	✧	✧	○	●
STRUCTURE LIFETIME Is the structure lifetime predictable?	✧	✧	○	✖	○	●
SYSTEM POTENTIAL FOR SUBSTANTIAL RECONFIGURATION Can the structural system be revised easily?	✧	✧	✧	✧	○	●
PHYSICAL EXPANSION POTENTIAL Can the system be expanded easily?	○				○	●
OVERALL RELIABILITY OF STRUCTURE Can we expect reliability of the structural system?	○	✧		✖	○	○
RUGGEDNESS OF STRUCTURE Can the system stand up to rugged use and abuse?	✖	✧	○	✖		●
EXTREME THERMAL STRESS Will the system be subject to extreme thermal stressing?	✖	✖	✖	✖	●	●
COMPLICATION OF STRUCTURE DUE TO MAINTENANCE REQUIREMENTS Will the need for access, inspection, and regular maintenance cause the structure to be more complicated?	✖	✖	✖	✖	●	○
EVA-INTENSIVE CONSTRUCTION OPERATIONS Will the construction method require an extensive human presence?	○	✖	✖	○	○	○
OVERALL ENERGY MANAGEMENT Does the system have any inherent advantages or disadvantages?	○	✧		✧	●	●
BEHAVIOR OF STRUCTURE DURING FAILURE In the event of sudden decompression, will the structure fail catastrophically?	✧	✧		✖		○
DEPENDENCE ON PNEUMATIC PRESSURE FOR STRUCTURAL SUPPORT Does system depend on internal air pressure for structural support?	○	○	●	✧		●

	SURFACE				SUBSURFACE	
	HABITAT MODULES S/S-DERIVED OVERCOVERED	THIN SHELL RIGID FRAME OVERCOVERED	MASSIVE SHELL RIGID FRAME OVERCOVERED	SOFT SHELL (INFLATABLE) OVERCOVERED	LAVA TUBE-A (AS SHELTER FOR OTHER STRUCTURES)	LAVA TUBE-B (FULLY ADAPTED HABITAT)
STRUCTURE COMPLICATION DUE TO ATMOSPHERE CONTAINMENT ISSUES Will the need for redundancy and perfect integrity mandate complication of the structural system? Of the construction process?	✖	✖	✖	✖	✖	○
RESTRICTIONS IMPOSED ON ARCHITECTURAL FORM BY ATMOSPHERE CONTAINMENT ISSUES Will architectural design be directed or restricted by the issues of pressure-vessel engineering?	✖	✖	✖	✖	✖	○
RANGE OF MATERIALS WHICH CAN BE USED Will the system be subject to environmental extremes which will limit the types of materials which can be used for construction?	✖	✖	✖	✖	○	●
DEPENDENCE ON EARTH-IMPORTED CONSTRUCTION MATERIALS/COMPONENTS Does the system depend heavily on earth imports? Can a transition to indigenous materials be achieved easily?	✖	✧	✧	✖		○
INHERENT RADIATION SHIELDING Does the system offer any inherent capacity for radiation shielding?			○		●	●
DEPENDENCE ON REGOLITH FOR SHIELDING Is the placement of large quantities of regolith required for shielding?	✧	✧	✧	✧	●	●
COMPLICATION OF THE STRUCTURE DUE TO SHIELDING Will the need for regolith shielding mandate complication of the structure? Of the construction method?	✧	✧	✧	✧	●	●
PASSIVE MEDIATION OF LOW-G CONDITIONS: PHYSICAL EXERCISE Does the architecture affect the course of living on the moon in such a way as to passively require physical exercise within the base?	✖					●
MACROMETEORITIC IMPACT PERFORMANCE Is the system inherently susceptible to macrometeoritic impact?	✧	✧	○	✧	●	●
CELSS INTEGRATION Is the system receptive to the close integration of advanced CELSS?	✧					●
CELSS EVOLUTION Is there an inherent capacity in the system to allow for the maturation and evolution of CELSS technology?	✧				○	●
POTENTIAL FOR EVENTUAL TERRAFORMATION Does the system offer any potential for interior terraformation?	✖			✧		●
POTENTIAL FOR EXPANSIVE OPEN INTERIORS Can the need for copious open space be satisfied?	✖		✧		○	●
HIERARCHICAL SPATIAL DIFFERENTIATION Is there a capacity for meaningful hierarchical spatial differentiation?	✧					●
ENVIRONMENTAL STRESS Does the system offer any inherent advantages or disadvantages with respect to psychological stress due to the environment?	✧	✧	○	✖	●	●
CULTURE/POLITICAL SYSTEM FUNCTIONAL ADAPTABILITY If the lunar base program is pursued by one nation, or alternatively, by a coalition of nations – how well can the system respond to varying C/P requirements?	○				○	●

*A more detailed comparative analysis of candidate basing systems awaits the framework of a specific lunar base program statement. The reader should note the important advantages that are offered by systems that depend on the sheltering capacity of lunar tubes, suggesting a course that sees an early transition from initial surface constructions to the deployment of facilities within nearby tubes.

suggest how these natural lunar caverns may have superior potential as habitat shelters. In summary, Hörz provided us with the following overview.

First, we know that lunar lava tubes exist. They are observable as being related to the numerous sinuous rilles, or lava flow channels, that are found abundantly on lunar basalt surfaces. These flow channels are believed to be collapsed sections of lava tubes and, in a number of instances, remaining sections of intact tube become apparent with the observation of uncollapsed roof segments. It is noteworthy that while the frequency and global distribution of lava tubes are not well understood, they are subsurface features, and fully intact tubes will not normally be recognizable from surface imagery.

We can also observe that lunar tubes are significantly larger and more sinuous than terrestrial analogs. By scaling various rilles and uncollapsed roof segments, typical widths and depths of tubes can be estimated in the hundreds of meters, with overall lengths commonly measuring a few kilometers. Restrictions and enlargements within the interior of lava tubes may occur (as they do in terrestrial lava tubes), but it is suggested that the relief scale of these features is typically small when compared to cross-sectional dimensions. Figure 1 indicates a number of lava flow features, including one known lava tube (scalloped linear feature at the lower center of the photograph); these observable features may be suggestive of lava tube morphology.

Fig. 1. The morphology of lunar lava tubes is suggested by these lava flow features, some of which may be depressions caused by the collapse of lava tubes. Note the variability of scale and the proximity of craters and mountains. Segments of uncollaped tube segments can be seen at the bottom center. (Lunar Orbiter V, frame M-19.)

Lava tube roof thicknesses seem to be more than sufficient to provide superior radiation shielding and protection from meteorite impacts. Deducing from beam-modeling techniques, basalt "bridges" (lava tube roofs) of at least 40 to 60 m in thickness would be required to span the observed widths of a few hundred meters. If the proportional relationship of roof thickness to cross-sectional dimension in terrestrial lava tubes is any indication, we should expect to see typical roof thicknesses ranging from 0.25 to 0.125 of cross section. Crater impact studies further support these estimates.

Uncollapsed lava tubes are further observed to have sustained substantial and repeated meteorite impacts. It is noted that the expended energy from some of the larger impacts would equate to several tons of TNT (Hörz, personal communication, 1988), and while lava tubes seem well capable of withstanding such a direct shock, similar performance by surface-situated superstructures is difficult to envisage.

Within the large and well-protected interiors of lava tubes, the concerns of material degradation, thermal fatigue, and related exposure problems are moderated or negated, and it becomes possible to utilize a far wider range of materials and electronic devices. The interiors of lava tubes also give direct access to lunar bedrock (a rare condition), and this could be a substantial asset to the operation of heavy equipment, the stabilization of vibrating machinery and scientific equipment, and the founding of structural partitions and building components. It is estimated that the interior temperature of lava tubes remains unaffected by diurnal surface temperature variations, and remains a constant -20°C.

Hörz also mentions a number of possible disadvantages of lava tube basing, most notably the difficulties associated with accessing the tubes, as well as the question of lunar resource distribution and lava tube site selection.

THE PROMISE OF SUBSELENE DEVELOPMENT

From an architectural standpoint, the most profound advantage to be attributed to subselene development concerns the practicality of achieving very large internal environments. It is difficult to conceive any form of human habitation on the Moon—beyond only the earliest outpost bases—that do not provide for very large and even vast volumes of internal space. The permanent transition from terrestrially scaled open spaces to the enclosure of a spatially limited lunar base is simply too much to demand from any human being.

How much space is enough space? In lieu of empirical data on the human need for space in autonomous lunar environments, perhaps the most effective way to appreciate this issue may be by imagining oneself inside a permanent lunar station, confined, where there is no "outside" to escape to. Ultimately, if we cannot answer the need for copious space, it may not be possible for us to adapt to the Moon.

Is confinement to small and unyielding rooms and corridors an acceptable condition in a lunar base? In the context of life on Earth, these conditions would be considered punishing. Even for lunar base volunteers engaged in the most interesting work, dedication and eager expectations may give way to the reality of a very dull and encumbering place. It becomes easy to see how a badly designed and unsympathetic environment can, at the very least, severely weigh on the minds of men and women. The argument for returning humans to the Moon (in lieu of robots) is based on our intrinsic ability to think, to learn, to react, and to be creative—all aspects of humanity that prisons are designed to defeat. Living permanently on the Moon will not be purposeful if we create places that effectively emulate penal institutions.

In time, research may yield some insight into this question of how much space is enough, and we should not be surprised if current expectations prove inadequate. It can be predicted, however, that if provided with essentially inadequate space, long-term lunar inhabitants will—in short order—seek more realistic designs that are not tied to a misconstrued or Earth-biased economy. Looking forward to the real needs of long-term basing, we should seek only those modes of architectural development that are capable of answering this essential need for space. The practical capacity to provide near-term expansive interior volumes seems to exist presently in lava tubes. Considering the limitations of even the largest plausible surface-deployed structures, it is stimulating to consider the architectural potential of a secure natural cavern with the multi-hundred-meter cross sections and multikilometer lengths that Hörz speaks of.

Indeed, if lava tubes are pursued as habitats, an early developmental problem will exist in that many tubes may be too large for practical purposes. Unfortunately, we are troubled because too little is known about the nature of these caverns, and we are forced to speculate about the dimensions of tubes that have defied detection. It does seem reasonable to expect, however, that a wide range of usable tubes will be found, and that modestly sized tubes could be made available for early stages of development. Eventually, larger tubes could be accessed and adapted. Conceivably, the progress of this adaptation could be staged, beginning with a small tube and advancing therefrom. Most importantly, it should be understood that the need for copious interior volumes can be accommodated by exploitation of a natural lunar feature.

Another beneficial aspect of lava tube exploitation involves the degree of internal complexity and variation that is typical of these features. Ironically, some have suggested that this very issue—the relief scale of restrictions and enlargements—is a negative aspect of lava tube deployments since it may inhibit the installation of various technologies, hinder trafficability, etc. From an architectural standpoint, however, this variability can only be viewed as an asset. Related in a sense to the need for copious space is the need for environmental stimulation, and here spatial variation and greater scales of surfacial relief may be seen as features that work to define the environment as an interesting place.

Issues that relate to base morphology and, in particular, the need to vary and revise the form of the base over time, are also well received in lava tubes. With reliance on the surrounding monolith for structure, enclosure, and radiation protection, the number of confounding form-determining factors can be reduced, and the design can be better aimed at the critical functional, behavioral, and political considerations.

We note that the environment within subselene voids is far less threatening than the surface environment and, in a sense, the lunar subsurface is more Earth-like than any other place on the Moon. Furthermore, the basalt mantle surrounding the tube is, in essence, a carvable matrix that can be cut and sculpted into the widest range of architectural forms, such as those suggested in Fig. 2. It is not difficult to imagine the manner in which tube development could proceed: Lava tubes could be enlarged and

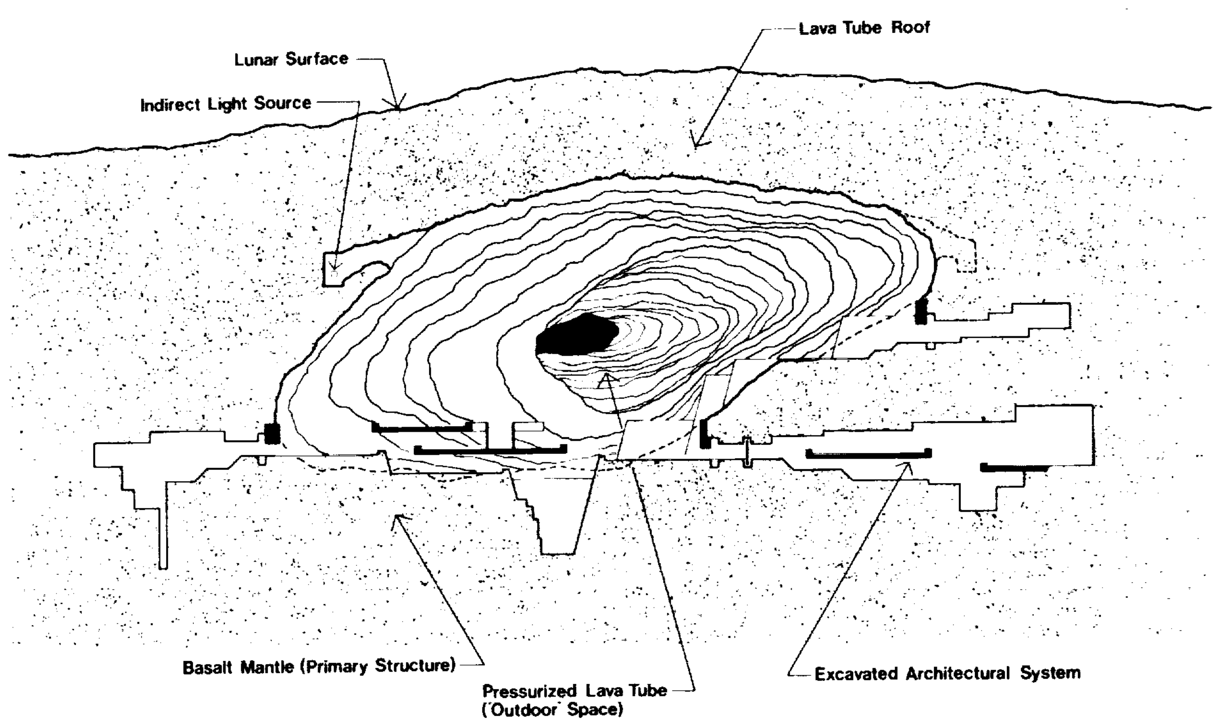

Fig. 2. While lava tubes may be exploited in the initial establishment of a lunar base simply as shelter for other structures, it is also conceivable that, eventually, entire tube segments could be sealed off and pressurized. In this role, the surrounding basalt mantle would provide the primary lunar base envelope. The architecture of the base could be created not only by placing structures within the tube, but also by excavating the tube walls, cutting away stone and creating usable spaces as required. The vast interior of the tube, measuring perhaps several hundred meters in cross section, could provide the spatial volumes and hierarchy necessary for permanent habitation.

reconfigured by the simple removal of material; new cavities could be created and appended to the tube by excavating through tube walls and floor; two or more proximally situated tubes could be connected by tunneling; penetrations through lava tube roofs could also be made, providing direct communication with surface constructions. Significantly, the option to revise, reconfigure, even to abandon particular spaces, would always remain available. It is conceivable that, from a primary lava tube, a virtual labyrinth of spatial successions and hierarchies could eventually be carved out, creating a very interesting place indeed. Traditional apprehensions concerning the high cost of mining and earth-moving put aside, the subselene milieu may well prove far preferable than any open field on the surface.

BUILDING IN THE SUBSELENE MILIEU

Lava tube interiors are far more conducive to a far wider range of construction operations and materials than the surface. We have already alluded to the fact that there are considerable advantages that relate to the performance and range of available construction materials. These advantages relate to the superior thermal and electromagnetic protection provided by the profound situation of tube environment. We can expand on these advantages by considering the possibilities for construction within tube environments, particularly in the case where entire tube segments are pressurized and transformed.

Construction Conditions

Within such a setting, the first great advantage for construction would be the substantially reduced danger to construction workers. Traditional notions of extravehicular activity (EVA) practice and precaution could, with care, give way to far more productive operations, quite possibly even within shirtsleeve conditions. With less need to rely on robots and teleoperation, more time devoted to actual construction, and fears allayed, we could expect dramatic improvements in construction capabilities, as well as related base activities such as mining and manufacturing. In the case of lava tubes used as shelters for habitat modules, EVA construction operations could be practiced with a greater level of safety than could be achieved at the surface.

Masonry Construction

Fully exploited tube segments allow architectural constructions within the enclosure that are adjunctive, and which are not necessarily prescribed by the need to contain atmospheric pressure. Various scales of habitational adaptation and spatial definition within pressurized tubes could indeed be achieved with forms and materials that would otherwise be inappropriate to pressure-differentiated structural skins. Within a pressurized lava tube, it is quite possible that simple masonry construction methods could find wide application. Here is a potential use of largely unprocessed indigenous material (stone) that could go a long way toward the goal of creating a very large and sophisticated environment without competing with other base operations and resources. The use of stone, the Moon's most abundant natural resource, seems to us a rather elegant proposition.

Concrete

The intriguing potential of lunar-sourced calcium cements for base construction has been pointed out by several authors. *Young* (1985), *Cullingford and Keller* (1991), *Lin* (1985), *Lin et al.* (1988), *Nanba et al.* (1988), and *Ishikawa et al.* (1988) are all notable in their discussion of lunar concrete from both experimental and practical views. If cementitious products prove to be viable on the Moon, we feel that there will be no better site for their application than within lava tubes, where environmental moderation during processing, application, and curing is a clear advantage.

Cementitious products may find a very wide range of applications within subselene environments, most notably in the form of concrete. Cementitious pargings may be a practical means of sealing lava tube interior surfaces and cracks. Simply poured concrete mass structures and floor slabs may provide a means of defining areas and reshaping spaces. Reinforced concrete may find great application as a highly adaptable structural system, for use in spanning large areas, and also as a means of partitioning lava tube segments. Given the unpredictable and highly irregular interior of a lava tube, the highly plastic and conforming nature of concrete will undoubtedly prove to be a great advantage.

Fused Structures and Surfaces

Khalili (1985, 1988) discusses the adaptability of masonry-type structures to the lunar scene as he asks us to recall the ways in which vernacular builders have come to rely on these methods throughout history. He also recalls for us a similar methodology whereby stone-masonry constructions can be thermally fused *in situ,* creating mass constructions and even spanning structures of exceptional strength. Such thermally fused mass constructions may find their best application where there is no need for atmosphere containment, and where the availability of cement constituents, principally water, is insufficient. This thermal-fusing technology may also be quite useful as a means of sealing the interior surfaces of lava tubes and excavated spaces, and of giving strength to any masonry construction used within the tube.

Inflatable Structures

Inflatable structures have been proposed for use as lunar habitats by many authors. While this class of structure may offer some advantages as a means of establishing a surface base (particularly in the early phases of development), we would like to mention their possible application in lava tubes. Because access to a lava tube is likely to be difficult, inflatable structures would seem to offer the advantage of improved mobility. If an early capability for subsurface lunar basing is sought, the use of packaged inflatable habitats within lava tubes would seem almost mandatory. The advantages of placing inflatable or nonrigid structures within the protection afforded by a lava tube are substantial, and the combination of these two elements may indeed evolve into a plausible outpost-phase strategy for lunar basing. Figure 3 illustrates the placement of an inflatable structure (as well as space-station-derived habitat modules) within a small lava tube.

Spaceframes

Modular three-dimensional trusses, or spaceframes, are another form of construction that we feel would be particularly well-suited for subselene situations. Spaceframe systems are in widespread terrestrial use, and they are finding growing application in space, where their performance is being studied. (The space station will eventually be structured around a spaceframe truss system.) It is conceivable that lessons learned with spaceframes in low Earth

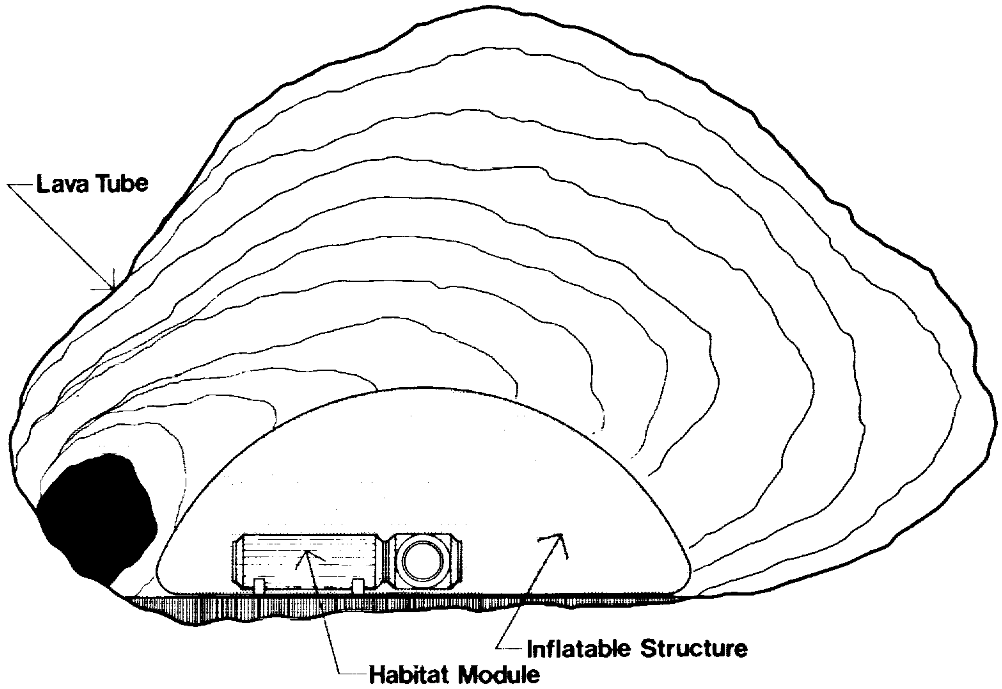

Fig. 3. The placement of habitat modules and inflatable structures within a lava tube may offer significant advantages as a means of base expansion following an initial surface deployment. Structures placed within the tube would not require any radiation shielding, and would not be subject to the thermal extremes normal at the surface. EVA operations and other activities could proceed with considerably less risk. The placement of "packaged" inflatable structures within an open tube may provide the best means of establishing an advanced lunar habitat.

orbit (LEO) may favor their application on the Moon. We are intrigued by this technology for several reasons.

Principally, spaceframes offer an extremely versatile technology for spanning large and irregularly shaped areas. While not moldable in the sense of concrete, spaceframes readily conform to a limitless range of two- and three-dimensional geometries, thereby allowing them to easily adapt to the variable shape of any lava tube or excavation. Spaceframes are versatile enough to be used for both surface and subsurface modes of development, and they represent one of the few practical modes of development that are well-suited to operate in both environments.

The two primary elements that combine to create the three-dimensional truss, the hubs and struts, are easily produced, and may be manufactured from a variety of materials. The source of these materials may be simply transitioned from the Earth to the Moon, without great disruption of construction practice. Spaceframes may be assembled and disassembled repeatedly, and while teleoperated and robot assembly are possible, construction by humans has been simplified to the point where assembly without tools is practical.

CONCLUSION

The purpose of this paper has been to present the authors' belief that subselene lunar basing may provide the most satisfactory and comprehensive solution to the extreme problems posed by lunar architecture. We have elucidated a number of key issues in an attempt to underscore the difficulty that we foresee, and to persuade the reader that a radical architectural solution is essential.

We believe that the development of a time-scaled architectural program is required for any serious future study of lunar base habitation. Using this as the basis for continuing study, various disciplines may begin to compare notes and work toward the eventual resolution of the architecture. Progress toward the definition of the architecture may in turn lead to revised expectations of lunar base potential.

What becomes clear as one begins to view even the most rudimentary version of this program is that the time-honored methods that have yielded our heritage of building structures on Earth (or, for that matter, in LEO) should not be allowed to prejudice our approach to building on the Moon. Certainly the materials and technologies in use in modern construction practice on Earth cannot be easily transferred to the Moon. But more profoundly, the very notion of constructing a "building" on the Moon must be questioned. Subselene development offers the real prospect that our most tenuous early foothold on the Moon may be allowed to evolve into an enduring settlement.

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