IAC-02-Q.4.3.08

SELECTED PRECEPTS IN LUNAR ARCHITECTURE

Marc M. Cohen
Senior Member, AIAA

53rd International Astronautical Congress
The World Space Congress – 2002
10-19 Oct 2002/Houston, Texas

IAC-02-Q-.4.3.08*

SELECTED PRECEPTS IN LUNAR ARCHITECTURE

Marc M. Cohen, Arch.D., Architect
Senior Member, AIAA
P.O. Box 243 Moffett Field, California USA
mcohen@mail.arc.nasa.gov

ABSTRACT

The 1997 NASA Habitats and Surface Construction Roadmap defined three classes of lunar and planetary architecture, ranging from habitats built entirely on Earth to habitats built on the extraterrestrial surface. The definitions are: Class 1 – Pre-integrated, landed complete; Class 2 – Pre-fabricated, assembled, deployed or inflated on the surface; Class 3 – In-Situ Resource Construction.

The extreme environmental conditions on the Moon shape and constrain Lunar Architecture in far-reaching ways. These environmental threats and stressors include vacuum, .18 G partial gravity, radiation, micrometeoroid impacts, the 28-day diurnal cycle, extreme thermal cycling, and pervasive dust. Also, the unique instance of the landing zone poses a human-made potential environmental hazard. The design and development of lunar construction technologies and habitats must respond effectively to these threats. For this reason, developing Lunar Architecture will be challenging and complex.

Although it is reasonable to characterize the individual elements of a lunar base as Class 1, 2, or 3, in actuality, none of them on the Moon (or Mars) would be purely of one class. To explicate this "hybrid" character of surface construction, this paper presents three further units of analysis in architectural design research: taxonomy, typology and morphology.

INTRODUCTION

This paper presents an overview of selected approaches to Lunar Architecture to describe the parameters of this design problem space. The paper identifies typologies of architecture based on lunar site features, structural concepts and habitable functions.

In 1993, Haym Benaroya, Professor of Mechanical and AeroSpace Engineering at Rutgers University edited a special issue of Applied Mechanics Review dedicated to lunar base construction (Benaroya, 1993). In this issue, A. Smith of the US Army Construction, Engineering and Research Laboratory in Champaign, IL proposed a three-phase evolutionary development process for lunar base construction. In Smith's prospectus, these three phases involved

- Prefabricated and pre-outfitted modules;
- Assembly of components fabricated on Earth with "some assembly required!"
- Building structures comprised substantially of indigenous materials (Smith, 1993, pp. 268-271).

In 1996-1997, NASA undertook an initiative to create "technology development roadmaps" for a variety of technical and scientific areas critical to exploration of the Moon, Mars and beyond the inner planets. The NASA Habitats and Surface Construction Working Group adopted a parallel but more sharply focused set of definitions.

TABLE 1. Comparison of three Habitat and Surface Construction Classes, adapted from the 1997 NASA Habitats and Surface Construction Roadmap (Cohen, Kennedy, 1997).

CLASS	DESCRIPTION	BENEFITS
1. Pre-Integrated Hard Shell Module delivered complete to the surface.	A **composite structure** that can be autonomously predeployed and operated on the Moon and Mars surface. Fully integrated. The capability for A.I. smart habitat for failure detection, analysis and self-repair.	High reliability & easy to repair. Near-current technology Add larger modules to ISS and Lunar Orbit
2. Pre-Fabricated Inflatable deployed or assembled structures.	An **inflatable structure** that can be autonomously predeployed and operated on the Moon and Mars surface. Partially integrated and flexible. The capability for A.I. smart habitat for failure detection, analysis and self-repair.	Larger usable habitable volume. Lower mass Higher crew productivity Higher crew moral and quality of life. (Lower stress) High reliability & easy to repair. Taking the steps toward building new civilizations
3. In-Situ Resource Construction Lunar concrete ("Lunacrete"), Masonry, In-situ vitrified caves, drilled tunnels or lava tubes.	An **ISRU-derived structure** that is manufactured using indigenous resources and constructed autonomously. It is autonomously operated and maintained utilizing A.I. and V.R. The capability for A.I. for failure detection, analysis and self-repair.	Least requirement for materials from Earth per usable habitable volume. Can build colony infrastructure to support sustained human presence and evolution. Self Sufficiency from Earth Higher level of society. Ability to manufacture, service and repair

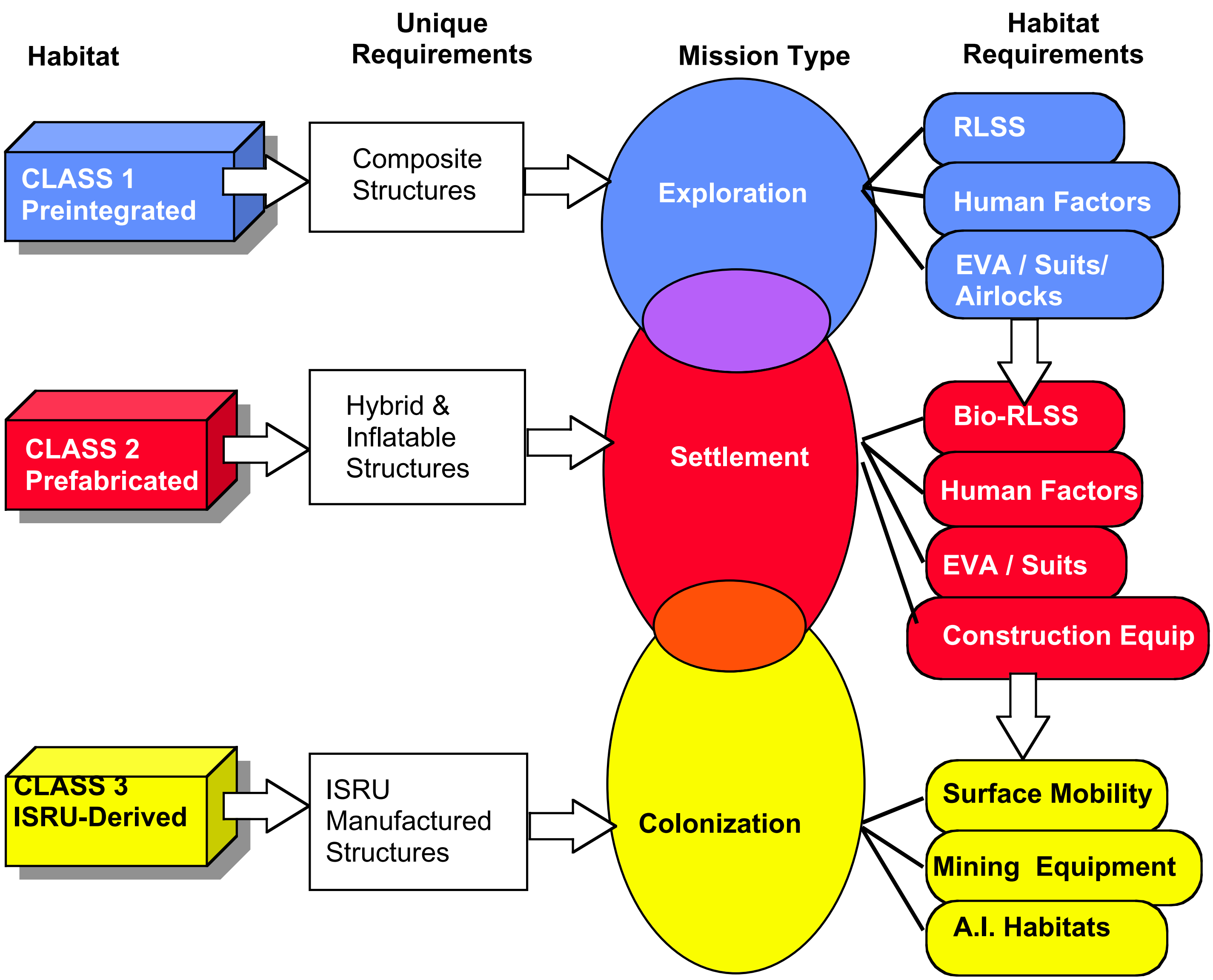

FIGURE 1. Surface Habitats and Construction Roadmap: Diagram of Three Classes of Lunar/Planetary construction and their application to progressive stages of development.

This paper develops an analysis of Lunar architectures based on the NASA Habitats and Surface Construction Road Map (1997) in which there are three major types of surface construction: Class 1) Pre-integrated, Class 2) Pre-fabricated --Assembled, Deployed, Erected or Inflated and Class 3) Use of In Situ materials and site characteristics. This set of definitions and their correlation to phases of lunar and planetary construction appear in FIGURE 1.

LUNAR DEVELOPMENT

In an ideal universe, the development of lunar bases, settlements and colonies would follow a path that corresponds in some way to the Habitat and Surface Construction Roadmap. Lynn Harper and Kathleen Connell of the

Advanced Life Support Division at NASA-Ames Research Center proposed a development scenario that suggests just such a parallel course. In their triad, the first step is to construct suitable artificial environments that provide not only life support, but also the amenities to promote health, well-being, productivity and crew acceptance of living in "a radically different environment for very long periods of time." The second step is to upgrade the artificial environment to the degree that crew members will be willing to "spend their lives and eventually bear and raise children" there. Third and finally, the settlement achieves self-sufficiency and growth through the use of in situ resources to regenerate consumables. "The Lunar Outpost component of SEI will provide the setting and drivers necessary to determine how these three conditions can be attained" (Harper, Connell, 1990, p. 2).

Class 1 Architectures include the following. The Apollo Program was intended to extend to a 14-day base in enhanced Lunar Excursion Modules. The Air Force was the first to propose pre-integrated cylindrical modules landed on the lunar surface (Richelson, 2000, pp.22-27). The University of Wisconsin proposed building a module and hub system on the surface. Madhu Thangavelu proposed assembling such a module and hub base in orbit and then landing it intact on the moon (Thangavelu, 1990).

Class 2 Architectures include: The NASA 90 Day Study proposed an inflatable sphere of about 20m diameter for a lunar habitat (Alred et. al., 1989). Jenine Abarbanel of Colorado State University proposed rectangular inflatable habitats, with lunar regolith as ballast on the flat top (Abarbanel, Criswell, 1997).

Class 3 Architectures include: Lunar masonry, concrete, caves, vitrified-in-situ structures, and other use of natural lunar landforms. Alice Eichold proposed a base within a crater ring (Eichold, 1996).

Further analysis shows that the development of any lunar or planetary base will necessarily involve all three types of construction, although perhaps in ways that are both not obvious and perhaps too obvious. The paper presents a comparative characterization and analysis of these and other examples paradigms of proposed lunar construction. It evaluates both the architectures and the NASA Habitats and Surface Construction Road Map for how well they correlate to one another.

This paper draws upon two general references – Cohen and Kennedy, (1997) "Habitats and Surface Construction Technology Development Roadmap," and Benaroya, (2002) "An Overview of Lunar Base Structures: Past and Future." Prof. Benaroya presents his review in the AIAA Space Architecture Symposium on October 11, 2002, the same day as this paper in the Lunar Development session at the World Space Congress in Houston.
This analysis shows the necessity of addressing the major environmental threats and stressors in the lunar (or planetary) environment that affect habitable architecture. An effective, reliable and safe strategy for dealing with these threats requires multiple responses. These multiple responses inform the design process and products for lunar architecture.

LUNAR ENVIRONMENTAL CONDITONS

To accomplish Harper and Connell's lofty goals, the lunar architecture must overcome the threats to health, life and safety from the extraordinarily hostile environment. These external environmental stressors will play a critical role in shaping lunar architecture, just as environmental forces shape architecture on Earth (Fitch, Bobenhausen, 1999), but to a far more radical degree. On the Moon, these threats include vacuum, radiation, micrometeoroids, extreme thermal cycling and partial gravity

While the architect recognizes the primacy of structure in building pneumatic habitats in such an extremely hostile environment as the moon, the architect is also acutely aware that each countermeasure against these threats imposes an effect upon the crew quality of life. Fujii, Midorikawa, Shiba and Nitta (1990) present these key needs as: food, clothing, housing, communication, and mental and physical requirements. They correlate these functions across three dimensions: *basal life, passive pursuits, and active pursuits*. In the following discussion of environmental threats, it is possible to see the role that construction techniques, materials, and other design considerations will play in shaping the quality of life in a lunar base.

Vacuum

All habitable space architecture is pneumatic, in which a pressure vessel contains a substantially higher pressure than exists outside it. On the moon, this vacuum is near absolute (on Mars it ranges from about 6 to 12 millibar). This pneumatic shell may be rigid or it may be inflatable. In either case, it will flex in response to changes in temperature and pressure. Interior outfitting must take this elasticity into account and handle the constraints that it imposes in connecting interior secondary structure to the primary structure wall, whether it is rigid or inflatable, but especially if it is inflatable. Note that in the TransHab prototype (Kennedy, 1999), all the secondary structure attaches to the axial core; none of it makes a connection to the inflatable shell that transfers loads such as shear or bending moment. The lunar habitat requires a life support system to provide the artificial atmosphere inside, and regular, ongoing air revitalization to remove CO_2 and to replenish the O_2.

The necessity of providing life support to sustain the crew in a lunar habitat and base means that the life support discipline plays a major, all-pervasive role in determining the quality of life at the lunar base. The atmospheric regime drives the life support system, perhaps more than any other factor. However, the life support system encompasses much more in the total "operating system" for a lunar base. Ferrall, Ganapathi, Rohatgi and Seshan at the Jet Propulsion Laboratory (1994) used the NASA-JPL Life Support Systems Analysis (LiSSA) software tool to perform a comprehensive life support and power economy modeling of a lunar habitat. Their model consists of three "baseline system definitions:" metabolic load basis, hygiene load basis, and baseline system configuration (Ferrall, et. al., 1994, pp. II-1 – II-4).

These load bases are significant. The metabolic load derives linearly from the number of crew members and the intensity of their activities, and it drives the sizing of the air revitalization system in particular, almost independent of total atmospheric volume. Hygiene load refers to the water necessary for washing and showering, which typically larger that the amount needed for drinking water or for preparing dehydrated foods. When the design of habitability systems includes washing machines, this hygiene load will increase substantially.

In situ resource utilization can play a role in providing life support consumables to produce water and air. Mike Duke, then at the NASA Johnson Space Center lunar and planetary exploration program predicts that "oxygen will probably be the first material produced on the Moon," primarily as a constituent of rocket fuel (Duke, 1994, p. 1). However, O_2 has obvious application in a life support system as well.

.18 G Partial Gravity

Perhaps the most obvious architectural attribute of the moon environment is the reduced acceleration of gravity, which at .18 G constitutes about 1/6 of the gravity on Earth. One might expect that this difference in gravity might translate into a difference in the forces ($F=Ma$) that lunar structures must resist. Unfortunately, for both Class 1 and Class 2 structure, there appears to be relatively little benefit in reducing the mass of structures for several reasons. First, all habitable architecture is pneumatic, so the atmospheric pressure to contain rules the design of pressure vessels. Second, all structures made on the Earth and transported to the moon must be sufficiently robust to resist launch loads. Third, when considering the use of layers of regolith to provide radiation shielding, there is a deadload mass to support considerably greater than the conventional roof deadloads found on Earth.

The presence of substantial gravity on the moon – even at 1/6 G -- poses one potential advantage over a microgravity environment. The lunar gravity field will allow the use of conventional fluidized beds for life support systems and contaminant filtration, which are not feasible on the International Space Station. The use of fluidized beds may help to reduce the cost and complexity of some life support systems.

The partial gravity regime also has an effect upon crew mobility, namely their ability to move and to travel over the lunar surface, and within the lunar base or habitat. What architectural considerations follow for the design of a habitat interior remain to be seen. However one early observation by Celantano and Amorelli of North American Aviation, builders of the Apollo Command and Service Modules is notable: "Design requirements specifically must consider this ease of motion and involve safety provisions" (Celentano, Amorelli, 1965, p. 747). Dava Newman of MIT led a team that investigated perambulation under varied gravity regimes in a neutral buoyancy water tank, and found significant differences in locomotion among the several regimes (Newman, Alexander, Webbon, 1994). Egons Podnieks of the US Bureau of Mines sounds a note of caution about the affect of lunar gravity on construction equipment and operations:

> The lunar gravity, being only one-sixth of Earth gravity, causes different dynamic conditions for equipment movements and operation. Stability of human and robot movements would be impaired, and tall equipment could easily topple when lateral loads are applied (Podnieks, 1990, p. 7).

By inference, one can expect similar effects of lunar gravity upon other activities besides mining, including construction, soil or regolith moving, and other machine activities.

Radiation

Radiation exposure is THE SHOWSTOPPER for lunar or planetary exploration missions that do not make a realistic assessment of this hazard to health and safety. While research on radiobiological damage is still ongoing, there are very grave concerns for effects upon astronauts. The actual exposure in space may reach 7 times the Earth allowable.

This radiation data shows that the regolith covering on a lunar habitat should probably be at least double the 50 cm used in the above analysis. For a Class 1, pre-integrated habitat, it will be extremely difficult to bring a mass of that size to the lunar surface as shielding.

Simonson, Nealy and Townsend at NASA-Langley Research Center make a prescient observation in concluding the discussion of the difference between prefabricated versus in situ radiation shielding:

> Lunar regolith still appears to be an attractive option for radiation protection for the habitat configurations considered in this analysis. However, if much smaller habitats are selected, then the mass of the regolith-moving equipment may approach the mass requirements of pre-fabricated shields launched from Earth. One of the major trade-offs will be the EVA time requirements, EVA risk, and the reliability of the regolith moving equipment. If it is deemed necessary to provide a flare shelter while the habitat is being covered, a viable option appears to be polyethylene or water (Simonson, Nealy, Townsend, 1992, p. 1355).

This analysis leads to the assessment that the Class 1 pre-integrated structures will almost certainly need to include their own radiation shielding. While in situ production of regolith as a form of shielding seems attractive in some respects, other materials present some significant advantages. Water, for example, is amorphous, and it would be possible to bring water shielding to the Moon separately from the habitat itself, and then pump the water into internal shielding tanks (Cohen, 1997, pp. 6-7). For Class 2 prefabricated structures, radiation shielding appears to delineate a trade space involving regolith such as Simonson et al describe above, water or externally applied polyethylene panels. For Class 3 structures, the use of in situ regolith for shielding is clearly consistent with the construction technology.

For the crew living in the Mars habitat, the fact that there is comprehensive radiation shielding presents implications for crew well-being and quality of life. Constance Adams discusses this issue within a buried habitat:

> Unlike the microgravity facilities, a Lunar or Mars habitat may be expected to be buried under a meter or more of soil for radiation protection. Designing Crew Quarters for a planetary habitat therefore involves taking into account the problem of how to mitigate claustrophobia without the benefit of windows. In the BIO-Plex HAB chamber [at NASA-Johnson Space Center in Houston, TX], strategies are being investigated for compensating for he lack of outside views which include the integration into partitions of flat-panel monitors which function as "Virtual Windows" as well as planning for upper-surface penetrations for optic-fiber light "straws" to draw external sunlight into light baffles designed to reflect that light into many interior spaces (Adams, 1998, p. 11).

Micrometeoroids

The lunar surface is exposed to a steady flux of micrometeoroid particles in a range of sizes and densities. Vanzani, Mazari and Botto (1997) analyzed the NASA Long Duration Exposure Facility results to extrapolate the micrometeoroid flux hitting the lunar surface. Their findings were dramatic. From their results, they predict a lunar meteoroid flux two to three times larger than previous estimates, indicating a larger risk of meteoroid impact – and collision damage -- on the lunar surface. They state:

> As an example, a surface of about 150m^2 located on the moon is hit, on average, by one micrometeoroid larger than 0.5 mm in diameter per year: a projectile that size, impacting with an average velocity of about 13 km/sec, excavates in aluminum alloy material of an hypothetical lunar basis structure a crater with diameter larger than about 1.8 mm and depth greater than about 1 mm. . . ..
>
> The actual risk to critical structures exposed on the Moon is difficult to estimate, but the flux of meteoroids represents a significant hazard and requires proper protection to critical structures — habitats, base support facilities, processing plants or research instruments, especially optical systems and detector packages—that are expected to last on the lunar surface for many years (Vanzani, Mazari, Botto 1997, p.2).

Vazani, et. al.'s findings should influence the design of lunar structures. Beyond this level of analysis and prediction also, it may well become necessary to predict larger impact collisions, much as the US Army Corps of Engineers makes predictions for 10 and 100-year floods. The risk assessment challenge will be to determine what is an acceptable level of risk to take in terms of the consequences of a structural failure.

28 Day Diurnal Cycle

The fact that the extreme thermal cycling on the Moon take place over a 28 day cycle, with 14 days of intense sun and 14 days of deep, dark cold, has direct implications for the performance and quality of life for the human crew. The most obvious example is the discrepancy from the normal 24 hour day night cycle and its relation to normal sleep and wakefulness cycles. Beyond this difference is the fact that the cycle will affect the availability of power, feasibility of EVA and other operations in the darkness. The difference between day and night operations poses a variety of safety and reliability questions.

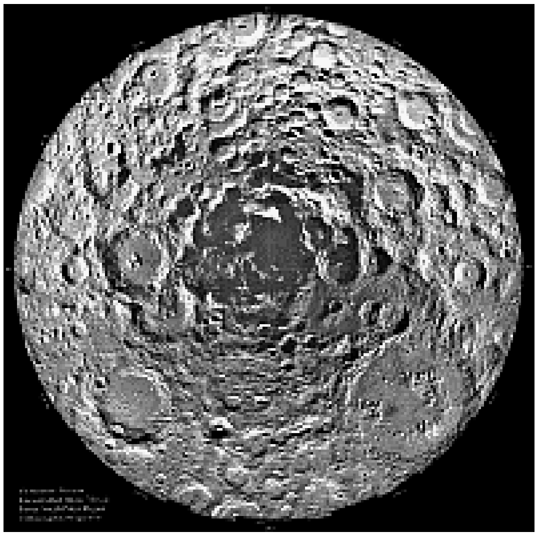

FIGURE 2. Clementine (1996) view of the Lunar South Pole (courtesy of NASA-GSFC). http://nssdc.gsfc.nasa.gov/planetary/ice/ice_moon.html

The 28-day cycle also tends to drive site selection for a lunar base. There have been numerous proposals to locate a lunar base at one of the lunar poles so that it can receive a constant and abundant solar energy source. In addition, the Air Force's *Clementine* mission detected an apparent abundance of water ice. Subsequently, the NASA-Ames *Lunar Prospector* confirmed this discovery and found even more indications of ice at the North Pole. These discoveries increased the incentives to situate a lunar base at the poles.

The NASA Space Science Data Center reports (NSSDC, 2002):

> Much of the area around the South Pole is within the South Pole-Aitken Basin, ... a giant impact crater 2500 km (1550 miles) in diameter and 12 km deep at its lowest point. Many smaller craters exist on the floor of this basin. Since they are down in this basin, the floors of many of these craters are never exposed to sunlight. Within these craters the temperatures would never rise above about 100° K.

However, the extreme ruggedness of the terrain and extreme cold are a disincentive for construction. Very low temperature effects include the possibility of material embrittlement and brittle fractures in structural members (Benaroya, Bernhold, Chua, 2002, p. 2). Because of the extreme depth of this ice, any lunar base that intended to take advantage of the constant sunlight would need to perch along with its solar collectors atop one of these crater rims. Building a base on top of such rugged terrain poses a host of issues such as how to land a propulsive vehicle on it, how to unload it, and all the other practical considerations of a construction project in difficult terrain.

Thermal Cycling

The thermal environment on the moon poses challenges to the design of lunar architecture at several levels. At the base-scale "macro level" the 28 day day/night cycle demands even and efficient performance under the extremely different conditions of Lunar day and Lunar night.

From the structural perspective, these severe temperature swings pose the threat of structural and material fatigue, especially for exposed structures (Benaroya, Bernhold, Chua, 2002, p. 2). This temperature stress suggests that the external materials for lunar habitats and bases must provide a thermal buffer to protect the structural members from failure.

Walker, Alexander and Tucker of NASA Marshall Space Flight Center describe "special problems" for lunar thermal control:

> Some types of lunar facilities will have unique thermal control requirements, which restrict the techniques available to the thermal designer. .
>
> Lunar bases with a long-term human presence (90 days or more) present a very challenging thermal control problem. Typical concepts propose power levels of 12 to 30 kW, which means that a great deal of waste heat must be rejected.

A significant part of coping with the thermal cycling involves thermal stability in the form of heat sinks or storage. Thomas Sullivan of the NASA Johnson Space Center suggests an ISRU heat sink/energy storage for the long lunar night. Specifically, he proposes cast basalt blocks. His concept would require no moving parts except a fan to circulate air around the blocks, which are spaced apart to maximize the heat exchange surface area (Sullivan, 1990, pp. 6-7).

During the day part of the cycle, the thermal regulatory system faces the opposite problem from the night cycle – rejecting waste heat. Walker, Alexander and Tuck address this issue.

> Solar power may be used to supplement other power generation methods, so peak heat rejections occurs during the lunar day. In addition, dust accumulation on thermal control surfaces is very likely. (Walker, Alexander, Tucker, 1995, pp. 30-31).

Keller and Ewer (2000) confirm the above concern about dust impinging on lunar base thermal control systems. They modeled dust on horizontal and vertical radiator surfaces, and also on a "parabolic shade." They recommend that any heat rejection system be located at least 1 km from any landing zone, because "lunar dust accumulations can drastically alter the thermal performance of those systems that have either secular, low absorptivity or low emissivity surfaces" (Keller, Ewert, 2000, p. 7).

Thermal control on the moon will also emerge as an issue on the "micro level" of the individual EVA-suited astronaut. Victor Koscheyev, MD, a former Soviet cosmonaut who now conducts physiological/thermal research at the University of Minnesota and his team report issues of uneven heating and cooling in both a space suited exposure during EVA and during IVA. In some cases, mainly EVA, where one side of the suit is in sunlight and the other in shadow, prolonged exposure can create stresses on both the portable life support system and the crew member's metabolic thermoregulatory system. However, in the area of IVA, microlevel thermal environment, Koscheyev et al report benefits from changeable thermal environments (Koscheyev, et al, 1996).

FIGURE 3. Apollo Astronaut Edwin "Buzz" Aldrin with gray lunar dust clinging thickly to his boots and his knees. Note how desolate the lunar landscape appears in this photo. Credit NASA SP-350.

Ironically, the most thermally stable areas on the Moon may be the coldest places – the deep craters at the poles. The floors of these craters have been in shadow since they were created by impacts. Ice in these craters could be billions of years old, promising a potential scientific bonanza. Whether it would be economic or practical to extract this water for consumption is an entirely different question because at a 1 to 2% concentration, the ice would constitute a very low grade ore that would require considerable equipment and processing. Even if it proves technically possible to extract water from this ice for life support consumables or fuel, due to the extreme cold and difficult access, such a use is probably very far in the future.

Dust

The extreme thermal cycling creates the deep dust on the lunar surface as the constant thermal cycling breaks regolith and rocks into smaller and smaller particles. Dust is perhaps *the ubiquitous* problem on the moon, as it will tend to get in everywhere and to cover everything. The lunar dust is highly abrasive, and can cause problems not only for thermal control emissive surfaces, but also for hatch seals and mechanisms, EVA suits and systems, and many other types of equipment. Judith Allton and Howard V. Lauer, Jr., of Lockheed Martin Corporation at the NASA Johnson Space Center Lunar Lab reported on the Apollo experience:

> The Apollo experience indicated that in a low-gravity, vacuum environment dust traveled easily from the surface and adhered ferociously to equipment. Four of the 12 Apollo rock boxes did not seal adequately (Allton, Lauer, 1991, p. 313).

FIGURE 3 shows a NASA photo of Buzz Aldrin, Apollo astronaut, taken by Neil Armstrong, with lunar dust clinging thickly to his boots and knees. The design of a lunar habitat or base must present some effective and pro-active measures to mitigate dust intrusion, degradation of equipment and other effects. Other Apollo astronauts returned from EVA on the lunar surface with the legs of their space suits completely coated in the dark gray dust.

Landing Zone (LZ) Safety

Keller and Ewert's recommendation above that the base should be at least one km from the LZ because of the dust that landing or take-off would kick up raises the larger question of transportation safety. In this respect, the LZ represents a "human-made" potential environmental hazard. The concern is what would happen if a vehicle crashed on landing or exploded on launch? Given the low lunar gravity, the shrapnel from such an impact or explosion could travel considerably farther than the same accident on Earth. Benaroya, Bernhold & Chua comment on the ejecta from such a propulsive event:

> Keeping in mind that a particle set in motion by the firing from a rocket from a lander could theoretically travel halfway around the Moon, the effects of surface blasting on the Moon would be something to be concerned about. (Benaroya, Bernhold, Chua, 2002, p. 3).

Note that this comment applies in the first instance to a normal landing or launch without an accident. The effects of an accidental crash or explosion could be far more severe. It suggests that the design of any Moon base or habitat must situate it at a considerable remove from the LZ. It also suggests that substantial shielding at the base site would be prudent.

The further implication of LZ safety is that once a payload lands in this designated area, it will be necessary to move it overland to the base site. It would not be safe to leave these payloads in the LZ where normal ejecta could damage them. How to move this habitat or payload mass is a topic that will require extensive further study, especially over the unprepared lunar surface. The first order issue is probably whether to make the habitat self-mobile such as walking, or to provide a tractor to pull it on wheels. Other concepts include off-loading a module from a lander platform and moving it on a different vehicle to the base site.

ASSESSMENT OF THE CONSTRUCTION CLASSES

The preceding discussion should show at the very least that lunar construction is a challenging and complex undertaking. Many of the environmental threats or constraints interact among themselves in sometimes surprising and difficult ways. Also, the initial 1997 NASA Habitats and Surface Construction Roadmap encounters the same complexity. As a result, few of the construction and structure types will be purely a product of one "class." Instead, they suggest a matrix of interactions that appears in TABLE 2. In this table, each class of construction intersects the other classes, as well as themselves to reveal the richness and diversity of potential outcomes.

TABLE 2 reveals two characteristics of lunar architecture. First, the three classes articulated in 1997 offer insufficient detail to cover all the possibilities. Second, there are additional properties and qualities of architecture that the taxonomic classification approach does not address. Since the introduction to this paper dwelled upon classification, the discussion will move on briefly to typology and morphology before returning to a deeper examination of architectural taxonomy.

Typology

Each class of structure serves a diversity of purposes; as such it takes on a variety of building types. ***Architectural typology*** derives from the functional and social origins of these purposes and their significance in the operation of the living and working environment. The typology is independent of form (morphology).

The typology of lunar base functions include the habitat; laboratory; EVA assess facility including airlock; the pressurized rover as an augmentation of the habitable environment; connecting tunnels or nodes; and outer protective shells. In addition, the lunar base would include building types for a green houses; in situ resource generating plants; scientific sample cataloging and storage facility;

Morphology

Morphology is the science or study of form. ***Architectural morphology*** pertains to how building types and structures take on the *shapes* that serve their purposes. It is not the purpose of this paper to convey a dissertation on all the possible forms of lunar architecture. Rather, it is necessary only to make a few salient points about the form of lunar facilities. The two most common forms of Class 1, hard pre-integrated modules are the ISS derived "long module" and the squat "tuna can" module. The most common forms of Class 2, deployed pre-fabricated modules are inflatables, notably the dome or sphere and the long "sausage shape." The most common ideas of Class 3 in situ construction are the lunar concrete or masonry dome or vault structure. The use of caves, bored tunnels or lava tubes to receive Class 1 or Class 2 habitat liners rather begs the question of shape and size. Whether the inflatable fits the cave or the cave fits the inflatable will be a field engineering decision.

Taxonomy

The three classes of habitats and surface construction constitute what is essentially taxonomy of structures. ***Architectural taxonomy*** pertains to the top-down view of how habitats are constructed, taking into account the classification of materials, structures and techniques.

CLASS 1. PRE-INTEGRATED

1.1. Hard Module, integrated completely on Earth, may be metal or composite.

- 1.1.1. ISS derived long module
- 1.1.2. Tuna Can
- 1.1.3. Spherical or hexagonal node

1.2. Inflatable Module, integrated completely in LEO, then landed on the Moon.

- 1.2.1. TransHab "Fat Tire" module
- 1.2.2. Other module

1.3. Completely pre-integrated lunar base, landed fully assembled, such as MALEO.

CLASS 2. PREFABRICATED, DEPLOYED OR ASSEMBLED.

2.1. Mobile module

- 2.1.1. Move it away from the LZ
- 2.1.2. Pressurized Rover as a contingency habitat.
- 2.1.3. Mobile Base Concept – the whole base moves like a caravan.

2.2. Deployed on surface

- 2.2.1. Inflatables
  - Transhab
  - Abarbanel & Criswell
  - FLO Sphere
  - Long "sausage" module
- 2.2.2. Telescoping or other expanding modules
- 2.2.3. Assembled Modules—move elements together on surface to form a base ensemble.

CLASS 3. IN SITU RESOURCE CONSTRUCTION

3.1. Use of Natural Features.

- 3.1.1. Lunar surface provides de facto shielding.
- 3.1.2. Cliff, steep crater wall or other vertical feature provides an additional increment of shielding.
- 3.1.3. Surrounding natural elements.
  - Natural cave
  - Lava tube
  - Other natural feature
- 3.1.4. Bored or drilled shelter.
  - Cave in cliff face
  - Tunnel through crater rim

3.2. Processed In Situ Materials

- 3.2.1. Minimally processed "raw" regolith, bagged and set upon a habitat.
- 3.2.2. Maximally processed concrete or masonry.
- 3.2.3. Vitrified in place cave, tunnel, concrete or masonry structures.

TABLE 2. Matrix of Classes of Habitats and Lunar/Planetary Structure

PRIMARY CLASS STRUCTURE	SECONDARY CLASS STRUCTURE		
	PRE-INTEGRATED	PREFABRICATED	IN-SITU
PRE-INTEGRATED	"Tuna Can"/Node ISS Long Module ISRU Fuel Plant EVA Access Module Power System	"Tuna Can" with node or flex-docking tunnel. Inflatable expansion of a hard, pre-integrated module.	Regolith packed on a hard module for radiation and micrometeoroid protection. Location on lunar/Mars surface affords a measure of protection. Location adjacent to high cliff face or crater wall may add protection
PRE-FABRICATED	Inflatable with Pre-Integrated Safe Haven, Telescoping Modules with Pre-integrated nodes.	Inflatable dome or sphere with flex tunnels or telescoping modules.	Regolith packed on an inflatable or telescoping module for radiation and micrometeoroid protection. Inflatable in a crater, surface depression, cave, or Lava tube.
IN-SITU	Concrete from regolith Masonry Vault or cave with a hard, Pre-integrated module inside.	Concrete shell, Masonry vault or Lava tube with an inflatable, pressurized habitat liner.	In Situ vitrification and pressure sealing of cave, bored tunnel, or lava tube with concrete or masonry pressure bulkheads.

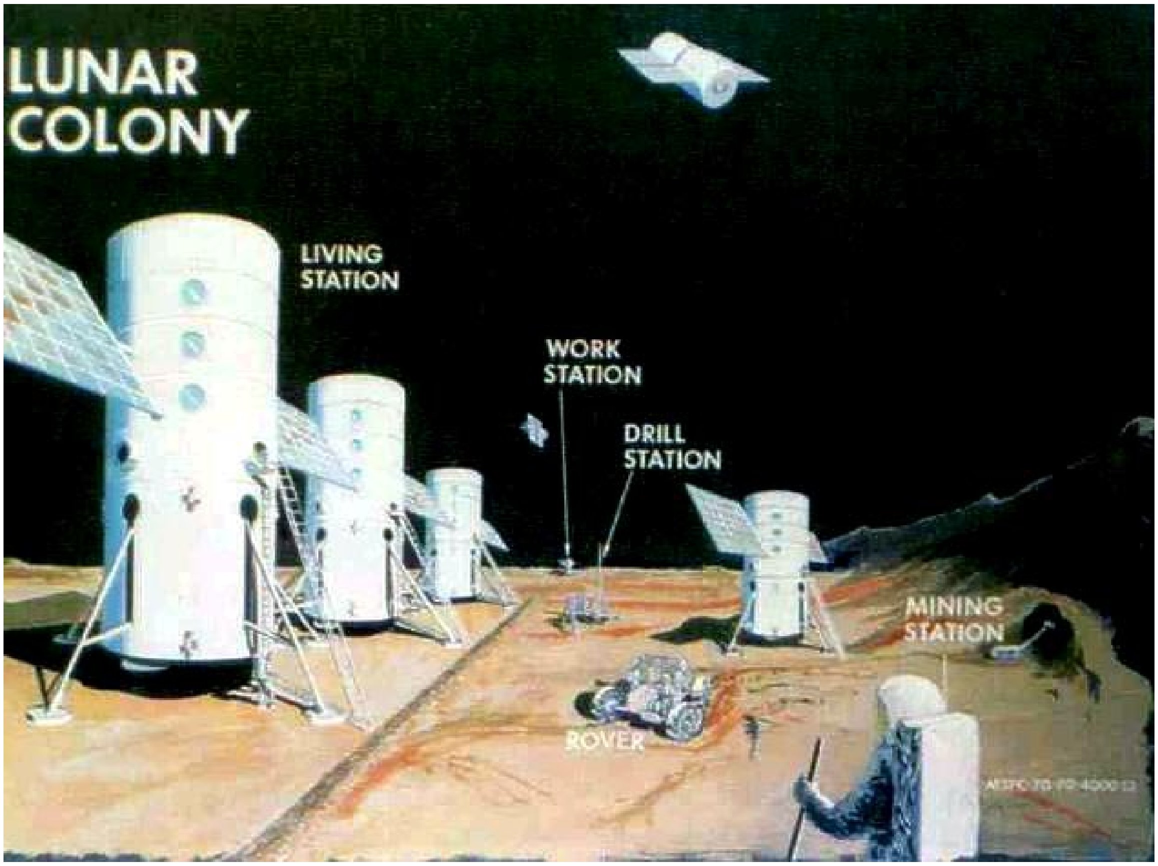

FIGURE 4. Early NASA Concept for a Post-Apollo temporary Lunar Base, using all Class 1, pre-integrated lander – hard modules. Credit NASA Marshall Space Flight Center.

ILLUSTRATED NARRATIVE

This narrative describes the key features that emerge from the architectural taxonomy of lunar construction. It is not intended to be comprehensive, but rather to highlight the salient points in this assessment.

CLASS 1

FIGURE 4 shows an early concept for a post-Apollo temporary lunar base, featuring the multiple, near-simultaneous landing of several vehicles that serve as lunar surface habitats or "living stations." There is no attempt to link them together with pressurized connectors so that the crew may visit in a shirtsleeve environment. The difficulty of always needing to don a space suit and cycle through an airlock, and then climb down the very long ladder to do anything outside the habitat lander soon became readily apparent. The unpressurized lunar rover seems to provide a taxi service among the habitat modules and the "work station" and "drill station" which are clearly an EVA enterprise. There are many apparent potential safety problems: landing the habitats so close together; having to carry a sick or injured crewmember up the long ladder to return him or her to safety in the pressurized cabin; and the lack of any pressurized emergency egress from the habitats.

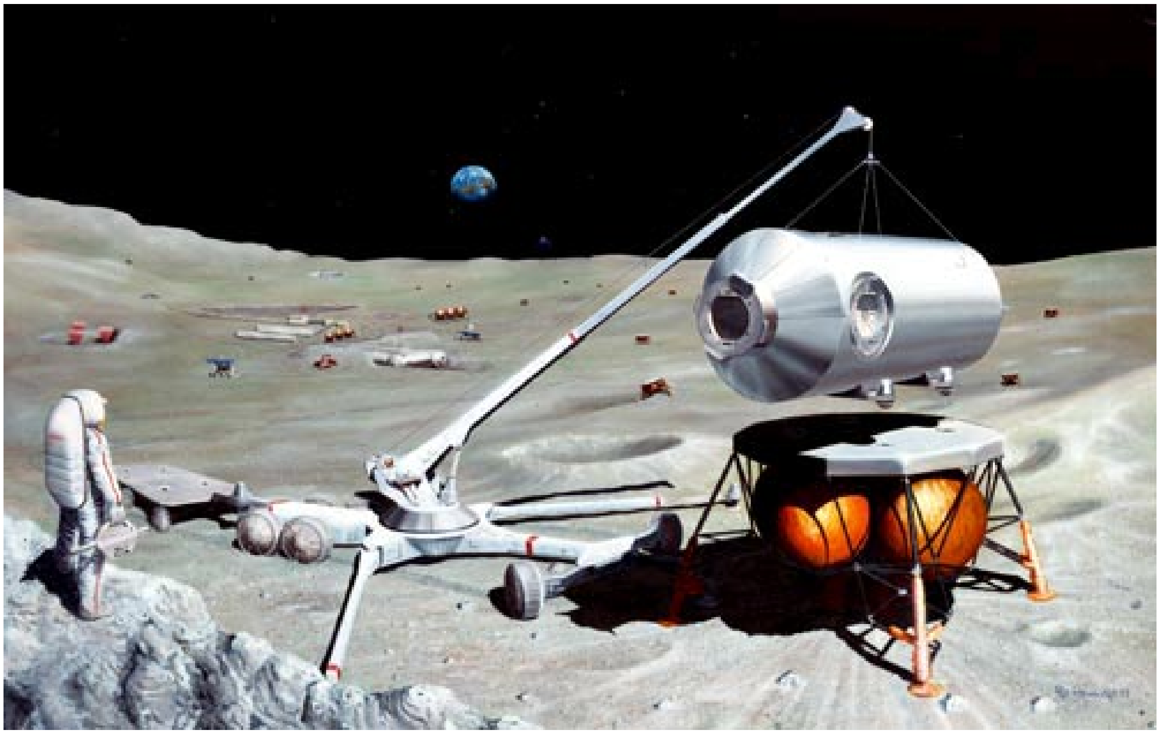

FIGURE 5. 1992 joint study by McDonnell Douglas (USA) and Shimizu Corporation (Japan) using the Artemis Lander concept. Courtesy of NASA-Johnson Space Center.

FIGURE 5 shows a design concept that derives from NASA's First Lunar Outpost (FLO) study. In this drawing, the EVA crewmembers are using a crane to unload a habitat module from the Artemis, multipurpose cargo lander before placing it on a flatbed transporter for transportation from the LZ to the Moon Base area.

The flatbed vehicle will move the habitat module to the lunar base in the background to the left, a distance that appears on the order of a kilometer. This arrangement solves the safety problems of setting up and living in the habitat modules right where they land in the LZ. However, in order to make this movement of cargo and modules possible, the crew needs an infrastructure of cranes and transporter vehicles. Neither the crane nor the flatbed appear to have pressurized crew compartments, which while it reduces the cost also limits the utility of these pieces of equipment.

FIGURE 6. Fully pre-integrated Class 1 MALEO lunar base arriving at the moon.

Credit: Madhu Thangavelu

FIGURE 6 shows Madhu Thangavelu's MALEO concept: Modular Assembly in Low Earth Orbit a creative solution to the problem of assembling a fully integrated lunar base. In this concept, the architect recognizes the significant cost of landing a Class 1, pre-integrated base piecemeal on the lunar surface. In fact, the necessity of assembling, deploying and integrating the modules and other elements on the Moon undermines the main benefits of the entire Class 1 pre-integration. Thangavelu, who teaches Space Architecture at the University of Southern California, found that it would be far less complex and costly to assemble the lunar base in Low Earth Orbit, and then inject it on a cislunar trajectory. The entire base would land in one piece.

For a pre-integrated lunar architecture, this design offers these advantages:

- Avoids the need to move the modules one at a time from the LZ;
- Eliminates the cranes, transporters and other mobility equipment necessary to move them;
- Saves the time, delay, expense and labor necessary to assemble all the components on the lunar surface, and
- Prevents dust intrusion at the critical module-to-module connections.

The MALEO assembly operation in LEO is lower energy, lower mass and cleaner than on the lunar surface. It is also possible to take advantage of existing ISS crews to perform much of the work, thereby saving the need to send a construction crew to the Moon who would need to live in a different, temporary habitat.

CLASS 2 Prefabricated, Deployed Habitat

FIGURE 7a and 7b show a Class 2 Lunar Return Habitat (LRH) designed by Kriss Kennedy at NASA-Johnson Space Center. FIGURE 7a shows the LRH as landed before any of its components are deployed or inflated. FIGURE 7b shows the LRH fully deployed, with the “accordion” type bellows habitat pressure vessel fully inflated. Note also the deployment of other elements such as the antenna and stair ladder.

The key attributes of the Class 2 habitat are that all components are manufactured on Earth and launched in a stowed configuration. Upon arrival on the Moon, the remotely operated or autonomous deployment system prepares the Class 2 habitat for use by unstowing, unfolding, assembling, erecting deploying or inflating the habitat – or by taking some combination of all these actions, probably as incremental steps.

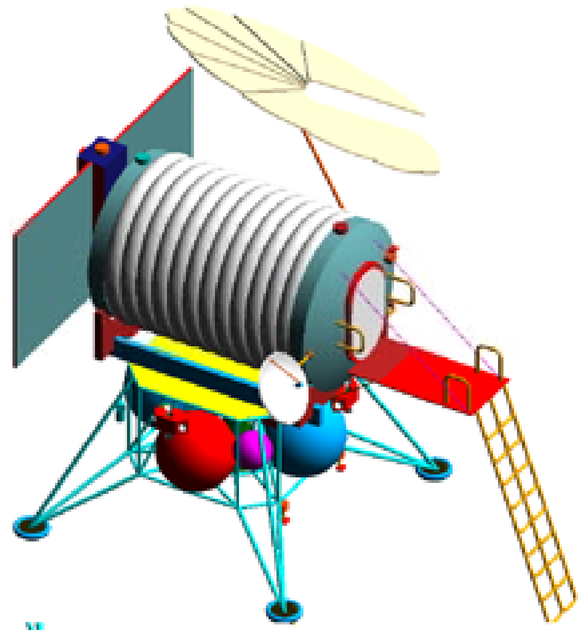

FIGURE7b. Lunar Return Habitat in deployed and inflated position for use on the lunar surface. Credit Kriss Kennedy, NASA-JSC.

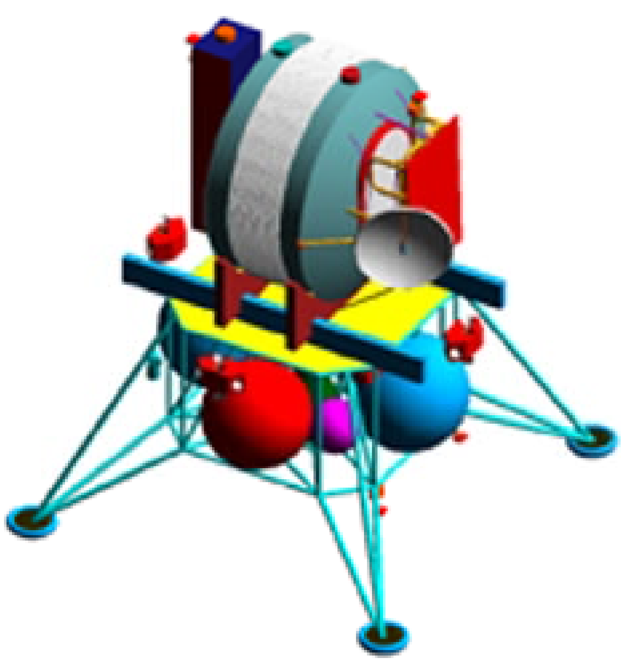

Figure 7a. Lunar Return Habitat in landing position with the inflatable habitat and equipment stowed. Credit Kriss Kennedy, NASA-JSC.

FIGURE 8. Class 1, Pre-integrated “Tuna Can” hard module, landed complete on the lunar or Mars surface. Credit: John Frassinito and Associates, circa 1993.

At a larger scale than Kennedy’s LRH, it is possible to make a comparison between Class 1 and Class 2 Habitats. FIGURE 8 shows a pair of pre-integrated “Tuna Can” modules landed and moved side by side on the lunar or Mars surface.

In this analysis, it is logical to consider movement of a module as a form of deployment. In this sense, any module that requires movement away from the LZ contains an aspect of the Class 2 characteristic or deployment. Each “Tuna Can” comes equipped with a set of four wheels on which to roll when a rover or tractor tows them from the LZ to the base site. When looking at such large modules in the 40 to 50 metric ton range, it becomes necessary to consider the surface conditions

Another important feature are the low-hanging EVA airlocks, which occur in a natural location to install inflatable vestibules or attach inflatable modules. Connectivity between two such modules is a key feature for crew productivity and safety. Ideally, there would be at least one pressurized tunnel connecting the two modules at the level of the airlock. Better still would be a second tunnel connecting pressure ports on the upper level of each of the two story Tuna Cans. These tunnels would clearly be Class 2 inflatable-deployable elements

FIGIRE 9 shows a concept for a larger scale inflatable dome, approximately 16m in diameter, proposed for the Lacus Veris site on the Moon. This dome would have five levels, including the subsurface “level zero,” and accommodate quite a large lunar population of 12 crewmembers. The long inflatable module attached to the dome is a different style of construction, but is still quintessential Class 2. However, the concentric rings that appear from the lunar surface up to the middle of the dome are radiation protection devices, packed or extruded into fabric containment tubes. In this image, these tubes are under construction as a machine to the right of the dome emplaces the regolith into a fabric tube and then places it on the lower concentric ring.

The oblong habitat to the right has a similar configuration of regolith tubes. However, it is difficult to discern whether the module they are protecting is another inflatable or a large, preintegrated Class 1 cylindrical module placed longitudinally on the surface. This module supports a solar photo-voltaic collector array, and additional “solar power farms” appear in the upper left and upper right corners of the image.

Running diagonally from behind the dome to the vanishing point at the horizon is an unusual feature for lunar schemes: a prepared road. On this road in the distance, a pressurized rover is driving. Another such pressurized rover appears at the left side of the inflatable dome, near the left center edge of the picture. This rover is docked to an airlock that clearly is a preintegrated element.

Thus, although the inflatable dome habitat is predominantly Class 2 structure it would also include smaller components of all three classes. In incorporates some Class 1 elements such as this airlock, Class 2 items such as the inflatable tunnel connecting the two large habitats, and Class 3 in-situ produced material in the form of regolith for radiation protection.

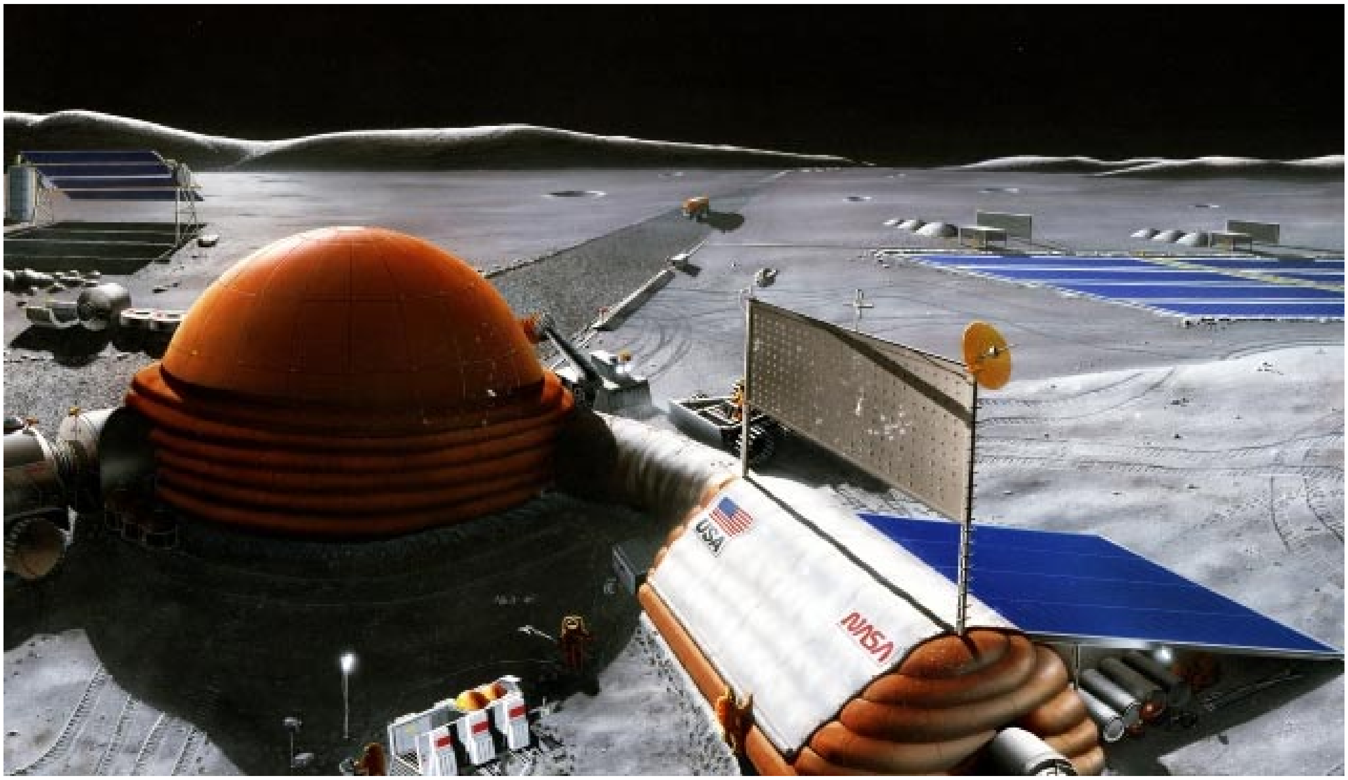

FIGURE 9. Lacus Veris Lunar Outpost, (NASA JSC, 1989).

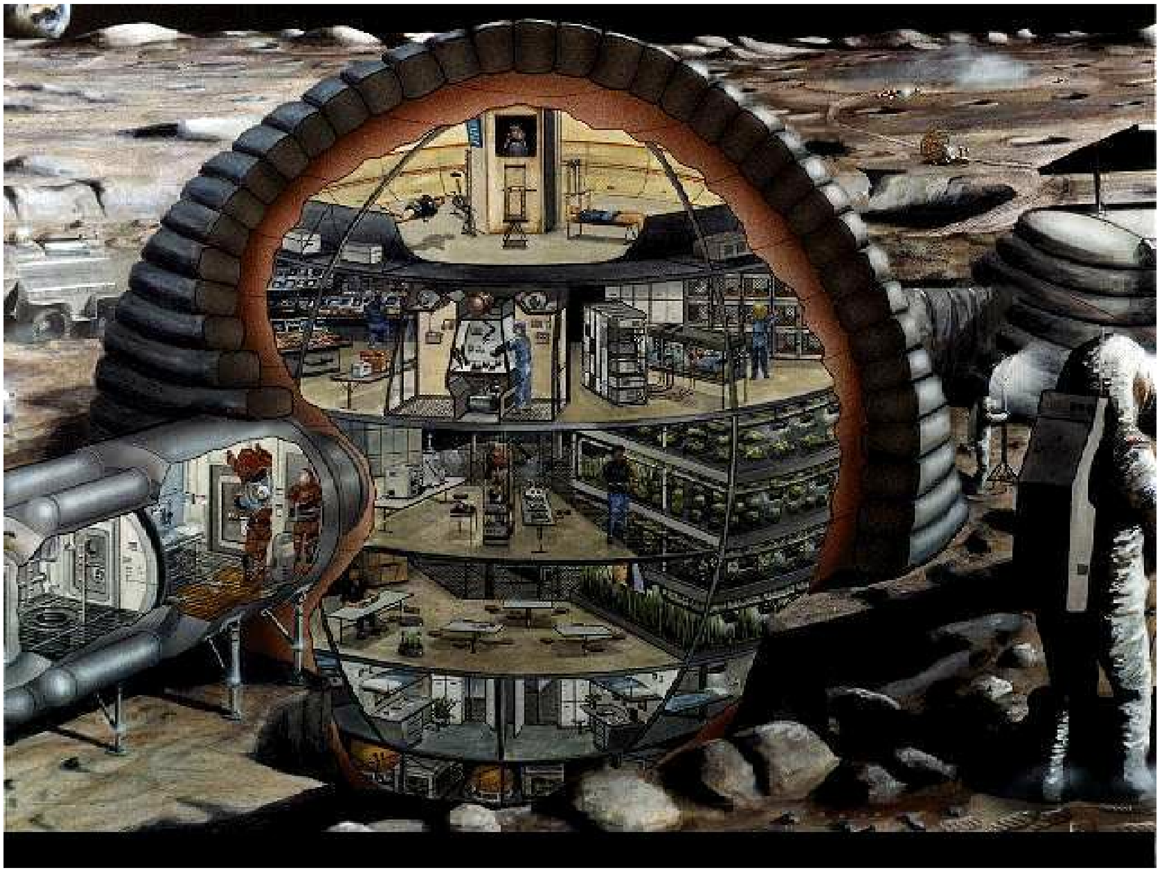

FIGURE 10. Detailed Cross-Section of the Lacus Veris Inflatable habitat.

FIGURE 10 shows a cutaway view of the Lacus Veris inflatable habitat interior. It provides four levels of living and working areas. In this design from 1989, these four levels are not particularly differentiated by function. At lower left is an airlock. The subsurface Level Zero contains the environmental control & life-support system. Levels One, Two, and Three accommodate relatively undifferentiated crew quarters. Level Four, at the top of the dome would house more specialized “crew support” functions, notably health and recreation facilities.

Levels One through Three would contain a mixture of living environment functions including private and group activity crew quarters, the wardroom, galley, and hygiene facilities. The working environment would include facilities for such activities as base operations, communications, landing operations, EVA operations support and monitoring, science field support, and science laboratories.

CLASS 3

Class 3 lunar architecture necessarily involves the use of in situ materials or landforms. These landforms include all parts of craters such as bottoms, rims, and walls; cliffs, maria, lava tubes and other features. In situ materials on the Moon generally refer to products made from regolith such as lunar concrete, lunar masonry, and radiation shielding.

FIGURE 11 shows a candidate type of “natural” landform in Oregon: a lava tube, produced by a volcano, now hopefully extinct. The technology to directly build into a lava tube with rigid materials is far beyond present capability. However, it is quite reasonable to imagine inserting a tube-shaped inflatable and then pressurizing it. The balloon would shape itself to the interior rock walls, which would provide excellent shielding against radiation and meteoroids and also provide a degree of thermal stability.

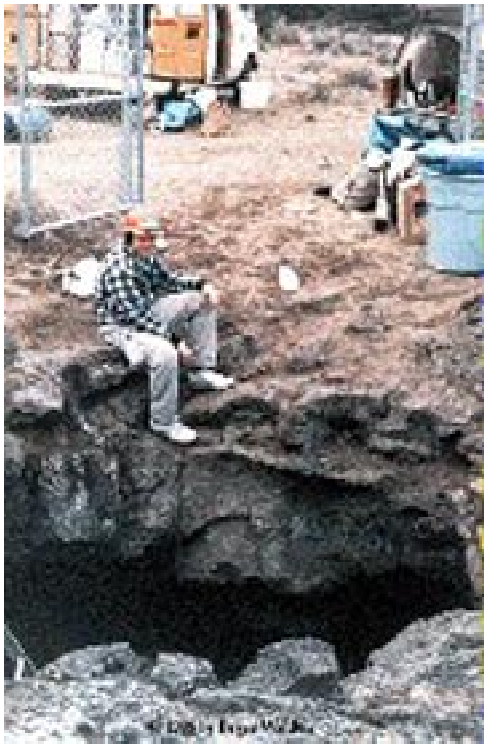

FIGURE 11. Oregon Lava tube, By permission of Bryce Walden, Oregon L5 Society. http://www.oregonl5.org/lavatube/,

FIGURE 12 shows a lava tube in Hawaii to illustrate the object lesson: make sure your lava tube is really dead, not just dormant. This picture illustrates the important feature that lava tubes can run horizontally for hundreds of meters, which would be much more manageable for a crew habitat than a tube that runs only vertically.

FIGURE 13 shows an innovative construction concept proposed by Alice Eichold, a Space Architect. Her idea is to use a crater as the structure to support a cable-suspended structure. This structure would most likely connect to an inflatable roof structure. However Eichold hopes eventually to find away to pressure-seal the compression ring to the lunar subsurface rock, assuming it is possible to find a location where the shock fractures do not make that scheme impossible.

FIGURE 14 shows a dome build of native masonry, created by the architect Nader Khalili at his CalEarth Institute in Hesperia California. The interesting aspect of Khalili's work is that after he builds his masonry structures, he coats the interior surface with a glaze. He then fires the glaze with an intensely hot incendiary source inside the dome, in this way achieving a well-sealed surface inside. Hopefully, it will be possible to develop this in-situ vitrification technology to the point that it can be used to seal pressurized lunar masonry or concrete domes.

FIGURE 12. View of a Hawaiian lava tube with an active flow of molten lava. Credit USGS, courtesy of R. D. "Gus" Fredricks, Oregon L5 Society. http://www.oregonl5.org/lavatube/

DISCUSSION

In some respects, Class 3 Structures are more ready-to-hand than Class 1 or Class 2 structures because they are more familiar to us, and more closely related to structures built of 3 native materials on Earth. However, the best approaches are still not well understood for extracting regolith and processing it for the various types of Class 3 building materials. One fascinating paradox concerns the question of water on the Moon, and extracting it for use by a human crew. Lunar concrete offers a particularly ironic example. ISRU advocates want to extract and mine the approximately 1 to 2% concentration of water in the polar regolith. Compare this “low grade ore” of ice mixed with soil to cured concrete, which typically has residual moisture content of about 3%. If lunar concrete existed naturally on the Moon, the ISRU advocates would be clamoring to mine it to extract the residual water content!

Beyond these types of questions of what is the best approach to process and apply lunar materials, the difficulties of constructing with these materials in the lunar environment are tremendous. On Earth, the construction industry has one of the highest injury rates of any vocation, rivaled only by commercial fishing, logging, and slaughterhouse work. According to the Centers for Disease Control, “Industries with the highest death rates were mining (30 per 100,000 workers), agriculture/forestry/fishing (19), and construction (15)” (CDC, 2001, p. 317). Thus, Crew Safety emerges as an increasing concern, the more work the astronauts must perform on-site to build habitats and lunar bases. The development of safe construction procedures, training for astronaut-builders, and safety monitoring at all times will be essential for safe and effective Class 3 lunar construction.

CONCLUSION

The selected precepts reviewed in this paper indicate the significant extent to which architects and engineers have thought through the problems and challenges of building lunar architecture. Most of this progress occurred in the past decade. In this respect, the discipline of Space Architecture is far ahead of current exploration programs in pursuing development plans for the moon.

Still, almost all of these designs are quite conceptual and even speculative. In order to seriously develop any of these concepts, the architects, engineers and builders will need to engage in a well-funded and supported technology development program. Each architecture type or concept will require rigorous testing in a field or simulated environment. None-the-less, the results of this review are encouraging. The hands and hearts and minds are here and ready to begin the work

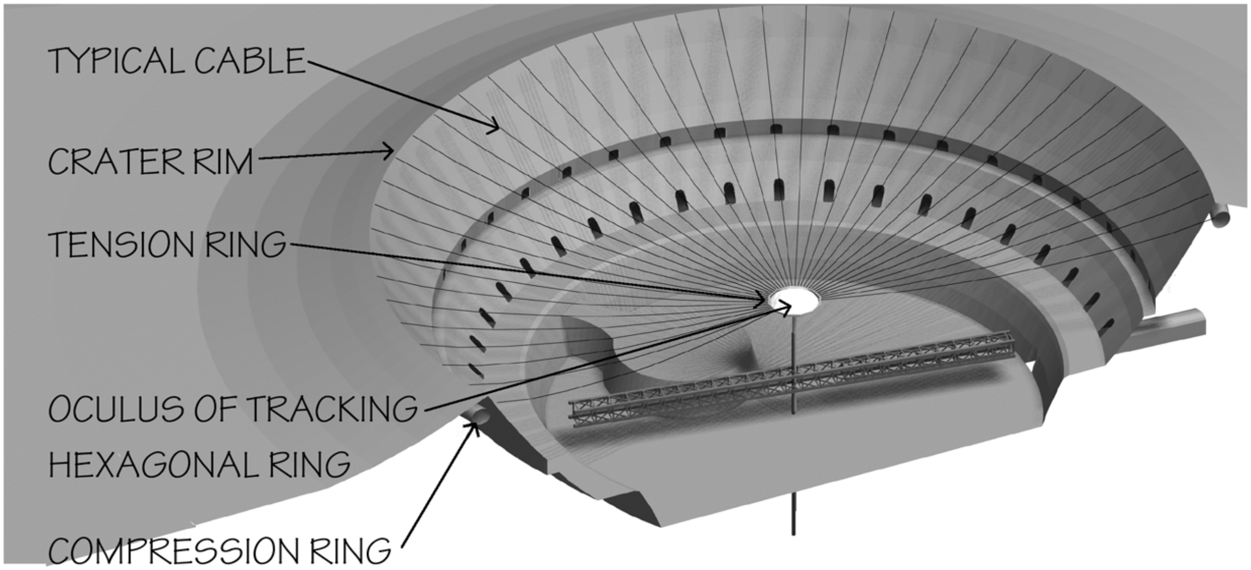

FIGURE 13. Transverse section through Alice Eichold's Class 3 concept for a lunar crater base.

FIGURE14. CalEarth Institute masonry dome, model for lunar masonry vitrified in situ.

ACKNOWLEDGEMENTS

I wish to thank the following people for helping me to prepare this paper:

Doug O'Handley, Lunar Development Session Chair for inviting me to submit this paper.

Hyam Benaroya for making his AIAA Space Architecture Symposium review paper available to me early in the process of writing.

Kriss Kennedy for all his excellent effort in collaborating with me on the Habitats and Surface Construction Roadmap, which he describes in part in his AIAA Space Architecture Symposium paper "The Vernacular of Space Architecture."

Bryce Walden for generously giving me permission to reproduce the photo of the Oregon lava tube.

GENERAL REFERENCES

Benaroya, Haym, (2002, October 11) An Overview of Lunar Base Structures: Past and Future, AIAA -6113, AIAA Space Architecture Symposium at the World Space Congress, Houston, TX.

Cohen, Marc M., and Kennedy, Kriss J. (1997, November). "Habitats and Surface Construction Technology and Development Roadmap," in Noor, Ahmed K.; Malone, John B.; Eds, *Government Sponsored Programs on Structures Technology*, NASA CP-97-20624.

REFERENCES

Abarbanel, Jenine E.; Criswell, Marvin E.; (1997) Design Development of an Inflatable Module for a Lunar/Martian Base, SAE 972487, 27th ICES.

Adams, Constance M., (1998) Four Legs in the Morning: Issues in Crew Quarter Design for Long-Duration Space Facilities, SAE 981794, *28th ICES*.

Allton, Judith H.; Lauer, Howard V., Jr. (1991) "Effects of Dust on Teflon Face Seals: Implications for Martian Soil Containers," *IDEEA ONE*, pp. 313-317.

Alred, John, et al (1989, Aug) Lunar Outpost, JSC-23613, Houston, TX: NASA Johnson Space Center.

Balin, Mark G.; Likens, William C.; Finn, Cory K.; Bilardo, Vincent J., Jr.; Ng, Yat Sun; (1991) Analysis of an Initial Lunar Outpost Life Support System Preliminary Design, SAE 911395, *SAE 1991 Transactions, Journal of Aerospace*, pp. 999-1015.

Benaroya, Haym; Bernold, Leonhard; Chua, Koon Meng; (2002, April) "Engineering Design and Construction of Lunar Bases," *Journal of Aerospace Engineering, Volume 15, No. 2.*, American Society of Civil Engineers, pp. 1-13.

Benaroya, Haym, Ed., (1993, June) Applied Mechanics of a Lunar Base, *Applied Mechanics Reviews, Volume 46, No. 6*, American Society of Mechanical Engineers.

Celentano, J. T.; Amorelli, D.; (1965) "Design Requirements for Manned Orbital Bases and Lunar Bases," *2nd Space Congress: New Dimensions in Space Technology, Cocoa Beach*, FL: Canaveral Council of Technical Societies. pp. 743-752.

Centers for Disease Control (Accessed 2001, April 27). "Fatal Occupational Injuries – United States 1980-1997," MMWR *Weekly, 50:16,* Atlanta, GA: CDC. pp. 317-320. http://www.cdc.gov/mmwr/preview/mmwrhtml/mm5016a4.htm, accessed October, 2002.

Cohen, Marc M. (1997, July). Design Research Issues for an Interplanetary Habitat, SAE-972485, *27th ICES.*

Duke, Michael B., (1994). Consideration for the Utilization of In-Situ Resources in Life Support Systems on the Moon, SAE 941258, *24th ICES*.

Ehrike, Krafft A., (1985) "Lunar Industrialization and Settlement — the Birth of Polyglobal Civilization," in Mendell, W. W., Ed., pp. 827-855.

Eichold, Alice (1996) Conceptual Design of a Crater Lunar Base, SAE 961464, *26th ICES*.

Ferrall, J. F.; Ganapathi, G. B.; Rohatgi, N. K.; Seshan, P. K.; (1994). Life Support Systems Analysis and Technical Trades for a Lunar Outpost, NASA TM 109927, Washington DC: NASA.

Fitch, James Marston; Bobenhausen, William; (1999). American Building: The Environmental Forces that Shape It, New York: Oxford University Press.

Fujii, T.; Midorikawa, Y.; Shiba, M.; Nitta, K.; (1990). "Human Requirements for Quality of Life in Lunar Base," SAE 901207, *SAE 1990 Transactions – Journal of Aerospace,* pp. 365-375.

Harper, Lynn D.; Connell, Kathleen M.; (1990). The Lunar Outpost: Testbed for Colonization and Extraterrestrial Evolution, AIAA-90-3850, AIAA Space Programs and Technologies Conference, Huntsville AL, Sept 25-28, 1990.

Howe, A. Scott; Howe, Jeffrey W.; (2000). Applying Construction Automation Research to Extraterrestrial Building Projects, SAE 2000-01-2465. *30th ICES*.

Keller, John R.; Ewert, Michael K.; (2000). Lunar Dust Contamination Effects on Lunar Base Thermal Control Systems, SAE 2000-01-2405. *30th ICES*.

Kennedy, Kriss J. (1999, July). ISS TransHab: Architecture Description, SAE 1999-01-2143, *29th ICES.*

Koscheyev, Victor S.; Greaves, Ian A.; Leon, Gloria R.; Hubel, Allison; Nelson, Eric D.; (1996) Comfort and Heat Control During Extended Space Flights, SAE 961538, *26th ICES.*

Lewis, John S.; Lewis, Ruth A.; (1987). Space Resources: Breaking the Bonds of Earth, New York: Columbia University Press.

Mendell, Wendell W., Ed., (1985). Lunar Bases and Space Activities of the 21st Century, Houston, TX: Lunar and Planetary Institute.

National Council on Radiation Protection (2000, Dec.) Radiation Protection Guidance for Activities in Low Earth Orbit, NCRP Report No. 132..

Newman, D.J., Alexander, H.L., and Webbon, B.W., (1994). "Energetics and Mechanics for Partial Gravity Locomotion," *Aviat. Space and Environ. Med*., 65: 815-823,

NSSDC (2002) National Space Science Data Center, NASA-Goddard Space Flight Center. http://nssdc.gsfc.nasa.gov/planetary/ice/ice_moon.html, accessed July 23, 2002.

Podnieks, Egons R., (1990). Lunar Mining Outlook, AIAA 90-3751, *AIAA Space Programs and Technologies Conference*, Huntsville AL, Sept 25-28, 1990.

NASA-Johnson Space Center (1989, November) Report of the 90-Day Study on Human Exploration of the Moon and Mars, Houston: NASA.

Richelson, Jeffrey T. (2000, Sept./Oct.). "Shooting the Moon," *Bulletin of the Atomic Scientists*. Pp. 22-27.

Simonson, Lisa C.; Nealy, John E.; Townsend, Lawrence W.; (1992). Concepts and Strategies for Lunar Base Radiation Protection: Prefabricated Versus In-Situ Materials, SAE 921370, *SAE 1992 Transactions, Journal of Aerospace*, pp. 1348-1359.

Smith, A., (1993, June). "Mechanics of Materials in Lunar Base Design," in Benaroya, Ed., 1993, pp. 268-271.

Space Studies Board (2000). Radiation and the International Space Station: Recommendations to Reduce Risk, Washington, DC: National Academy Press.

Sullivan, T. A.,(1990). Process Engineering Concerns in the Lunar Environment, AIAA-90-3753, AIAA Space Programs and Technologies Conference, Huntsville AL, Sept 25-28, 1990.

Thangavelu, Madhu; (1990) MALEO: Modular Assembly in Low Earth Orbit, An Alternative Strategy for Lunar Base Development, IAF-90-443, 41st Congress of the International Astronautical Federation, Dresden, October 6-12, 1990.

Vanzani, V.; Marzari, F.; Dotto, E.; (1997). Micrometeoroid Impacts on the Lunar Surface, Lunar and Planetary Science Conference XXVIII, 1025.pdf, Houston, TX: Lunar and Planetary Institute. http://www.lpi.usra.edu/meetings/lpsc97, assessed July 23, 2002.

Walker, Sherry T.; Alexander, Reginald A.; Tucker, Stephen P.; (1995) "Thermal Control on the Lunar Surface," *JBIS*, Vol. 48, pp. 27-32.

Wilson, J. W., et. al., (1999) Astronaut Exposures to Ionizing Radiation in a Lightly-Shielded Spacesuit, SAE 1999-01-2173, *29th ICES*.

Wilson, J. W.; Miller, J.; Konradi, A.; Cucinotta, F. A.; (1997, December) Shielding Strategies for Human Space Exploration, NASA CP 3360, Hampton VA: NASA Langley Research Center.

ADDITIONAL SOURCES

Aldrin, Buzz; McConnell, Malcolm; (1989) Men From Earth, New York: Bantam Books.

Benaroya, Haym, (1998, Oct) "Economic and Technical Issues for Lunar Development," *Journal of Aerospace Engineering*, Vol II, No. 4. pp. 111-118.

Brooks, Courtney G.; Grimwood, James M.; Swenson, Lloyd S., Jr., (1979) Chariots for Apollo: A History of Manned Lunar Spacecraft, NASA SP-4205, Washington, DC: NASA.

Budden, Nancy Ann, Ed. (1994, August) Catalog of Lunar and Mars Science Payloads, NASA RP 1345, Washington DC: NASA.

Carr, Michael H. ; Greeley, Ronald, (1980). Volcanic Features of Hawaii: A Basis for Comparison with Mars, NASA SP-403, Washington, DC: NASA.

Elrod, Molly, (1995). "Considerations of a Habitat Design," *JBIS, Vol 48.*, pp. 38-42.

Gitelson, J. I.; Shepelev, Ye. Ya.; (1996). Creation of Life Support Systems for the Lunar Outpost and Planetary Bases: History, Present State of Research in Russia (Former Soviet Union) and Prospects, SAE 961553, *26th ICES.*

Iwata, Tsutomu, (1994) "Evolutionary Scenario of Lunar Manufacturing," *JBIS Vol. 47*, pp. 539-542.

Kelly, Thomas J., (1990) A Review of the Apollo Lunar Program and Its Lessons for Future Space Missions, AIAA 90-3617, *AIAA Space Programs and Technologies Conference*, Sept. 25-28, Huntsville, AL.

Mankins, John C.; (1995) Strategies to Begin and Sustain a Lunar Exploration Program — Revisited, AIAA 95-4060, *AIAA Space Programs and Technologies Conference*, September 26-28, Huntsville, AL.

Moore, Gary T. ; Huebner-Moths, Janis; (1991). "Genesis II Advanced Lunar Outpost Human Factors Design Response," IDEEA ONE, pp. 517-531.

Moore, Patrick, (1976) Guide to the Moon, London: Butterworth Press.

Nash, Douglas B.; et al. (1989, June) Science Exploration Opportunities for Manned Missions to the Moon, Mars, Phobos, and an Asteroid, JPL 89-29, Pasadena, CA: JPL.

Sadeh, Willy Z.; Criswell, Marvin E.; Abarbanel, Jenine E.; (1996). "An Inflatable Module for Use on Mars," in *The Case for Mars VI*, McMillan, Kelly R.; American Astronautical Society, Science and Technology Series, Volume 98, San Diego: Univelt, Inc. pp. 303-308.

Wilson, John W., et. al., (1991) Transport Methods and Interactions for Space Radiations, NASA RP-1257, Washington DC: NASA.

DEFINITIONS

AIAA American Institute of Aeronautics and Astronautics.

cSv centi-Syvert, SI unit of absorbed radiation dosage equal to one rem., which it replaces as the unit of choice.

EVA Extravehicular Activity

GCR Galactic Cosmic Ray

Gy-Eq Gray equivalent, SI unit measure of incident radiation, incorporating relative biological effectiveness (RBE), replaces the rad and Q quality factor.

ICES International Conference on Environmental Systems.

IDEEA ONE The first International Design of Extreme Environments Assembly, November 1991, University of Houston.

IVA Intravehicular activity, including crew activity inside a lunar or planetary base.

JBIS Journal of the British Interplanetary Society

JPL NASA's Jet Propulsion Laboratory, Pasadena, CA

JSC NASA Johnson Space Center

LEO Low Earth Orbit

LRH Lunar Return Habitat

LZ Landing Zone

Mophology The science of form (OED).

NASA National Aeronautics and Space Administration.

NCRP National Council on Radiation Protection

NSSDC National Space Science Data Center, located at NASA-Goddard Space Flight Center, Greenbelt, MD

OED Oxford English Dictionary

SAE Society of Automotive Engineers

SPE Solar Proton Event

Taxonomy Classification, especially in relation to its general laws or principles (OED).

Typology The study of symbolic representation, especially of origin and meaning. . . (OED). Architectural typology concerns the functional and social origin of building types.