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Lunar Base Habitat Designs: Characterizing the Environment, and Selecting Habitat Designs for Future Trade-offs

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ABSTRACT

A survey of distinct conceptual lunar habitat designs covering the pre- and post-Apollo era is presented in this report. The impact of the significant lunar environmental challenges such as temperature, atmosphere, radiation, soil properties, meteorites and seismic activity on the habitat design parameters are outlined. Over twenty habitat designs have been identified and classified according to mission type, crew size, total duration of stay, modularity, environmental protection measures, and emplacement. Simple selection criteria of 1) post-Apollo design, 2) uniqueness of the habitat design, 3) level of thoroughness in design layout, 4) habitat dimensions are provided, and 5) materials of construction for the habitat shell are specified, are used to select five habitats for future trade studies. Habitat emplacement scenarios are created to examine the possible impact of emplacement of the habitat in different locations, such as lunar poles vs. equatorial, above ground vs. below ground, etc.



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1. INTRODUCTION

This report is a deliverable from the ISRU-LS Systems Analysis task under NASA-OACT Systems Analysis RTOP No. 506-49-21. This task, initiated by OACT direction, was planned to be a multi-year effort consisting of a number of systems analysis tool development tasks to enhance LiSSA, the NASA/JPL Life Support Systems Analysis Tool funded by OAST and OACT over a five year period. The planned tasks were:

1. Integration of lunar habitat technology modules into LiSSA,
2. Integration of *in situ* resource utilization system with LiSSA,
3. Integration of power generation and storage system,
4. Integration of propellant production and storage system.

As of the date of this report, this effort has been abruptly terminated by OACT. Therefore, no further reports will be issued under this task. However, the technical challenge of extended human presence and creativity on the Moon persists and the planned activities may be pursued with NASA's renewal of support at a later date.

1.1 Historical Perspective - Pre- & Post-Apollo Lunar Habitat Designs

The Moon has always held the fascination of man, a symbol of cosmic proportions. It has inspired lovers, poets, writers, and scientists through time. The Apollo missions, by placing man on the moon have not destroyed that inspiration, but have directed it towards people who envision the full utilization of what the moon has to offer to mankind, i.e., lunar bases to house people, resource development, answers to questions on planetary formation and early development of the Earth, etc. Long term exploration of space needs a laboratory for testing out equipment, and human limits, and the closeness of the moon provides an obvious stepping stone to further space exploration in the future. (At the time of this report, Code X at NASA has been dissolved, bringing the Space Exploration Initiative envisioned by President Bush, to a standstill, hopefully only temporarily).

The evolution of lunar base concepts has been recorded by Johnson and Leonard (1985) and Lowman (1985) in their papers. The research of pre-Apollo authors such as Slizard (1959), Holbrook (1958), DiLeonardo (1962), DeNike and Zahn (1962), and Helvey (1960) has shown that during the early Apollo days, while intense studies for lunar bases were being conducted, the requirements for a lunar base became fairly well characterized, i.e., requirements for good thermal control and for meteorite and radiation protection. Use of

regolith for radiation protection was suggested by Helvey (1960); dust problems were anticipated by Rinehart (1959).

The lunar base development was projected to be evolutionary in nature, proceeding from an initial landing in the 1969-71 time frame, followed by exploration in 1972-74, experimentation in 1974-1976, resource utilization in 1976-1978, and further resource exploitation in 1978-1980.

One item of the development plan for the launch vehicle was the Saturn V transportation system, planned to be systematically upgraded to 111 percent and then 188 percent of basic payload capacity.

The LESA Initial Concept Base Model 2 (Boeing, 1963) was designed for accommodating six men for six months on the Moon, including 46,000 pounds of payload, a 10-kW nuclear power unit, a 3765-lb. roving vehicle with an extended mobility module, and equipment to move lunar soil for shielding. Later studies were done by Lockheed (1965), North American Rockwell (now Rockwell International) (1971). A bibliography of these studies and others is given in the paper by Lowman (1984).

Following a lull in activities after the Apollo days, a significant amount of research has been ongoing since the mid to late 80s, and to the present time, providing innovative lunar habitat concepts.

1.2 Purpose and Scope of Present Report

The purpose and scope of the report are as follows:

1. Identify distinct conceptual lunar habitat designs from the literature.
2. Summarize environmental challenges to lunar habitat designs.
3. Conduct qualitative/semi-quantitative emplacement studies; i.e. study the consequences of emplacement of the lunar habitat around lunar poles, equatorial locations, under ground, within a lava tube, etc.

Planned integration of habitat technology candidates into LiSSA (Life Support Systems Analysis tool), developed at JPL to support system and technology trade studies for human life support on the Moon, will not occur for reasons mentioned earlier.

2. LUNAR ENVIRONMENT CHALLENGES TO HABITAT DESIGN

The lunar surface provides a challenging environment for establishing a base. In this section, some of the challenges are outlined in the various subsections dedicated to environmental parameters such as temperature, atmosphere, radiation, soil properties, meteorites, and seismic activity.

2.1 Temperature

The lunar surface experiences a large temperature excursion ranging from approximately 380 K during the lunar day to approximately 100 K during the lunar night, and heat flowing out of the subsurface is lost by radiation into space (a complete cycle from one sunrise to the next is known as the lunation period, which is 29 days, 12 hours, 44 minutes and 2.8 secs in length -- approximately 29.53 days). These very large excursions are due to a couple of factors (Langseth et al. 1974):

1. Extremely low thermal conductivity, which inhibits the flow of energy into and out of the subsurface,
2. A very low volumetric heat capacity of the regolith,
3. A very tenuous atmosphere.

At low lunar latitudes, the average surface temperature is approximately 220 K; this average temperature is determined

by the balance of solar energy flowing into and thermal energy radiated out of the surface during a complete lunation. Due to increased efficiency of radiative heat transfer between particles at higher temperature (varies as the cube of temperature), heat flow into the Moon during the day is higher than the heat flow out of the Moon during the night. As a result, the steady-state temperature gradient within the top few cms of the subsurface can be quite significant. To illustrate the significance of this thermal gradient, the estimated mean surface temperature for the Taurus-Littrow site (Apollo 17; Langseth *et al.*, 1974) was 215 K (\pm 5 K); the mean subsurface temperature (over the lunation period) as measured by the top probe sensors was an average of 253 K. The mean temperature gradient is mainly due to the contribution of radiative heat transfer within the highly porous dust layer approximately 2 to 3 cm thick at the surface. Temperature fluctuations due to the diurnal cycle become virtually undetectable below 100 cm. (See Figure 1.)

The low thermal conductivity of the regolith has some very important implications for thermal protection schemes. From the numbers presented above, it can be seen that it is sufficient to have a regolith covering of just 50 cm to 100 cm over the habitat to damp out the diurnal extremes experienced on the lunar surface.

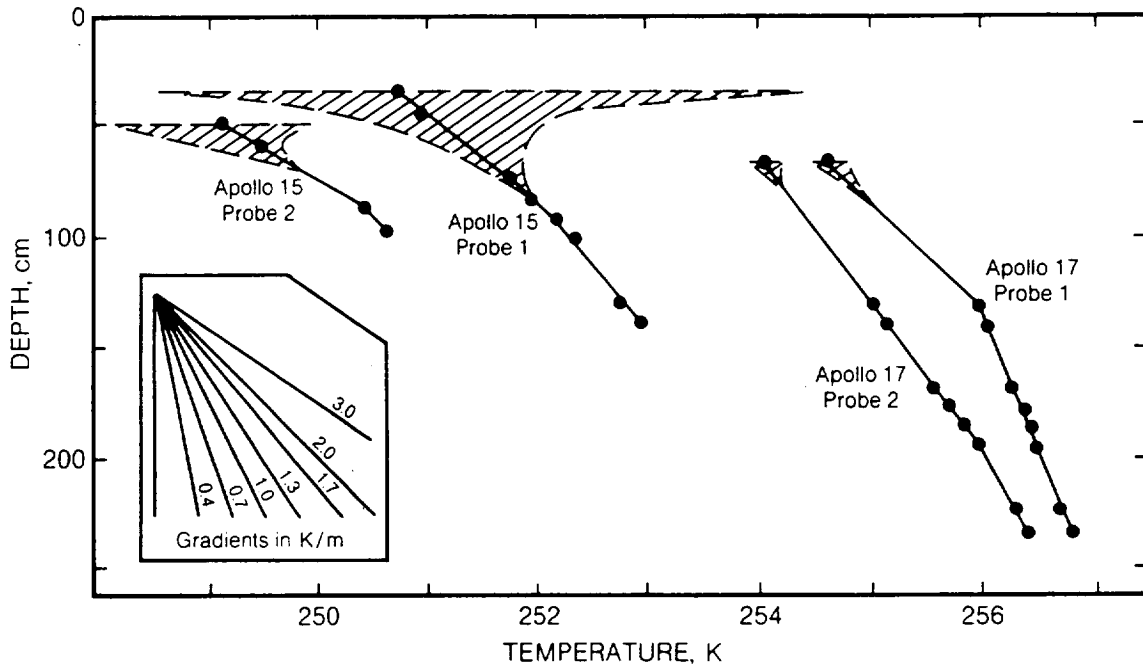


Figure 1. Temperature fluctuations in the lunar regolith as a function of depth (after Langseth and Keihm, 1977). The temperature excursions less than ~ 30 cm below the surface are not included, due to the large swings. Hatched areas show day-night fluctuations below ~30-70 cms. (Vaniman, et al., 1993b; used with the permission of Cambridge University Press)

The original heat flow experiments were conducted on the lunar surface to make a direct measurement of the vertical component of heat flow from the lunar interior through the surface and to determine the thermal properties of the upper 3 m. of the lunar surface (Langseth, et al., 1974). The governing equation for the heat flow, F_z is given by:

$$F_z = -k_m \left[\frac{dT}{dz} \right]$$

where the unit of F_z (thermal flux) is $W\ cm^{-2}s^{-1}$; k_m (thermal conductivity) is $W\ cm^{-1}\ K$; T (temperature within the regolith) is K , and z (cm) is depth from the surface. The essential parts of the heat flow instrument are two identical temperature-sensing probes, containing Wheatstone-like resistance bridges.

For the Apollo 15 mission, two probes were located 10 m apart, at the Hadley Rille ($26^\circ N$, $3.6^\circ E$), and for the Apollo 17 mission, two probes were located 10 m apart, at the Taurus-Littrow Valley ($20^\circ N$, $30.6^\circ E$) (Langseth et al., 1972). A wealth of information was obtained from the measured temperatures from the initial cool-down of the probe, and heater-activated conductivity measurements. Based on studies over 3.5 years for the Apollo 15 mission, and 2 years for the Apollo 17 mission, the thermal conductivity ranged from $1.5\ W\ cm^{-1}\ K^{-1}$ to $2.95 \times 10^{-4}\ W\ cm^{-1}\ K^{-1} \pm 20\%$, compared with a range of 1.1 to $2.93 \times 10^{-2}\ W\ cm^{-1}\ K^{-1}$ for terrestrial soil (Tosoukian, Y.S. et al., 1970). In general, the thermal conductivity increased with depth, as a result of higher bulk density (due to compaction). Heat flow, probably generated by radioisotopes (mainly ^{40}K , ^{232}Th , ^{235}U , and ^{238}U) (Vaniman et al., 1993a), was calculated to be approximately $3.1 \times 10^{-6}\ W\ cm^{-2} \pm 20\%$, which agrees very closely with the value of $3 \times 10^{-6}\ W\ cm^{-2}$ to $4 \times 10^{-6}\ W\ cm^{-2}$ estimated from Earth-based observations of thermal emissions from the Moon in the microwave band (Krotikov and Troitsky

(1964), Tikhonova and Troitsky (1969)).

In addition to the actual measured values from the Apollo missions, estimated average and extreme values of the surface temperatures were made by the Lunar Colony Study Group (Dalton and Hoffman, 1972) and referenced in Vaniman et al. (1993b).

Table 1: Estimated Lunar Surface Temperatures (Vaniman et al., 1993b; used with the permission of Cambridge University Press)

	Shadowed Polar Craters	Other Polar Areas	Front Equatorial	Back Equatorial	Limb Equatorial	Typical Mid-Latitudes
Average Temp.	40 K(?)	220 K	254 K	256 K	255 K	220<T<255 K
Monthly Range	none	±10 K	±140 K	±140 K	±140 K	±110 K

These estimated values, based on Earth-based observations, need to be updated with actual measurements on the Lunar surface, and projects such as the Artemis (Saucier, 1993) would provide these answers.

In summary, surface temperatures can be very severe and can impose severe thermal stresses on the materials of construction. "Structural elements exposed to these extreme conditions, 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 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" (Daga et al., 1992).

2.2 Atmosphere

On the surface of Earth, atmospheric concentration is in the range of 10^{19} molecules/cc (STP), and decreases to 10^7 molecules/cc at 500 km and 10^5 molecules/cc at 1500 km above the surface of the Earth. In comparison, the atmosphere on the surface of the Moon ranges from 2×10^5 molecules/cc to 10^7 molecules/cc from lunar night to day (Johnson et al., 1972). The daytime concentration of 10^7 molecules/cc represents an upper limit, as it is thought to include local contamination.

Little was known of the lunar atmosphere prior to the Apollo missions. As part of the Apollo Lunar Surface Experiments Package (ALSEP), during the Apollo program, several atmospheric and ionospheric monitors were emplaced, which included the

following (Vondrak, 1992):

1. Cold Cathode Gauge Experiment (CCGE): Measurement of total gas pressure.
2. Lunar Atmospheric Composition Experiment (LACE): Measurement of Density and Flux of Neutral Gases.
3. Suprathermal Ion Detector Experiment (SIDE): Measurement of atmospheric ions.
4. Charged Particle Lunar Environment Experiment (CPLEE): Measurement of surface photoelectrons and lunar plasma environment.

G. Jeffrey Taylor (1992) has listed a number of natural and artificial sources for the lunar atmosphere. The primary natural sources include the following:

1. *Solar wind*: Due to the lack of any significant magnetic field or atmosphere, the solar wind flows directly onto the lunar surface. The total amount of solar wind input to the lunar atmosphere is 50 g/s, almost all of which is H (40 g/s) and He (8 g/s).
2. *Meteorite and Comet Volatilization*: Micrometeorites hitting the Moon are volatilized and the volatiles are released into the atmosphere. The contribution from this source is in the order of 2 g/s.
3. *Internal Degassing*: The Moon is continually outgassing which can be in the order of 10^4 kg/yr, (or .32 g/s).

In addition to the natural sources, the following artificial sources could contribute to the lunar atmosphere.

1. *Rocket Exhaust*: Based on an estimate of 18 trips/yr, Vondrack (1974) estimated the amount of 100 g/s contaminants released into the atmosphere.
2. *Habitat Leakage*: Based on Space Station Freedom cylindrical module size of 14.3 m long and 4.6 m dia., each module would release 48 g/s (the leak rate for the structures is 2×10^{-4} g m⁻² s⁻¹). In addition, EVA operations are expected to contribute, albeit to a smaller extent (7×10^{-2} g/s).
3. *Mining*: Based on rough estimates for ISRU mining for ³He, and for O₂ production and glass production, the estimates for the total gases released can be in the order of 1000 g/s, of which the major contribution will be from the ³He mining.

By far, the largest contribution would be from the ³He mining, considering all the sources mentioned above.

Table 2: Sources of gas near a lunar base (G.J. Taylor, 1992)

Source	Rate (kg/s)
Mining and Manufacturing (³ He, O ₂ , glass)	1
Habitat Venting	0.5
Rocket Exhaust	10 ⁻¹
Solar Wind	5x10 ⁻²
Meteoritic Volatilization	2x10 ⁻³
Internal Degassing	<3x10 ⁻⁴

The absence of a significant atmosphere makes the Moon an attractive site for astronomical observatories and for material processing requiring a high vacuum (Vondrak, R.R., 1992). However, the lack of a life-supporting atmosphere would mean that the lunar base activities would have to rely extensively on enclosed habitats which must retain the required atmosphere under the severe environmental conditions.

On the other hand, the lack of a significant atmosphere would mean that heat transport processes through the atmosphere would be limited to radiation only; convection and diffusional processes will be non-existent. Objects that are exposed to direct sunlight will get heated, while objects in the shade will remain cold. One of the difficulties in habitat design is the design of an efficient lightweight thermal control system. The amount of heat that can be rejected depends on the temperature and radiating surface area of the radiator. Thus, if the amount of heat that has to be rejected and the temperature at which it needs to be rejected are known, the area required to do the job is completely defined. As the radiator size is increased, the unit masses also need to be increased to provide protection against micrometeorite penetration. An alternate scheme which has been studied for some time, includes the concept of using a 2-phase system such as the dust-radiator (Hedgepeth, J.M., 1978). Here the approach is based on the fact that the small dust particles can have almost unlimited ratios of area to mass since the ratio is inversely proportional to the size of the

particles. Thus, the particles are heated in a container and projected in a stream to be caught by another container, and the cycle is repeated again. While the particles are in transit between the container nodes, they radiate heat to the atmosphere. Hedgepeth (1978) has provided optimal conceptual designs for the dust-radiators, using particle geometry parameters such as particle diameter, and particle spacing, as well as stream length and stream unit mass as functions of the radiated heat. Buckner, G.L. and Tuttle, R.F. (1988) have presented a liquid droplet radiator, which is similar to the dust-radiator, except that it uses silicone oil, Trimethylpentaphenyltrisiloxane, which has a low vapor pressure. The authors claim that their system can be seven times lighter than conventional heat pipe radiators of similar size.

2.3 Radiation

Radiation encountered during orbital flight can be classed as primary cosmic radiation, geomagnetically trapped radiation (Van Allen belts) and radiation due to solar flare events. Thanks to the thick atmosphere on Earth (1000 g/cm^2) and a significant magnetic field, a great amount of the radiation which would otherwise impinge directly on the Earth gets attenuated or deflected. Very few cosmic ray particles reach the surface, among which are the weakly interacting muons and a few neutrons (Vaniman, D., et al., 1993b).

The lack of a significant atmosphere or magnetic field, makes the Moon a target of continuous bombardment by cosmic rays, both from within the solar system and outside. They are large fluxes of low-energy solar-wind particles, smaller fluxes of high-energy galactic cosmic rays (GCR), and rare but occasionally intense fluxes of particles emitted during a solar flare. The energy spectrum and the constituents of cosmic rays vary and their impact on the lunar habitat designs can range from insignificant to substantial. Table 3 presents a summary of the three major types of radiation in the lunar environment (Vaniman, D., et al., 1993b).

Solar Wind

In addition to the radiant energy, the sun also emits plasma, which is composed of equal numbers of ions and electrons. The solar wind is electrically neutral and its composition is listed in Table 3. The main source of volatiles on the lunar surface and in the atmosphere, the solar wind is also responsible for some long-term erosion of the surface. The bulk of the erosion is caused by micrometeorite bombardment.

Solar Flare

Approximately every 11 years or so, the sun produces high fluxes of energetic charged particles, known as solar cosmic rays (SCR). The term "energetic particles" is used to refer to the high-energy particles that are emitted with energy levels noted in Table 3. The extremely high fluxes associated with these particles can pose a

serious concern for men and material exposed on the lunar surface. An astronaut caught outside his shielded habitat can be exposed to lethal levels of radiation. Given the short arrival times of the solar protons (~10 hours or less for energy levels of ~20-80 MeV), it will be imperative that prediction of SCR events is accurate and rapid access is made available for the astronauts to enter their shelters.

Table 3: Summary of the three major types of radiation in the lunar environment (Vaniman, D., et al., 1993b; used with the permission of Cambridge University Press)

Type	Solar Wind	Solar Cosmic Rays	Galactic Cosmic Rays
Nuclei energies	~0.3-3 keV/u *	~1 to >100 MeV/u	~0.1 to >10GeV/u
Electron energies	~1-100eV	<0.1 to 1 MeV	~0.1 to >10GeV/u
Fluxes (protons cm ⁻² s ⁻¹)	~3x10 ⁸	~0-10 ⁶ †	2-4
Particle Ratios ‡			
electron/proton	~1	~1	~0.02
proton/alpha	~22	~60	~7
L(3≤Z≤5)/alpha	n.d.	<0.0001	~0.015
M(6≤Z≤9)/alpha	~0.03	~0.03	~0.06
LH(10≤Z≤14)/alpha	~0.005	~0.009	~0.014
MH(15≤Z≤19)/alpha	~0.0005	~0.0006	~0.002
VH(20≤Z≤29)/alpha	~0.0012	~0.0014	~0.004
VVH(30≤Z)/alpha	n.d.	n.d.	~3x10 ⁻⁶
Lunar Penetration Depths			
protons and alphas	<micrometers	millimeters	meters
heavier nuclei	<micrometers	millimeters	centimeters

* eV/u = electron volts per nucleon

† Short-term SCR fluxes above 10 MeV; maximum is for the peak of the August 4, 1972 event. Fluxes above 10 MeV as averaged over ~1 million years come to ~100 protons cm⁻²c⁻¹

‡ Ratios often vary considerably with time for the solar wind and SCR particles and with energy for SCR and GCR. The symbols L(light), M(medium), H(heavy), VH(very heavy), etc. are historical terms for nuclei charge (Z) groups greater than those in the cosmic rays.

n.d.=not determined (usually because the ratio is too low to measure). Composition data from Feldman et. al. (1977) and Bame et al. (1983) for the solar wind, McGuire et al. (1986) for the SCR, and Simpson (1983) for the GCR.

Galactic Cosmic Rays

These are particles that originate outside our solar system. The energies of these particles can range from 10^{15} eV up to 10^{20} eV. These particles can take up to 10^7 years to reach the Moon, during which time a significant amount of the energy is attenuated by collisions with other particles in the interstellar matter. The activity of the GCR varies inversely with the number of solar energetic particles. Thus, when there is a solar flare event, the plasma from the sun attenuates the energies of the GCR; particles with energies greater than 10 GeV/u are not affected by the solar flare event.

These particles, interacting with lunar matter, cause different types of nuclear reactions, depending on nuclei charge and weight. The most energetic GCRs, with energies typically in the GeV/u range, are not stopped with matter < 1000 g cm^{-2} . High-energy particles with $E > \sim 10$ MeV usually initiate a cascade of particles. These secondary particles are an important part of the radiation environment. Charged particles interact with matter by ionizing atoms and molecules and losing energy. Heavy nuclei are stopped rapidly within the matter, transferring their energy. Radiation damage induced by nuclei with $Z > 20$ can be so high that etched holes, caused by preferential dissolving of the damaged areas, can be seen by Transmission Electron Microscopy. These effects are of great significance when one is considering the effects of radiation on the human body, and will be discussed later.

To correctly predict the transport of the charged particles as they make their way through a barrier of different materials, transport codes have been developed at various laboratories, which include the BRYNTRN ("Baryon transport") (Wilson, J.W., et al., 1989) at NASA Langley Research Center, MCNP ("Monte Carlo Neutron and Photon Transport Code") (MCNP, 1983) at the Oak Ridge National Laboratory, HETC ("Monte Carlo High Energy Nucleon-Meson Transport Code") (Prael, R.E., 1985) at the Oak Ridge National Laboratory, and a synthesis of the MCNP, HETC and custom-made UPROP ("Universal Heavy-Ion Propagation Code") by John Letaw et al. (1989) at the U.S. Naval Research Laboratory.

Radiation effects on the human body are characterized by several interrelated units such as the following (Nicogossian, A.E., and Parker, J.F., 1982):

Roentgen

Not being a directly measurable quantity, the roentgen's magnitude is determined by the ionization caused by the passage of radiation through a medium. The roentgen refers to the ionization produced by the passage of X- or gamma radiation in air, which results in 0.001293 of a gram of air ions carrying one e.s.u. of electricity. This unit is rarely encountered in the literature.

Rad

One rad (radiation absorbed dose) of any type of radiation corresponds to the absorption of 100 ergs by any medium. For

biological systems, one rad is equivalent to 10^{-5} J energy absorbed/g of tissue.

Rem

One rem (roentgen equivalent, man) equals the absorbed dose of any ionizing radiation which produces the same biological effect in man as that resulting from the absorption of one roentgen of X-rays. The rad measure is qualified by an RBE (relative biological effectiveness) measure in order to arrive at an expression in rems. The RBE differs for various types of radiation, from a value of one for X-rays and gamma rays, to values to as high as 15 to 20 for alpha particles at different energy levels.

Gray

One gray is equal to 100 rads.

Sievert

One sievert is equal to 100 rems.

In addition to the units mentioned above, the unit LET (Linear Energy Transfer) is used commonly to account for the deficiencies that are the result of using the single dose parameters such as rads, rems, etc.

Due to the risks involved in exposure to space radiation, NASA has adopted guidelines for maximum radiation exposures for its

astronauts, which set a career limit of 4.0 Sv (400 rem). With better understanding of radiation effects, and considering the fact that NASA recruits women astronauts for space travel, newer radiation guidelines are being recommended. The newest career limits recommended at this time range from 1.0 Sv for a 24-year-old female to 4.0 Sv for a 55-year-old male. The career limit for the lens of the eye has been reduced from 6.0 Sv to 4.0 Sv, while the skin exposure level has been reduced from 12.0 Sv to 6.0 Sv (Stanford, M., Nachtwey, D.S., 1990).

Table 4: Ionization Radiation Exposure Limits as recommended to NASA by the National Council on Radiation Protection and Measurements (NCRP); approval pending (Stanford and Nachtwey, 1990; used with permission of the American Society of Civil Engineers).

Exposure Interval	Depth (5 cm)	Eye (0.3 cm)	Skin (0.01 cm)
30 days	25 rem	100 rem	150 rem
Annual	50 rem	200 rem	300 rem
Career	100-400 rem	400 rem	600 rem

Table 5: Career Exposure by Age and Sex (Stanford and Nachtwey, 1990; used with permission of the American Society of Civil Engineers).

Sex	Age			
	25	35	45	55
Male	150 rem	250 rem	325 rem	400 rem
Female	100 rem	175 rem	250 rem	300 rem

Using their transport model, Silberberg et al. (1985) have derived the minimum thickness of the lunar regolith for radiation protection to be 400 g cm^{-2} if the annual dose equivalent is to be less than 5 rem, which is the permissible limit for radiation workers (Figure 2).

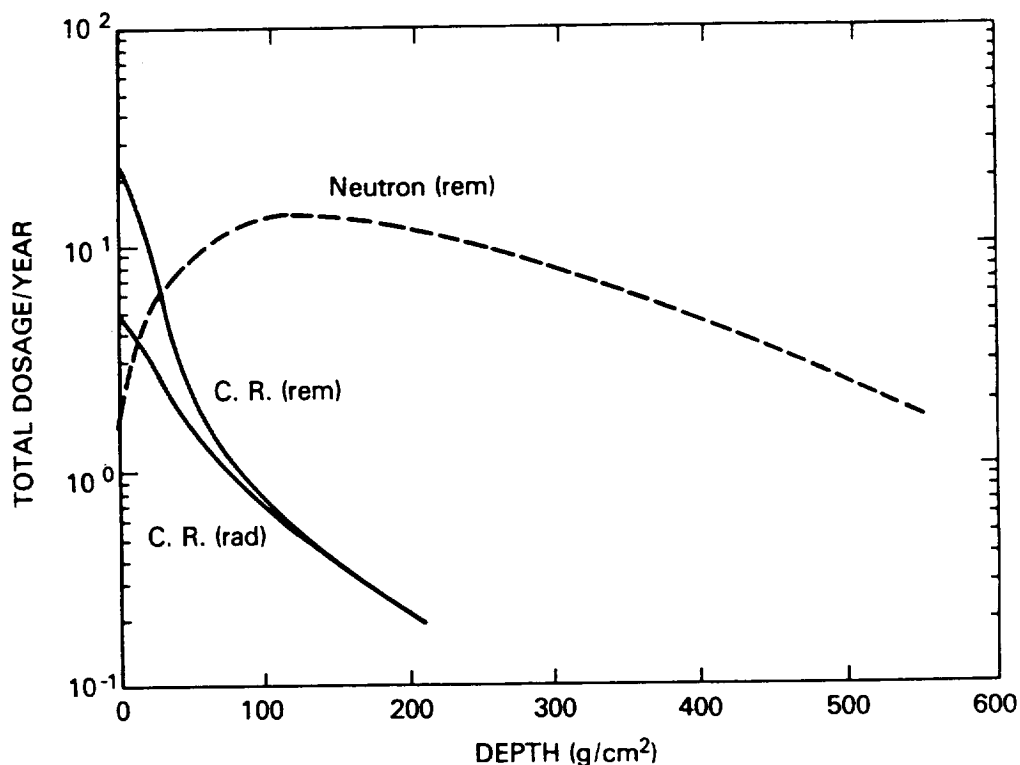


Figure 2. A comparison of the annual dose equivalent due to secondary neutrons, "Neutron (rem)", and cosmic-ray nuclei, "C.R. (rem)", as a function of shielding. Also, the absorbed dose rate due to cosmic-ray nuclei, "C.R. (rad)", is shown. (Silberberg, R. et al., 1985)

In another paper, Letaw, J.R. et al. (1989) have shown that astronauts can be protected from the initial effects of an acute

exposure to radiation from SPE with a storm shelter having $>7 \text{ g cm}^{-2}$ aluminum shielding or its equivalent, based on the worst case scenario of the anomalous solar flare event of August, 1972. In the same paper, they have also presented results for protection against GCR using different materials, such as lead, copper, aluminum, water, methane, and hydrogen (Figure 3).

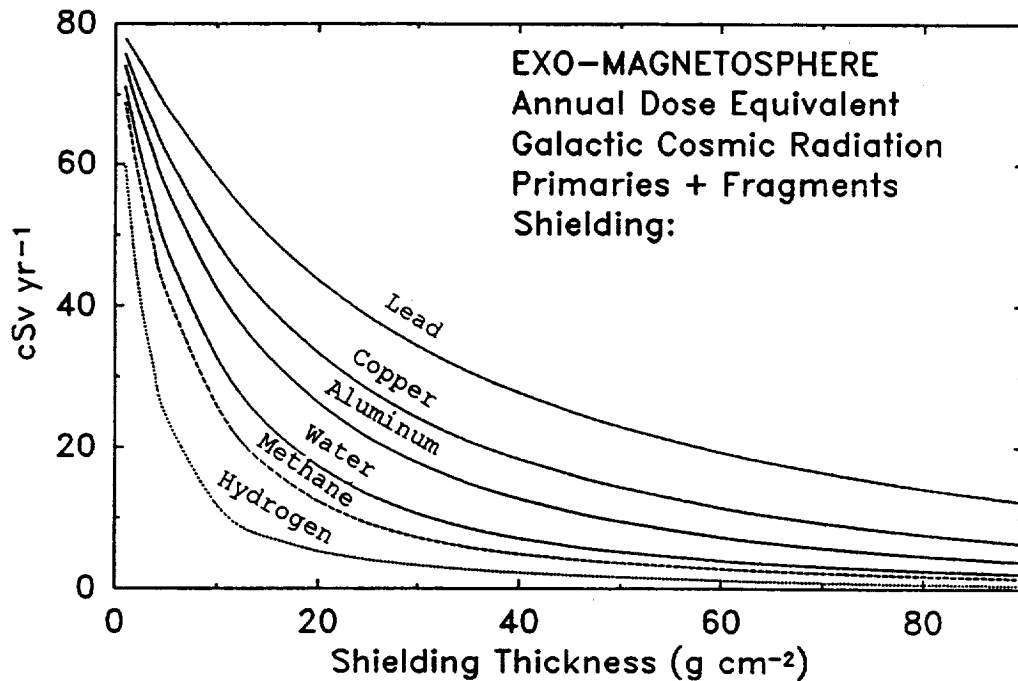


Figure 3. Annual dose equivalent from Galactic Cosmic Radiation (GCR) as a function of shielding thickness for several possible spacecraft shielding materials (Letaw, J.R., et al., 1989; used with permission of COSPAR).

In addition, they have derived the very useful formula, given

below, to estimate the aluminum shielding equivalent (X) of any thickness, $x \text{ g cm}^{-2}$, of another material having a mean atomic mass, \bar{A} .

$$\ln X = 1.16 + (0.977 + 0.018 \ln \bar{A}) \ln x - 0.371 \ln \bar{A}$$

for $\bar{A} > 1$, and

$$\ln X = 1.47 + 0.966 \ln x$$

for $\bar{A} = 1$ (hydrogen).

This formula represents their data to within 10% for shielding in the range $0.5 \text{ g cm}^{-2} \leq x \leq 80 \text{ g cm}^{-2}$ (of aluminum). For rough estimates, the equivalent aluminum shielding for any thickness of liquid H_2 , liquid CH_4 , H_2O , Cu(Fe) or Pb may be obtained by multiplying by 4.35, 2.07, 1.64, 0.684 or 0.441, respectively. Thus, liquid H_2 shielding is equivalent in effect to 4.35 times its weight (or thickness in g cm^{-2}) of aluminum. Approximately 50% more iron than aluminum is required to produce the same level of radiation protection.

Table 6. Equivalent of 1 g/cm^2 of aluminum shielding

Shielding Material	Equivalent Surface density gm/cm^2
Liquid Hydrogen	0.23
Liquid Methane	0.48
Water	0.61
Solid Copper or Iron	1.46
Solid Lead	2.27

2.4 Soil Properties

A total of 381.7 kg of lunar soil samples were brought back from the six Apollo missions to the Moon. A significant amount of literature has been generated in characterizing the chemical and physical properties of the lunar regolith. In this section only a brief summary is provided. Further information can be obtained by referring to articles by Papike et al. (1993), McKay, D.S. et al. (1993), Carrier, W.D. et al. (1993), McKay D.S. and Ming, D.W. (1989).

The top layer of the lunar surface is made of loose, rocky material which ranges from a few microns to millimeters in diameter. The finer components (<1 mm) are referred to as soil. The surface material is being constantly bombarded by micrometeorites, and this constant reworking has made the soil very loose, with bulk densities ranging from 0.9 to 1.1 g/cc in the top few centimeters and increasing with depth to as high as 1.9 g/cc. The average bulk densities range from 1.58 g/cc for 0- to 30-cm regolith depths to 1.74 g/cc for 30- to 60-cm regolith depths. The particle-size distribution (<1 mm) for Apollo 11 mare soil is given in Table 7 below.

Table 7: Grain-size distribution (<1 mm) for Apollo soil 10084,853. (McKay, D.S., and Ming, D.W., 1989)

Grain Size	Weight	Cumulative Wt.
mm	----- 8 -----	
10-4	1.67	1.67
4-2	2.39	4.06
2-1	3.20	7.26
1-0.5	4.01	11.27
0.5-0.25	7.72	18.99
0.25-0.15	8.23	27.22
0.15-0.090	11.51	38.72
0.090-0.075	4.01	42.73
0.075-0.045	12.40	55.14
0.045-0.020	18.02	73.15
<0.020	26.85	100.00

Lunar regolith consists of lithic and mineral debris as well as glass formed by impact-melting. Based on morphological characteristics, the regolith can be divided into:

1) **Agglutinates:** These are particles composed of lithic, mineral, and glass fragments welded together by a glassy matrix containing extremely fine-grained metallic Fe and formed by micrometeorite impact. Up to 60% of the regolith is made up of agglutinates.

2) **Crystalline, Igneous Rock:** Made up of basaltic fragments, which are composed of plagioclase feldspar $(Ca, Na)(Al, Si)_4O_8$, pyroxene $(Ca, Mg, Fe)SiO_3$, ilmenite $(FeTiO_3)$, and sometimes olivine $(Mg, Fe)_2Si_4$. Mare basalt can be either high-Ti (TiO_2 contents > 9%

wt.) or low-Ti (TiO_2 contents < 5.0 % wt.) Other crystalline fragments include basalts rich in K, Rare-Earth Elements, and P (KREEP), as well as anorthosites.

3) **Breccias:** Breccias are formed from lithification of crystalline lithic fragments and regolith components, during complex impact-driven processes. A wide variety of breccias are classified as either:

- a) vitric-matrix breccias,
- b) fragmental-matrix breccias,
- c) cataclastic anorthosites,
- d) crystalline-matrix breccias, and
- e) granulitic-matrix breccias.

4) **Mineral Fragments:** During meteorite impact, lithic fragments are broken, and the mineral fragments separate and get deposited into the regolith.

5) **Glass:** Different types of glasses formed by impact or of volcanic origin are found in lunar regolith. They come in a variety of shapes, such as ropy glasses, and spheres.

These different components contribute to the physical properties of the regolith, such as specific gravity, porosity, compressibility, shear strength, permeability, diffusivity, ultimate bearing capacity, (static and dynamic), slope stability, trafficability,

electrical conductivity, dielectric permittivity, etc. For more details on these topics the reader can refer to Carrier, W.D. et al. (1993). These physical characteristics impact excavation, as well as the stability of regolith-based radiation protection schemes, the movement of vehicles on the lunar surface, dust control schemes, etc.

2.5 Meteorite Impacts

Meteoroid impacts on the Moon of about 10^{-6} g can produce craters of 500 μm in diameter in metal; the depth of the crater is usually comparable to the diameter of the crater, except in the case of brittle materials, where the damage can extend further down. According to Vaniman (1993b), two to three millimeters of a tough composite material is relatively effective shielding against damage by micrometeorites in the milligram range. Thus, for all practical purposes, if the habitat is protected for radiation, it will be adequately protected for micrometeorite damage. On the other hand, while the chance of a meteorite of mass 1 gram or greater striking an astronaut is relatively small (probability of such a meteorite striking is about 1 in 10^6 to 10^8 for one year of cumulative time that the astronaut is exposed on the surface), the hazards of striking a habitat are greater, due to its longer duration on the surface. At this point, meteorite hazards are not fully known, and are dependent on the nature of the structure considered.

2.6 Seismic Activity

Unlike the Earth, which is continually undergoing tectonic activity even now, the Moon is relatively inert. The forces that produce the faults, folds, mountain ranges, etc. on the surface of a planet are largely absent on the Moon. The energy released by internal tectonic activity on the Moon is a minor process; the energy released by lunar earthquakes ("moonquakes") is in the order of 10^{-12} times as much as the seismic energy released by the Earth (Hörz, F. et al. (1993)). In addition, the crust of the Moon appears to be relatively thick, rigid, immobile and cool in comparison to the crust of the Earth. Most of the lunar tectonic activity is driven by forces external to the Moon - tidal stresses and large meteorite impacts. Thus seismic activity is not a significant design issue for lunar habitation.

3. HABITAT DESIGNS IN LITERATURE

The document commonly referred to as the "Stafford Report" (Stafford, T.P., 1991) has identified four combined Moon-Mars mission scenarios to enable human presence on these extraterrestrial locations, exploration and science, and space resource development for the benefit of Earth. The mission scenarios (referred to as "architectures" in the report) vary with the degree of human presence, the magnitude of exploration and science effort, and the extent to which space resources are

developed, in addition to the relative emphasis on lunar and Martian activities. The mission scenarios proposed were as follows:

Mars Exploration (Architecture 1): This architecture emphasizes Mars exploration and science. The lunar infrastructure would be developed only to the degree necessary to test and gain experience with Mars systems and to rehearse on the Moon, the extended duration Mars mission. The Moon would be explored while developing operational concepts for Mars.

Science on the Moon and Mars (Architecture 2): The Moon and Mars are equally emphasized. Life science data required for Martian missions would be generated through extensive operations on the Moon. Initial instrumentation on the Moon would be portable, while in latter stages of implementation of the architecture, emphasis would shift to larger scientific experiments and emplaced instruments after developing surface capabilities for construction, maintenance and operations.

The Moon to Stay and Mars to Explore (Architecture 3): This architecture emphasizes permanent human presence on the Moon, combined with exploration of Mars. One of the major objectives would be to build life-support self-sufficiency for breathing gases and food production on the Moon. Impressive scientific capabilities are planned. Extensive space and lunar surface operations are

planned on the Moon to provide the necessary life science and engineering data to prepare for future exploration missions to Mars.

Space Resource Utilization (Architecture 4): This architecture makes maximum use of available space resources to support the exploration missions directly. It also seeks to develop a large class of available resources for a broader range of transportation, habitation, life science, energy production, construction and many other long term activities. As in the previous architectures, the initial visit would be to the Moon, followed by a visit to Mars.

Given the proximity of the Moon, and the Apollo experience which has actually placed men on the Moon, it would be reasonable to expect that habitat designs in the literature would be dominated by Lunar scenarios. This is so, in particular since significant literature has been generated that characterized the lunar soil, lunar surface temperature, radiation levels, magnetic field and seismic activity.

3.1 Lunar Habitat Classification Schemes.

In order to provide a framework to conduct trade studies for lunar habitat designs, it is necessary to classify the habitat designs according to a few basic characteristics. These are:

- 1) *Mission type* - Initial Operational Capabilities, Long or Short Duration, Scientific Experiments, *In-Situ* Resource Utilization capabilities.
- 2) *Crew Size* - can vary from 3 to 18 or more.
- 3) *Total Duration of Stay* - A lunar day or more, up to indefinite.
- 4) *Modularity* - Level of modularity of the habitat design and types of habitat modules; i.e. Space Station Freedom modules or others.
- 5) *Environmental Protection Measures* - Radiation protection, thermal stress protection, leak protection and dust control.
- 6) *Emplacement* - Above/below the surface, equatorial/polar locations.

In addition to the primary classification scheme outlined above, the habitats can be categorized by types of man-made structures such as (Toups, L., 1990):

- 1) *Prefabricated Modules*: These consist of self-contained pressurized vessels, constructed on Earth, and the finished habitat delivered to the lunar surface.
- 2) *Pneumatic Structure*: Any structure supported by the action of pneumatic pressure differentials, using gases. This could be achieved by either a) inflatable structural members such as columns, beams, etc., or b) the entire structure could be a

single (or double) membrane supported by air pressure differentials.

- 3) *Prefabricated Frame Structures:* These are composed of individual structural members. The members are usually fabricated in metallic tubular shapes with separate pieces, and connectors. The individual tubes would be interconnected with the help of connectors and would be stressed axially either in tension or compression. A common terrestrial example would be the geodesic dome.
- 4) *Tent Structures:* These consist of suspended or supported roofs, made of stressed fabric, in the form of a tent. The stressing would be accomplished by arches or ribs.
- 5) *Tunneling:* Tunnel passages through the surface could be created by soil melting, drilling, coring, shafting and explosives. The resulting tunnels would provide the volume required for habitat emplacement within.

A second category would include crater and lava tube applications:

- 6) *Craters:* Craters are formed by meteorite bombardment which is believed to have occurred over 4 billion years ago. These craters could be used to emplace habitats, especially in polar regions.

7) *Lava Tubes*: Lava tubes are formed as a result of volcanic activity. These could provide natural protection against radiation and thermal stresses, as the thickness of the regolith can be on the order of many meters, providing ample radiation protection.

A third category would include habitats made from locally available materials.

8) *Concrete*: Concrete could be made from locally available regolith; some substitute for water would be needed since water is scarce on the Moon.

9) *Basalt*: Sintered, spun, or cast basalt could be used for producing bricks, pipes, conduits, reinforcement, insulation and other building materials.

10) *Glass Matrix/fibre*: Composites reinforced with these materials could be used to serve as building material.

11) *Metals*: Aluminum, iron, and titanium from processed lunar ore could provide building materials with the required strength.

3.2 Habitat Design Concepts

A literature search covering the range of almost thirty years has yielded over twenty habitat design concepts. In the following, a brief summary of these habitat concepts is presented. The earliest post-Apollo lunar habitat designs were the ones mentioned earlier, i.e., Boeing (1963), Lockheed (1965), and Rockwell Intl. (1971). Following the Space Shuttle era in the early 80s, interest in lunar habitat designs started picking up, and the designs summarized below reflect the period from the early eighties to the present.

Burke, J.D. (1985) provides an example of a habitat (Figure 4) that is designed to be emplaced in the polar regions of the Moon. The unique geographical conditions around the lunar poles suggest the possibility of the existence of ice in these locations. In addition, some polar regions would be continuously lit, enabling light piping into the habitat using heliostats. By emplacing the habitat under the lunar regolith, the crew members are protected adequately against radiation effects and extreme thermal stresses.

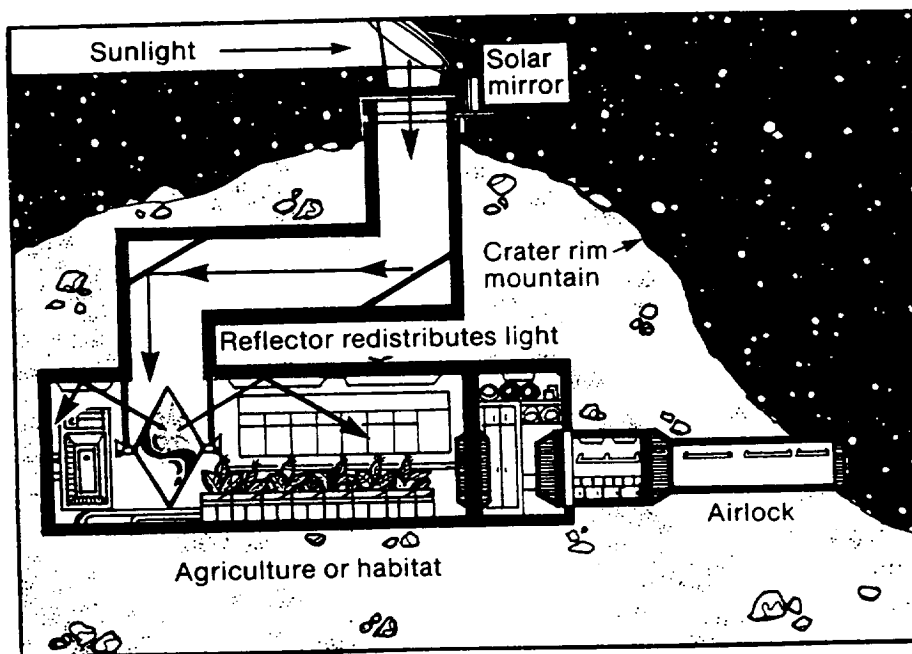


Figure 4. Habitat emplaced on lunar pole. (Burke, J.D., 1985)

Duke, M.B., et al. (1985) have presented a phased evolution of their lunar base, for three scenarios, i.e., scientific research, production, and self-sufficiency (Figure 5), which would be accomplished in four stages as follows:

Phase I: Preparatory Exploration

Phase II: Research Outpost

Phase III: Operational Base

Phase IV: Advanced Base

The first lunar habitats and laboratories could be space station modules, buried in the lunar regolith for protection from solar flare radiation.

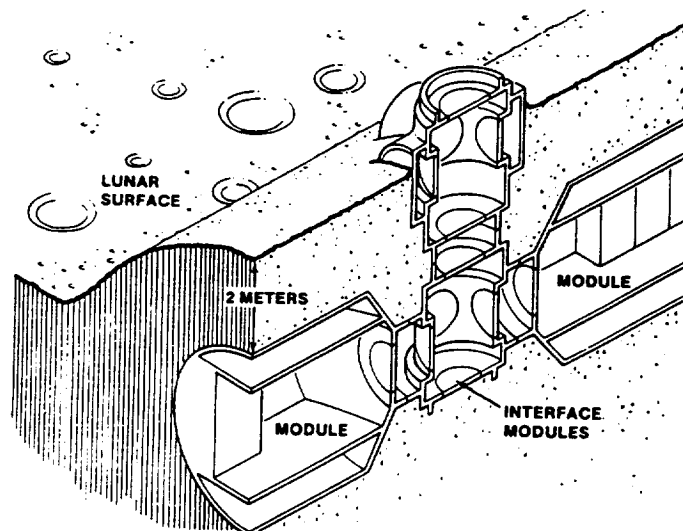


Figure 5. Phased Evolution of Lunar Base (Duke, M.B. et al., 1985).

Kaplicky, J. and Nixon, D. (1985) have provided an alternative to burying the habitats within the soil as suggested by Duke et al. (1985) and Burke (1985). Instead, they envision a scenario, where it is possible to develop a simple, manually deployable, superstructure to enclose and envelop the module complex at the lunar surface level and provide the necessary shielding by means of a "stand-off" layer of regolith deposited over the upper surface of the envelope (Figure 6). The plan calls for 6 modules (SSF) each 10 m length by 4.5 dia. and capable of accommodating up to six persons; the initial aim is to provide a research outpost, with modules for habitation, logistics and laboratories. The fully stowed envelope system, complete with tools and accessories, would be delivered to low-Earth orbit by the shuttle, with transit from LEO to lunar surface by means of an Earth-to-Moon transportation system.

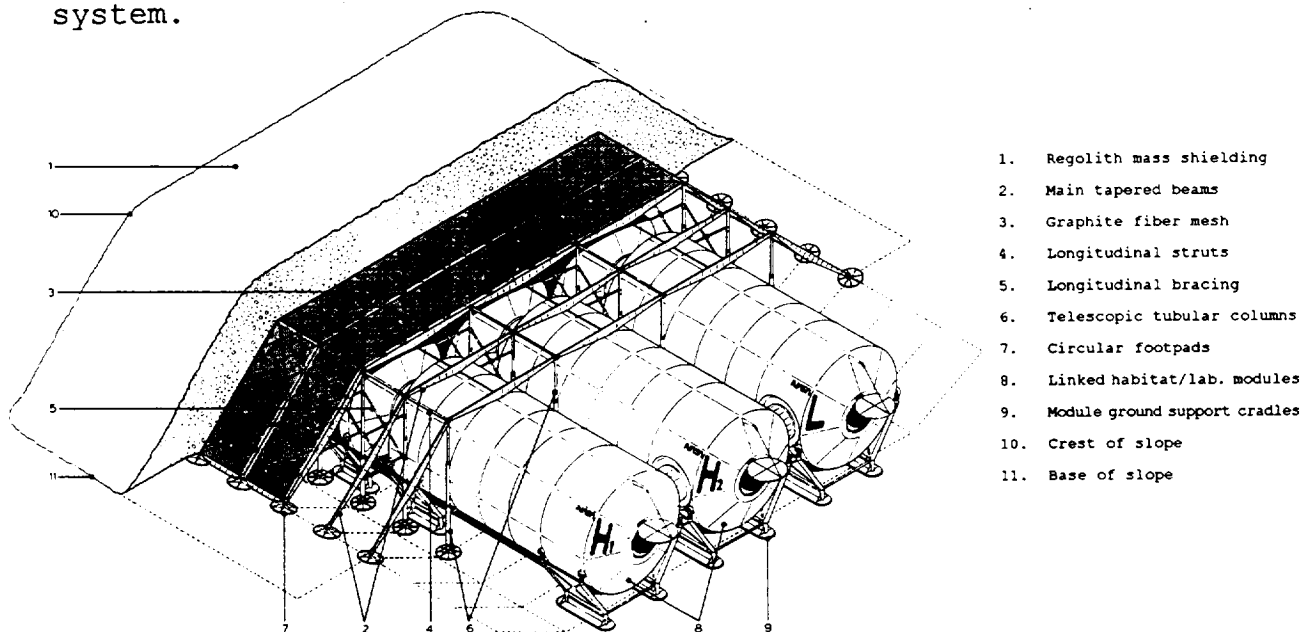
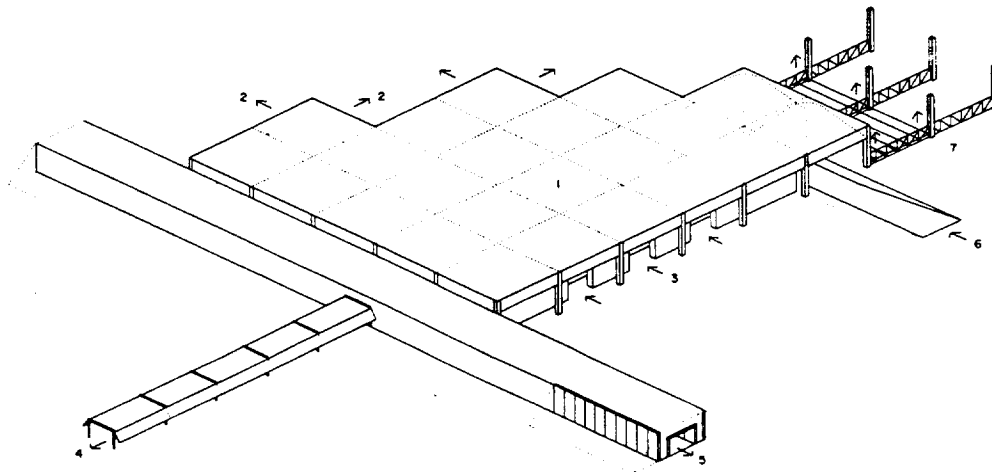


Figure 6. Manually deployable superstructure envelope over SSF modules (Kaplicky, J. and Nixon, D., 1985).

Land, P. (1985) provides habitat concepts consisting of two independent parts: 1) pressurized enclosures under 2) radiation shielding canopies (Figure 7). The size and shape of the enclosures would be determined by the extent of the operations they would accommodate. The height and extent of the shielding canopies would be influenced by the structural system. The canopies would be made from lunar resources, while the pressurized enclosures made from the pneumatic structures would be lightweight and packageable into small volumes for transport and terrestrial manufacture. No details on the specifications and dimensions for the base functions are provided in this publication.



- | | |
|---|--|
| 1. Regolith Shielding | 4. Solar shaded links to other parts of base |
| 2. Perimeter expansion | 5. Shielded links to other parts of base |
| 3. Base entry through overlapping radiation barrier walls, from lunar surface equipment and installation "park" | 6. Ramp access to lower levels |
| | 7. Initial erection sequence |

Figure 7. Pressurized Enclosures under radiation shielding canopies (Land, P., 1985).

Kennedy, K. and Cerimele, M.P. (1990) have detailed different initial habitats, laboratories, airlocks, expanded habitats and logistics modules, as part of a study for the Planetary Surface Systems Office (PSS) of the New Initiatives Office (NIO) at JSC. One of these designs is a 16 m dia. spherically constructible habitat (Figure 8). This habitat was designed to provide a living and working environment for a crew of 12. The total structural volume is 2145 m³, with five levels of living and working areas, and 742 m² of floor space. The habitat is composed of a spherical pneumatic envelope (the primary structure) and an internal structure (the secondary structure). The primary structure's function is that of a pressure vessel designed to withstand an internal pressure of 14.7 psia. The inflatable envelope would be a composite of high-strength lightweight multiple-ply fabric with a non-permeable bladder inside and a thermal coating on the exterior. The internal structure is composed of six telescoping hexagonal core columns, six peripheral ribs, radial floor beams, circumferential joints, intermittent floor joists and secondary bracing. The habitat would be supported by a mat foundation that transferred the loading from the interior to the exterior support structure at seven hard points. The initial structural sizing analysis was based on T851 Aluminum alloy, similar to the metal used for the lunar rovers of Apollo.

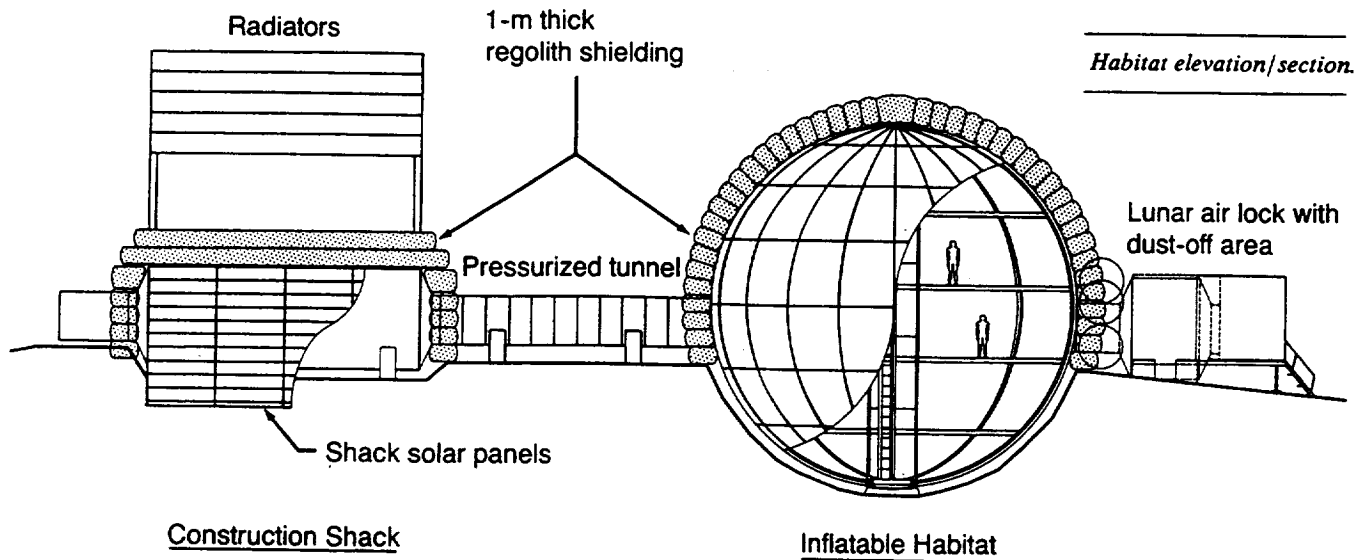
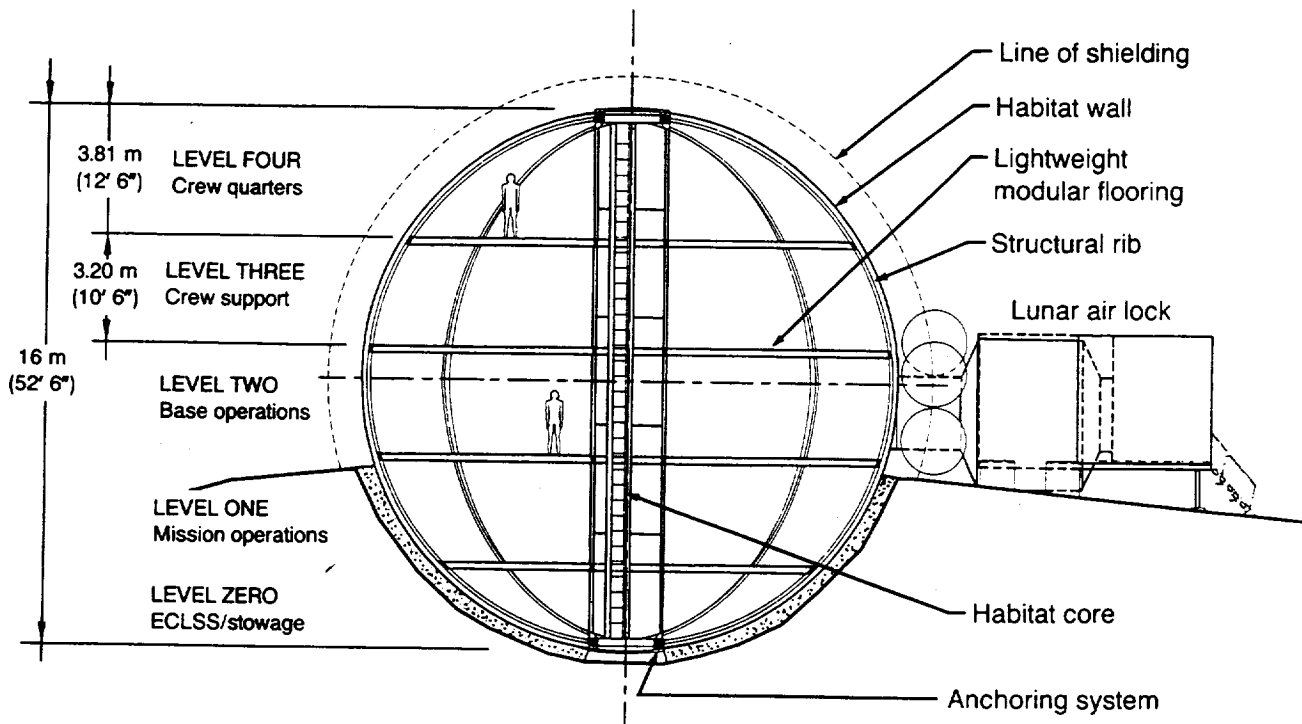


Figure 8. Spherical 16 m dia. habitat (Kennedy, K., and Cerimele, M.P., 1990).

Kennedy, K. (1992) has provided an alternate design for an inflatable habitat, composed of a cylindrical pneumatic envelope (the primary structure) and a secondary support structure (Figure 9). The pneumatic envelope would be designed to operate at a pressure of 14.7 psia. The secondary support structure would consist of an internal floor system, a second level arch-frame structure and an external exo-structure. The secondary structure's function would be to support the internal equipment, furnishings, and crew members and also support the fabric in case of a pressure loss. The inflatable envelope is composed of high-strength lightweight multiple-ply fabric with a non-permeable bladder inside and a thermal coating on the exterior. Inflatable fabric materials under consideration at NASA-JSC include composites of Kevlar, Mylar and Spectra. The internal structure would be composed of a pallet-type space frame flooring system that would connect to ten hard-points on each side of each level in the membrane wall, a total of 40 hard-points. As in the case of the spherical structure mentioned in the previous concept, the habitat would be designed to provide a living and working environment for 12 crew members. The cylinder would be 8 m dia. and 43.34 m long, providing 2145 m³ of internal volume and a floor space of 547 m².

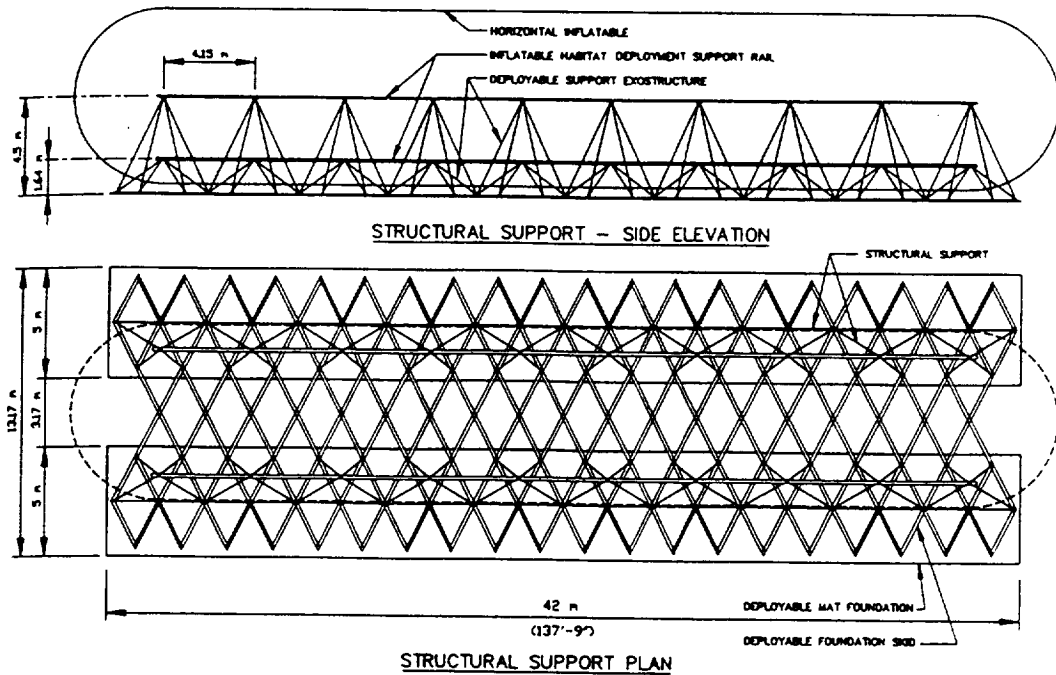
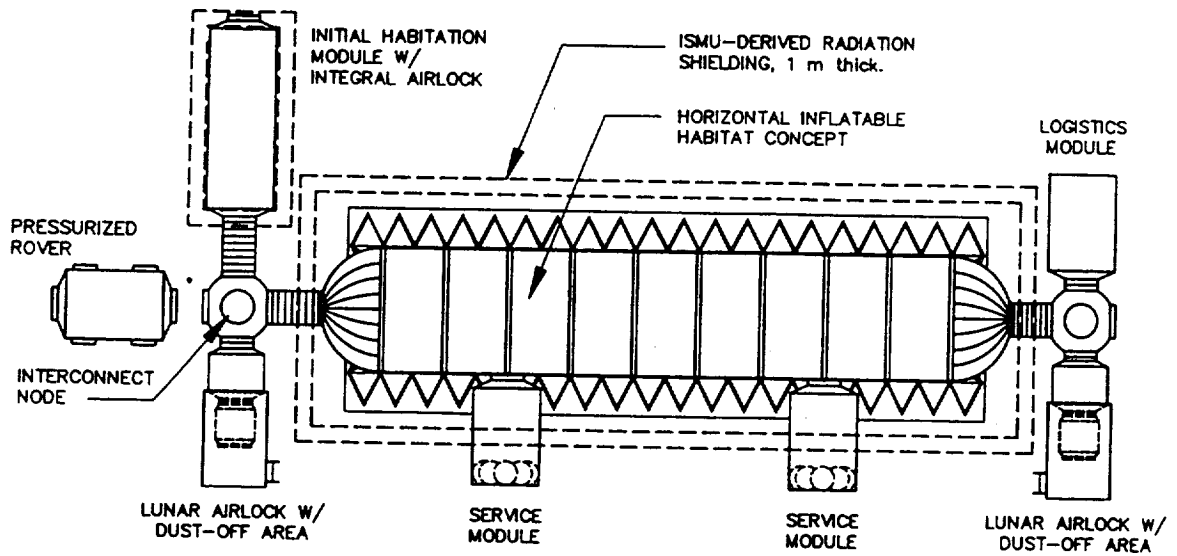


Figure 9. Cylindrical habitat (Kennedy, K., 1992; used with permission of the American Society of Civil Engineers).

Hypes, W.D. et al. (1992) have presented three concept designs for initial habitats, which are capable of supporting a crew of four for 28-30 days. Two of these utilize Space Station Freedom structural elements, while the third utilizes an earlier expandable-module-technology base. The third concept is the most interesting among them (Figure 10), and features a hybrid rigid-expandable habitat that utilizes the most favorable features while avoiding the design weaknesses of earlier expandable designs. The low packaged volume to deployed volume ratio achievable with this design makes it a very useful one. The habitat has a double airlock arrangement utilizing metal pressure vessels, making the habitat appropriate for pressure cycling of the airlock. The double airlock elements are also coupled with a regolith coverage technique to provide a safe haven in the event of failure of the expandable habitat and also as a special safe haven in the event of a solar flare.

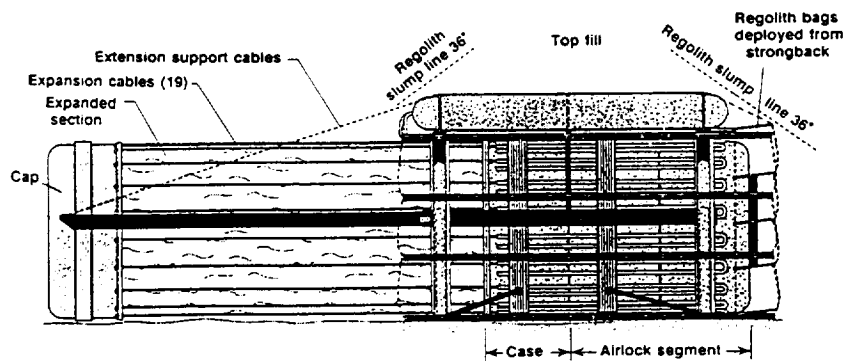


Figure 10. Hybrid expandable/rigid habitat (Hypes, W.D. et al., 1992; used with permission of the American Society of Civil Engineers).

Moore, G.T. (1991) has presented the Genesis II Advanced Lunar Outpost design (Figure 11), which includes launch and landing facilities, a solar power array field, a mining facility, habitat and laboratory facilities, a nuclear power generator, and a far-side astronomical observatory. The habitation/laboratory complex is a five-level structure, with the following components:

- 1) At Level 1, are two EVA modules which contain the suit stowage, maintenance, and airlocks. This level would be on the lunar surface. These modules are covered with regolith to provide the required radiation protection.
- 2) Level 2 consists of a Shuttle-C module which serves to connect the modules above the surface to the ones below the surface, within a lava tube.
- 3) Connected to Level 2 (the Shuttle-C cylindrical module), and within the lava-tube are two two-level inflatables, the habitation module and the laboratory module (Level 3 & 4). The habitation module would be physically separated from the rest of the base, and would be attached only through a connection node and an emergency hatch. It would face the entrance to the lava tube, thus providing access to great views of the moonscape. The laboratory module faces the interior of the lava tube, and contains the scientific equipment. These inflatables would be made of a double-layered membrane (Kevlar) within the space of which structural foam would be inflated, raising the structure to its final shape, and rigidizing it.

4) On Level 5, would be three modules: the EVA module, Suit Storage and Maintenance Module, and the Crew Support Module. These modules would be hung from a space frame, needed to overcome the unevenness of the interior of the lava tube.

The lunar base was designed to accommodate 12 crew members for an indefinite period of time.

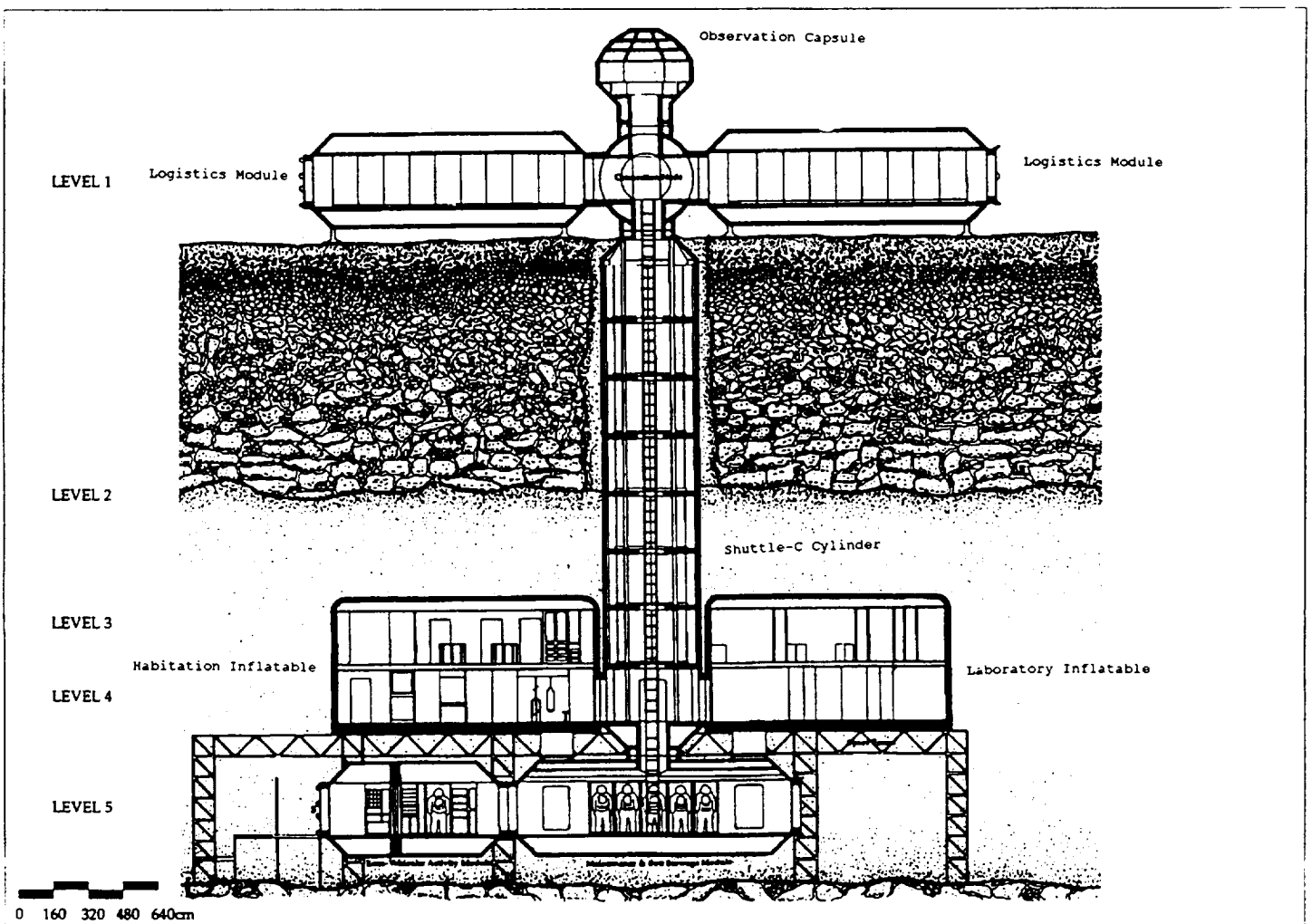


Figure 11. Genesis II Advanced Lunar Outpost (Moore, G.T. (1991)).

Nowak, P.S. et al. (1992), in their paper discuss the use of inflatable modules which structurally resemble pillows connected to one another (Figure 12). Their contention is that if the structure is properly designed, only tensile stresses are induced in the membrane materials used in making the inflatable habitats. Each module consists of the following structural components: 1) Four external wall membranes; 2) a roof and a floor membrane; 3) four columns with footing; and 4) four rigid arches. The habitat is covered by 2.7 m of regolith to provide the necessary radiation shielding. The modules are 6.1 x 6.1 x 3 m, selected on the basis of the size of a typical office and/or living room on Earth. The radius of curvature of the roof membrane was chosen based on a compromise between reducing wasted internal volume (a low radius) and lowering the induced stresses (a higher radius). The advantages quoted by the authors are increased modularity, a minimal number of structural components to facilitate manufacturing, expandability through any of the exterior wall membranes, the ability to isolate pressure losses with interior-pressure-resistant partitions, and a low ratio of volume to usable floor space. Rigid arches, formed from structural foam filling membrane tubes, rigidize when exposed to the vacuum of the lunar atmosphere.

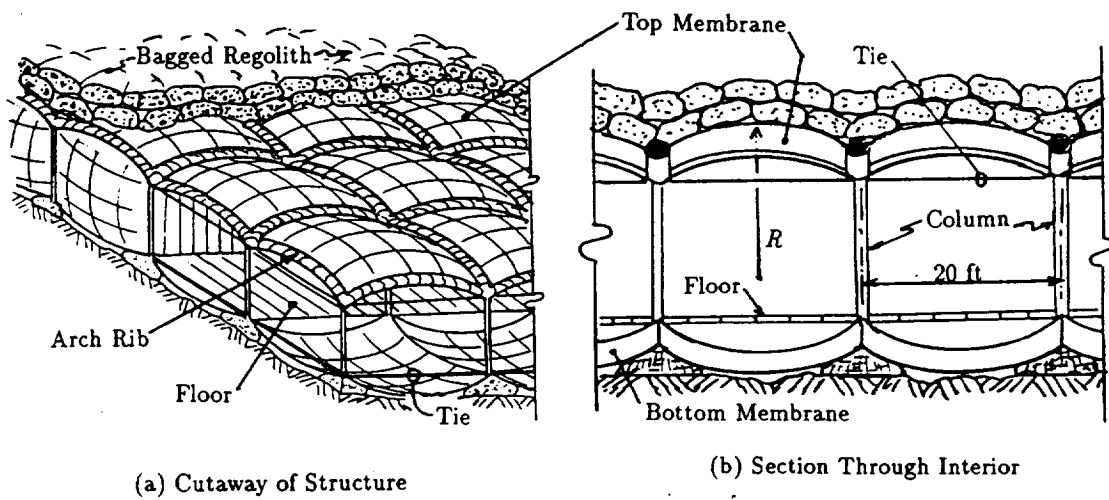


Figure 12. Inflatable Habitats (Nowak, P.S. et al., 1992; used with the permission of the American Society of Civil Engineers).

Soil confined within a three-dimensional space, could provide structures with excellent compressive strength, shear strength and stiffness. Structures comprising these as building blocks have many advantages, claims Harrison, R.A. (1992). The fabric could be fashioned into cylindrical tubes, creating Cylindrical Fabric-Confined Soil (CFCS) structures. The length, diameter, and curvature of the tubes would depend on the intended application. These tubes could be fashioned into beams, columns, arches, walls, etc. These structural support materials could be used in building pressurized and unpressurized modules, over which regolith would be heaped to provide the required radiation protection. Shown in Figure 13 is an example of a cylindrical inflatable design, with the shaded region indicating regolith coverage.

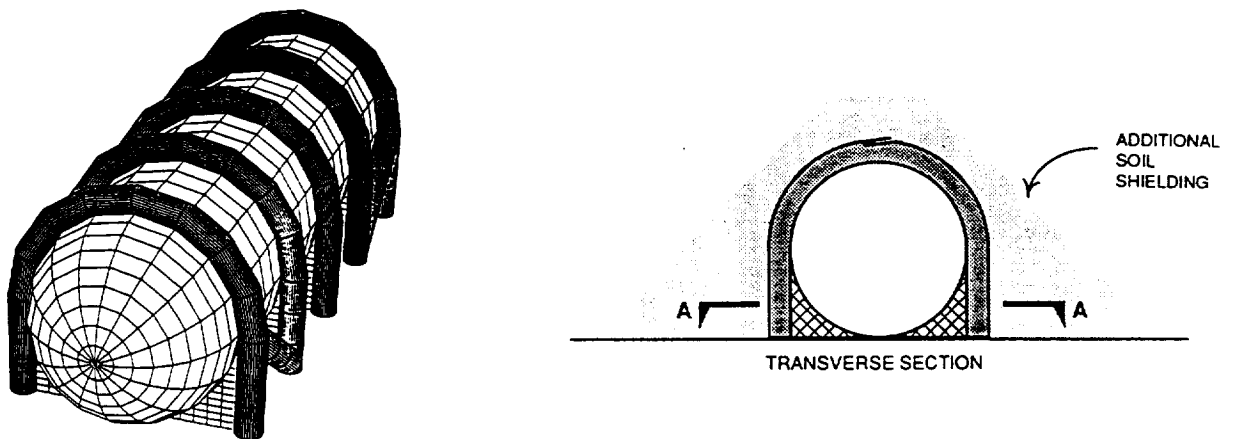


Figure 13. Cylindrical Fabric-Confined Soil Structures (Harrison, R.A., 1992; used with the permission of the American Society of Civil Engineers).

Circular cross-sections used in cylindrical and spherical constructions could lead to wasted space. Matsumoto, E.E. *et al.* (1992) provide examples of inflatable structures with non-circular cross sections (Figure 14). A non-circular cross section could provide a large ratio of usable-space to total-space and would limit excavation into the hard lunar subsurface. Six approaches to obtain the required non-circular cross sections are suggested by the authors: A) cable-reinforced membranes, B) external cable anchorage, C) membranes designed through formfinding, D) regolith ballast restraint, E) membranes combined with rigid structural members, and F) tension columns and partitions. The authors did not provide any specifications or details on a lunar base design which would include these structural features.

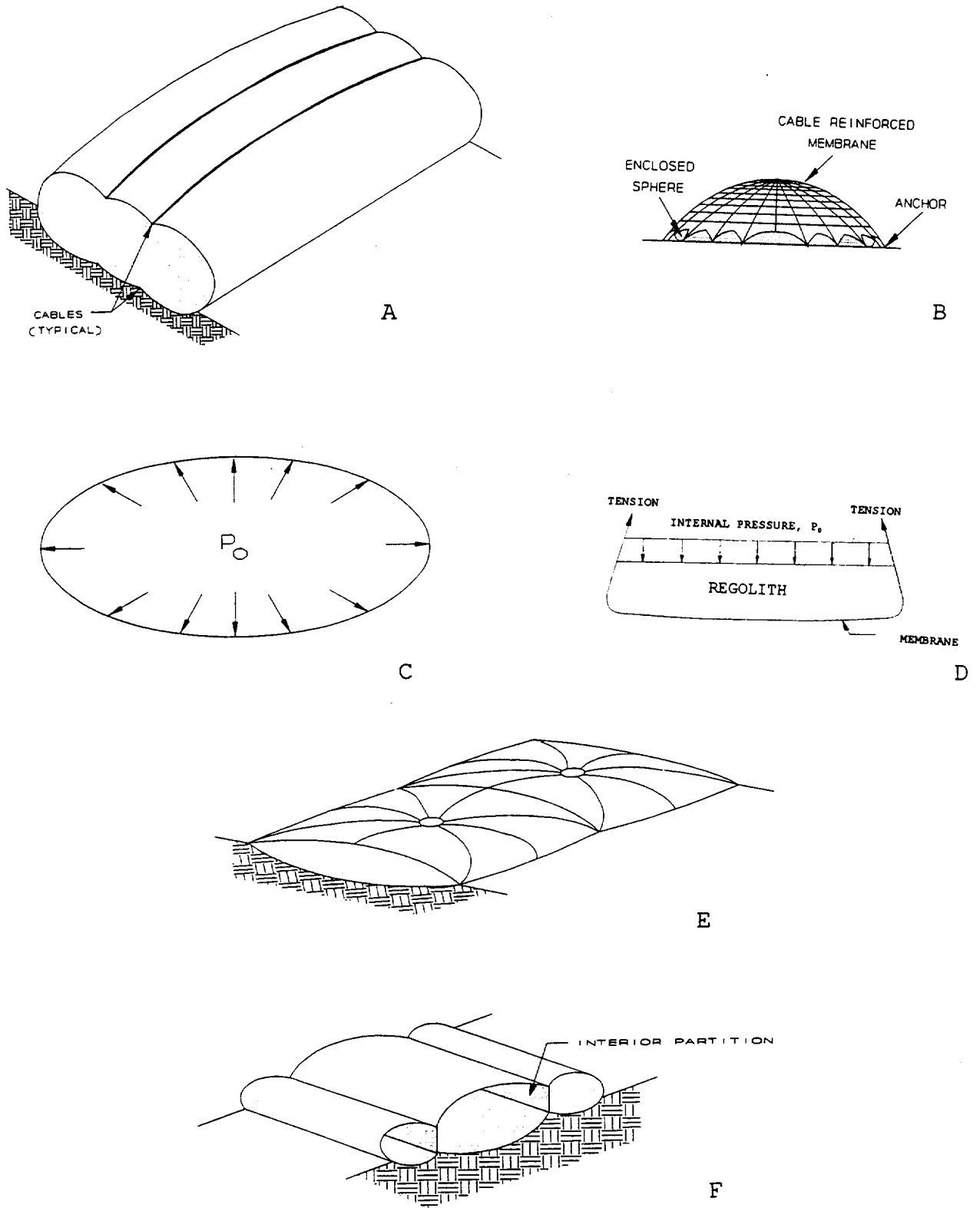


Figure 14. Inflatable habitats with non-circular cross-section (Matsumoto, E.E., et al., 1992; used with permission of the American Society of Civil Engineers).

Haninger, E.R. and Richter, P.J. (1992) provide a description of cubically shaped aluminum modules which could be variously arranged to form living and working quarters for a lunar base (Figure 15). The cubic shape was chosen as it offered certain advantages over other shapes. Though it is not as structurally efficient as a circular or spherical shape, the cube is space efficient, both in terms of internal space as well as in external arrangements. Cubes could be formed from flat panels, which are easy to stack for storage and shipment. As in other modular construction, compartmentalization of pressure drop would provide a safety feature; in the case of an emergency, certain modules could be sealed off with automatic closures. The module size is dictated by shipping and assembly considerations; the module is composed of six primary exterior panels, plus other interior structural members. A panel width of 12 ft could be easily accommodated within a 15 ft dia. cargo bay; the height of the module would be based on internal space requirements, and a working space of 8 ft was chosen as a reasonable dimension. The modules are designed to handle internal pressures of 13 psi and regolith thickness of up to 10 ft for regolith protection. The most practical choice of material for these panels would be titanium or aluminum, which have high strength-to-weight ratios.

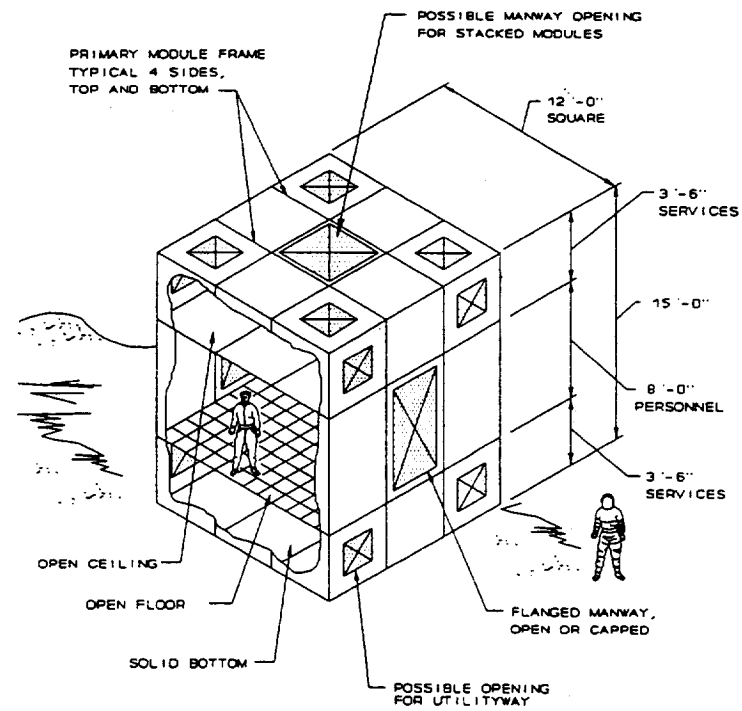
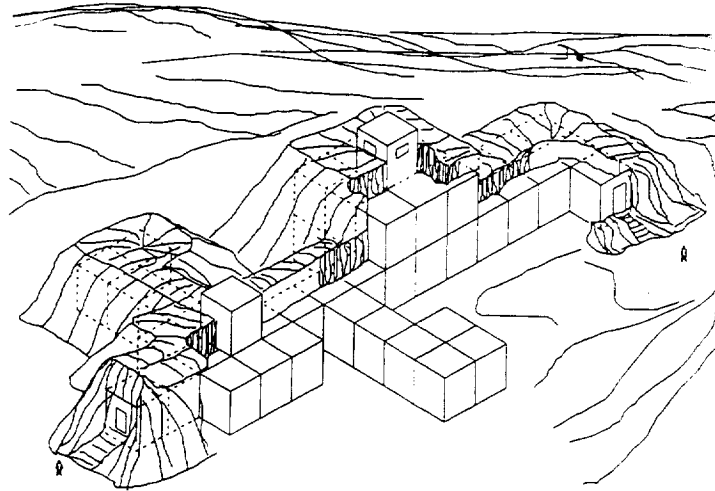


Figure 15. Cubical modular habitat (Haninger, E.R. and Richter, P.J., 1992; used with permission of the American Society of Civil Engineers).

Cement prepared from lunar soil materials could make a good construction material, and Bialla, P., et al. (1992) provide some examples of how modular habitat units could be designed from the lunar concrete (Figure 16). From almost totally local resources, concrete could be manufactured; crushed regolith could be used to manufacture aggregate, extracted calcium silicate could be used for cement, and oxygen obtained through electrolysis combined with Earth-delivered hydrogen could provide the required water. The lunar concrete would be formed into prestressed modules capable of being assembled into structures which could then be used in making larger structures. The concrete used in these structures would provide protection from thermal stresses, radiation and micrometeorite bombardment on the lunar surface.

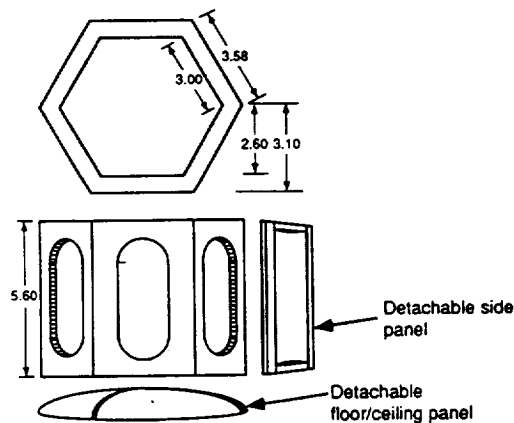


Figure 16. Concrete habitats using lunar resources (Bialla, P. et al., 1992; used with permission of the American Society of Civil Engineers).

In another example of using some form of lunar regolith for construction purposes, Cliffton, E.W. (1990) suggests the use of fused regolith. Concentrated solar radiation would be used to manufacture fused regolith at temperatures between 900 °C and 1000 °C. Fusion of the soil would provide modest soil compaction, without the use of vibratory or other heavy machinery. The compressive and tensile properties of the fused regolith material would be comparable to concrete. The building form envisaged by Cliffton takes the shape of an inverted truncated pyramid, and is modular, allowing for linking of multiple modules for extended functionality. The buildings are two-storied to limit dust-intrusion; design pressure would be 0.5 MPa, allowing for increased partial pressure of oxygen. It is not clear how many crew members could be accommodated in each of these modules.

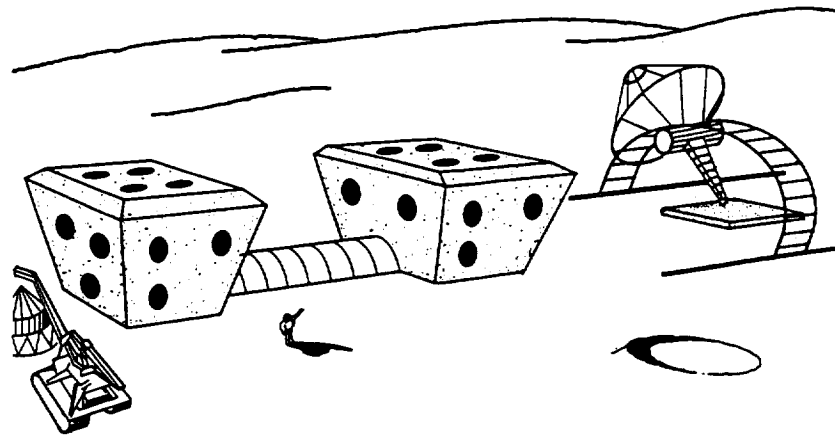


Figure 17. Fused regolith habitat (Cliffton, E.W., 1990; used with permission of the American Society of Civil Engineers).

3.3 Narrowing Habitat Design Choices

For conducting a trade study of habitat designs, a limited number of distinctly different habitat concepts had to be selected. The following simple set of criteria were applied:

1. Post Apollo designs
2. Uniqueness of the habitat design
3. Level of thoroughness in design layout
4. Habitat dimensions are provided
5. Materials of construction for the habitat shell are specified.

Based on these simple criteria, the following 5 designs were chosen:

- 1 Spherical habitat on lunar surface design by JSC-Advanced Systems Engineering Team. (Kennedy, K. and Cerimele, M.P.; 1990)
- 2 Cylindrical habitat on lunar surface design by JSC-Advanced Systems Engineering Team. (Kennedy, K.; 1992)
- 3 Genesis II habitat within lava tube design by University of Wisconsin-Milwaukee (Moore, G.T.; 1991).
- 4 Linked Space Station Freedom modules on lunar surface design by Future Systems Consultants (Kaplicky, J., and Nixon, D.; 1985).
- 5 Hybrid Expandable/Rigid module on lunar surface design by Science & Technology Corp. (Hypes, W.D. et al.; 1992).

A matrix of key lunar habitat design parameters is shown in Table 8 against the five chosen designs.

Table 8. Lunar Habitat Design Parameter Matrix

Habitat Design Top-Level					
Design Team	Design 1	Design 2	Design 3	Design 4	Design 5
JSC-Adv. Systems Engg. Division	JSC-Adv. Systems Engg. Division	JSC-Adv. Systems Engg. Division	Univ. of Wisconsin	Future Systems Consultants	Integrtd. Corp., VA
Mission Scenario	Permanent Outpost	Permanent Outpost	Permanent Outpost	Initial Operations	Initial Operations
Crew Size	12	12	12	6	3
Number of Days	Indefinite	Indefinite	Indefinite	~ 100 days	28-30 days
Habitat Design Details					
Habitat Shape	Spherical	Cylindrical	Cylindrical & box	Cylindrical	Cylindrical
Habitat dimensions	16 m dia.	8 m dia x 45 m lt.	Cyl: 4 m dia x 10m Box: 12.4 m sq.	4.5 m x 10 m lt.	3.65 m dia x 73.(11) m lt.
Construction Material	Prim: spherical Second: Internal rigid struct	Prim: Spherical Second: Internal rigid struct	Rigid Cyl. (SSF**) Inflatable square	SSF** modifications (rigid) + envelope	Rigid airlock + flexible expansion
Habitat Type	Inflat./Rigid Hybrid	Inflat./Rigid Hybrid	Hybrid	Rigid	Hybrid
Modular Type	Single unit; 5 levels above ground	Single unit; 2 levels above ground	Multilevel; Above & below ground	Multiple, linked, above ground	Single unit
Thermal Stress Protection	Bagged Regolith	ISMU* derived	Upper - regolith Lower - lava tube	Regolith over envelope	Regolith
Micrometeorite Protection	Bagged Regolith	ISMU* derived	Upper - regolith Lower - lava tube	Regolith over envelope	Regolith
Radiation Protection	Bagged Regolith	ISMU* derived	Upper - regolith Lower - lava tube	Regolith over envelope	Regolith
Pneumatic Pressure for support; inside pressure	Yes; 14.7 psia	Yes; 14.7 psia	No, rigidized foam; 14.7 psia	No; 14.7 psia	No; 14.7 psia
Functional Adaptability	Very adaptable	Very adaptable	Adaptable	Very adaptable	Not adaptable
Horizontal Growth Potential	Very good	Good	Moderate on upper level	Very good	Poor
Vertical Growth Potential	Poor	Poor	Poor	Poor	Poor
Reference	Kennedy, K., and Cerimele, M.P. (1990)	Kennedy, K. (1992)	Moore, G. T. (1991)	Kaplicky, J. and Nixon, D. (1985)	Hypes et al. (1992)

* ISMU - In situ materials utilization

** SSF - Space Station Freedom

4. HABITAT EMPLACEMENT SCENARIOS AND THEIR POSSIBLE IMPACT

In this section, brief "what-if" scenarios are created to examine the possible impact of emplacement of the habitat in different locations, such as lunar poles vs. equatorial, above ground vs. below ground, etc. Given the diversity of shapes and types of habitat designs considered, no attempt is made to individually emplace the habitats (with their inbuilt protection schemes, etc.) in the different lunar regions; instead a more general approach is used. Thus a generic shell is hypothetically placed on the regions of interest and examined for possible impact.

The basic stratigraphy of the Moon was reasonably well understood prior to the first manned lunar landing in 1969. The oldest regions observable are the lunar highlands, saturated with large craters (50-100 km dia.); giant basins with concentric ring structures are another feature, also a result of the excavation process induced by impact-melting of the surface. Over 30 such basins have been mapped that have diameters in excess of 300 km. These are all attributed to the "great bombardment" about 3.9 billion years ago (Taylor, S.R., 1982). Following and even overlapping the intense cratering, floods of basaltic lava started, and continued for at least 800 million years. These formed the maria, which in contrast to the highlands, are wide plains. These are typically darker regions, as can be seen by a telescope; the dominant mare is the Mare Imbrium. Superimposed on lava plains and highlands are craters, some older

and subdued such as Eratosthenes, and others younger with bright rays such as Kepler, Copernicus, etc. An interesting feature of the lunar surface is the completeness of the mantle or blanket of debris; bedrock exposures are extremely rare. The regolith is the continuous layer, usually several meters in thickness, covering the entire lunar surface. The size variation has been mentioned in an earlier section. The top 2-3 cms on the lunar surface are a loosely packed porous layer, with highly insulating properties.

Thermal protection and radiation protection schemes are an important aspect of a habitat emplaced on the Moon. The regolith offers an inexpensive alternative to carrying special materials, for radiation protection and thermal insulation. The loose regolith could be easily manipulated, and options of burying the habitat fully or partially vs. mounding regolith on top of the habitat could be considered. Regolith could also be bagged and piled on top of the habitat. These options are more easily implemented in the mare regions, where the regolith thickness could be many meters, as mentioned earlier. The highlands would be more inaccessible in terms of human mobility. When it comes to studying impact of emplacing a habitat around the lunar poles and the equatorial regions, other factors come into the picture. On the poles, the craters could impact habitat emplacement positively. Due to the roughness of the terrain, there are likely to be elevated spots on the rims of large craters where the entire horizon mask is depressed $1\frac{1}{4}^{\circ}$ or more so that at least a part of the solar disc

is always visible. At such sites it would be possible to operate a heliostat, providing continuous solar heat and power for a base. On another front, the polar surface temperature will be lower and more nearly constant than on the equator. In the permanently shadowed regions, the temperatures can presumably be lower than 40°K or lower. At these cold temperatures, volatiles such as water ice could survive as permafrost, argues Burke (1985). These cold traps could also ease the problem of designing and operating cryogenic equipment consisting of superconductors, cold optics, low-noise photon detectors, and gravitational-wave experiments. Because the south ecliptic hemisphere is very rich in objects of interest to modern astronomy, the lunar pole would probably be preferred as the first astrophysical site. This would impact the habitat emplacement by necessitating adequate thermal protection for the low temperatures that can be expected. Offsetting the disadvantage of half-sky coverage are the prospects of unlimited tracking time for all objects at moderate to high celestial latitudes, and of continuous operation with very cold optics and detectors as needed for advanced infrared and microwave astronomy. A possible disadvantage of the polar site is the difficulty of maintaining continuous communication with Earth. This would impact the communication considerations for a lunar habitat. Lunar day/night impacts are dependent on the location of the base. If the base is located closer to the pole, the temperature variation will be not as drastic ($\pm 10^\circ\text{K}$) as on the equatorial regions ($\pm 140^\circ\text{K}$); these large shifts can seriously impact the thermal control systems.

Radiation control will dominate the habitat design; this may dictate whether it is more advantageous to bury the habitat underground or pile the regolith on top of the habitat. By having a layer of regolith piled on top of a habitat, the pressures induced on the habitat will have to be accounted for. The net force at the top of the habitat will be the resultant of the downward pressure of the regolith and the upward pressure of the habitat internal pressure (typically, 14.7 psia for crew considerations), while there is a continuous change in pressure as one goes down from the top. Changing this internal pressure could impact the thickness of regolith that can be piled on top of the habitat. Silberberg et al. (1985) recommend a thickness of 400 g cm^{-2} of regolith for the radiation protection. This is also adequate to shield the habitat from the temperature excursions, thanks to the very low conductivity of the lunar regolith. In fact, as mentioned earlier, the problem will become one of heat rejection, for which good radiator designs become important. Emplacing the habitat on the dark-side, i.e., on the side that is never seen by the Earth, will have the same impact as placing the habitat on the pole as far as astronomical studies are concerned. However, there will be no significant difference in impact as far as radiation or thermal considerations go; in these cases, the lunar latitude would be the key driver.

The type of habitat could impact the life support system in different ways. Leakage rate for the different habitats would be

design dependent, thereby requiring the making up of O_2 , N_2 , and H_2O or additional regeneration capabilities. The waste heat generated by the life support system must be discarded; the type of habitat design could affect the amount of heat that would have to be transported to the habitat exterior and disposed of via radiators. Different habitat materials will generate airborne trace contaminants that must be removed in a closed, circulating air environment. The control of these trace contaminants can require processing of the circulating air to remove contaminants, and possibly water processing to remove contaminants that are trapped or dissolved in the water that is condensed in a temperature and humidity control unit.

Different lunar emplacements could impact the life support systems in different ways. The availability of *in situ* water will have a dramatic effect on the life support system. Burke (1985) has postulated the existence of water ice in the polar regions. If water indeed is available, processing equipment to clean and prepare the water will be necessary. Trade studies of regenerative technologies vs processing technologies will be required to determine the best life support system. If water is available, then the process to recover O_2 from CO_2 in a physical/chemical life support system might be unnecessary. Oxygen could be generated from water hydrolysis. If sufficient water were available to generate propellants, then human requirements for O_2 would be a small incremental addition to the H_2/O_2 propulsion production. Similar to

the impact of habitat type on life support systems, the waste heat dissipation will be impacted by the different lunar emplacements. If the emplacement of the habitat allows for discarding of solid and liquid waste outside the habitat, then storage and/or processing of these wastes such that they do not contaminate the interior of the habitat could be minimized or possibly eliminated.

In conclusion, it is clear that a variety of trades would be required to assess lunar emplacements. While qualitative "what-ifs" are presented here, it is necessary to make use of quantitative models to obtain accurate trade assessments.

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