Lunar Habitat Micrometeoroid and Radiation Shielding: Options, Applications, and Assessments

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Abstract: Various shielding approaches to protect lunar habitats from micrometeoroid and radiation hazards present major trade-off considerations. Popular scenarios that envision covering modules with in situ regolith will necessitate means to excavate and move large amounts of material; will complicate evolutionary outpost growth; and may require long tunnels between connecting pressurized elements. Strategies that incorporate shielding materials into module structures or internal shelters add very substantial launch mass penalties. Utilization of water bladders can make efficient use of consumable/recyclable supplies, but may impose excess capacity deliveries at early development stages. This paper addresses these different shielding approaches from a top-level application perspective, highlighting pros and cons of each. Examples draw upon research and design investigations undertaken by the Sasakawa International Center for Space Architecture in support of separate National Aeronautics and Space Administration (NASA) contracts awarded to teams headed by Boeing and ILC-Dover for a "Minimum Functionality Habitation Systems Concept Study." Comprehensive team study results were presented to NASA in February 2009, and have been released as public information.

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Introduction

Lunar surface habitats and crews must be provided with protection from micrometeoroid and radiation hazards at levels "as low as reasonably achievable" (ALARA). With regard to micrometeoroids, the goal is to afford a 0.993 "probability of no penetration" over each 5-year period. And while no firm radiation dose limits have been established for exploratory class missions, those which have been applied for low-Earth orbit are presently recommended as guidelines. These have been set by National Aeronautics and Space Administration (NASA) [NASA-STD-3001 (National Aeronautics and Space Administration (NASA) 2007)] and the National Council on Radiation Protection and Measurements (National Council on Radiation Protection and Measurements 2000a,b,c) (see Table 1). The most applicable dose limits for typical mission design consideration are the 30-day 250 milligray equivalent (mGy-Eq) and the annual 500 mGy-Eq limits for blood forming organs (BFO) (1 Sievert(Sv) = 100 rem = 1,000 mGy-Eq, therefore, 250 mGy-Eq = 25 rem = 0.25S v) (Townsend 2007).

With no atmosphere to impede them, micrometeoroids enter the lunar surface from cometary and asteroidal sources at very high velocities. Since larger modules present bigger targets, they present greater hazard risks. A popular shielding strategy applies a "micrometeoroid and secondary ejecta" (MMSE) (secondary particles or ejecta are produced when micrometeoroid or microdebris impact lunar surface itself or structures placed on the lunar surface) barrier to the external module structures, with particular attention to vulnerable top and side locations that comprise about 3/4 of the surface areas. A typical approach that was proposed this study provides an exterior β-cloth fabric layer with an interior Nextel/Kevlar blanket over the pressure shell. Estimated required MMSE shield mass is 10 $\mathrm{kg/m^2}$ (see Table 2) (Lin 2008; Rais-Rohani 2005). Micrometeoroid protection strategies may be combined with radiation shielding approaches and may help to minimize structural mass and simplify assembly procedures. Radiation protection materials and layers incorporated into MMSE protective blankets offer additional shielding against micrometeoroids and secondary ejecta from the lunar surface when used for outer shell applications.

Radiation emanates from two space sources. Solar particle events (SPEs) arise from activity on the Sun's surface and are comprised of high energy protons. Released doses generally occur over average 11-year cycles, with greatest hazards experienced during maximum solar activity periods. SPEs represent the dominant concern from a shielding standpoint. In addition to health hazards, they also deform the Earth's magnetic field to disrupt communications.

Galactic cosmic rays (GCR) from deep space are comprised of protons, electrons and ionized light elements. Due to high energy levels, they are nearly impossible to fully shield against, and biological effects are not well understood (Rais-Rohani 2005).

Unlike the Earth, the Moon does not have a magnetic field to deflect or trap GCR or materially influence its effects. On the other hand, SPE surface exposures are only about half experienced in deep space due to the 2-h view shadowing provided by

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Table 1. Recommended NCRP Radiation Dose Limits

Organ	30-day limit	1-year limit	Career
Lens[a]	1,000 mGy-Eq	2,000 mGy-Eq	4,000 mGy-Eq
Skin	1,500	3,000	4,000
BFO	250	500	Not applicable
Heart[b]	250	500	1,000
Central nervous system (CNS)[c]	500	1,000	1,500
CNS[c] ($Z \geq 10$)		100 mGy	250 mGy

[a]Lens limits are intended to prevent early (<5 years) severe cataracts (e.g., from a SPE). An additional cataract risk exists at lower doses from cosmic rays for subclinical cataracts, which may progress to severe types after long latency (>5 years) and are not preventable by existing mitigation measures; however, they are deemed an acceptable risk to the program.

[b]Heart doses calculated as average over heart muscle and adjacent arteries.

[c]CNS limits should be calculated at the hippocampus.

the Moon itself. Applying skin shell concepts currently proposed for NASA's Crew Exploration Vehicle design (5.0–7.0 mm thick aluminum), no additional shielding is expected to be required for GCR protection over short-duration surface missions that were baselined in this study. This could be expected to keep the dose exposures below a designated 500 mGy-Eq annual limit (Mukhopadhyay 2006).

Shielding Strategies and Design Concepts

SICSA proposed six different SPE shielding strategies that might be incorporated into lunar habitat modules in connection with the NASA Minimum Functionality Habitation Systems Concept Study (Fig. 1). The first of these schemes can also provide protection from micrometeoroids (see Fig. 2). These options were simultaneously presented for consideration by both the Boeing and ILC-Dover teams. An option that would involve covering habitats with lunar regolith was not recommended for reasons that are discussed later.

All of the shielding schemes were predicated upon applications for a "Minimum Functionality Habitat Element" (MFHE), the smallest, lightest module deemed feasible by each team to support a four-person crew for 1 month without contingencies. The study program also involved the development of growth concepts to expand crew sizes and mission lengths over time to lunar "outpost" capacities.

The first shielding strategy would place radiation and micrometeoroid barriers above the upper pressure shell section, such as over the dome of a vertical module. These areas "under the curve" can serve well as partial-height sleep/work station locations (see Fig. 3). Two geometric/dimensional examples are illustrated for the purpose of surface area and mass estimates.

Table 2. Recommended Micrometeoroid Protection Based on the ISS Meteroroid and Orbital Debris System (MDPS) Design

Description	Material	Area density (kg/m^2)
Front bumper	Kevlar composite fabric 0.25 cm thick-5 layers of 300 g/m^2 Kevlar fabric	1.5
Rear Bumper	Nextel 0.30 cm thick	2.8
	Kevlar 0.64 cm thick	4.0
Spacer		1.7
Total		10

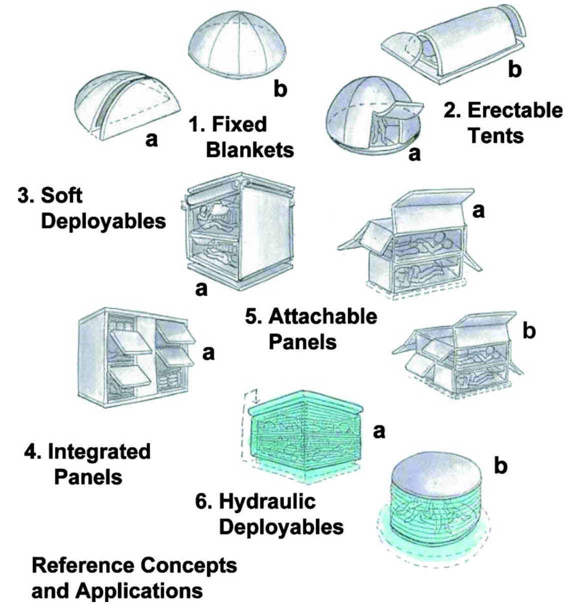


Fig. 1. Radiation shielding strategies (Image courtesy of Sasakawa International Center for Space Architecture)

For purposes of this study, it was assumed that shielding for SPE occasions must completely surround the sheltered volume. Accordingly, floor and side/end panels are included in the surface area projections. Sasakawa International Center for Space Architecture (SICSA) proposed two general types of erectable tent-type

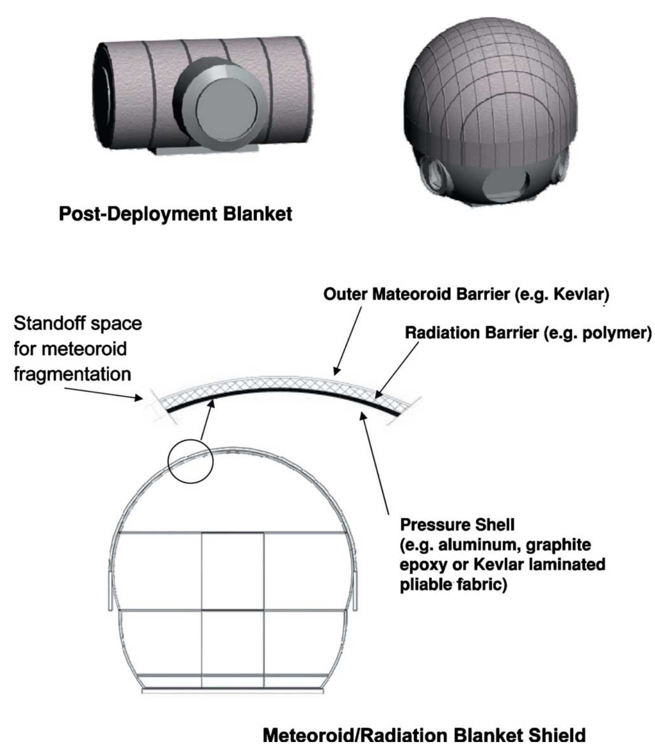


Fig. 2. Radiation and micrometeoroid protection (Image courtesy of Sasakawa International Center for Space Architecture)

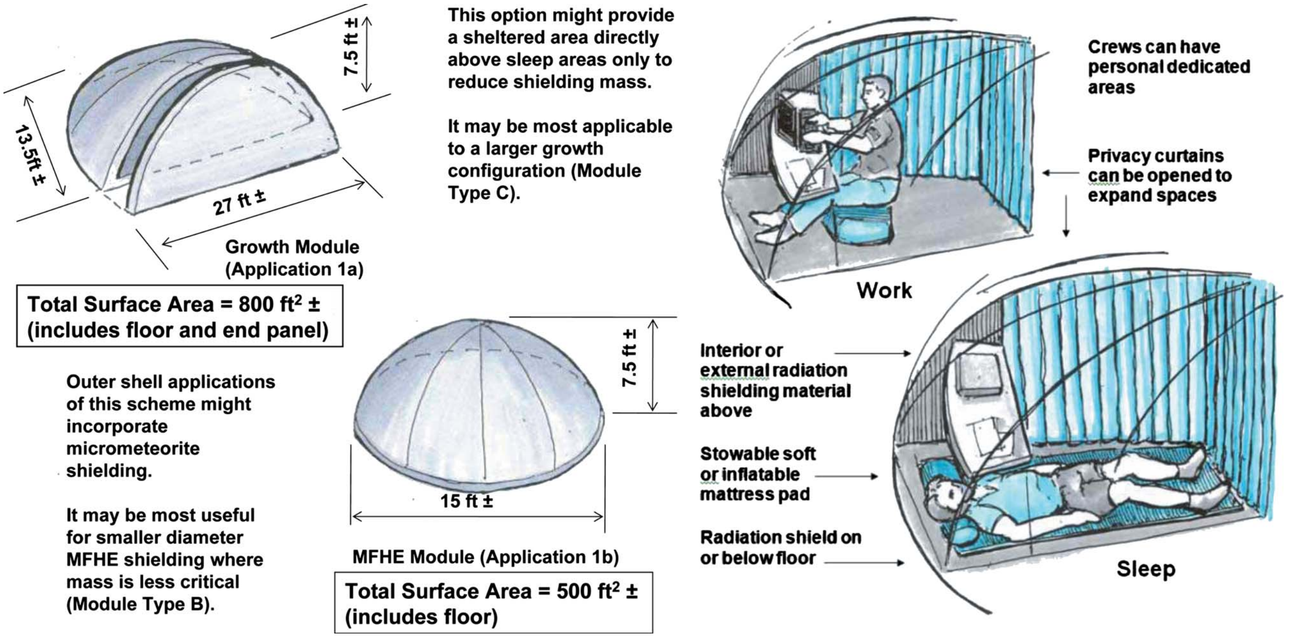


Fig. 3. Fixed blanket radiation and micrometeoroid shielding (Image courtesy of Sasakawa International Center for Space Architecture)

SPE shelters. Both can be stowed flat when not in use, and rapidly deployed over tensioned wire plug-in armatures (Fig. 4).

SPE shielding can be incorporated around crew sleeping units. This might be accomplished using soft deployable or rigid polyethylene materials. (Fig. 5). A variation of the integrated panel sleeper is an attachable shielding scenario depicted in Fig. 6. Water can provide an effective SPE shielding material for application to sleeping units or radiation storm shelters (Fig. 7).

A prevalent radiation countermeasure advocated by many lunar development researchers and planners is to cover habitats with regolith. The principle rationale is to use in situ surface materials, thereby eliminating the need to transport shielding mass. SICSA did not recommend this approach for MFHE application for a variety of reasons (Fig. 8):

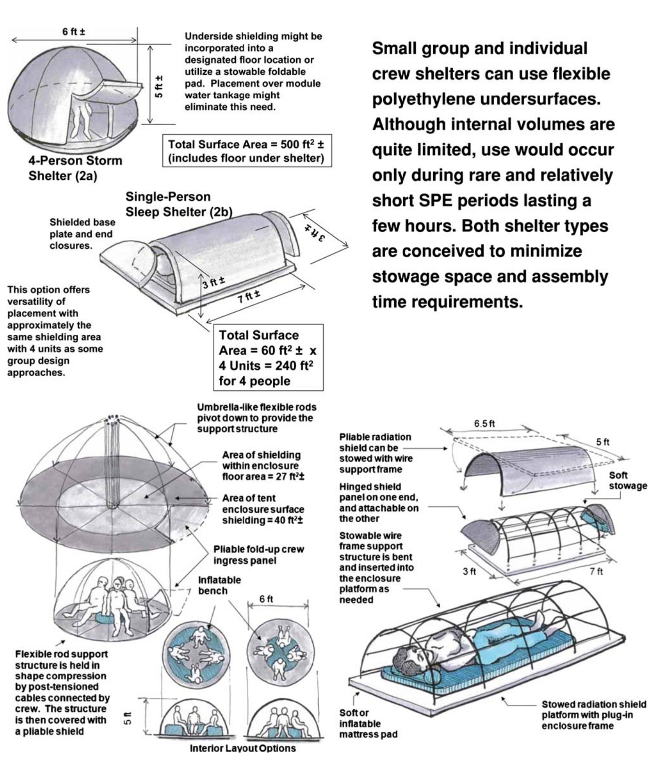


Fig. 4. Erectable tent shelters (Image courtesy of Sasakawa International Center for Space Architecture)

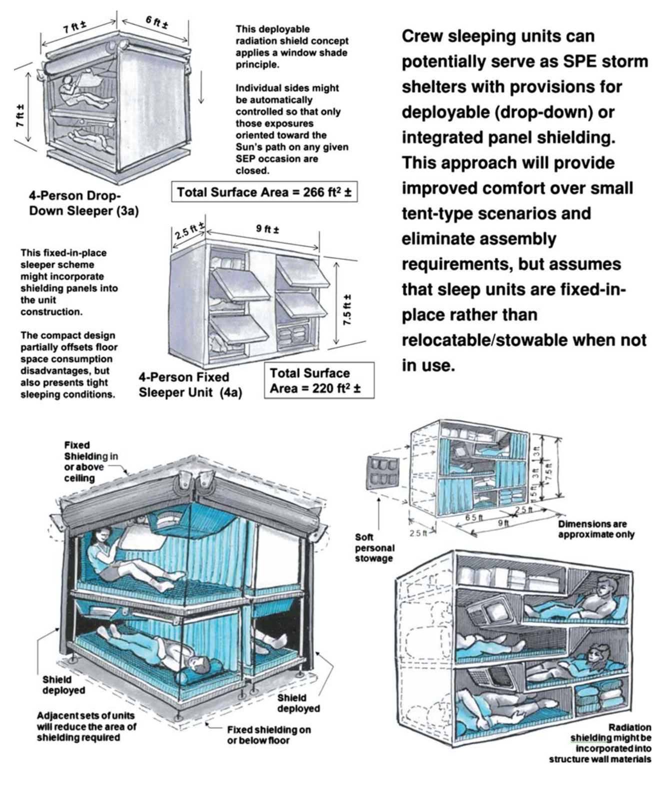


Fig. 5. Soft deployable and integrated panel sleeper shielding (Image courtesy of Sasakawa International Center for Space Architecture)

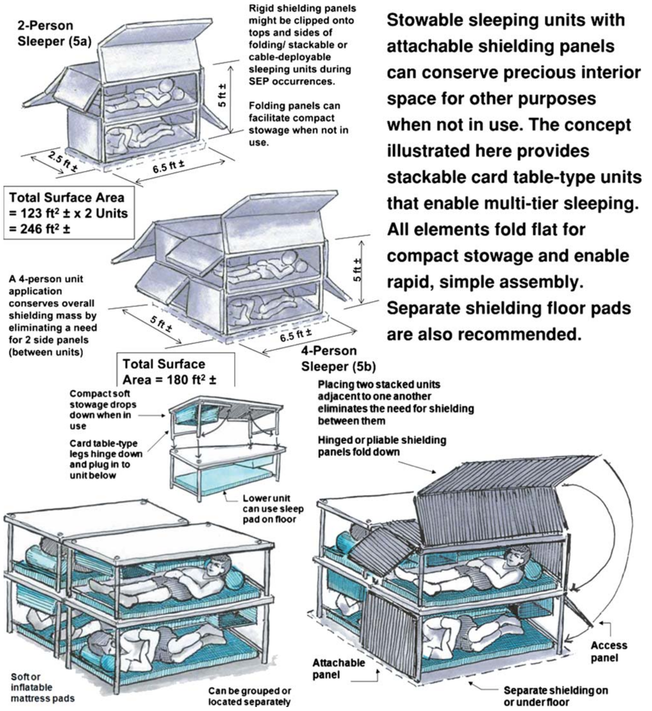


Fig. 6. Stowable sleeping units and shielding panels (Image courtesy of Sasakawa International Center for Space Architecture)

- Covering modules with regolith will require substantial equipment for collection and placement;
- It must be accomplished following operational module deployment (also creating major dust problems);
- Long pressurized tunnels will be required for connections between modules, for EVA ingress/egress, and for shirtsleeve access to pressurized rovers;

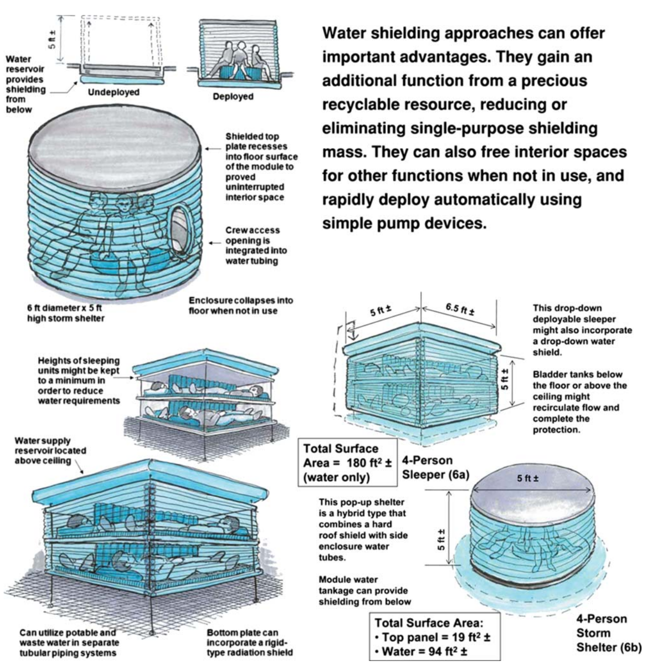


Fig. 7. Hydraulic deployable radiation shielding (Image courtesy of Sasakawa International Center for Space Architecture)

- External equipment such as solar arrays, radiators, and communication antennas must be emplaced following burial; and
- Regolith covering will preclude direct outside viewing from habitats.

Fig. 9 summarizes estimated surface areas for each of the radiation shielding options that were recommended for MFHE application consideration by SICSA. Each scenario was subsequently correlated with many other influential factors that were specific to each team's particular planning assumptions and design approaches. For example, while fixed blanket shielding may be heavier in terms of gross mass, the simplicity of this method along with benefits for making optimal use of low-ceiling/curve-in areas for combined sleep and work functions might justify the weight penalty. Stowable sleep and group shelters can conserve limited internal space and afford multiple-function advantages. Hydraulic shelter systems can provide large mass-saving dividends providing that there is sufficient on-board water to accommodate this strategy.

Selected MFHE Shielding Applications

The Boeing and ILC-Dover study teams each selected radiation and micrometeoroid shielding strategies that were determined to be most compatible with their respective MFHE and growth concepts. The Boeing team adopted a vertically oriented 15-ft diameter MFHE configuration that was originally proposed by SICSA as a logical option. Called the "pressurized interim lunar lodge," the layout provides three floor levels: a lower airlock and hatch/tunnel interface area; a middle living/work space; and a sleeping volume for four crewmembers under the upper dome. A later evolutionary expansion stage would place a 30-ft diameter, two-level inflatable element on top, relocating primary crew living spaces, including dedicated sleeping stations to this section (see Fig. 10).

The Boeing team selected an individual/stowable tent-type radiation shelter as their preferred scheme. Micrometeoroid protection would utilize a double-walled aluminum pressure shell with a 1/16-in. outer bumper and 1/8-in. inner structure separated by a 4-in. standoff space (Fig. 11).

The ILC-Dover team proposed a 10-ft diameter, 15-ft long horizontal scheme with an inflatable airlock for its initial MFHE module. This original stage could commence operations from the lander deck with vertical surface access provided by a SICSA lift concept (Fig. 12).

The ILC-Dover MFHE design incorporated SICSA's hydraulic pop-up SPE radiation shelter concept with a perimeter water wall and polyethylene top cover that collapses into the module floor when not activated. The unit is placed over the water containment reservoir to afford shielding from below. It was estimated that approximately 2,000 kg of water would be needed for a four-person shelter.

While the water shelter approach will add considerable mass over consumable supply requirements, it can substantially reduce deliverable mass over multiple missions. Unlike special-purpose blanket shielding, water will remain to be a precious renewable resource. It can be transported in a frozen solid state to eliminate "sloshing" during launch/landing, and can be augmented by unused reserves scavenged from landers (see Fig. 13).

A second-stage ILC-Dover module configuration would incorporate a soft deployable side pod to expand interior volume. This development would retain the pop-up hydraulic storm shelter and

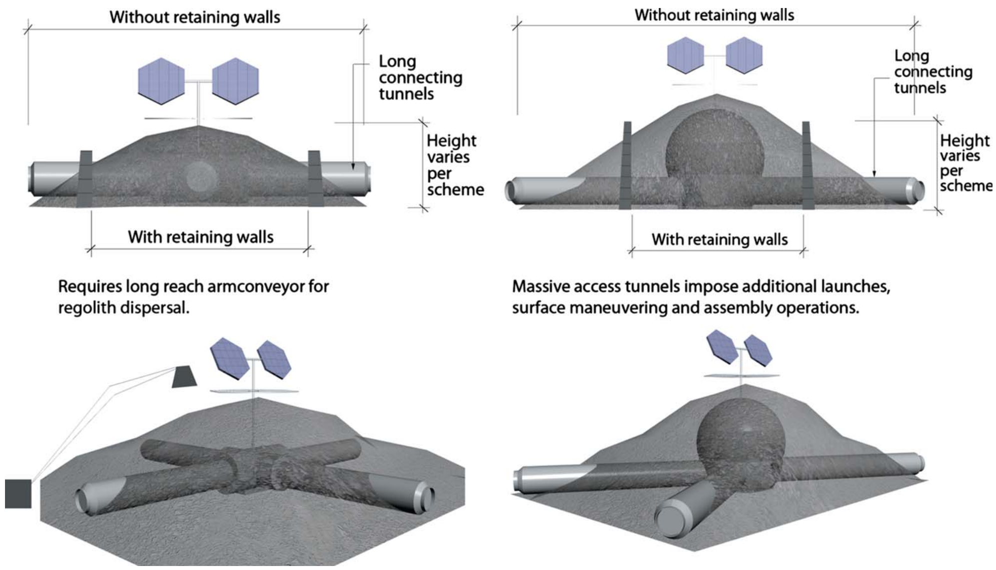


Fig. 8. Regolith shielding issues (Image courtesy of Sasakawa International Center for Space Architecture)

accommodate dedicated crew sleeping and work stations (see Fig. 14).

The ILC-Dover team adopted a SICSA "Crew Lunar Accommodation Module" (CLAM) configuration concept for an evolutionary growth stage which transitions to a vertical, middle-expandable, 30-ft diameter module. This configuration can apply the same pop-up hydraulic storm shelter as others, but provide greatly enlarged crew living and work spaces (Fig. 15).

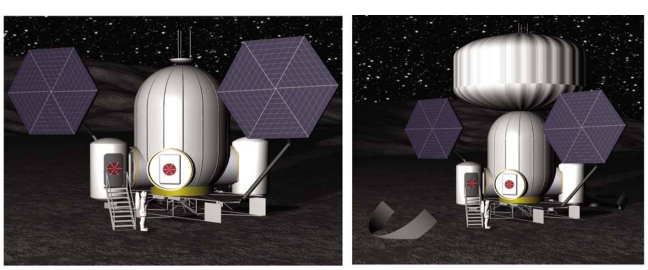
Sleeping Options

1. 1-Person Dedicated
2. 1-Person Relocatable
3. 2-Person Deployable
4. 2-Person Relocatable
5. 4-Person Deployable
6. 4-Person Fixed

Shielding Concept Options	Surface Areas
1. a. Large Dome Shield	800ft^2/74m^2
b. MFHE Dome Shield	500ft^2/46m^2
2. a. 4-Person Erectable Tent	580ft^2/54m^2
b. 1-Person Erectable Tent (x4)	240ft^2/22m^2
3. a. 4-Person Drop-Down	266ft^2/25m^2
4. a. 4-Person Integrated Panels	220ft^2/20m^2
5. a. 2-Person Attachable Panels (x2)	246ft^2/23m^2
b. 4-Person Attachable Panels	180ft^2/17m^2
6. a. 4-Person Hydraulic Deployable	180 ft^2
b. 4-Person Hybrid Deployable	94 ft^2 (water) 19 ft^2 (solid)

Shielding surface areas were estimated as a basis for preliminary option comparisons which allow thickness/mass assumptions to be consistently altered. Based upon density, polyethylene ranges from about 0.92 to 1.06 g/cc, and water is 1 g/cc. Both contain hydrogen, an effective SPE barrier.

Fig. 9. Preliminary shielding strategy area/mass comparisons (Image courtesy of Sasakawa International Center for Space Architecture)



Mission 5 Stage   Mission 7 Stage

Fig. 10. Boeing's proposed MFHE concept (Image courtesy of Sasakawa International Center for Space Architecture)

Summary and Conclusions

Radiation and micrometeoroid protection present important issues and challenges that must be addressed as a vital aspect of lunar development planning. It is evident that the design of any radiation shielding intervention will be dominated by SPE countermeasures. Following the ALARA principle, strategic options must consider a great variety of factors including: module configuration (geometry and layout options); multiuse and single-purpose material characteristics (integrated and applied); and total impacts

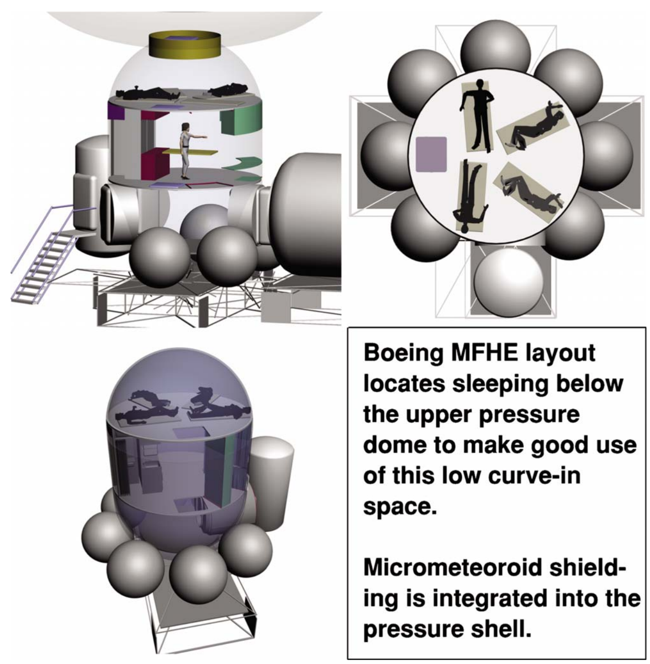


Fig. 11. Boeing's radiation and micrometeoroid shielding approach (Image courtesy of Sasakawa International Center for Space Architecture)

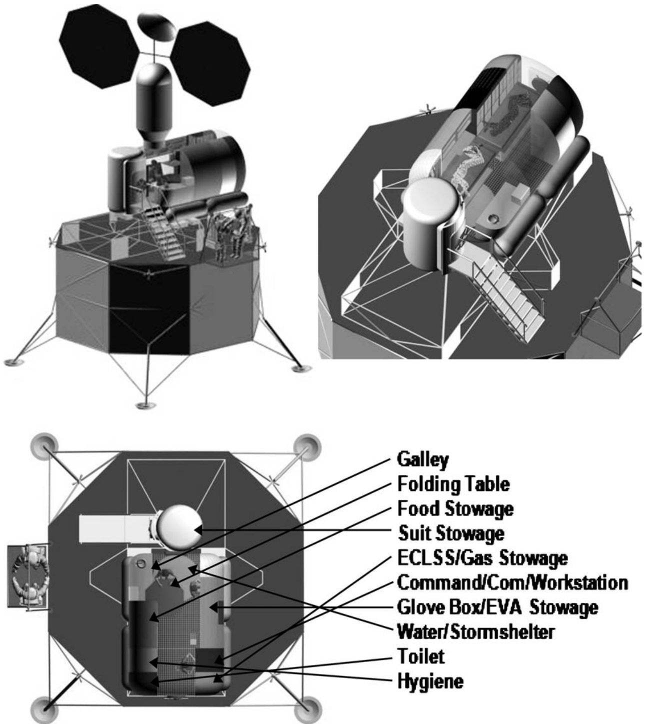


Fig. 12. ILC-Dover's proposed MFHE concept (Image courtesy of Sasakawa International Center for Space Architecture)

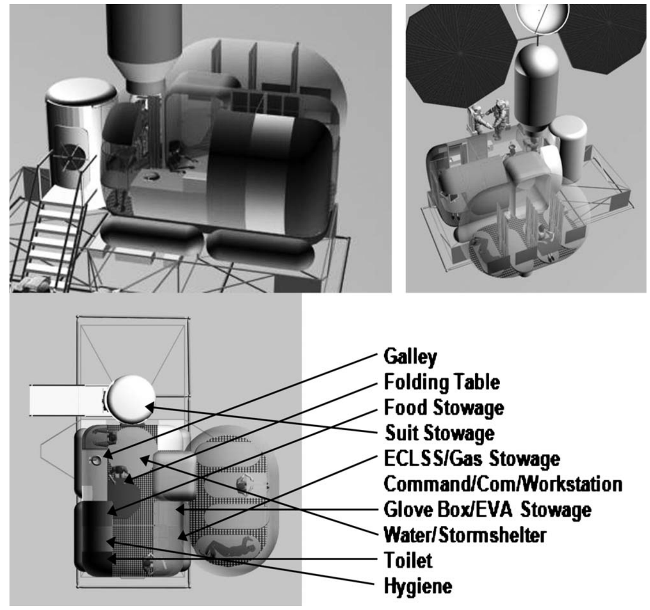


Fig. 14. ILC-Dover's second-stage MFHE proposal (Image courtesy of Sasakawa International Center for Space Architecture)

upon delivery mass (per launch, and throughout a mission campaign).

This report has emphasized SPE mitigation strategies which focus upon local areas within a habitat module. It is reasoned that full surface attached or integrated shielding using any known materials will greatly exceed practical launch mass limitations. Use of regolith covering was ruled out for early missions due to requirements for large specialized excavation and material manipulation equipment that is not likely to be available. The preferred approach by both MFHE teams applied temporary erectable or deployable shelters which free up interior space for other functions when not in use.

It appears evident that materials with high hydrogen content are leading SPE shielding candidates. Included are water, polyethylene and lithium hydride. Use of hydrogenated graphite nanofibers with a herringbone structure (HGNF) is another possibility. Aluminum is regarded to be a relatively poor shielding material due to hazards presented by secondary radiations. For example, NASA radiation studies indicate that polyethylene is approximately 30% more effective than aluminum as an absorber of radiation from high charge and energy (HZE) particles (Tripathi and Nealy 2007; Wilson et al. 1997). HGNF is estimated to be 4–6 times more efficient than aluminum.

Use of localized water storm shelters is an attractive option because it draws upon a multipurpose resource that can be reclaimed and recycled with little or no mass penalty. The ILC-Dover team estimated that the amount of water required for a small four-person shelter is about 2,000 kg, with associated equipment contributing an additional 200 kg. While this exceeds the amount of water needed for early crew consumables, it can afford large mass-saving dividends over the course of multiple missions.

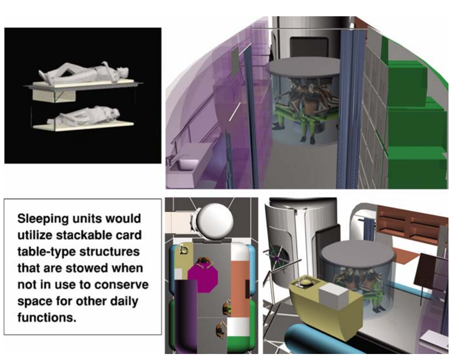


Fig. 13. ILC-Dover's radiation shielding and sleeping approaches (Image courtesy of Sasakawa International Center for Space Architecture)

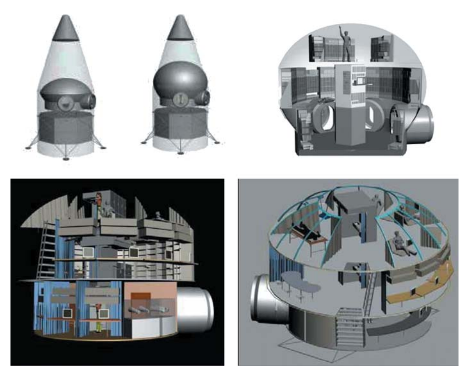


Fig. 15. ILC-Dover CLAM proposal (Image courtesy of Sasakawa International Center for Space Architecture)

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