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David V. Smitherman, Vinay Dayal and Daniel J. Dunn

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David V. Smitherman, Jr.[1], Vinay Dayal[2], Daniel J. Dunn, II[3]

[1]*Advanced Projects Office, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA*
[2]*Department of Aerospace Engineering, Iowa State University, Ames, IA 50011, USA*
[3]*Undergraduate Student Research Program, NASA Marshall Space Flight Center, Huntsville, AL 35812, USA*
[1]*David.Smitherman@nasa.gov*

Abstract. During the summers of 2004, and 2005, several studies were conducted in the Future Concepts Office at the NASA Marshall Space Flight Center (MSFC) with assistance from summer faculty and student program participants to develop concepts and architectures for mobile lunar habitats. This work included conceptual designs for a launch architecture derived from existing expendable launch systems; a lunar walker based on existing technology for the robotics; compatible hardware from the *International Space Station* (*ISS*) program for pressurized modules; and lunar resources utilization for environmental shielding. This paper provides a brief summary of some of the key findings from these studies, and identifies areas for future work that could lead to more robust lunar exploration architectures in the future. In conclusion, it is recommended that future exploration missions consider reusable depot / transfer vehicles, robotic walking technology for lunar exploration, and lunar resources utilization for environmental shielding of surface habitats.

Keywords: Mobile Habitat, Hab-Bot, habot, Robotic Walkers, Walking Machines, Propellant Depots, Lunar Shelters, Space Vehicles.
PACS: Space vehicles, 07.87.+v.

INTRODUCTION

A renewed interest in space exploration is evidenced by the Administration's direction to NASA to complete the space station, lead in a return to the Moon, and eventually human exploration beyond the Earth / Moon system including Mars and other destinations. The mission architecture described in this paper is designed specifically to address an approach to exploration that can be expanded incrementally to involve the commercial sector, accommodate international participation, and put in place systems that can provide safe environments for long-term human occupation of habitats on the lunar surface without time-limiting concerns for radiation exposure. The basic concept behind this mobile lunar base, sometimes referred to as Hab-Bots (Cohen, 2003; Mankins, 2001; Smitherman, 2005), is that these modules reside inside a protective shelter covered with several meters of regolith until exploration of that area is completed, and then undock and move to a new site where another shelter has been constructed. In each case, the crew arrives after the mobile habitats are in place, and then depart while the mobile habitat modules move to the next exploration site where a shelter has been robotically constructed. The primary objective of this paper is to show how an overall mission architecture with transportation systems supported by depots, mobile surface systems, and shelters can create a more reusable, and thus sustainable infrastructure for ongoing exploration missions of the moon and eventually more distant destinations.

MISSION ARCHITECTURE

The first group of launches in this mission architecture will deliver to the moon all the materials and equipment required to construct a lunar shelter. The shelters will be permanent constructions covered in about 2 to 3 meters of lunar regolith, and open at the ends for the insertion of mobile lunar habitat modules. Figure 1 provides a notional view of how the shelter would be delivered and constructed on the moon. Yet to be determined is the amount of human interaction required, which means some systems will be autonomous, and some operated robotically by humans in a remote location. The goal is to have no humans on the surface until after the shelter is completed.

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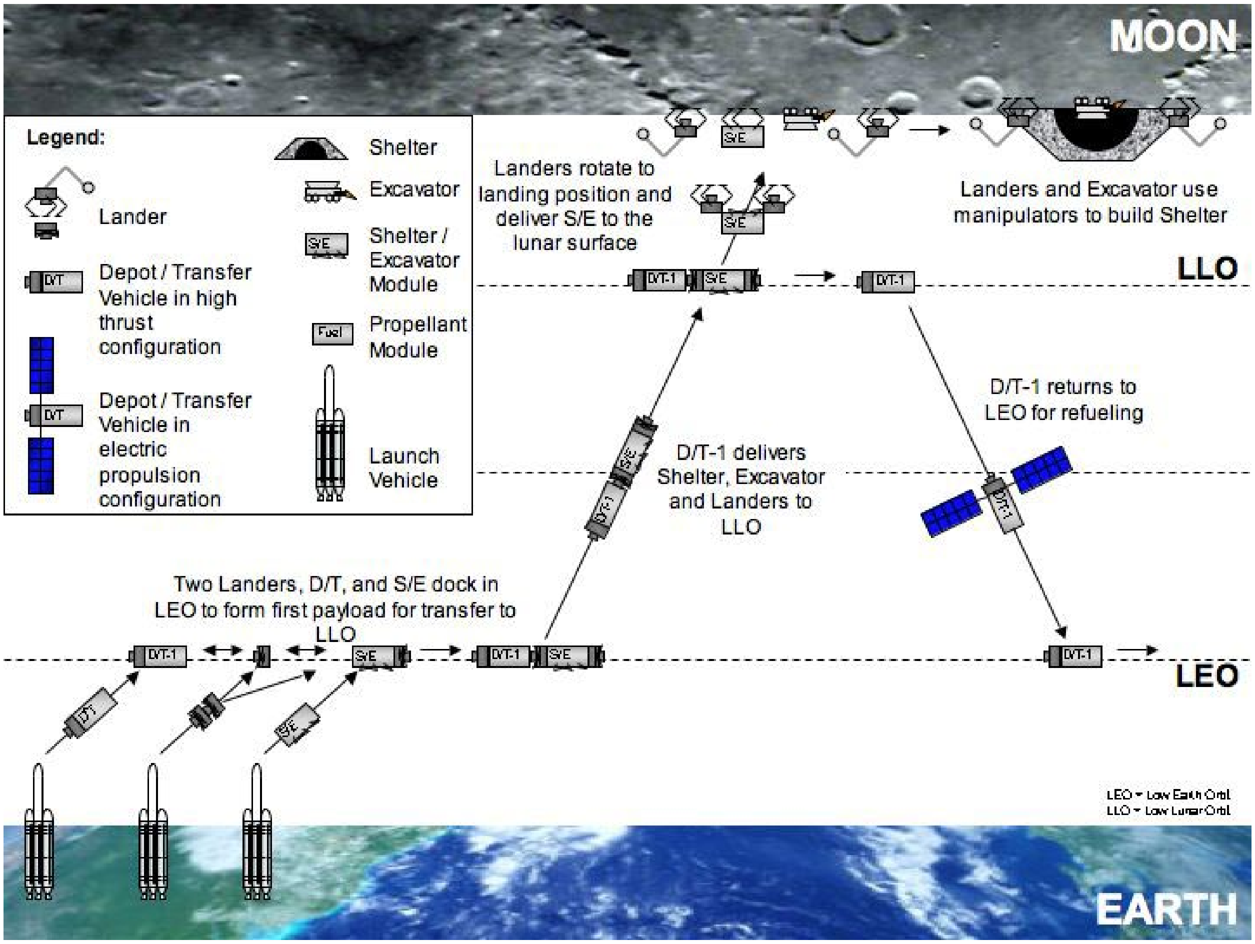


FIGURE 1. Mission Architecture Concept for Shelter Delivery.

This scenario assumes existing expendable launch vehicles (ELV) will be utilized to launch all assets into low Earth orbit (LEO) for assembly of a delivery vehicle. Payloads include a transfer vehicle (D/T-1), two Landers, and the Shelter / Excavator Module (S/E) which contains the prefabricated form for the shelter and an excavator vehicle for covering the form with lunar regolith. The Landers are walkers equipped with robotic manipulators designed to assist with the deployment of the form for the shelter construction. These are reusable systems that will be discussed again later in the paper. The transfer vehicle is also reusable. The delivery configuration for D/T-1 from LEO to low Lunar orbit (LLO) is a high thrust mode, and the return configuration shows solar arrays deployed using electric propulsion for a slow but efficient low thrust return back to LEO for refueling.

Habitat Delivery

The habitat modules are delivered in a similar way, but begin with the delivery of propellants to LLO for refueling the reusable Landers, Figure 2. D/T-2 transfers from LEO to LLO using electric propulsion to conserve the bulk of its propellant for use at the moon. This is the 'depot' capability that this common depot / transfer vehicle is designed to accommodate. The D/T-2 forms the first robotic lunar space station where the Landers refuel and dock with each of the habitats delivered to LLO. The Landers deliver each Mobile Habitat module to the surface in the same way they delivered the shelter / excavator module. The Mobile Habitat module is a walker designed to walk to the shelter and dock with other modules to form a complete base inside the protective environment provided by the shelter. It is anticipated that 3 modules and a Pressurized Walker will be required to form a completed base. These modules would consist of a Habitat Module, Science Module, and an EVA / Airlock Module (Smitherman et al., 2005).

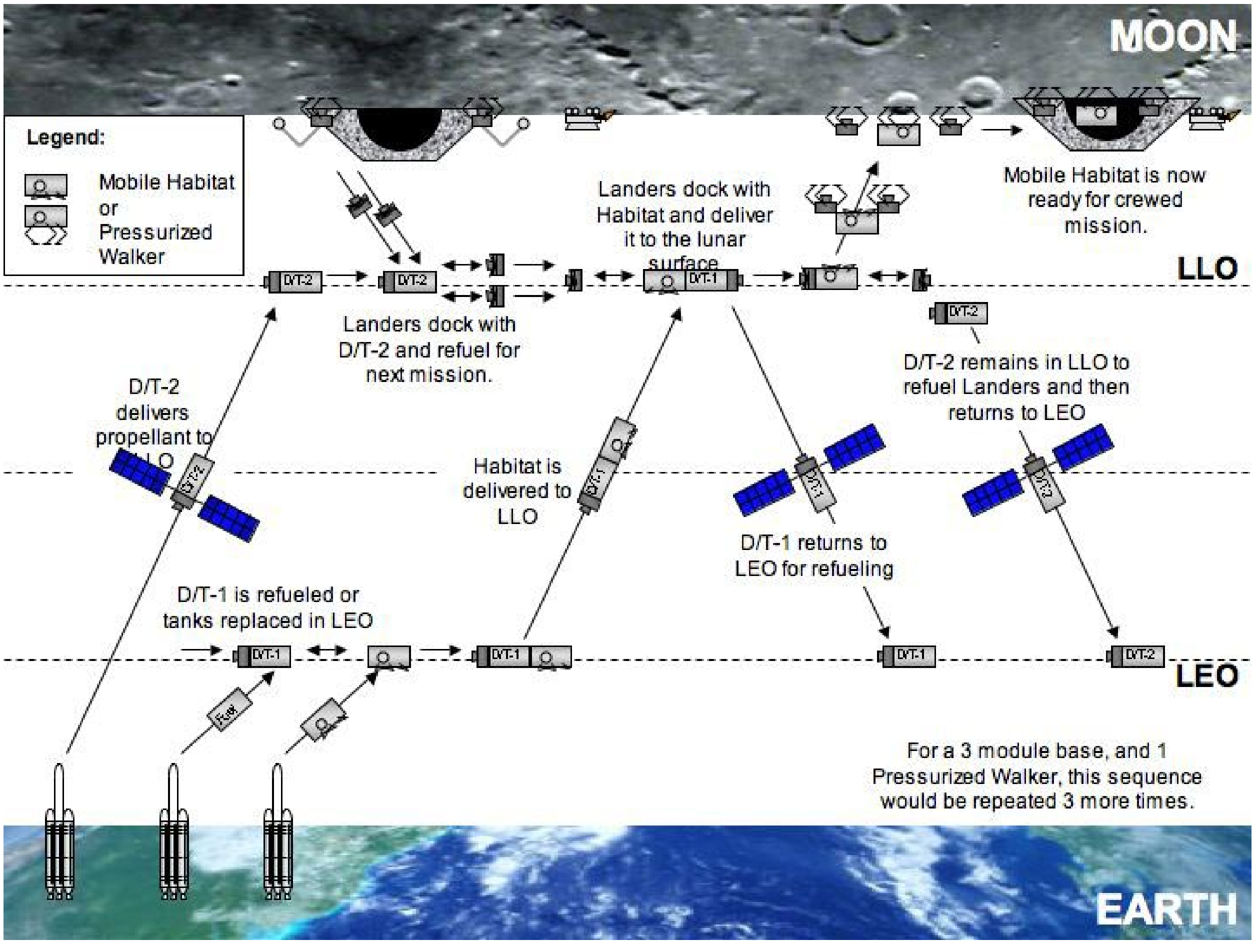


FIGURE 2. Mission Architecture Concept for Mobile Habitat Delivery.

The Mobile Habitat concept utilizes *ISS* technology extensively. The modules are of similar proportions to the *ISS* Lab and Node modules, and have the same internal rack configurations. This commonality is important to maintaining modular and reconfigurable systems that can be both upgraded and interchangeable with existing space assets. Although not indicated in this paper, utilization of the *ISS* in the long-term is possible and desirable to support future human exploration missions.

Reusable Propellant Depot and Transfer Vehicle Concept

The Depot / Transfer vehicles, D/T-1 and D/T-2 introduced in the architectures shown in Figures 1 and 2 have a more long-term market potential in the commercial sector. Expendable upper stages have been utilized for delivery of every satellite to LEO, GEO, the Moon, and beyond since the beginning of space exploration and satellite services. A reusable in-space transfer capability would replace many of these upper stages and provide several advantages and new capabilities that simply are not practicable with expendable systems. Figure 3 illustrates the concept where each D/T is refueled in LEO either by propellant transfer from a tanker, or by tank replacement. Some efficiency is anticipated from numerous launches to support Lunar and commercial missions. But, this initial efficiency, if any, is not as important as the new capabilities that will be possible. These capabilities in the near-term would include capture and removal or relocation of dead satellites, upper stages, and other orbital debris; capture of satellites on failed upper stages for delivery to their proper orbital position; and transfer of existing satellites for sale to new orbital slots. Far-term capabilities would include delivery of satellites from LEO to GEO with a mass more than twice current capabilities, refueling and servicing of a new generation of satellites designed with servicing capabilities; and support to new markets like space tourism and other new space industries (Smitherman, 1998).

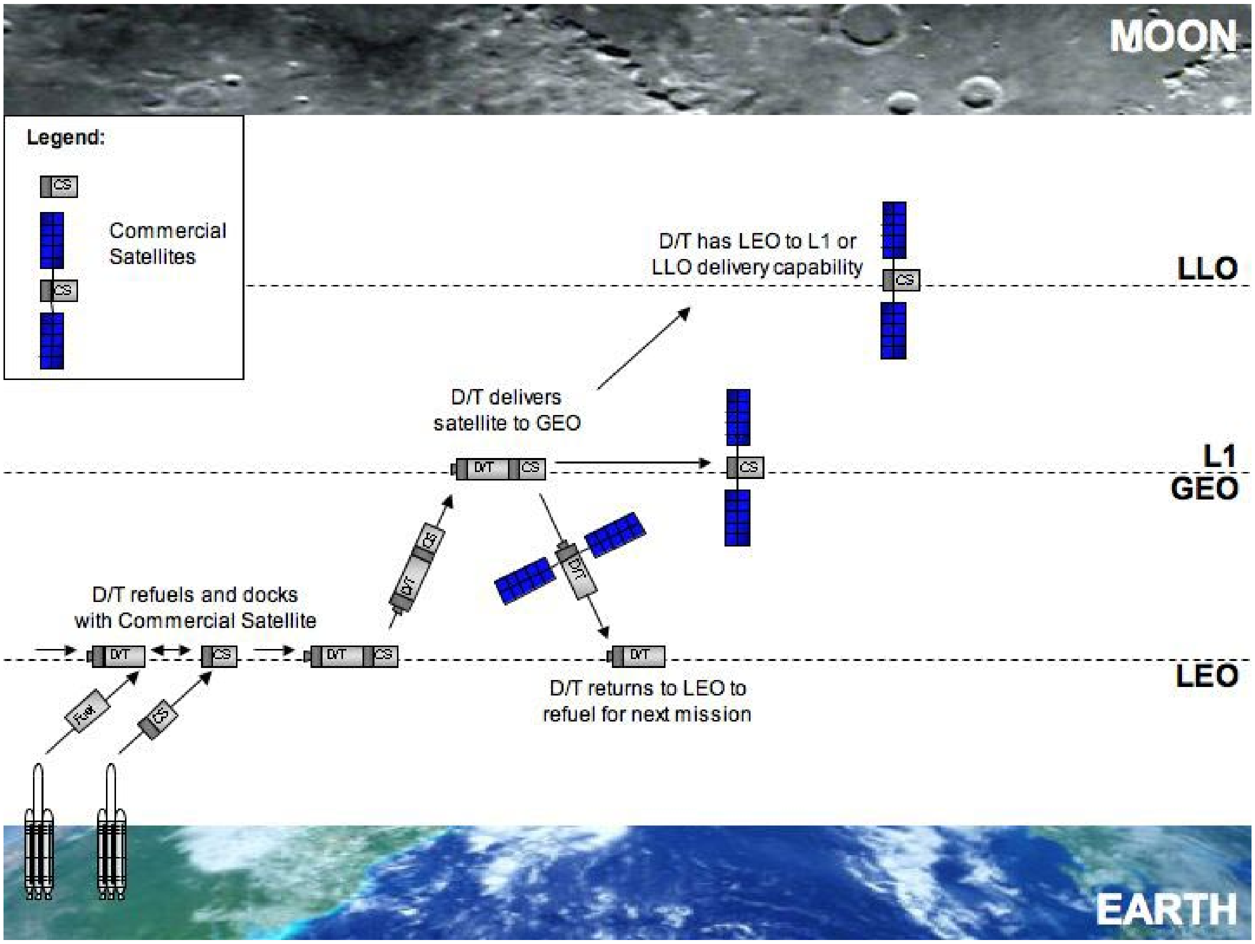


FIGURE 3. Mission Architecture Concept for a Commercial Transfer Vehicle.

There are a variety of scenarios for implementing a depot / transfer vehicle system. In general, water-based propellants (hydrogen and oxygen) are preferred since water and oxygen are two of the basic components also required for human life support. The delivery system, be it water vs. cryogens, or propellant transfer vs. tank replacement, are details that need further economic trades. There is nothing wrong with beginning with one approach for economic or technology reasons and migrating to another approach later when market demand or key technologies have matured. Figure 4 is an illustration of the depot / transfer vehicle concept.

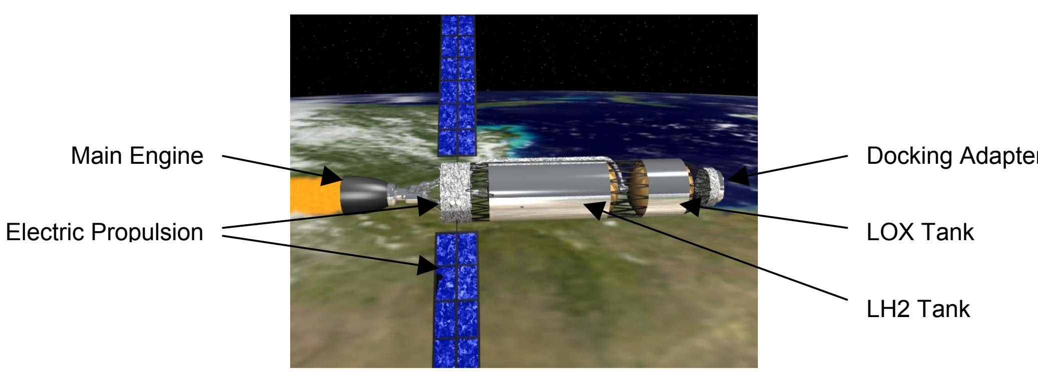


FIGURE 4. Commercial Depot / Transfer Vehicle Concept.

ROBOTIC WALKING TECHNOLOGY

Robotic walking technology has matured to the point that it can now be considered over the use of wheeled rovers. During the Apollo missions it was discovered that lunar dust is very fine (10-230µ) and abrasive to the point that many seals and mechanisms would have failed had the astronauts planned to stay on the lunar surface for another day or two. The wheeled rovers stirred up large plumes of dust that settled on everything. Lunar dust examined under a microscope is a sharp irregular glass and ceramic type of material called agglutinates. This material can work its way through joints and woven fabrics, will adhere to all surfaces, and will cause extensive abrasion to rotating joints and extensive etching in the process of dust removal from finished surfaces. Walkers have the distinct advantage of solving two of the dust related problems by first eliminating the wheels that cause dust plumes, and utilizing legs with joint mechanisms that can be completely enclosed with dust jackets.

The walking mechanisms for this scenario, shown in Figure 5, were derived from state of the art work seen in industry today. Of particular note is a walking machine under development by Plustech Inc., Figure 6, (Shachtman, 2005). The Plustech walker is a 6-legged, human operated, walking machine designed with attachments for harvesting timber. It can maneuver on terrain and slopes that would be difficult for wheeled vehicles. Alternatives to its diesel engine power system include electric motors powered by batteries, fuel cells, and nuclear thermal generators. Actuation systems considered for the legs fall into two main drive sources: hydraulic and electrical. Hydraulic systems are often ruled out early in a selection process due to the temperature extremes, but may in fact be plausible. Krytox, a lubricant designed by DuPont, was used on the Apollo rover. It is an extreme-condition tolerant lubricant; is capable of withstanding high temperatures much greater than the peak daytime on the moon; and can remain liquid to temperatures as low as -80ºF. Supplemental thermal systems could make hydraulic systems feasible for operation through the lower temperatures that will be encountered in shaded areas and the lunar night.

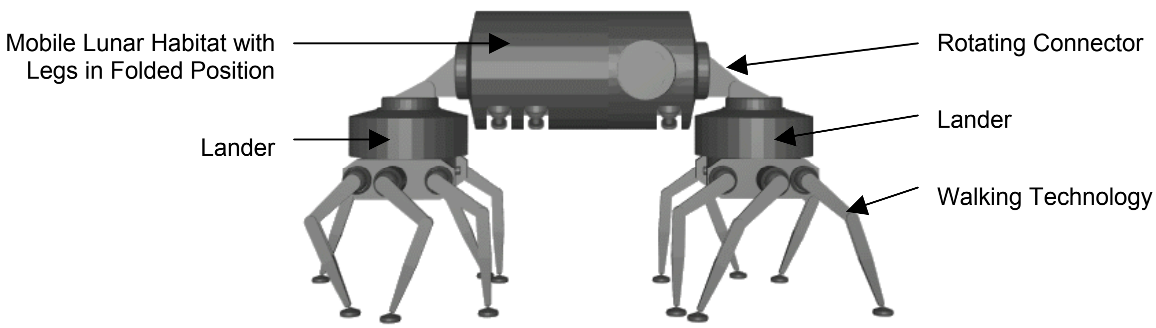


FIGURE 5. Landers and Mobile Lunar Habitat with Walking Technology.

FIGURE 6. PlusTech Oy Walking Machine.

LUNAR SHELTER OPTIONS

One of the primary limiting factors to crew time on the lunar surface is their exposure to the radiation environment. Radiation shielding for humans in space to date has experience derived from the Apollo program, and the Russian and US systems in LEO, like the Space Shuttle, and the *ISS*. All systems in LEO have some protection provided by the Earth's atmosphere and magnetic field, which deflects much of the solar and space radiation particles. Outside the Earth's protective magnetic field is a much harsher environment that has been dealt with only by the Apollo astronauts. Their spacecraft had very little shielding, but radiation exposure was mitigated by the fact that they were in space for about a week, and not the months or years that will be required for future mission scenarios. Shielding can be added to the habitats to provide adequate protection, but it is massive and could be cost prohibitive and not as efficient when compared to the use of lunar regolith. A habitat module under a shelter covered with regolith has the potential to provide radiation protection nearly equivalent to the Earth's environment; and can provide significant thermal control, and protection from micrometeoroid impacts. Figure 7 shows a concept for a completed lunar shelter with habitats docked together inside to form a lunar base.

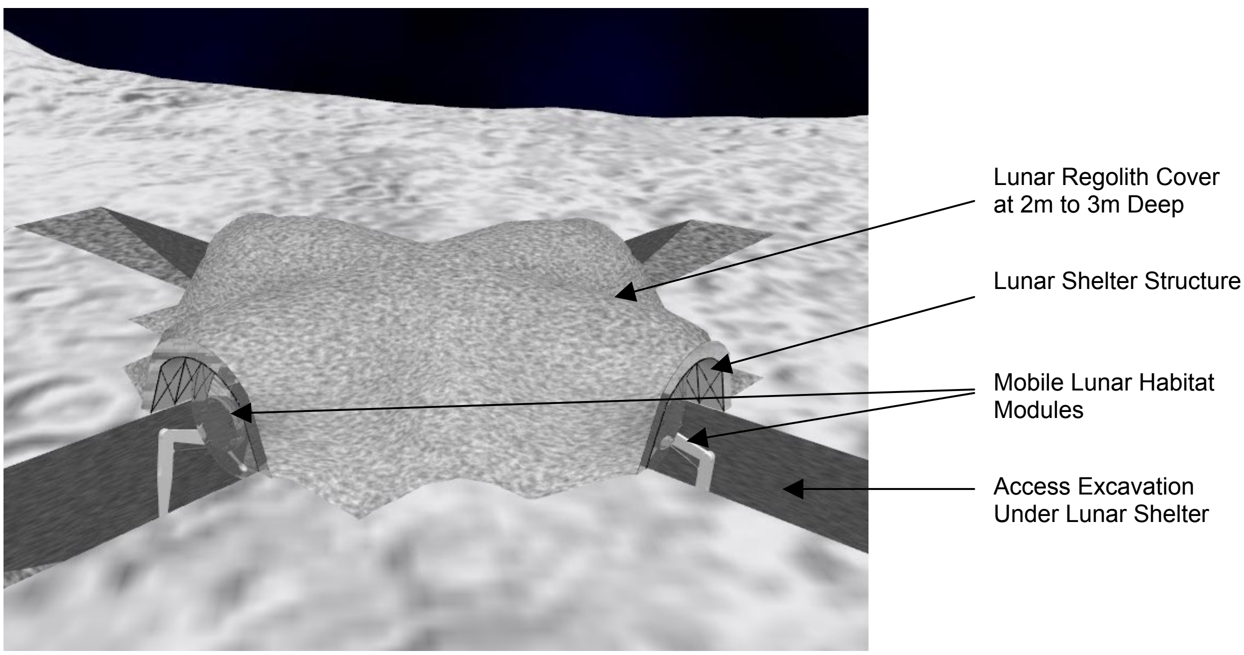


FIGURE 7. Completed Shelter Providing Protection for Mobile Lunar Habitat Modules.

Environments

The maximum recommended radiation dose for astronauts is 0.25 Sv per shuttle mission. In general, a life time exposure of 0.01 Sv times your age in years is considered safe, while a whole body dose of 4-6 Sv is fatal. In the lunar environment a moderate solar event produces up to 4 Sv more than 10 times per year, and the large events can go up to 10 Sv for up to a 200 hour duration. Designing habitat modules with shielding that can provide adequate protection during these severe solar events will be difficult. The shelter concept above provides an alternative to massive shielding on individual modules by utilizing lunar regolith for protection during the most hazardous events. It has been determined that about 2 meters of lunar regolith would be sufficient to filter out all of the radiation. Analysis was done of lunar shelter construction covered with at least 2m of regolith with a density of 1500 Kg/m.

Protective Shelter Construction Concept

As previously mentioned, the shelter / excavator module delivers all the required materials and equipment for shelter fabrication. The module contains a shelter form of coiled titanium or composite construction that deploys into a half-cylinder form. Once anchored in place the excavator removes lunar regolith from under the form cutting a trench 0.5 to 2 meters in depth and places the material on top of the form to build up the protective shielding. Floor depth under the shelter will depend on form design, local regolith conditions, and excavator capabilities.

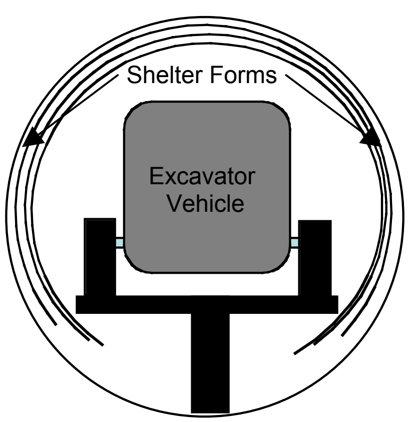
Coiled sheets of titanium and carbon composite form constructions were analyzed for the roof support. In the rolled condition the material was designed to fit inside a standard module, but in an elastic state, such that when the restraints are removed it will bounce back to its original half-cylinder shape. The main advantage of this type of roof is that it does not need any external equipment for deployment. A finite element analysis on the construction was performed for several roof form materials, and the thickness of regolith at any point on the shell was at least 2m.

Table 1 provides a summary of the form materials considered and the mass each system would likely have based on the anticipated loads. All three examples are of sufficiently low mass that packaging of the forms with other equipment should be feasible. Titanium sheets in both 5mm and 2mm thicknesses were examined for consideration of both a robust configuration that could sustain more construction damage, and a minimum thickness for load, respectively. Carbon Composite sheets were also examined, but there are long-term materials durability issues still to be considered. Thus, from a structural standpoint, it can be observed that the rolled Ti or composite shells would be feasible roof materials.

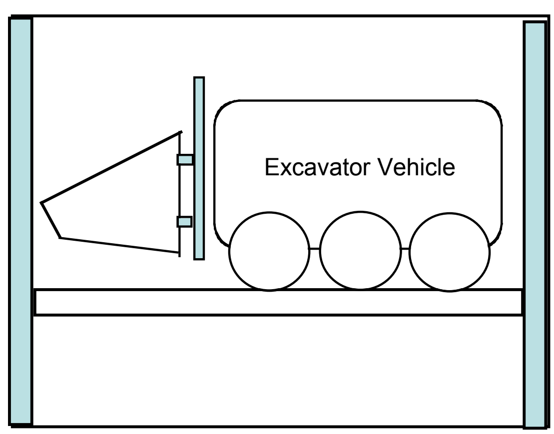
TABLE 1. Compendium Of Results For Shelter Form Materials.

Shelter Form Materials (mm)	Roof Displacement (m)	von Mises Stress (MPa)	Regolith Displacement (m)	Material Mass (kg/m)
Ti 5	0.056	44	0.271	212
Ti 2	0.077	70	0.278	84
Carbon Composite 2.25	0.088	76.6	0.28	33.75

In addition, it appears that coiled forms for the shelter can be easily carried in a standard sized module and safely stored along the wall. A convenient method of transportation of the shells and the excavator can be seen in the schematic drawing of such a configuration as shown in Figure 8. The excavator is shown schematically as a standard wheeled vehicle, however future plans are to explore a similar leg system for this vehicle, too.



(a) Cross-Section.



(b) Elevation.

FIGURE 8. Shelter Forms and Excavator in a Shelter/Excavator Module.

Other materials and methods were examined for the shelter construction, assembly, and packaging system, but presented here were what appears to be the most feasible approach.

CONCLUSION

Future missions to the moon must utilize architectures and develop technologies that will provide for long-term sustainable growth of space infrastructure. The three primary findings from the summer research activities described in this paper support this long-term view:

1) Future exploration missions should develop reusable depot / transfer vehicles that can be utilized by commercial markets for space transfer services. Adopting a mission architecture that will develop a reusable transportation capability will make it possible for future commercial markets to develop.

2) Robotic walking technology for lunar exploration will be more robust, durable, and compatible with the lunar environment than wheeled vehicles. This walking technology is available today, and can be utilized to make surface exploration systems more robust, mobile, and thus reusable for ongoing exploration missions.

3) Lunar resources utilization for environmental shielding of surface habitats can provide protection equivalent to earth, thereby enabling long-term human missions. The Apollo lunar landings were limited to short duration missions in part due to the hazardous radiation environment. Radiation shielding is a massive system that need not be transported from earth when lunar resources are available for this purpose.

The combination of these three developments will help create more reusable systems to support a long-term sustainable infrastructure for ongoing human exploration missions on the moon and beyond. In addition, these systems will provide opportunities for international cooperation, and a potential for the development of new commercial markets in space that are not feasible today.

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REFERENCES

Cohen, Marc M., “Mobile Lunar and Planetary Bases,” AIAA 2003-6280, Space 2003 Conference, Long Beach, CA, 2003.

Mankins, John C., “Modular Architecture Options for Lunar Exploration and Development,” *Space Technology,* **21(1-2)**, 53-64. (2001).

Shachtman, Noah, defensetech.org, “Giant Spiderbot Steps Out,” March 15, 2005, http://www.defensetech.org/ archives 001436.html, accessed October 31, 2005.

Smitherman, et al., “Hybrid Robotic Habitat for Lunar Exploration,” in proceedings of *Space Technology and Applications International Forum (STAIF-2005)*, edited by M. S. El-Genk, AIP Conference Proceedings 746, Melville, New York, 2005, pp. 1078-1087.

Smitherman, Jr., D.V., “New Space Industries For The Next Millennium,” NASA/CP-1998-209006, Marshall Space Flight Center, Alabama, 1998, pp. 1-20.