AIAA SPACE 2007 Conference & Exposition
18 - 20 September 2007, Long Beach, California

AIAA 2007-6274

The Intermediate Outpost - An Alternate Concept for Human Lunar Exploration

Wilfried K. Hofstetter[*], Timothy A. Sutherland[†], Paul D. Wooster[‡], and Edward F. Crawley[§]
Department of Aeronautics and Astronautics, MIT, Cambridge, MA, 02139

This paper describes and evaluates a lunar outpost concept called the "intermediate outpost", which is a design with low development cost and risk based solely on technologies that are either at TRL 8 / 9 at the present time or required for either the Lunar Surface Access Module (LSAM) or the Crew Exploration Vehicle (CEV). The intermediate outpost is an integrated crewed outpost system that contains all subsystems and consumables necessary to enable extended-duration lunar surface stays with up to 4 crewmembers. The intermediate outpost is delivered to the lunar surface on one dedicated uncrewed cargo flight utilizing an Ares V launch vehicle. Due to anytime abort and Earth return constraints for crewed missions to the outpost, possible landing sites for missions to an intermediate outpost are the lunar polar regions and the lunar equatorial region (near-and far-sides). Performance analysis shows that multi-month stays are possible per crewed visit at such an intermediate outpost; surface stays of this length allow for Mars preparation as well as significant surface exploration. The intermediate outpost may therefore offer a low-investment / high pay-off alternative to a permanently inhabited outpost that would likely require additional technology development and possibly lunar surface assembly operations.

I. Introduction

IN December 2006, NASA's Lunar Architecture Team publicly presented a point of departure concept for a crewed outpost at the lunar south pole, to be fully implemented by the year 2025[1,2]. After the build-up and implementation phase, continuous or near-continuous habitation ("utilization") is begun to achieve the various lunar exploration program objectives such as Mars exploration preparation, establishment of a human presence on the Moon, and scientific investigation on the lunar surface. While such an outpost could provide a significant cumulative capability, it also has a distinct drawback: the LAT point of departure campaign takes about 5 years to deploy the outpost before long-duration stays can commence; this is somewhat reminiscent of the way the International Space Station was and is being assembled[15,16,17]. Along with the gradual build-up of capability on the lunar surface, there is also significant overhead for supporting all the intermediate operational configurations. During this 5-year deployment phase utilization of the growing outpost is limited. The use of dedicated cargo flights and switching to a single full-size habitat would significantly speed up deployment; however, a reduction of the deployment phase below 1-2 years seems unlikely.

We propose an alternative low-investment lunar outpost concept that requires minimum deployment operations and is ready for utilization virtually immediately after deployment: the "intermediate outpost". The following is an overview of the defining characteristics of the intermediate outpost:

- Components: the intermediate outpost consists of a full-size habitat, with subsystems based on ISS heritage or on technologies to be developed for LSAM or CEV[3], solar panels for power generation and batteries for eclipse power generation, and unpressurized rovers for surface mobility. These components are mounted on a LSAM descent stage; integration takes place in a controlled facility on Earth. The outpost is stocked with consumables up to the payload capacity of the lunar lander.

[*] Graduate Research Assistant, AIAA Student Member.
[†] Graduate Research Assistant
[‡] Research Scientist, AIAA Member.
[§] Professor of Aeronautics and Astronautics and Engineering Systems, AIAA Fellow.

- Deployment: the intermediate outpost is deployed to the lunar surface using a single Ares V dedicated cargo flight[3]. After landing, any items that need to be deployed (such as ramps, solar panels, and possibly radiators) do so by remote control; after that the outpost is ready for utilization and habitation.
- Utilization: a deployed intermediate outpost is visited once or multiple times by crew with an LSAM; the crew uses consumables pre-stored on the outpost and re-supply brought along on the LSAM. While deployment and utilization of an intermediate outpost is conceivable at any site on the lunar surface, anytime abort and Earth return constraints would limit extended-duration utilization missions to polar or equatorial locations.

The remainder of this paper will provide a more detailed description of the design and capabilities of the intermediate outpost concept.

II. Historical Role Models

The intermediate outpost concept is not a new invention, but is based on historical concepts that serve as "role models" of sorts. Specifically these concepts were: Skylab[14], the first US space station, the 1992 NASA First Lunar Outpost (FLO) concept[13], and the series of Salyut space stations of the Soviet Union[10,11,12] (see Figure 1).

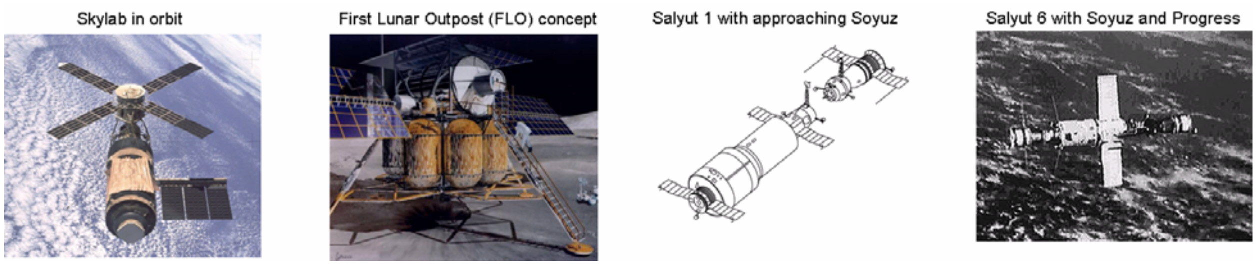

Figure 1: Historical systems and concepts similar to the intermediate outpost

For each of these systems, a brief description is provided here:

- Skylab was launched by a single Saturn V in 1973 as the first US space station and was visited by 3 crews in 1973 / 1974 using Apollo CSMs launched on Saturn IB rockets. The design of Skylab was based on the use of a converted S-IVB stage as pressure vessel, with an attached airlock module and a solar telescope unit. Apart from the loss of a micrometeoroid and thermal shield and a solar array during launch, Skylab was very successful and yielded significant experience in the novel field of operation and utilization of a space station, as well as the longest-duration US human space flight at that time (84 days, Skylab 4)[14].
- First Lunar Outpost (FLO) was proposed by the NASA Office of Exploration in 1992 as an initial low-investment lunar outpost concept. The FLO habitat was to be delivered using one cargo launch on a Saturn V derived heavy-lift launch vehicle. It would then be visited by crews using a lunar direct return transportation architecture; this allowed for location of the outpost at any site on the lunar surface, while maintaining anytime abort and Earth return. The design of FLO habitat unit was based on the Space Station Freedom habitat design[13].
- The Soviet Salyut civilian program included four space stations: Salyut-1, Salyut-4, Salyut-6, and Salyut-7. Three other space stations with Salyut designations were intended for military purposes only and are not considered here. Salyut-1 and Salyut-4 only had one docking port, allowing for visits with crew but not for re-supply (beyond what could be brought up with the crew in the Soyuz). This meant that the space station could only be used for crewed visits until its stock of consumables was used up. Salyut-1 had one visiting crew, and Salyut-4 two; the longest stay achieved was ~63 days[10,11,12]. Salyut-6 and Salyut-7 had two docking ports, allowing for crew rotation and re-supply while the space station was crewed. On Salyut-6, orbital stays in excess of 180 days and on Salyut-7 in excess of 200 days and permanent inhabitation over extended periods of time were achieved[10,11,12]. Each space station in the civilian Salyut program was based upon the same general concept, but improved upon the design of its predecessor, leading to the designs implemented for the MIR core module and the ISS Zvezda module[10,11,12].

All of the systems described above share the characteristic that they are outposts deployed with a single launch and ready for use after very limited deployment operations which are achieved remotely. The intermediate outpost concept is based upon this fundamental characteristic, allowing for significant utilization on the first visiting mission; the following sections describe the design and utilization details of a reference concept.

III. Intermediate Outpost Design

A conceptual reference design was carried out for the intermediate outpost with one variant suitable for operation at lunar polar sites and one variant for equatorial sites[4,5,6,7,8,9]; the two configurations are shown in Figure 2:

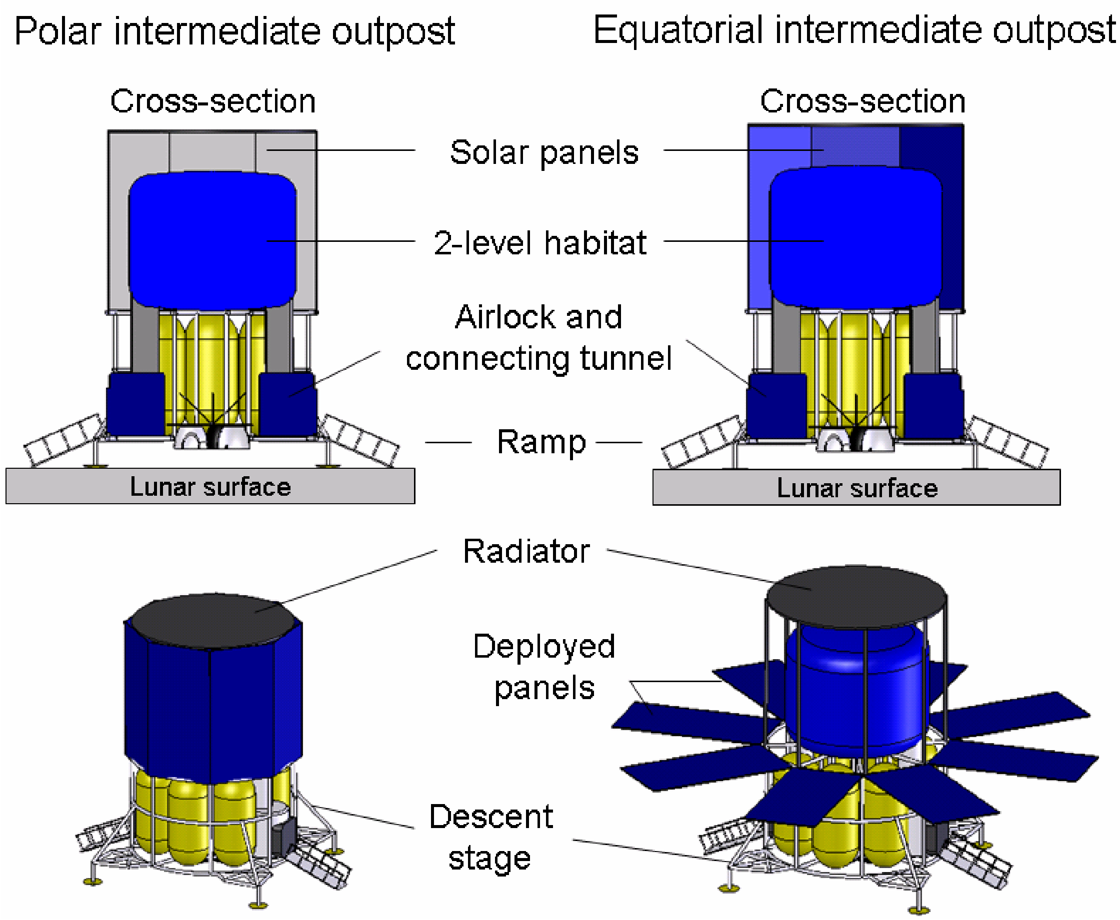

Figure 2: Overview of the intermediate outpost reference design for polar and equatorial sites

The outpost consists of the following elements (see Table 1 for component quantity and mass):

- A 5-m diameter habitat module of ~5 m height; the habitat consists of a cylindrical section and two ellipsoid end-caps, and has two internal levels providing significant floor area. The habitat is located on top of the descent stage which was assumed to have a 7.5 m external diameter.
- Two airlock modules with tunnels connecting each one to the habitat. The airlock modules are mounted in-between the descent stage tanks and next to the descent stage engines; this means that on the lunar surface the airlock modules are close to the ground. Ramps provide access from the airlock hatch to the lunar surface. The airlocks also provide storage volume for space suits and EVA-related equipment.
- Non-tracking solar arrays which either face outward and are mounted vertically to a structure on top of the descent stage (for polar locations), or face inwards, mounted vertically and then rotated into a horizontal position once on the surface (for equatorial sites). Somewhat different solar array areas are required at polar and equatorial locations due to the increased energy storage needs at an equatorial site. The arrays provide 15 kW BOL, 12 kW EOL power for a lifetime of 10 years.

- Battery units for energy storage; Lithium-ion batteries were assumed (energy density of 150 Wh/kg). The battery units are designed such that 1 kW of average eclipse power can be provided for keep-alive of the dormant intermediate outpost. Due to the increased duration of the equatorial night (354 h vs. 72 h at a high-illumination polar location), a different number of battery units is required for polar and equatorial locations.
- A radiator facing space, located above the habitat on top of the solar array structure. The radiator is connected to the external active thermal control loop as well as an internal active loop for control of the cabin atmosphere and outpost systems.
- Unpressurized rovers which are mounted on the descent stage and deployed on the surface. Two 2-person rovers were assumed, each with the ability to carry two additional crew in case of an emergency. When used together on traverse, these rovers provide an exploration radius of at least 20 km around the outpost. The rovers could also be deployed with the first crew in exchange for additional consumables deployed with the intermediate outpost.
- Consumables pre-stored on the outpost, including medical supplies, spares, food and EVA water, science equipment, etc. Conceptual design analysis indicates that 8.6 kg / person / day are required for consumables stored in the outpost habitat (including packaging), whereas 12.1 kg / person / day are required if consumables are delivered in pressurized containers on the LSAM; this indicates that it is desirable to maximize the amount of consumables delivered with the outpost.

Table 1: Overview of intermediate outpost component quantities and masses

Item	Mass [kg]	Polar outpost		Equatorial outpost	
		Quantity	Mass [kg]	Quantity	Mass [kg]
Full-size habitat structure & protection	4500	1	4500	1	4500
Habitat outfitting for 1 crew member	800	4	3200	4	3200
Airlock & connecting tunnel	1037	2	2073	2	2073
2- person unpressurized rover (can carry 500 kg cargo or 2 additional crew members)	500	2	1000	2	1000
Body-mounted solar array unit, power generation of 15 kW per unit [polar]	786	1	786	0	0
Body-mounted solar array unit, power generation of 15 kW per unit [equatorial]	858	0	0	1	858
Eclipse power storage unit (based on Li-Ion batteries)	120	4	480	20	2400
Active thermal control unit	882	1	882	1	882
Margin / growth			1144		1151
		Total	**14066**	**Total**	**16065**

In addition to the parametric design analysis of mass, volume, and power / energy properties of the intermediate outpost, a conceptual layout of the habitat interior was created to assess the feasibility of internal storage and habitability. Figure 3 shows floor plans for the two levels of the intermediate outpost habitat. On level 1 are located: the outpost systems (life support, avionics, communications, etc.), a galley with consumables storage, hygiene facilities (toilet and shower), and further storage compartments, some of which could be used for intravehicular science. On level 2, sleeping compartments for the crew are located, each with a bed and storage space for personalized items and equipment as well as clothing. Both levels could have a ceiling height of 2.1 m or more. While somewhat spartan, this internal layout suggests that sufficient habitable volume could be provided with the given volume, as well as some personal space; extended-duration stays of several months should be feasible.

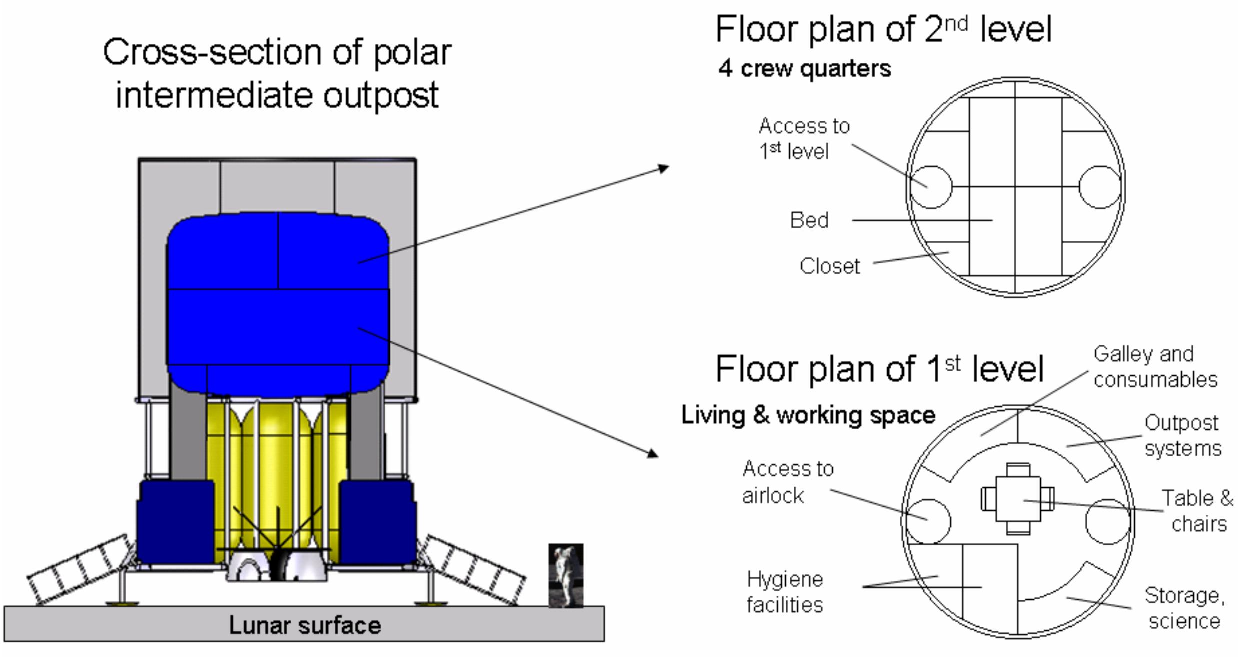

Figure 3: Outpost habitat conceptual internal layout

IV. Intermediate Outpost Campaign Performance

As described above, the utilization scenario of the intermediate outpost involves visits with crewed LSAMs that bring re-supply and surface equipment. During the visit, the LSAM is connected to the intermediate outpost for keep-alive power; the cabling required for this transfer would be delivered on the first visiting LSAM and could then be reused for each following visit. For lunar polar locations with high illumination fractions (maximum 72 hours of lunar night), crewed visits would be conducted only when the outpost site is illuminated; this way the outpost power system needs to provide eclipse power only during the lunar day.

Figure 4 shows a plot of the cumulative surface crew time (for a crew of 4) achievable at such a site as a function of intermediate outpost infrastructure mass (see total mass in Table 1); the contours represent different numbers of visits to the intermediate outpost as indicated by the labeling (the time reference indicates how long it would take to carry out the missions, including deployment of the outpost) and icons of the intermediate outpost and the visiting LSAMs. For an outpost infrastructure mass of 14 mt, a single crewed visit could stay for approximately 300 days because about 200 days worth of consumables are pre-stored in the outpost and the visiting LSAM brings another 100+ days (as would any subsequently visiting LSAM). When spread over multiple crewed visits, significant surface stay times are achievable: for 3 crewed visits, each crew could stay for 180 days; for 4 crewed visits, the average stay time goes down to about 165 days, etc.

With surface stay times of this length, the intermediate outpost can provide many characteristics of a permanently inhabited outpost, such as crew rotation on the lunar surface, re-supply, and continuous active usage of a habitat over durations similar to that of a conjunction class Mars surface mission[18]. In case several intermediate outposts are deployed over the course of the campaign, different locations on the lunar surface could be subject to in-depth scientific investigation and exploration, something not possible with a long-term outpost at a single site.

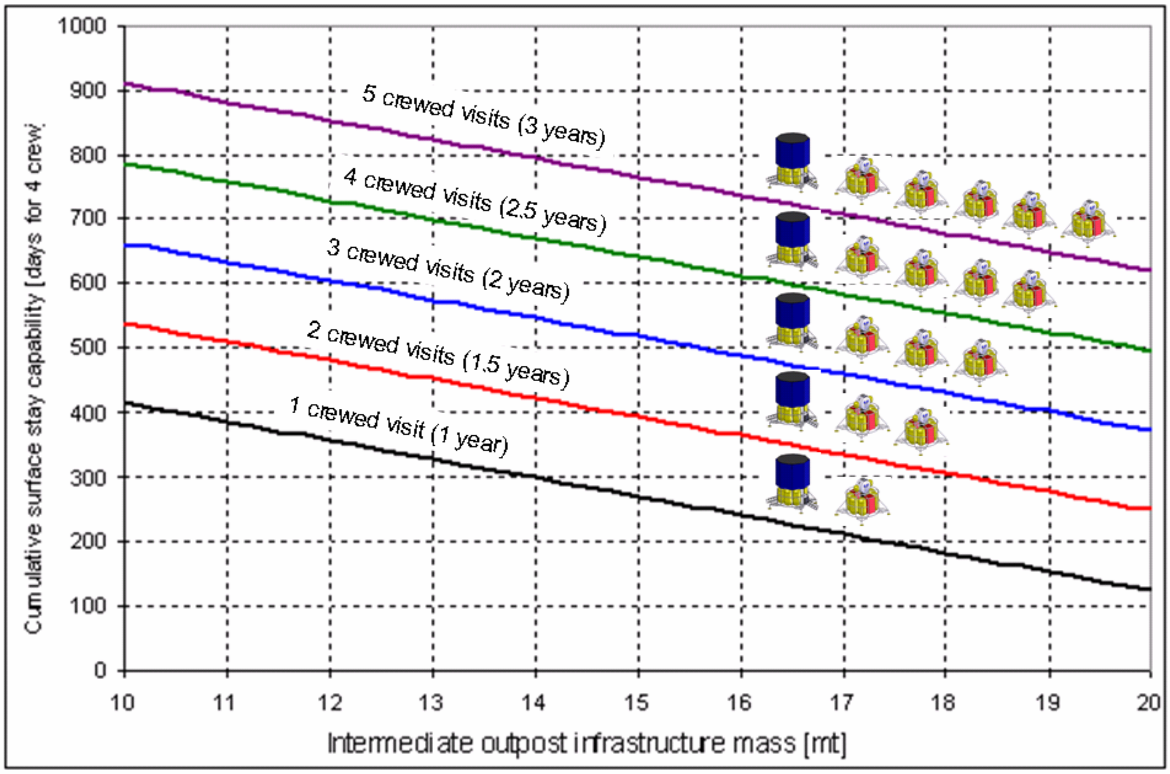

Figure 4: Cumulative surface crew time achievable as a function of intermediate outpost infrastructure mass and number of crewed visits to the intermediate outpost

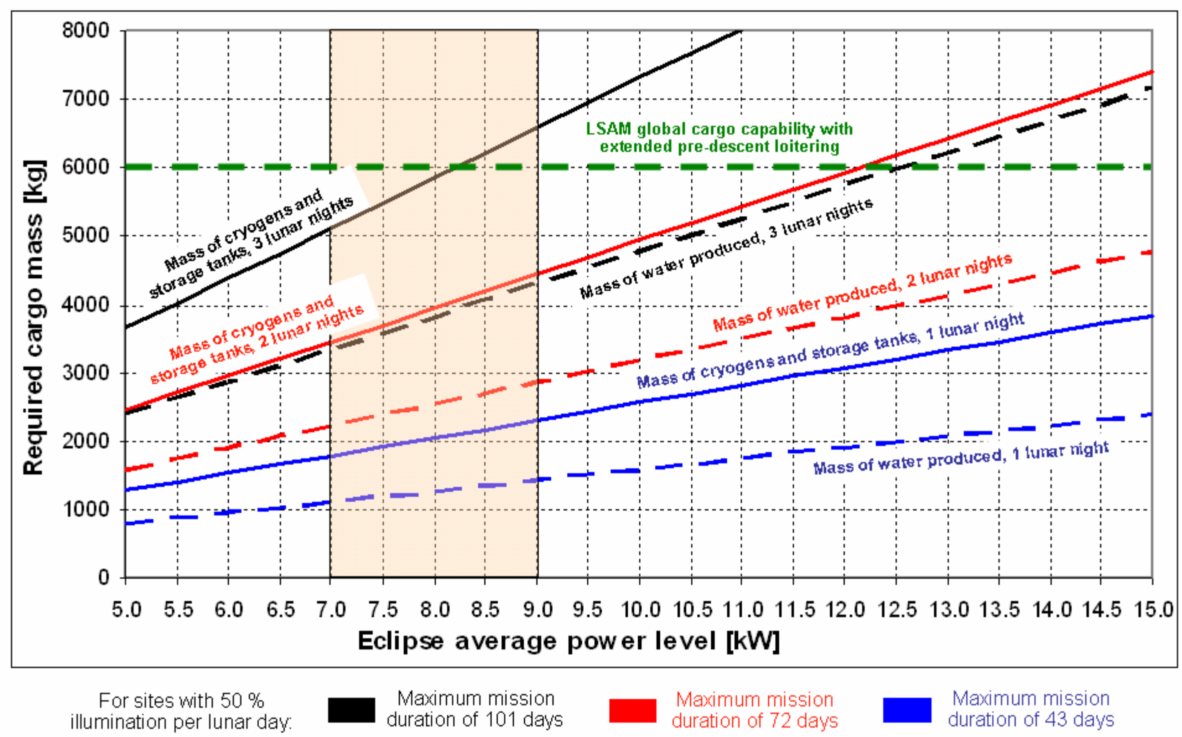

Figure 5: Cryogen storage requirements on LSAM for eclipse power generation at equatorial sites

For intermediate outposts located at the lunar equator, the crew needs to be able to stay over night during its visit to the intermediate outpost. An initial analysis of the energy storage requirements for such a crewed stay during the 354 hour lunar night suggested that batteries and even a regenerative fuel cell system would have masses that prohibited their use for the intermediate outpost concept. An alternative means of providing eclipse power was selected: the LSAM is utilized to bring along cryogenic hydrogen and oxygen stored in tanks mounted to the descent stage (alternatively the cryogens could be stored in the propellant tanks). During the lunar night, these cryogens are consumed to generate power using the LSAM fuel cells, i.e. during the night the LSAM transfers power to the intermediate outpost. During the day, the LSAM would receive keep alive power from the outpost, although it would not regenerate the fuel cell reactants. Figure 5 shows mass requirements for cryogens and associated storage tanks as a function of average eclipse power for outpost operations and LSAM stay-alive and as a function of the number of lunar nights; the shaded area indicates a range of likely average eclipse power requirements. Given that the LSAM payload delivery capacity is limited to 6 mt (if the minimized ascent stage concept is used); a maximum of three lunar nights can be sustained during one crewed visit in case sufficient consumables are pre-stored on the intermediate outpost. If consumables for the surface stay have to be brought along, then only two lunar nights can be sustained. Given that the lunar day following the last lunar night spent on the surface is available to the crew (because solar power is available), surface stay times of 101 days can be achieved for the first one or two visits to an equatorial intermediate outpost; subsequent visits would be limited to 72-day stays. While somewhat lower than the capabilities of a polar intermediate outpost, these stay-times still allow for surface operations with significant relevance towards Mars exploration preparation while also providing a robust scientific exploration capability.

V. Conclusion

This paper investigated the intermediate outpost as an alternate concept for long-duration lunar surface exploration. The intermediate outpost is based on technologies currently at TRL 8 or 9 and technologies required for the LSAM and/or CEV; the components of the outpost (habitat, outfitting, airlocks, power generation and energy storage) are pre-integrated on Earth and deployed to the lunar surface using a single dedicated cargo flight. Conceptual design indicates that the infrastructure mass of the intermediate outpost is about 14 mt; the remaining payload delivery capability of the dedicated cargo flight is used to pre-deploy consumables along with the intermediate outpost (with a capacity for ~ 200 days for 4 crew). Each crewed visit to the intermediate outpost provides cargo capacity for an additional 100 days of total stay-time.

A campaign based solely on the delivery of three intermediate outposts to the polar regions of the Moon over a 10-year period and subsequent crewed visits could provide a cumulative surface crew time of approximately 2400 days for a crew of four. 2400 days are equivalent to four Mars surface mission durations or more than two entire Mars missions. If only two intermediate outposts are deployed, the cumulative crew time could be increased further. The average length of stays would be 140 days, although individual longer stays are possible. Surface stays of this duration permit significant Mars exploration preparation as well as lunar surface exploration. These are significant capabilities for the modest investment in development and design required by the intermediate outpost. Also, it should be noted that the production of additional intermediate outpost units for deployment during the campaign would very likely be less expensive than the development of the additional equipment required to establish a long-term outpost with permanent inhabitation capability.

The intermediate outpost could also be used as a true "intermediate" system that is used following sorties and prior to investment into a long-term outpost with more extensive development and infrastructure deployment needs. This utilization of the intermediate outpost concept is more in-line with the use of the Salyut space stations, as well as the intended use of NASA's First Lunar Outpost (FLO). In this scenario, it may also be possible to utilize the intermediate outpost as the basis for development of a long-term outpost habitat design, thereby reducing the customized development needed for a long-term outpost. It is also conceivable that a deployed intermediate outpost could be retrofitted to serve as a core for a more permanent outpost.

Based on the above characteristics, the authors conclude that the intermediate outpost represents an attractive option for a low-investment initial lunar outpost that has the capability to quickly produce relevant operational experience on the lunar surface. The intermediate outpost provides programmatic flexibility due to its ability to react to changing needs, including establishing additional intermediate outposts at new lunar locations or by evolving into a long-term outpost. The intermediate outpost concept should be the focus of additional technical and operational analysis to assess its attributes and evaluate its potential as part of NASA's lunar exploration program.

Acknowledgments

This paper was prepared at the Massachusetts Institute of Technology (MIT) under a grant from NASA's Exploration Systems Mission Directorate (ESMD). The authors would like to thank NASA for the support of this work. Special thanks go to MIT student Ryan McLinko for his help in generating the CAD drawings and models of lunar outpost concepts shown in this paper.

References

[1]NASA Lunar Architecture Team (LAT), Briefing on Lunar Exploration Strategy and Architecture, 2nd Exploration Conference Houston, December 2006.

[2]The President of the United States of America, Vision for Space Exploration, The White House, January 2004.

[3]Exploration Systems Architecture Study Team, Final Report, NASA, November 2005.

[4]Larson, W. J., Pranke, L. K. (editors), Human Spaceflight – Mission Analysis and Design, McGraw-Hill, New York, 2000.

[5]Wertz, J., Larson, W. J., Space Mission Analysis and Design, Space Technology Library, Microcosm, October 1999.

[6]Eckart, P., Spacecraft Life Support and Biospherics, Space Technology Library, Microcosm, 1997.

[7]Eckart, P., The Lunar Base Handbook: An Introduction to Lunar Base Design, Development, and Operations, Space Technology Series, McGraw-Hill, New York, 1999.

[8]Messerschmid, E., Bertrand, R., Space Stations: Systems and Utilization, Springer, 1999.

[9]Hamilton Sundstrand, Space Systems International, http://www.snds.com/ssi/ssi/index.html, 2006.

[10]Mark Wade, www.astronautix.com, August 2007.

[11]National Space Science Data Center, http://nssdc.gsfc.nasa.gov, August 2007.

[12]Bluth, B. J., Helppie, M., Soviet Space Stations as Analogs, NASA-CR-180920, August 1986.

[13]NASA, 3rd SEI Technical Interchange Proceedings, NASA-TM-107979, 1992.

[14]Belew, L. F. / NASA-MSFC, SKYLAB, Our First Space Station, NASA SP-400, NASA, Washington D.C., 1977.

[15]Jorgensen, C. A., International Space Station Evolution Data Book - Volume 1: Baseline Design, NASA/SP-2000-6109/VOL1/REV1, NASA, October 2000.

[16]Jorgensen, C. A., International Space Station Evolution Data Book - Volume 2: Evolution Concepts, NASA/SP-2000-6109/VOL2/REV1, NASA, October 2000.

[17]Mission Operations Directorate / Spaceflight Training Division, International Space Station Familiarization, Johnson Space Center, NASA, July 1998.

[18]Hoffman, S., Kaplan, D. (editors), The Reference Mission of the NASA Mars Exploration Study Team, NASA SP-6017, Johnson Space Center, Houston, Texas, 1997.

[19]Wooster, P. D., Practical Approaches to Cost Effective Human Moon and Mars Exploration, Master's thesis, Department of Aeronautics and Astronautics, Massachusetts Institute of Technology, Cambridge, 2007.

[20]Hofstetter, W. K., Wooster, P. D., Crawley, E. F., Analysis of Human Lunar Outpost Strategies and Architectures, AIAA-2007-6276, AIAA Space 2007, September 18-20, 2007, Long Beach, California.

[21]Hofstetter, W. K., Wooster, P. D., Crawley, E. F., Extending NASA's Exploration Systems Architecture towards Long-term Crewed Moon and Mars Operations, AIAA SpaceOps 2006, June 19-23, 2006, Rome.