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Analysis of Human Lunar Outpost Strategies and Architectures

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Recently published plans for a human lunar exploration campaign as part of the Vision for Space Exploration focus on the establishment of an outpost at the lunar South Pole with the intent of permanent or near-permanent inhabitation. This paper investigates potential lunar exploration alternatives to this strategy based on a small number of so-called campaign elements which could be placed end-to-end to build a lunar exploration campaign. Results indicate that special consideration should be given to campaign strategies that include what we term "intermediate outpost" missions, as such missions can provide significant value for Mars preparation early in the campaign and under certain conditions may obviate the need for a long-term outpost altogether. The paper also includes conceptual design analysis for technical lunar surface architectures based either on a full-size habitat pre-integrated on Earth or on a habitat that is assembled on the lunar surface out of multiple modules. Comparison of campaign performance shows that the differences between the technical surface architectures are small compared to the differences in campaign strategy; technical architectures therefore need to be compared on cost and risk. Based on cost and risk considerations, a lunar surface architecture with a full-size habitat pre-integrated on Earth is preferred. In general, the lunar surface system architecture should be designed to support all or most of the campaign elements in order to provide flexibility and robustness to programmatic change over the next decade before the actual implementation of the campaign.

I. Introduction

IN December 2006, NASA published their initial plan for a lunar exploration campaign based on 6 guiding themes as part of the implementation of the Vision for Space Exploration[1,2,3]. The campaign strategy is based on the establishment of an "outpost first" with continuous or near-continuous habitation capability on the rim of Shakleton Crater at the lunar South Pole; the outpost infrastructure is delivered on crewed flights in units of 6 mt size. While detailed campaign objectives and requirements have not been published by NASA, the overall campaign strategy appears to be focused on the exploration preparation and human civilization themes[1].

The LAT strategy presented in December 2006 is one of a large number of conceivable campaigns and associated lunar surface architectures. Different weightings between the guiding themes and high-level objectives could favor a different set of missions in the campaign and therefore drive towards a different surface systems architecture, i.e. there is a strong sensitivity of campaign and architecture design on the program-level requirements. An extreme example for this would be a campaign solely driven by selenology, which would tend to favor sortie missions to a large variety of sites while de-emphasizing the need for long-duration stays. Given the long time span before the lunar exploration system will actually be put into operation and the associated changes in Administration and Congress, it seems likely that changes in program-level requirements may occur. The lunar surface system architecture should therefore be robust to such changes and flexible to support a variety of campaigns strategies.

The analysis presented in this paper was carried out to determine the possible scope of lunar exploration campaigns and derive recommendations for the design, development, and operation of a lunar surface system architecture. Initially, possible campaign elements are defined, and a number of reference campaigns with varying

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sets of objectives are laid out. This is followed by a discussion of the two major technical implementation options for the lunar surface system architecture based either on full-size or modular habitat elements. The performance and cost of the example campaigns is then assessed for both of the architecture options, and an analysis of the sensitivity of campaign performance to changes in the 1.5-launch TLI capability is carried out. The paper concludes with a comparison of the technical architecture options and a summary of major findings and recommendations.

II. Campaign Elements

Ideally, the design of a lunar surface systems architecture would be based upon detailed and unchanging requirements which are derived from stable lunar campaign objectives which in turn flow from guiding themes traceable to stakeholder needs; this process if outlined in Line 1 in Figure 1. In reality, however, the actual campaign objectives may not be known until the campaign is being implemented, i.e. when it is too late to make significant changes to the lunar surface system architecture (Line 2 in Figure 1). This uncertainty is on one hand due to changes in Administration, Congress, and NASA leadership which are bound to occur over the course of the next decade until the campaign is implemented; on the other it is due to operational experience and discoveries that may occur before the implementation. The result of this uncertainty is that it may be very difficult to arrive at a detailed and unchanging set of requirements that can serve as the basis of lunar system architecting.

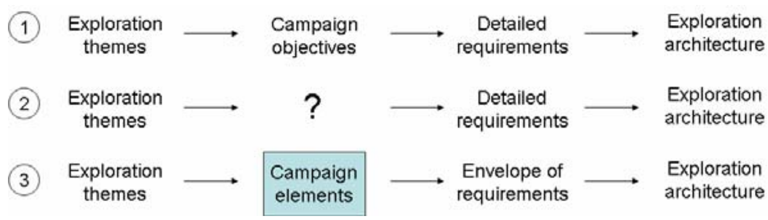

Figure 1: Architecting approach using campaign elements

Borrowing from scenario analysis methodology[4], we propose a different approach to solving this dilemma: based on the available constraints on the lunar architecture and the guiding themes, a comprehensive enumeration of the possible sets of missions (called "campaign elements") that could conceivably be performed in a lunar campaign is carried out. For each of these campaign elements, detailed requirements can be derived; i.e. by considering all campaign elements, an envelope of requirements for a lunar surface system architecture can be constructed. The architecture is the designed to support all or the majority of the requirements in the envelope (Line 3 in Figure 1).

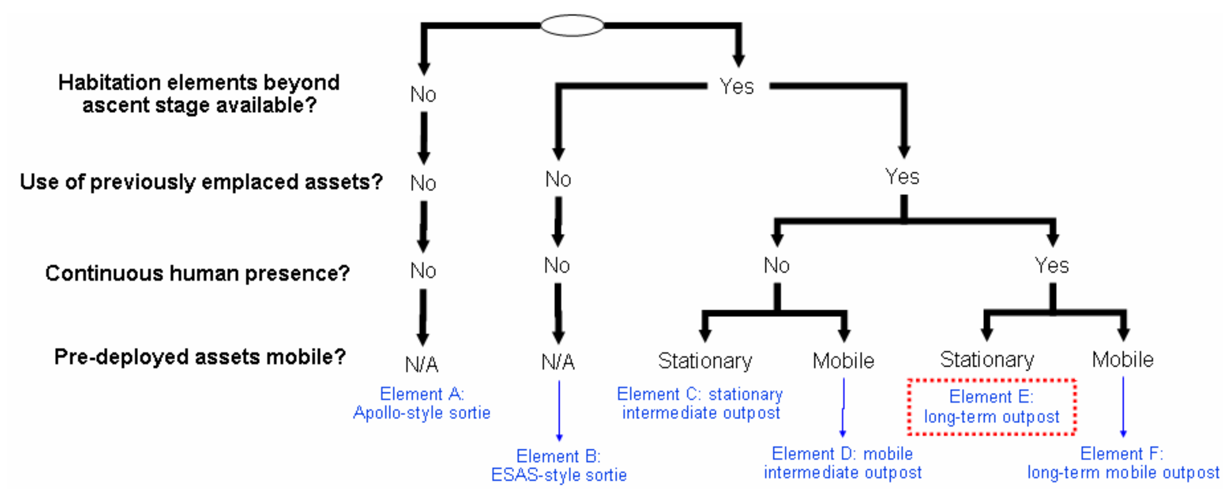

Figure 2: Campaign element enumeration

Figure 2 provides an overview of the campaign elements enumerated based on 4 factors:

- Whether or not additional habitation elements (i.e. a crew compartment or habitat) beyond the ascent stage are available on the lunar surface
- Whether or not previously emplaced assets are utilized during the mission or set of consecutive missions
- Whether or not continuous habitation is achieved

- Whether or not the pre-deployed assets are mobile

Logic and feasibility constraints lead to the 6 campaign elements outlined in Figure 2:

- The Apollo-style sortie (campaign element A) is based on habitation in the ascent stage only; the duration of the surface stay is therefore likely limited by pressurized volume constraints. It should be noted that Apollo-style sorties based on the Ares launch vehicles, CEV, and LSAM could provide significantly more capability than Apollo J-class sorties[21] due to the increased surface crew size (4 vs. 2), increased payload mass (6 mt vs. 600 kg), and a potential increase in the surface stay duration beyond 2-3 days (pressurized volume constraints permitting)
- The ESAS-style sortie[3] (campaign element B) is a sortie mission with an additional crew compartment / airlock module to augment the pressurized volume of the ascent stage. This increased pressurized volume enables an increase in the duration of the surface stay which is now either constrained by consumables or by CEV plane change capability.
- The stationary intermediate outpost (campaign element C) is based upon the pre-deployment of an integrated outpost (including habitation along with integrated power generation and storage, and optionally including emplacement of surface mobility systems) on a dedicated cargo flight and subsequent visits by crewed flights for long-duration (6 – 25 weeks depending on location) stays[16, 24,25]. Given the limitation to a single dedicated cargo flight, the intermediate outpost would be spartan in outfitting and would not feature advanced life-support capability (in particular not including closure of the oxygen loop) for continuous habitation.
- The mobile intermediate outpost (campaign element D) is a variant of campaign element C with an additional mobility system that permits surface transportation of the pre-deployed intermediate outpost. The advantage of adding this system is that the outpost can now be moved to a different region on the lunar surface in-between visits with crew, allowing for exploration of more sites. Assuming a desire to maintain an anytime return capability, the mobile intermediate outpost would be most relevant for the equatorial regions. This is because there is very limited terrain for a mobile outpost to explore at the pole, and providing an anytime return for extended stays requires a stay either at one of the poles or the equator.
- The stationary long-term outpost (campaign element E) is a larger outpost which is aimed at continuous inhabitation. Such an outpost would likely require more than a single dedicated cargo flight for delivery.
- The mobile intermediate outpost (campaign element F) is a transportable version of an outpost intended for permanent inhabitation. Given the potential complications due to the need of moving with the crew onboard and abort considerations, the applicability of this campaign element is doubtful.

A lunar exploration campaign can be generated by selecting certain building blocks from the above list, and placing them end-to-end for sequential execution; a large number of possible campaigns exist. This shows the degree of flexibility that can be achieved with a campaign element approach, and providing robustness against programmatic change.

Figure 3 shows example campaigns based upon these campaign elements; changes in shading (between white and gray) from flight to flight indicate changes in lunar surface landing site. The flight labeled "Test" is a mission that leaves the crew in lunar orbit while the LSAM descends to the lunar surface[1]; this test mission is assumed to be the first flight for all campaigns to fully demonstrate the lunar transportation system.

	Flight number																			
	Year 1		Year 2		Year 3		Year 4		Year 5		Year 6		Year 7		Year 8		Year 9		Year 10	
	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B	A	B
Focus on long-term polar outpost	Test	A	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
Sortie, stationary intermediate and long-term outposts (both polar)	Test	B	C	C	C	C	C	E	E	E	E	E	E	E	E	E	E	E	E	E
Sortie and stationary intermediate outposts (polar locations)	Test	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C

Figure 3: Example campaigns based on campaign elements

III. Lunar Surface Architecture Families

After the definition of the campaign elements and the associated requirements, the next step is to design a lunar surface system architecture to meet the envelope of requirements. Possible architectures are shaped by decisions relating to a number of high-level technical factors such as the design of the lunar surface habitat (pre-integrated on Earth or assembled on the lunar surface), power generation and energy storage technologies (solar vs. nuclear), the surface mobility system configuration (pressurized vs. unpressurized rovers or both) among others. Based on a review of the design and operational history of US and Soviet / Russian space stations[13,15,17,18,19,20], which are the most applicable projects of comparable scope and with relevant constraints, it was determined that the design of the lunar surface habitat was the paramount distinguisher between lunar surface system architectures.

Two major types of lunar surface system architectures are distinguished:

- Type 1 features a lunar surface habitat which is built out of smaller habitat modules delivered individually to the lunar surface. Given that the smaller habitat modules are delivered individually and assembly is assumed for this type, it makes sense to size the habitat modules such that they can be transported on crewed flights as well as on dedicated cargo flights; thus one type of module fulfills all lunar surface habitation requirements[1].
- Type 2 is centered around a single large surface habitat which provides sufficient pressurized volume for long-duration (6+ months) stays with 4 crew-members which is pre-integrated and outfitted on Earth and deployed on the lunar surface on a dedicated cargo flight.

For both architecture types, a conceptual design[7,8,9,10,11,12] was carried out to assess technical and operational feasibility and generate high-level mass / volume / power properties for manifesting and performance analysis. A number of assumptions were made for the design:

- The design is driven by the stationary long-term outpost (campaign element E), because NOT designing around it would result in significant penalties in case the campaign element is required.
- Logistics and re-supply of an outpost is accomplished using 500 kg packages (322 kg useful cargo) for pressurized logistics which can be transferred using unpressurized mobility only. Fluids (in particular water) are transported in separate tanks and transferred to the habitat using smaller tanks mounted on unpressurized mobility.
- Solar power generation with batteries providing energy storage for eclipse power is assumed in all cases. Non-tracking solar panels are used, body-mounted for polar landing sites, and deployable into a horizontal position for equatorial sites.

The two reference architectures are described in the subsections below. Conceptual designs for the mobile long-term outpost are not shown and are assumed to be based on elements from the stationary long-term and mobile intermediate outposts.

Architecture Based on Habitat Module Assembled on Lunar Surface (Type 1)

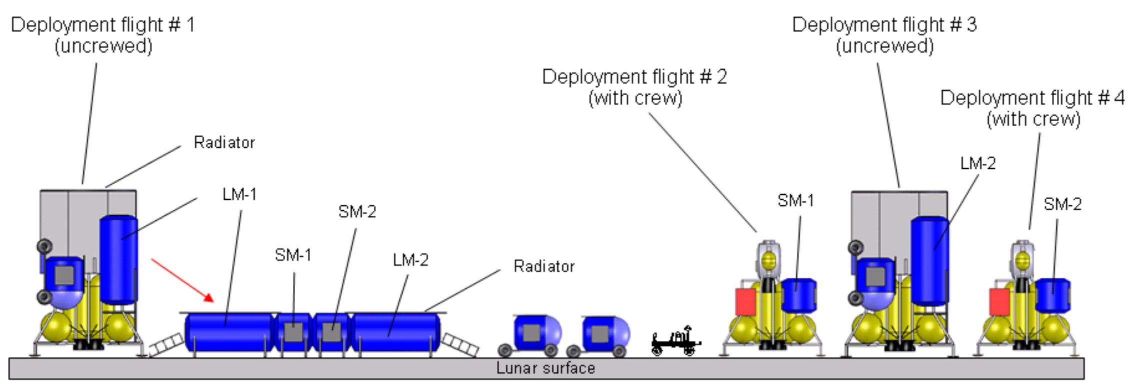

Figure 4: Stationary long-term outpost based on assembly of habitat modules

The Type 1 long-term stationary outpost is shown in a cross-section view in Figure 4 above. Deployment of the outpost infrastructure (defined here as all elements which are not consumed and re-supplied regularly during outpost utilization) requires 4 flights with the following manifests:

- Deployment flight # 1: long habitat module (LM) & internal outfitting (ECLS and crew systems), power generation, energy storage for eclipse power, thermal control, 2-person pressurized rover
- Deployment flight # 2: two 2-person unpressurized rovers, one short habitat module (SM), consumables
- Deployment flight # 3: long module & outfitting, power generation, energy storage, thermal control, 2-person pressurized rover
- Deployment flight # 4: science package, short module, consumables

The first long module is simply rotated off its lander and remains in its final offloaded position. Short modules 1 and 2 and long module 2 are consecutively offloaded, transported across the surface, and connected to the preceding module, resulting in a linear habitat configuration. Due to the gradual assembly of the habitat, at least 3 different operational configurations of the outpost need to be sustained; each on them requires customized documentation, operating procedures, testing, and simulation.

The overall outpost infrastructure mass is estimated to be 48 mt with a gross logistics & re-supply requirement of 3.5 mt / person / year (including the mass of re-supply vessels and packaging for transportation). The short and long habitat modules are based on a pressure vessel platform consisting of cylinder elements and end-cones (not unlike the Spacelab[22]). The long module has 3 cylinder segments, and the short module 1; a medium-size could be created as well using 2 segments but was not included in the reference architecture. The primary motivation for designing smaller habitation modules which then need to be assembled on the lunar surface is the ability to transport these modules with the crew; this would be possible with the short and medium modules.

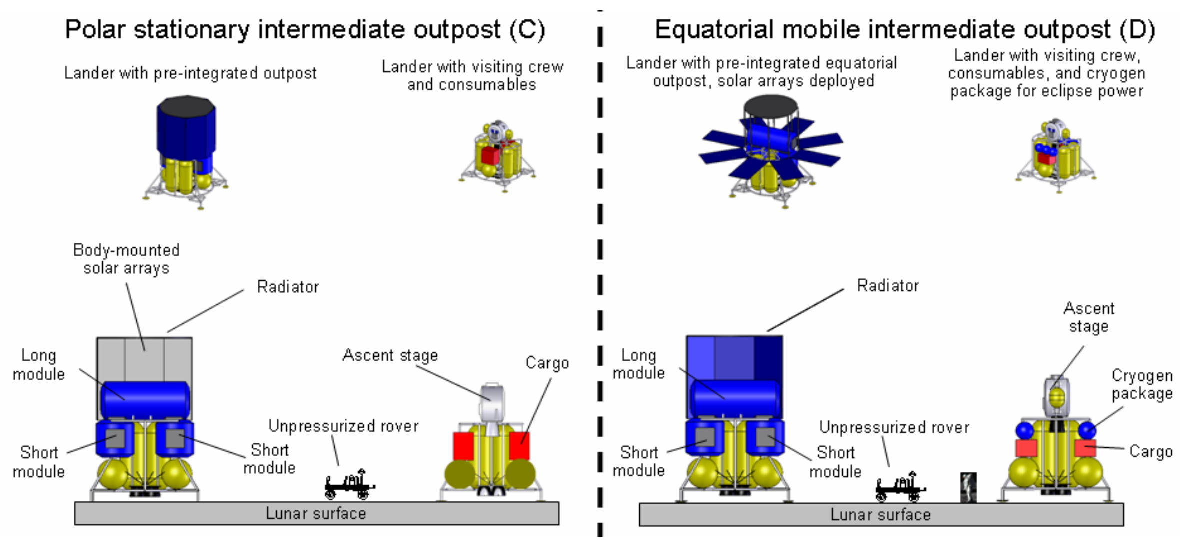

Figure 5: Stationary and mobile intermediate outpost concepts based on small habitat modules

Views of the intermediate outpost designs are shown in Figure 5. The polar stationary intermediate outpost includes a long module and two short modules mounted on the descent stage along with solar arrays, batteries for unmanned eclipse operations, and unpressurized surface mobility. Beyond unloading the unpressurized rovers and extension of ladders and ramps, no deployment is required. The stationary intermediate outpost is visited by landers with only an ascent stage and the maximum amount of cargo / re-supply. The infrastructure mass of the stationary polar intermediate outpost is estimated to be 15 mt with a gross logistics and re-supply requirement of 4.4 mt / person / year.

In addition to the elements from the stationary polar intermediate outpost, the mobile equatorial intermediate outpost requires more dormant-period energy storage due to the longer eclipse time (354 h vs. 72 h) as well as a mobility system that is used to transport the lander with the outpost elements from site to site across the lunar surface (mobility system is not shown in Figure 5). Given the preference for equatorial locations for the intermediate outpost, the solar panels are mounted with the photovoltaic cells facing towards the habitat for launch and are deployed into a horizontal position after landing. Eclipse power during the 354 hour lunar night is provided by LSAM fuel cells and cryogenic hydrogen and oxygen brought along on the LSAM, i.e. during the lunar day power is transferred from the outpost to the LSAM and vice versa during the lunar night; the reactant water is transferred to the outpost and used for habitation and EVA cooling. The mass required for cryogens and associated storage tanks and plumbing was estimated to be 2 mt per lunar night given an eclipse average power of 8 kW.

The outpost is moved from site to site in-between crewed visits during the lunar day, i.e. when the majority of solar power can be utilized for transportation; the outpost is stationary during visits by the crew. The infrastructure mass of the mobile intermediate outpost is estimated at 20 mt, and the gross logistics requirement is 4.4 mt as for the stationary outpost.

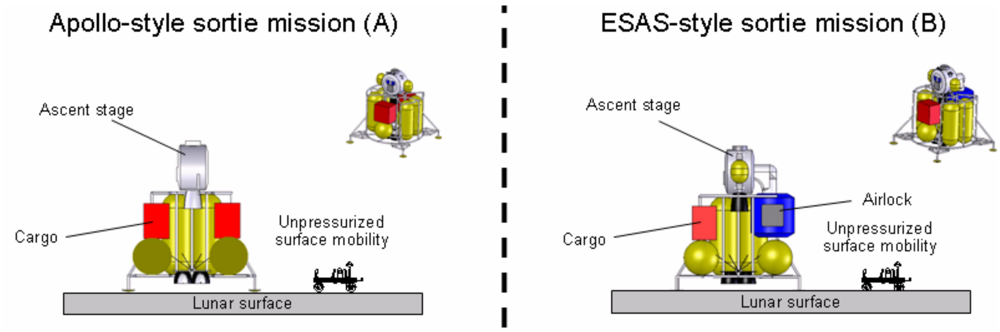

Figure 6: Type 1 sortie lander concepts

The Type 1 sortie lander concepts are shown in Figure 6. An Apollo-style sortie would be carried out solely using the ascent stage for crew habitation. An ESAS-style sortie is carried out using a short module in addition to the ascent stage; this module is connected to the ascent stage until ascent from the lunar surface and serves as an airlock and storage space. It should be noted that the mass of the airlock module reduces the payload mass available for mobility and experiments, although the airlock may be required for extended-duration (week-long or longer) sortie missions.

Architecture Based on Full-Size Habitat Module (Type 2)

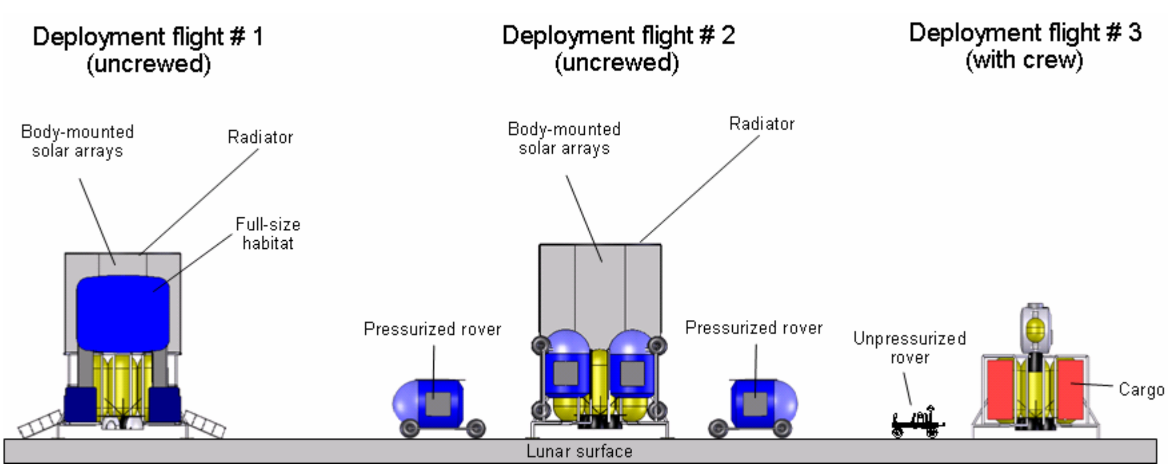

Figure 7: Stationary long-term outpost based on pre-integrated full-size habitat module

The long-term lunar outpost for a full-size habitat is shown in a cross-sectional view in Figure 7. Three deployment flights are required (2 uncrewed and 1 crewed), with the following manifests:

- Deployment flight # 1: full-size habitat module & outfitting, airlocks, power generation, limited energy storage, thermal control, consumables
- Deployment flight # 2: pressurized rovers, power generation, energy storage, associated thermal control

- Deployment flight # 3: unpressurized rovers, science package, consumables

Based on our conceptual design analysis, the long-term stationary outpost has an infrastructure mass of 44 mt and a logistics requirement of 3.5 mt / person / year. The only major assembly operation required is the installation of power transfer cables between the two dedicated cargo landers. Only one outpost configuration needs to be supported in terms of documentation, procedures, testing, and simulation. Ground-level access to the lunar surface is provided by two airlocks mounted in-between the descent stage tanks which are connected to the habitat by pressurized tunnels.

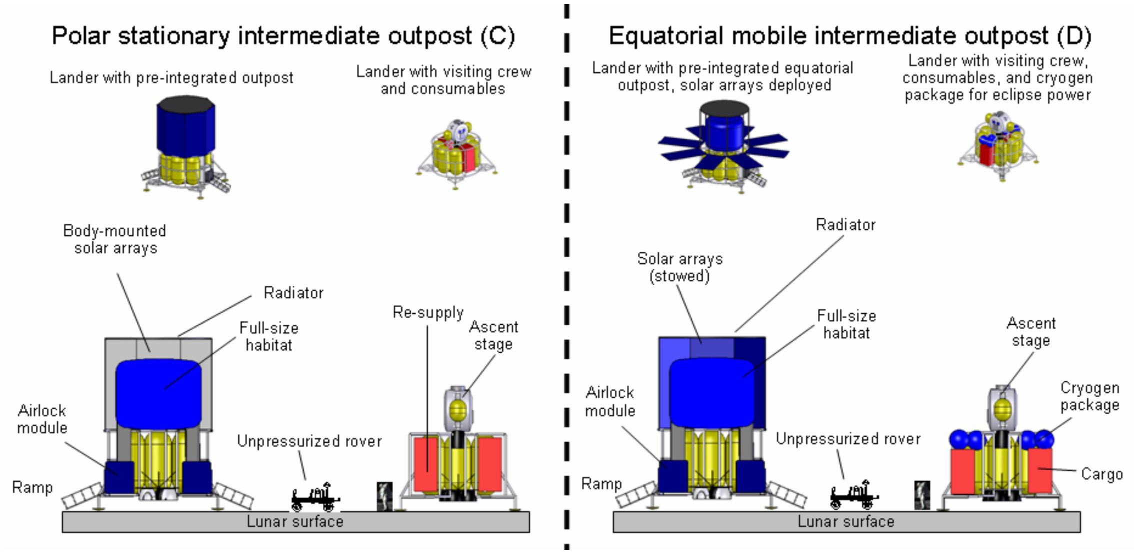

Figure 8: Stationary and mobile intermediate outpost concepts based on full-size habitat module

The stationary intermediate outpost configuration is identical to long-term outpost deployment flight # 1, except that the intermediate outpost has significantly less internal outfitting (see Figure 8). Power generation and energy storage systems are identical to those of the long-term outpost. The stationary polar intermediate outpost infrastructure is estimated to be 14 mt, with a logistics requirement of 4.4 mt / person / year.

The mobile equatorial intermediate outpost also requires more energy storage and a mobility system for translation along the lunar surface, but is otherwise identical to the stationary polar intermediate outpost. Eclipse power is provided by LSAM fuel cell and reactant packages mounted on the LSAM; the reactant water is used for habitation. The mobile intermediate outpost is estimated to have an 18 mt outpost infrastructure mass and a logistics requirement of 4.4 mt / person / year. Per lunar night, about 2 mt of cryogens and storage tanks are required for eclipse power generation.

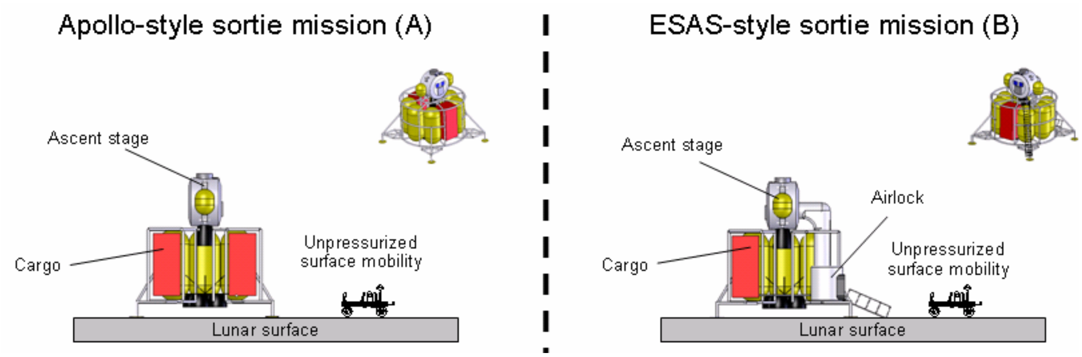

Figure 9: Type 2 sortie lander concepts

The Type 2 sortie landers are very similar to the Type 1 configurations (see Figure 9); the major difference is the somewhat decreased size of the custom airlock module for Type 2, allowing for increased cargo capacity.

IV. Architecture Option Performance Assessment

Based on the conceptual designs described in the preceding section, an analysis of campaign performance was carried out for the two architecture options. The primary metrics for campaign performance were the number of different sites visited on the lunar surface (equivalent to the number of regions of the Moon that have been visited), and the cumulative surface stay time capability provided by the architecture for a particular campaign[23]. The number of sites is purely a function of campaign "design" (i.e. the choice of campaign elements and the landing locations during the campaign); the cumulative surface crew time is a function of both the campaign design and the architecture option.

Figure 10 shows results from a high-level logistics assessment for a campaign duration of 10 years with two flights to the Moon per year (crewed or uncrewed). The cumulative surface time is plotted over the cumulative infrastructure mass delivered to the lunar surface; the contours represent different numbers of dedicated cargo flights during the campaign (lowest line: no dedicated cargo flights, highest line: 4 dedicated cargo flights). Given the number of dedicated cargo flights and number of crewed flights, the logistics requirement for re-supply and spares, and the total infrastructure mass delivered to the lunar surface, the calculation of the stay-time capability is straight-forward: it is the difference of the total mass delivered to the lunar surface and the infrastructure mass divided by the logistics requirement.

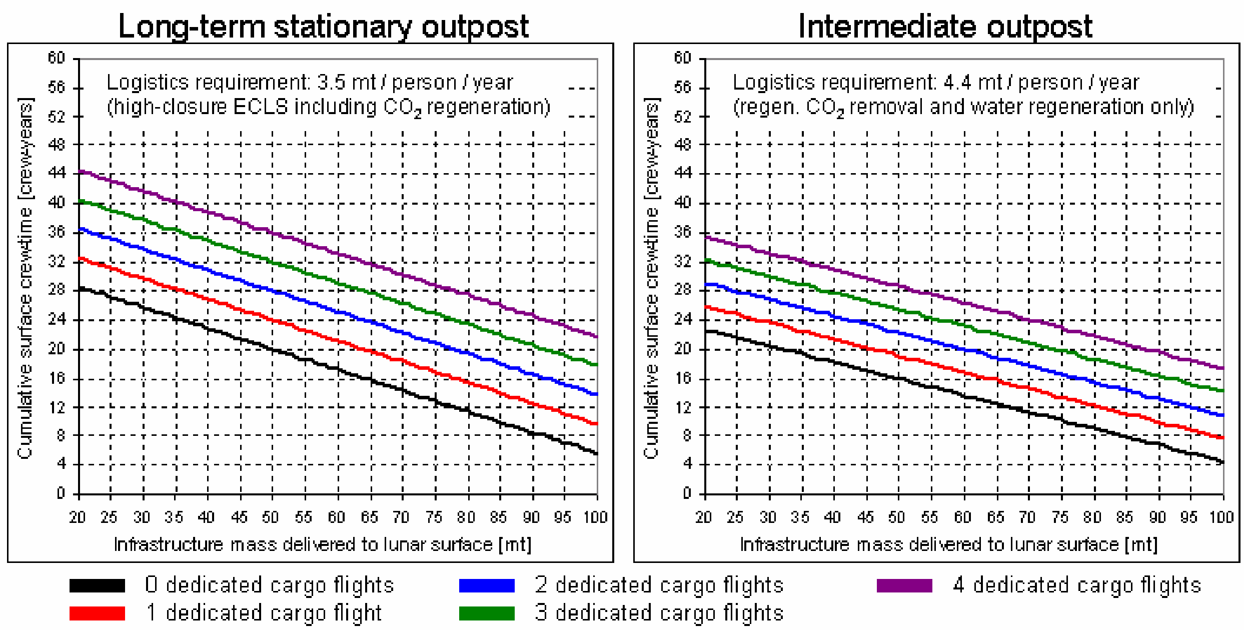

Figure 10: Logistics diagrams for the long-term outpost (left) and intermediate outposts (right)

For a long-term outpost of 45-50 mt infrastructure mass, results indicate that 28 crew-years on the lunar surface are achievable if 2 dedicated cargo flights are used, i.e. 7 years with 4 crew (see diagram on left-hand side). This is equivalent to more then 4 conjunction class Mars mission surface mission durations or more than 2 entire conjunction class Mars mission durations. Each additional dedicated cargo flight buys another 4 crew-years, i.e. another year with 4 crew on the surface, although the total number of crewed flights will go down by one. For a campaign based solely on polar intermediate outposts (diagram on right-hand side), comparable cumulative surface durations can be achieved[23]: if 3 intermediate outposts are deployed (i.e. 3 dedicated cargo flights, infrastructure mass ~ 45 mt), then a cumulative surface stay time of 26 crew-years can be achieved, i.e. 6.5 years with 4 crew. It should be noted that the capabilities shown for the intermediate outpost represent a lower limit, because the same packaging overhead was assumed for consumables pre-stored on the outpost and consumables re-supplied with the crew; as the packaging for consumables pre-stored in the outpost would be lower than that for re-supply, the actual surface duration capabilities would be somewhat higher than shown for an intermediate outpost.

Figure 11 and Figure 12 provide an overview of a more detailed assessment of the three example campaigns outlined in the introduction for the Type 1 and Type 2 architectures. The cumulative surface stay time to date is plotted over campaign elapsed time, enabling a direct comparison of value delivery over time for the campaigns.

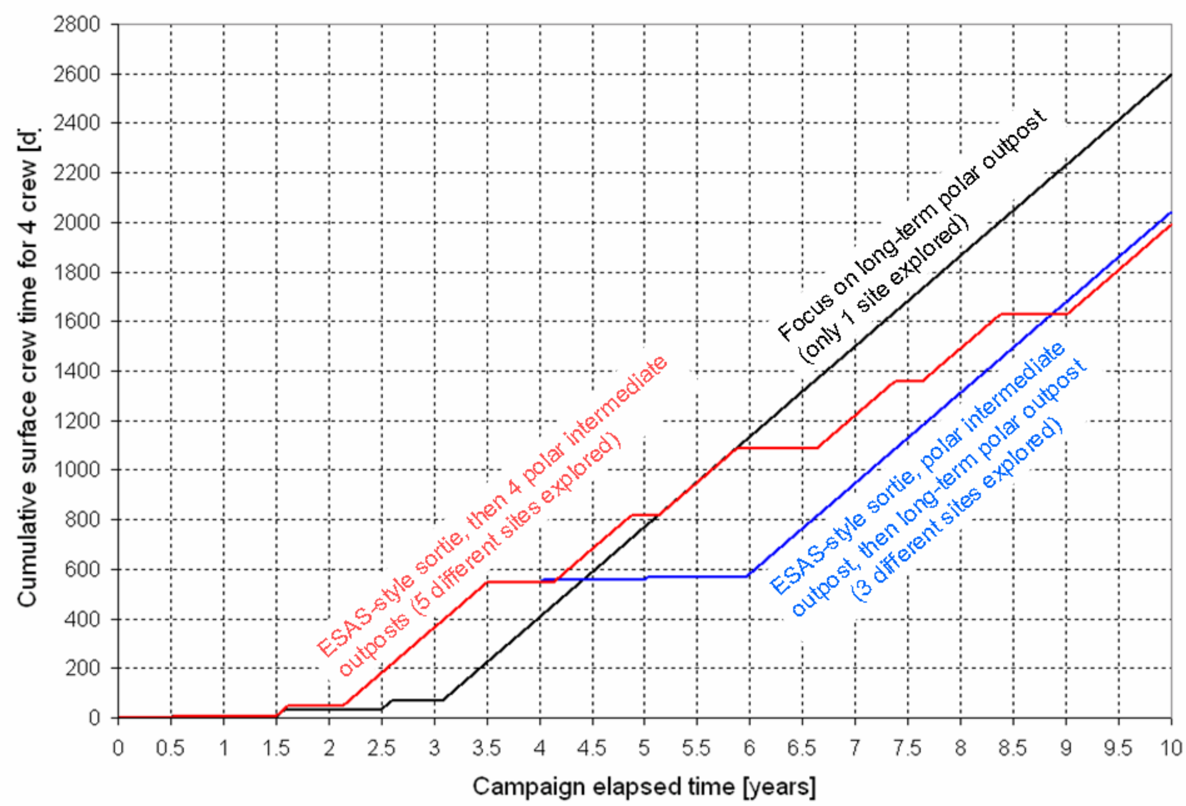

Figure 11: Comparison of example campaign performance for the Type 1 architecture

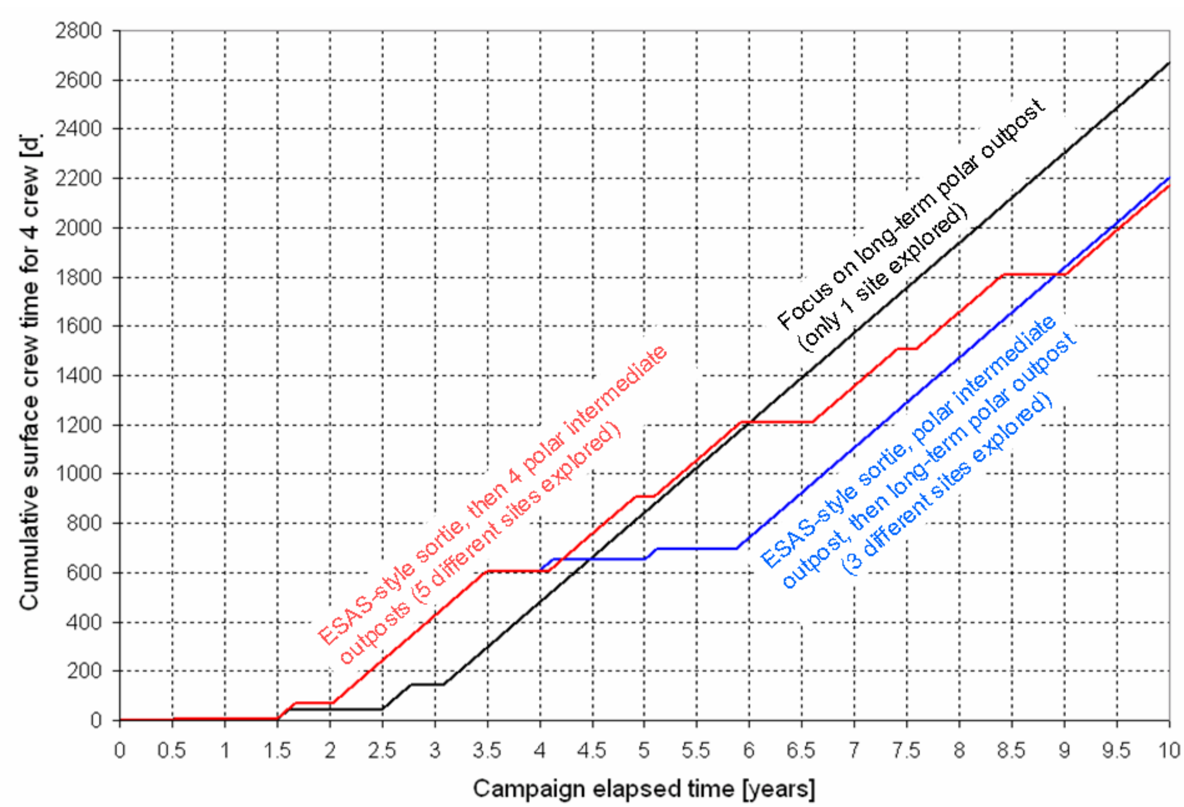

Figure 12: Comparison of example campaign performance for the Type 2 architecture

Some major insights can be gained from the results shown in Figure 11 and Figure 12:

- The cumulative surface stay time of the Type 2 architecture is 50 – 100 days higher than that for the Type 1 architecture; for overall campaign performances of ~2000 days and given the accuracy of the parametric models used for sizing the infrastructure this difference is insignificant.
- The campaigns differ significantly in their cumulative surface stay times and their profiles of surface stay time over campaign elapsed time, in addition to the inherent differences in the number of surface locations (1 for long-term outpost focus, 4 for intermediate outposts only, 2 for intermediate and long-term outposts).

V. Sensitivity to Changes in LSAM Payload Delivery Capabilities

The analysis described in this paper so far was based on the assumption of specific payload delivery capabilities along with the crew (6 mt) and on dedicated cargo flights (20 mt)[1,3]. In order to assess the robustness of the surface architectures, a sensitivity analysis was carried out with regard to changes in the 1.5-launch TLI capability which was assumed to be nominally 65 mt. A degradation to 90% (or 58.5 mt) leads to approximately a 2.8 mt degradation of the payload capability both with the crew (to 3.2 mt) and on dedicated cargo flights (to 17.2); correspondingly an increase of TLI mass to 110 % (71.5 mt) leads to an increase of payload delivery capability of approximately 2.8 mt for both payload with the crew (to 8.8 mt) and on dedicated cargo flights (to 22.8 mt).

We analyze the impact of degraded TLI capability first; Figure 13 shows the logistics diagrams for long-term and intermediate outposts for this case. Despite a significant loss in surface stay capability, a long-term outpost with a crew of 4 (infrastructure mass in the 40-45 mt range) could still provide at minimum 12 crew-years on the lunar surface if 2 dedicated cargo flights are utilized. For an average crew size of 4, this translates into the equivalent of 2 Mars surface durations[5] (conjunction class, ~1.5 years). Per additional dedicated cargo flight, about 4 crew-years can be gained. The average crew size at the outpost can be reduced to enable a longer operating time on the lunar surface.

For campaigns based solely on intermediate outposts, significant capabilities can still be provided (see Figure 13, right-hand side): the emplacement of three intermediate outposts (~45 mt infrastructure mass) leads to a cumulative surface stay capability of ~14 crew-years or more than the equivalent of two Mars surface durations with 4 crew.

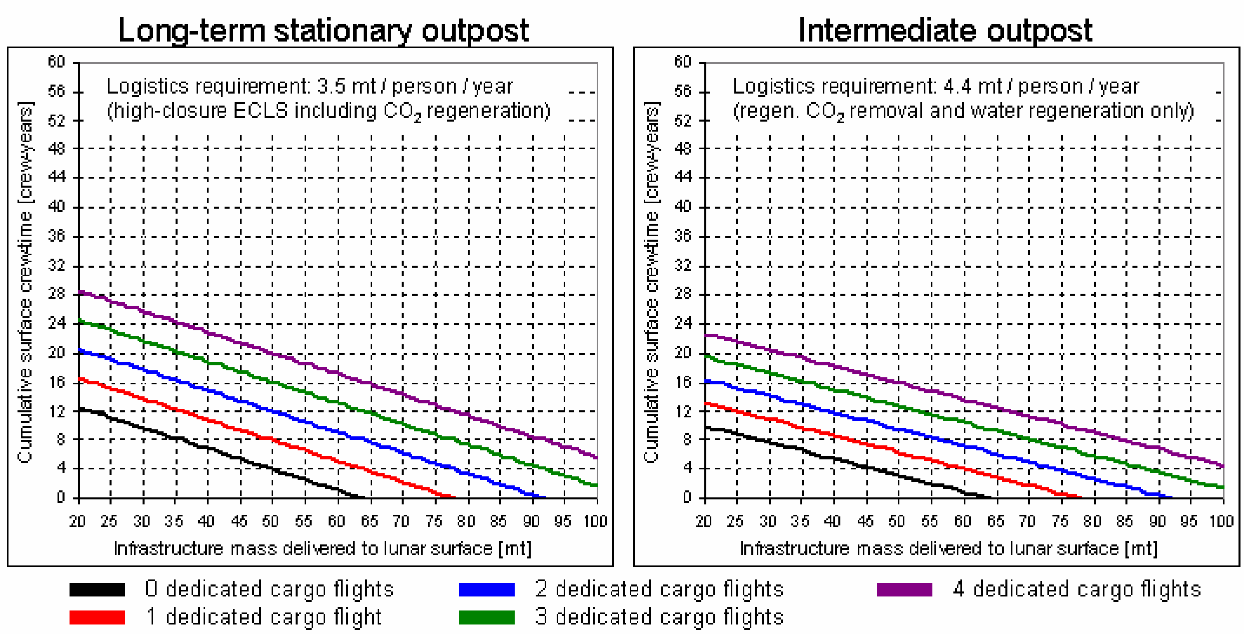

Figure 13: Logistics diagrams for degraded TLI capability

It should be noted that the reduction in capability affects the architectures differently: the architecture based on a full-size habitat is virtually unaffected by a change in payload capability as long as the habitat and all its outfitting can be delivered on a dedicated cargo flight; if this is no longer the case, some of the internal outfitting such as crew systems will have to be brought later as pressurized logistics and installed in the habitat. The architecture based on smaller habitats assembled on the lunar surface is more strongly affected by the change in payload capacity: a significant reduction in payload capacity would likely prohibit transportation of the habitat module with the crew, and therefore would take away the driving requirement for having a small habitat in the first place. Given that in this case all habitat modules would be delivered on dedicated cargo flights, there seems to be no reason to have multiple smaller habitats if a full-size habitat could also be delivered on a dedicated cargo flight.

Also, for a decrease in payload capability, it may be challenging to bring an airlock on a sortie mission because the airlock and associated structure may exceed the allowable payload or may lead to a significant imbalance on the descent stage. This may eliminate ESAS-style sortie missions[3] for both architecture options; Apollo-style sorties would still be possible albeit with decreased cargo capability relative what was previously described (although still significantly larger than for the actual Apollo missions).

For an increase in TLI capability, the cumulative surface stay capabilities increase significantly (see Figure 14). For a campaign with a 40-45 mt long-term stationary outpost and one dedicated cargo launch, and for an alternative campaign with three stationary intermediate outposts (~45 mt infrastructure), ~40 crew-years in the surface are achievable, i.e. near-continuous presence of 4 crew on the lunar surface for the duration of the entire campaign.

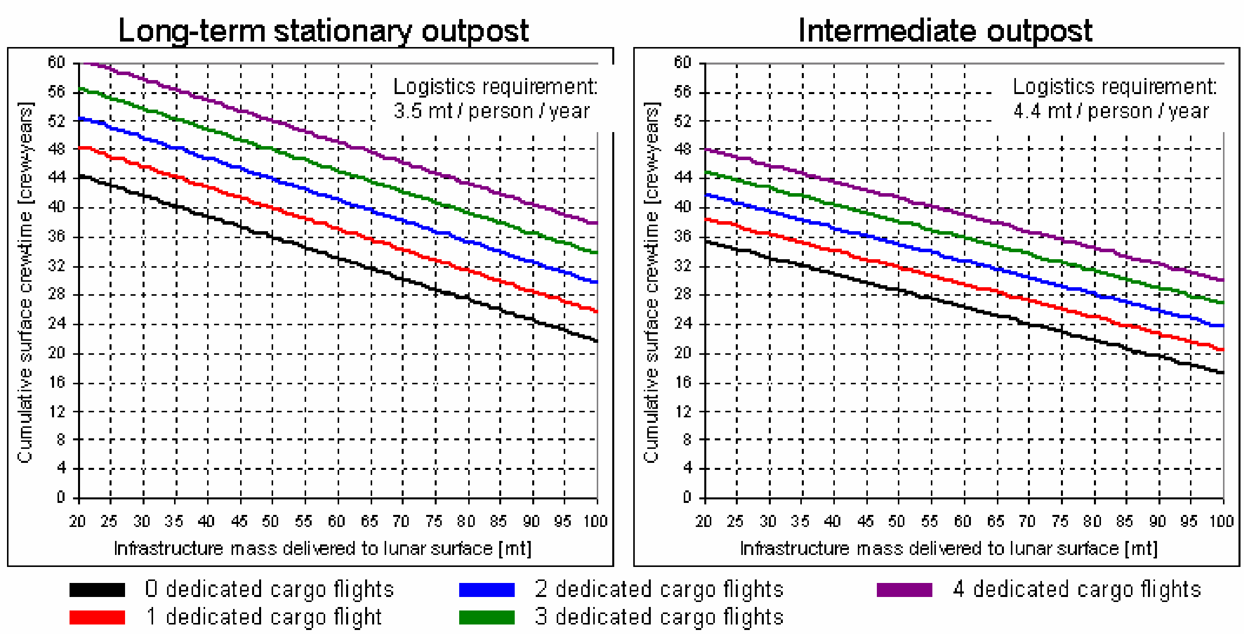

Figure 14: Logistics diagrams for improved TLI capability

VI. Architecture Comparison

The analysis of campaign performance in the preceding section clearly showed that the differences in performance between the two technical architecture types are minor compared to the differences introduced by changes in campaign design (i.e. the sequence of campaign elements). This clearly indicates that a comparison of technical architectures must be based on considerations of cost and risk rather than performance (in other words an “iso-performance” analysis in which performance is held constant). The following criteria were selected as proximate metrics for cost and risk to carry out a high-level comparison of the architecture types:

- Number and complexity of required elements (proxy for development cost and risk)
- Required technical and operational capabilities (proxy for development cost and risk)
- Number of operational configurations and operational complexity (proxy for operational cost and risk)
- Mars-relevance of surface systems (proxy for life-cycle cost and extensibility, and degree of Mars preparation achieved)

For each of these proximate metrics a comparative assessment of the Type 1 and Type 2 architectures is provided below.

Comparison of Required Architecture Elements

As mentioned above, the two architecture types can be largely identical in all elements required except the lunar surface habitat. For Type 1, the lunar surface habitat for the long-term outpost is assembled out of 4 modules delivered to the lunar surface on 4 separate flights (see Figure 15). For Type 2, one larger habitat module that provides the full volume required for long-duration surface stays is delivered on a dedicated cargo flight along with 2 airlock modules. While the Type 2 habitat structure is larger than that for the Type 1 long module (and of course also for the Type 1 short module), the development of the habitat structure for the long module will likely be more costly than that for the full size habitat because the long module carries requirements associated with the ability to offload it from the lander, attach it to a mobile surface transportation system, transport it on the surface, align it with other modules, and attach it to other modules. These requirements will translate into additional required effort for the development and testing of the structure.

In terms of internal outfitting, the Type 1 and Type 2 habitats are not significantly different, because redundancy in critical systems such as life support has to be provided in both cases.

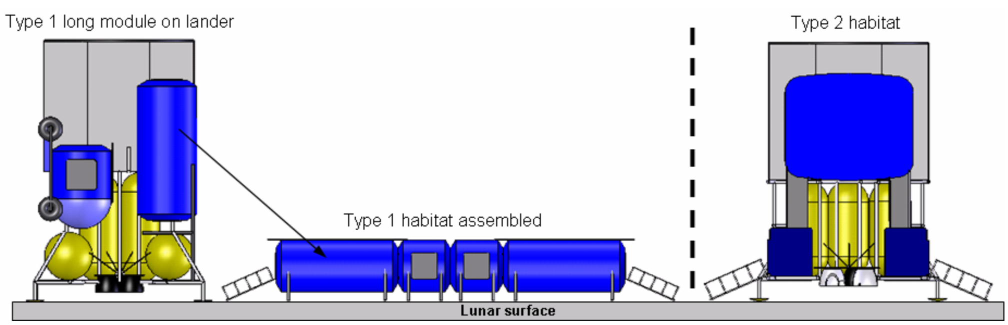

Figure 15: Comparison of long-term outpost habitats for Type 1 and 2 architectures

Comparison of Required Advanced Technical and Operational Capabilities

A number of advanced technical and operational capabilities such as high-closure life support, habitat re-supply on the lunar surface and power transfer between elements on the lunar surface are required for both the Type 1 and Type 2 architectures in order to support the campaign elements; Table 1 provides an overview of these capabilities.

Table 1: Comparison of advanced capabilities required for the lunar surface architecture options

Capability	Small habitats	Full-size habitat
High-closure life support	Required	Required
Re-supply with consumables and spares	Required	Required
Power transfer between outpost elements	Required	Required
Unpressurized surface mobility	Required	Required
Pressurized surface mobility	Desired	Desired
Ground-level access from habitat	Desired	Desired
Offloading of large cargo elements	Required	Desired / optional
Surface transportation of large cargo elements	Required (hab module)	Not required
Pressurized connection of modules	Required (hab module)	Desired / optional

The Type 1 architecture requires, however, a number of capabilities which are not crucial or required for a Type 2 architecture:

- Offloading of large cargo elements from a lander: this capability is crucial for the assembly of the Type 1 long-term habitat due to the need to offload the long and short modules. While the capability may be desirable for a Type 2 architecture, it is not crucial to achieving the campaign objectives and could therefore be sacrificed in case development difficulties arise.

- Surface transportation of large cargo elements: this is required in order to bring the second long module and the two short modules to the site of habitat assembly. No such operation would ever be required for the Type 2 architecture.
- Pressurized connection of modules: this capability is critical only for the assembly of the Type 1 long-term outpost habitat. The capability could be desirable for the operation of pressurized rovers (direct access to the rover crew compartment from the habitat), but this is not crucial to achieving the campaign objectives in a Type 2 system with a single full-size habitat.

Comparison of Required Operational Configurations

Experience with the ISS suggests that each operational configuration of a complex space system requires a significant amount of procedures development and documentation, testing, and simulation / training for ground operators as well as the flight crew. The number of operational configurations that have to be supported will therefore have a major impact on operational cost and risk.

The operational configurations required for sortie and intermediate outpost missions are largely identical for the Type 1 and Type 2 architectures. The long-term outpost configurations, however, are different: the need for assembly of the outpost habitat out of 4 modules necessitates a minimum of 3 operational configurations; possibly more (see Figure 7 and Figure 15). For the Type 2 long-term outpost, only one configuration needs to be supported, and the only assembly operation required is the establishment of a power transfer capability between the 2 dedicated cargo landers (see Figure 7); the crewed deployment flight brings unpressurized rovers and science equipment that is offloaded from the lander but not assembled.

Mars Relevance of Lunar Architecture Elements

One of the primary objectives of the lunar campaign is preparing for human Mars exploration; the lunar architecture should therefore be designed such that it provides elements and capabilities with significant relevance towards human Mars exploration. Based on the conceptual design of the lunar surface architectures described in this paper, the following capabilities are strongly relevant for Mars:

- Long-range roving using pressurized rovers: during the long surface stay of conjunction class human Mars missions (~600 days), the exploration range of unpressurized mobility may be insufficient to provide exploration targets for the entire stay. In this case, a pressurized transportation capability is required to extend the range; operation of such a capability on the Moon could provide valuable insight.
- High-closure life support systems: the long transfer durations between the Earth and Mars and the long stay on the Martian surface make a high-closure life support system very desirable. Implementation of a precursor / prototype system for lunar surface missions would provide valuable operating experience.

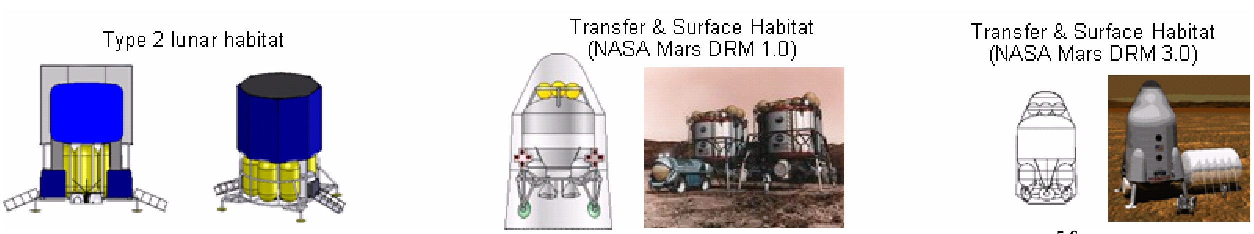

Figure 16: Type 2 lunar surface habitat in relation to proposed Mars habitats[5,6]

With regard to habitation, a full-size habitat is clearly more relevant to Mars exploration than a surface habitat assembled out of smaller modules: all near-term feasible mission modes for conjunction class Mars missions feature either a transfer & surface habitat, a Mars surface habitat, or a landing and surface habitat. In the case of the transfer & surface habitat, the crew lands on Mars in the habitat, i.e. the habitat needs to provide full volume and capability before ever touching the surface. In the case of a pre-positioned surface habitat, the habitat would have to be ready for operation before the crew ever leaves Earth. The need to assemble the habitat robotically out of smaller modules would introduce significant additional risk without any additional advantage. This indicates that a full-size habitat with airlock modules is most relevant to human Mars exploration; existing concepts for human Mars missions[5,6] are also all based on full-size habitats (see Figure 16).

VII. Findings, Recommendations, and Future Work

A number of important findings pertaining to program-level decisions as well as architectural decisions can be derived from the work and results presented in this paper:

- Finding 1: There are a small number of elements that could conceivably make up a lunar campaign. Specifically, these elements are: sortie missions with and without habitation beyond the ascent stage, intermediate outpost missions based on pre-deployment of additional habitation with a single dedicated cargo flight, and long-term outpost missions based on multiple pre-deployment flights with the intent of continuous habitation on the lunar surface.
- Finding 2: For the intermediate outpost, mobility for the outpost may be appealing because of the ability to explore a different site every visit; due to lighting and abort constraints, such a mobile intermediate outpost would likely be most applicable to the lunar equatorial region.
- Finding 3: It is likely that future Administrations and Congresses may require changes in the objectives of the lunar campaign. In the absence of a stable set of detailed objectives and requirements for the lunar campaign, designing a common lunar surface architecture with the ability to support all or most of the campaign elements can provide essential programmatic flexibility and robustness.
- Finding 4: Based on the design of the stationary long-term outpost habitat, two major families of lunar surface system architectures can be distinguished:
    - The first family is based on multiple small habitat modules assembled on the lunar surface into the outpost habitat; the exact number of habitats is a design variable within this architecture family.
    - The second family is based on a single full-size habitat module that is pre-integrated on Earth and is pre-deployed with a dedicated cargo flight.
- Finding 5: Due to the significantly reduced need for assembly, the architecture concept with the pre-integrated full-size habitat will likely have reduced development cost and risk (fewer requirements levied on habitat and fewer advanced capabilities required) and deliver more value early in the campaign (reduced need for assembly on the lunar surface frees up EVA time for exploration).
- Finding 6: The value delivered by a lunar campaign is mostly influenced by the sequence of campaign elements and the surface locations of their landing sites. While there are differences in campaign performance between the surface architecture options, these differences are small compared to the changes in campaign performance induced by changes in the sequence of building blocks.
- Finding 7: There is a trade-off between cumulative crew-time and the # of sites explored / visited on the lunar surface; this trade-off is due to the need to emplace more infrastructure on the lunar surface and potentially increased logistics requirements for intermediate outpost and sortie missions.
- Finding 8: Campaigns including only sortie and intermediate outpost missions can provide significant cumulative crew time on the lunar surface and extended-stay durations with significant value for Mars preparation while enabling access to multiple sites and reducing program development cost and risk.
- Finding 9: Sensitivity analysis for changes in TLI capability (and correspondingly surface payload capability) indicates that even for a 10% degradation of TLI capability, a cumulative surface crew time in excess of two full Mars surface mission durations with 4 crew can be achieved.
- Finding 10: The Type 2 architecture (single, full-size habitat) dominates the Type 1 architecture (multiple, smaller habitat modules) with regard to all proximate metrics evaluated primarily due to the reduced complexity of infrastructure operations on the lunar surface.

Associated recommendations:

- Recommendation 1: The lunar surface system architecture should be designed around supporting at minimum the Apollo-style sortie, stationary intermediate outpost, and stationary long-term outpost campaign elements in order to be flexible and robust with regard to programmatic changes that are likely to occur over the next decade.
- Recommendation 2: Lunar surface long-duration habitation should be based on a full-size habitat module that can be integrated in a controlled facility on Earth; in doing so significant development and operational overhead for offloading, transport, and assembly of habitat modules on the lunar surface can be avoided. A full-size habitat design is also more applicable to human Mars exploration.
- Recommendation 3: Serious consideration should be given to pressurized lunar surface logistics using small pressurized packages of ~500 kg size (exact size to be determined); such a logistics approach would offer significantly more flexibility with regard to logistics design and planning, as well as the capability to re-supply an outpost with only unpressurized rovers.

- Recommendation 4: Campaigns based on intermediate outpost missions as opposed to building up a long-term outpost should be taken under consideration, given that these campaigns can provide significant Mars preparation and lunar surface exploration capability.

Figure 17 shows a proposed development plan for the lunar architecture elements, organized into 4 tiers: Tier 1 provides the capabilities required for a human lunar return (Apollo-style and ESAS-style sorties); Tier 2 includes the full-size intermediate outpost configuration which can also serve as core of a long-term outpost; Tier 3 provides the remaining advanced elements required for a long-term outpost; Tier 4 includes systems for operational use if ISRU determined to be worthwhile in the lunar campaign. As indicated, opportunities for international and commercial participation exist throughout the architecture, from the provision of basic communications and navigation to pressurized surface mobility, etc. The outpost lander with the full-size habitat is the key element in this plan: once it has been developed, long-duration stays on the lunar surface are possible without complex assembly and requirements for surface transportation of infrastructure.

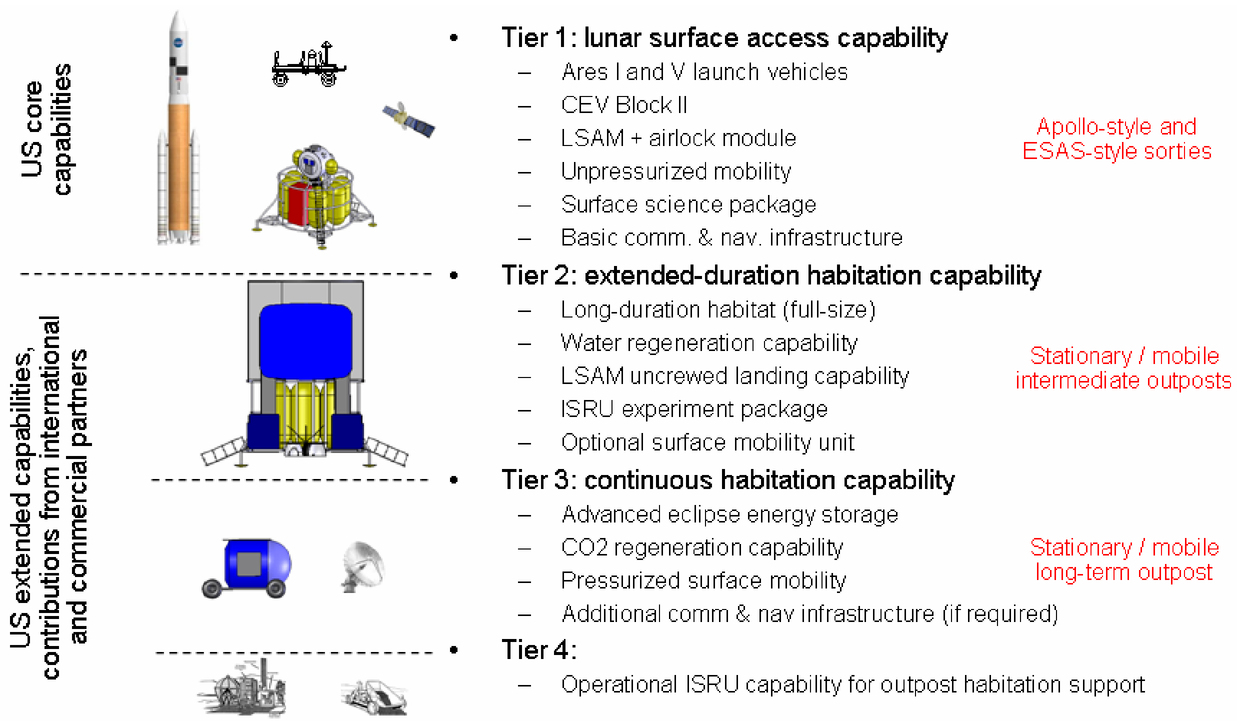

Figure 17: Proposed development plan for lunar architecture elements in accordance with the assumptions of the Global Exploration Strategy (GES)[1]

This assessment of lunar campaign surface system architecture design strategy leaves room for a number of opportunities for future work, including:

- More detailed analysis and design of the full-size lunar surface system architecture family
- More detailed analysis and design of the mobile intermediate outpost concept
- Comprehensive sensitivity analysis of long-term outpost deployment to LSAM payload delivery capability

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