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Analysis of Human Lunar Outpost Strategies and Architectures

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The Vision for Space Exploration includes sustained human exploration of the lunar surface as a prelude to human Mars exploration. Previous approaches to the architecting of planetary exploration architectures have been based on campaign objectives and derived architectural requirements and are therefore not capable of coping with expected programmatic uncertainty. This paper presents a novel approach to architecting of planetary surface systems under programmatic uncertainty based on the comprehensive enumeration of requirements based on campaign elements. The application of this approach to the comparative analysis of lunar surface system architectures indicates 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. Comparison of different lunar surface systems architectures shows that the cost and risk are the primary distinguishers between architectures, not lunar campaign performance as measured by the total cumulative time and the number of surface sites visited. Based on cost and risk considerations, a lunar surface architecture with a full-size habitat preintegrated on Earth is preferred compared to a module-based architecture requiring significant assembly in situ on the lunar surface.

I. Introduction

IN DECEMBER 2006, NASA published their initial plan [1] for a lunar exploration campaign based on the transportation architecture outlined in the Exploration Systems Architecture Study [2] (ESAS) as part of the implementation of the Vision for Space Exploration [3] (VSE). The campaign strategy is based on the establishment of an "outpost first" with continuous or near-continuous habitation capability, possibly on the rim of Shakleton Crater at the lunar South Pole; the outpost infrastructure is delivered only on crewed flights in units with a maximum mass of 6 metric tons (mt) [4]. Although detailed campaign objectives and requirements have not been published by NASA, the overall campaign strategy and architecture appears to be focused on two out of six guiding themes [1]: exploration preparation and human civilization. The other themes are also partially addressed by the campaign.

The NASA Lunar Architecture Team lunar surface systems architecture [1,4] is one representative of a large number of conceivable lunar surface systems architectures. Different weightings between the guiding themes and high-level campaign objectives could favor a different set of missions in the campaign and therefore drive toward a different surface systems architecture. This indicates that there is a strong sensitivity of campaign and architecture design to changes in program-level objectives. An extreme example for this would be a campaign solely driven by lunar geology, which would tend to favor sortie missions to a large variety of sites while deemphasizing 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 the administration and Congress, it seems likely that changes in program-level objectives may occur. The lunar surface system architecture should therefore be robust to such changes and flexible to support a variety of campaign strategies.

Previous approaches to the architecting of planetary surface systems have generally been based on a set of predeveloped campaign objectives which could be translated into requirements for the architecture: these approaches include those of the Lunar Architecture Team [1,4], the ESAS team [2], most of the architecting for the First Lunar Outpost [5], Lunox [6], as well as the approaches for the Mars design reference missions [7–9]. For the First Lunar Outpost it was recognized that the concept intrinsically provided programmatic flexibility and could support a variety of possible campaigns, including shortened campaigns with an early transition to human Mars exploration [10]. Generally, however, the existing approaches do not provide guidance for dealing with architecting under programmatic uncertainty as is the case for the VSE. This paper introduces a novel approach based on exploring the envelope of possible operational scenarios and deriving an envelope of requirements for a flexible lunar surface systems architecture. This approach is outlined in the following section; the remainder of the paper provides an applied case study of the approach for the comparative analysis of two lunar surface system architecture families.

II. Architecting Approach Based on 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 is outlined in line 1 in Fig. 1. In reality, however, the actual campaign objectives may not be known until the campaign is being implemented, that is, when it is too late to make significant changes to the lunar surface system architecture (line 2 in Fig. 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 before the campaign is implemented; on the other hand it is due to operational experience and discoveries that may occur before or even during implementation (for example, based on robotic lunar exploration). The result of this uncertainty makes it difficult to define a stable set of programmatic requirements that can serve as the basis of lunar system architecting.

Borrowing from scenario analysis methodology [11], we propose a different approach to solving this dilemma: based on the available constraints on the lunar architecture and NASA's guiding themes, a

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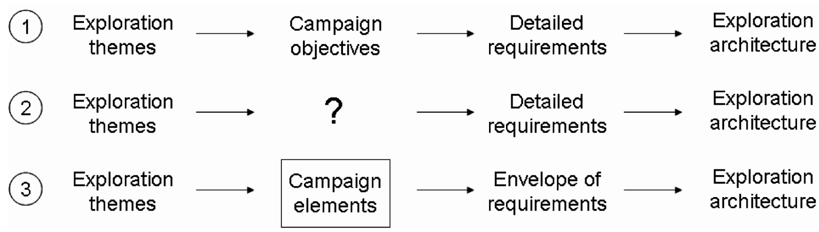

Fig. 1 Architecting approach using campaign elements.

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 and by considering all campaign elements, an envelope of all requirements for a lunar surface system architecture can be constructed. The architecture is then designed to support all or the majority of the requirements in the envelope (line 3 in Fig. 1).

Figure 2 provides an overview of the campaign elements enumerated based on four factors: 1) whether or not additional habitation elements (i.e., a crew compartment or habitat) beyond the ascent stage are available on the lunar surface; 2) whether or not previously emplaced assets are used during the mission or set of consecutive missions; 3) whether or not continuous habitation is achieved; and 4) whether or not the predeployed assets are mobile.

Logical and feasibility constraints lead to the six campaign elements outlined in Fig. 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, the Crew Exploration Vehicle (CEV), and the Lunar Surface Access Module (LSAM) could provide significantly more capability than Apollo J-class sorties [12] due to the increased surface crew size (four vs two), increased payload mass (6 mt vs 0.6 mt), and a potential increase in the surface stay duration beyond 2–3 days (pressurized volume constraints permitting).

The *ESAS-style sortie* (campaign element B, named after the sortie concept proposed in NASA's 2005 ESAS [2] 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 predeployment 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 [10,13,14]. 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 predeployed 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 while providing an anytime return for extended stays requires a stay either at one of the poles or the equator when using the lunar orbit rendezvous transportation mode.

The *stationary long-term outpost* (campaign element E) is a larger outpost which is aimed at continuous habitation. Such an outpost would likely require more than a single dedicated cargo flight for delivery. This outpost would also be limited to polar or equatorial sites to enable anytime return with the lunar orbit rendezvous transportation mode.

The *mobile long-term outpost* (campaign element F) is a transportable version of an outpost intended for permanent habitation. 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, 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 the 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 [4]. This test mission is assumed to be the first flight for all campaigns to fully demonstrate the lunar transportation system.

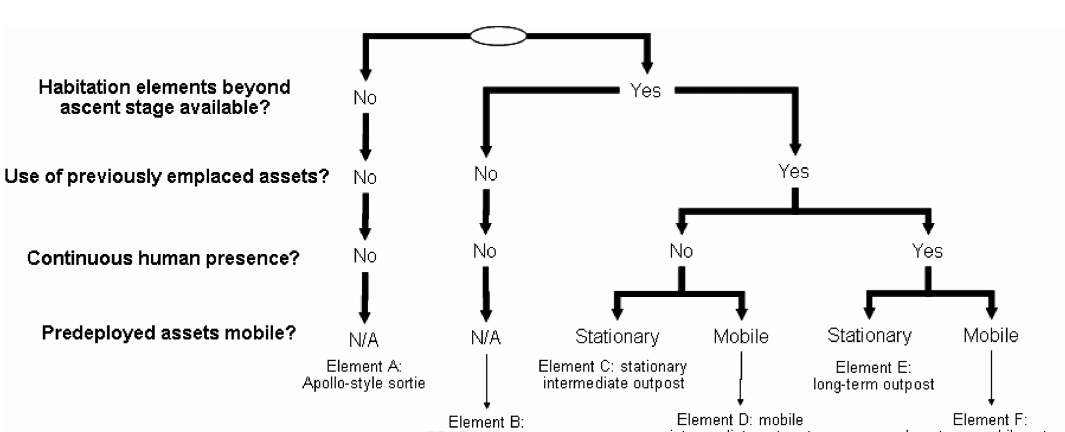

Fig. 2 Campaign element enumeration.

	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	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	Test	B	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C	C

Fig. 3 Example campaigns with associated flight sequences; the letters represent the campaign elements particular flights belong to (A for Apollo-style sortie, E for stationary long-term outpost, see Fig. 2).

III. Lunar Surface System Architecture Families

After the definition of the campaign elements, 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 (preintegrated on Earth or assembled on the lunar surface), power generation and energy storage technologies (solar vs nuclear), and the surface mobility system configuration (pressurized vs unpressurized rovers or both) among others. Based on a review of the design and operational history of U.S. and Soviet/Russian space stations [15–19], 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 as follows: 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. Type 2 is centered around a single large surface habitat which provides sufficient pressurized volume for long-duration (6 + months) stays with four crew members which is preintegrated and outfitted on Earth and deployed on the lunar surface on a dedicated cargo flight. This type is similar to NASA's First Lunar Outpost [5,10] and to Skylab [16].

For both architecture types, a conceptual design [20–24] 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: 1) 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. 2) Logistics and resupply 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 systems. 3) Solar power generation with batteries providing energy storage for eclipse power is assumed in all cases. Nontracking solar panels are used, body mounted for polar landing sites, and deployable into a horizontal position for equatorial sites.

The two architectures based on type 1 and type 2 are described in the sections 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.

A. Architecture Based on Habitat Modules Assembled on Lunar Surface (Type 1)

The type 1 long-term stationary outpost (an outpost based on a habitat that is assembled on the lunar surface) is shown in Fig. 4. Deployment of the outpost infrastructure (defined here as all elements which are not consumed and resupplied regularly during outpost utilization) requires four flights with the following manifests:

1) Deployment flight no. 1: long habitat module (LM) and internal outfitting (life-support and crew systems), power generation, energy storage for eclipse power, thermal control, and 2-person pressurized rover.

2) Deployment flight no. 2: two 2-person unpressurized rovers, one short habitat module (SM), and consumables.

3) Deployment flight no. 3: long module and outfitting, power generation, energy storage, thermal control, and 2-person pressurized rover.

4) Deployment flight no. 4: science package, short module, and 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. Because of the gradual assembly of the habitat, at least three different operational configurations of the outpost need to be sustained.

The overall outpost infrastructure mass is estimated to be 48 mt with a gross logistics resupply requirement of 3.5 mt/person/year (including the mass of resupply vessels and packaging for transportation). The short and long habitat modules are based on a pressure vessel platform consisting of cylinder elements and end

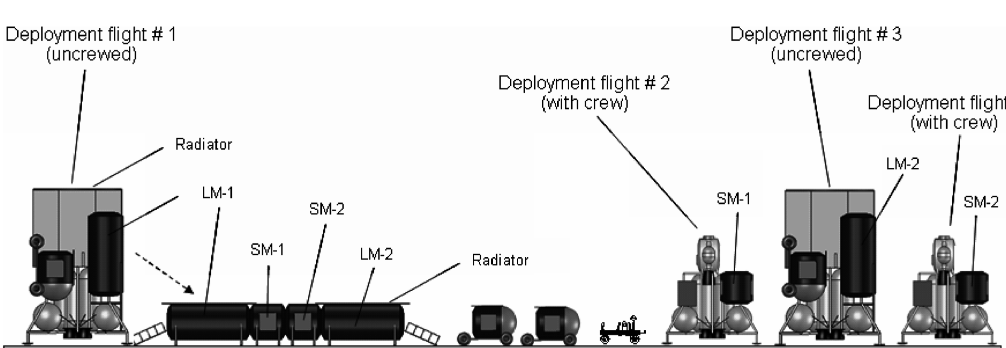

Fig. 4 Stationary long-term outpost (E) based on assembly of habitat modules (type 1).

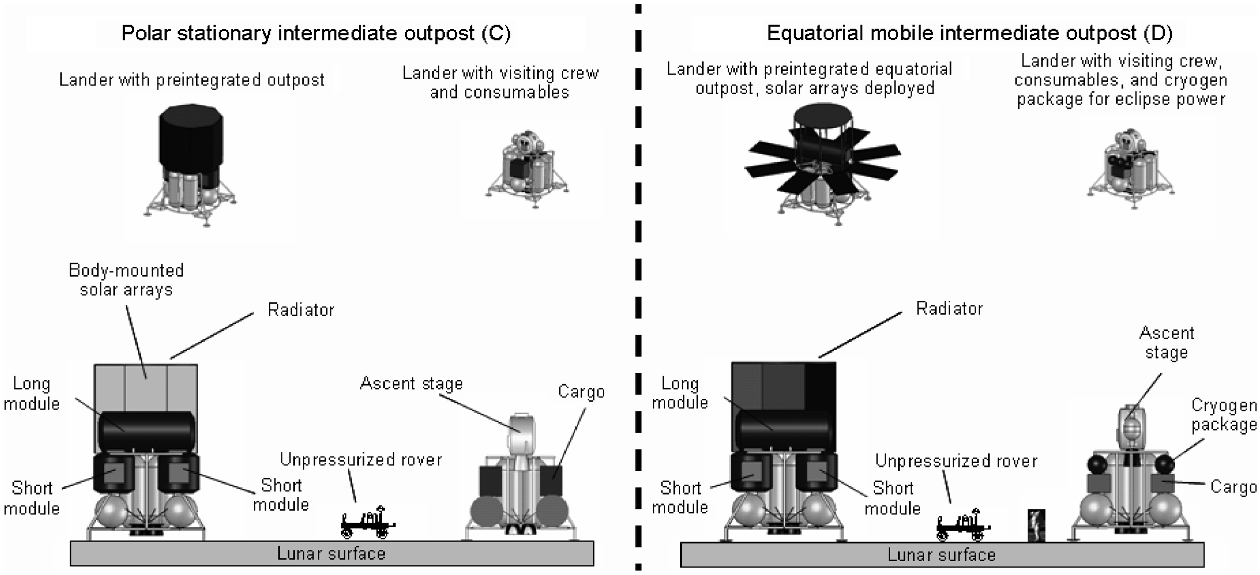

Fig. 5 Stationary (C) and mobile (D) intermediate outpost concepts based on habitat modules (type 1).

closeouts (not unlike the Spacelab [25]). The long module has three cylinder segments, and the short module one; a medium size could be created as well using two 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-size modules.

Views of the intermediate outpost designs are shown in Fig. 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/resupply. The infrastructure mass of the stationary polar intermediate outpost is estimated to be 15 mt with a gross logistics and resupply requirement of 4.4 mt/person/year.

In addition to the elements used for the stationary polar intermediate outpost, the mobile equatorial intermediate outpost requires more dormant-period energy storage with batteries 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 Fig. 5 but accounted for in the mass budget). Given the preference for equatorial locations for the mobile intermediate outpost, the solar panels are mounted with the photovoltaic cells facing toward the habitat for launch and are deployed into a horizontal position after landing. Eclipse power when occupied during the 354-h lunar night is provided by LSAM fuel cells and cryogenic hydrogen and oxygen brought along on the LSAM. The reactant water is transferred to the outpost and used for habitation and extravehicular activity 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; this would allow for up to two lunar nights to be spent with one visiting LSAM.

The outpost is moved from site to site in between crewed visits during the lunar day, that is, when the majority of solar power can be used 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/person/year as for the stationary outpost.

The type 1 sortie lander concepts are shown in Fig. 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 connected to the ascent stage which also serves as an airlock. It should be noted that the mass of the airlock module reduces the payload mass available for mobility systems and experiments, although the airlock may be required for extended-duration (week long or longer) sortie missions.

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

The long-term lunar outpost for a full-size habitat is shown in Fig. 7. Three deployment flights are required (two uncrewed and one crewed), with the following manifests:

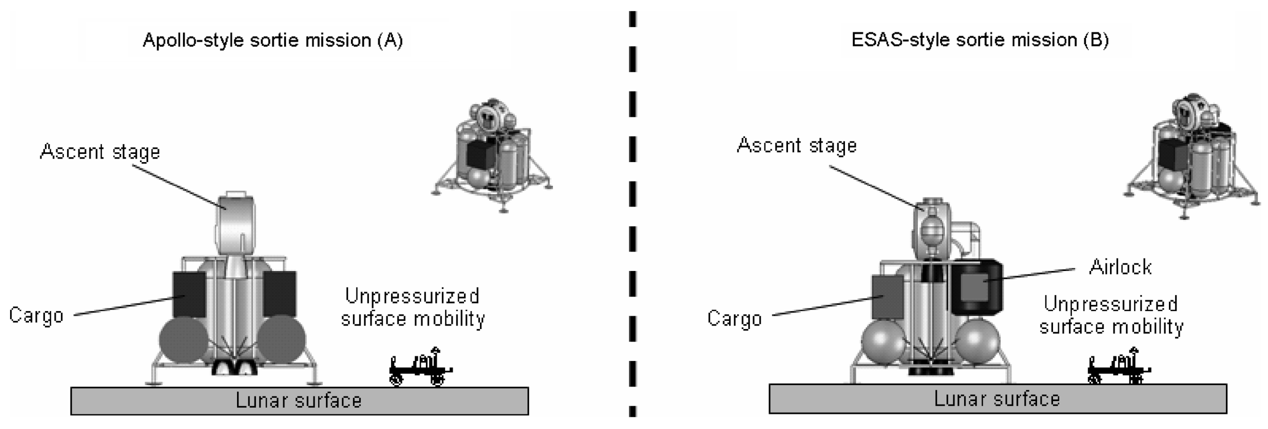

Fig. 6 Sortie lander concepts (campaign elements A and B) using type 1 design.

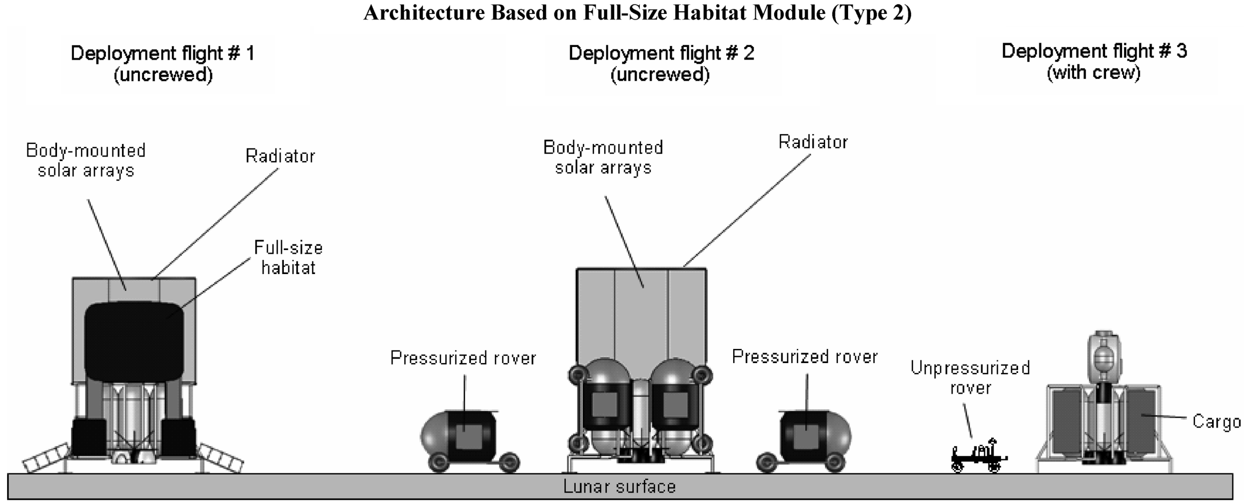

Fig. 7 Stationary long-term outpost (E) based on preintegrated full-size habitat module (type 2).

1) Deployment flight no. 1: full-size habitat module and outfitting, airlocks, power generation, limited energy storage, thermal control, and consumables.

2) Deployment flight no. 2: pressurized rovers, power generation, energy storage, and associated thermal control.

3) Deployment flight no. 3: unpressurized rovers, science package, and 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. 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.

The stationary intermediate outpost configuration is identical to long-term outpost deployment flight no. 1, except that the intermediate outpost has significantly less internal outfitting due to a reduced need for pressurized science and high-closure life support equipment (see Fig. 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 (not shown in Fig. 8), but is otherwise identical to the stationary polar intermediate outpost. The power generation and energy storage operations for the mobile intermediate outpost are the same as for the type 1 mobile intermediate outpost. 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 (same as for type 1).

The type 2 sortie landers are very similar to the type 1 configurations (see Fig. 9). The major difference is the somewhat decreased size of the airlock module (same design as for the habitats) for type 2, allowing for increased cargo capacity.

IV. Architecture Performance Assessment

Based on the type 1 and type 2 conceptual designs described in the preceding section, an analysis of campaign performance was carried out for the two architecture options. The primary performance 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

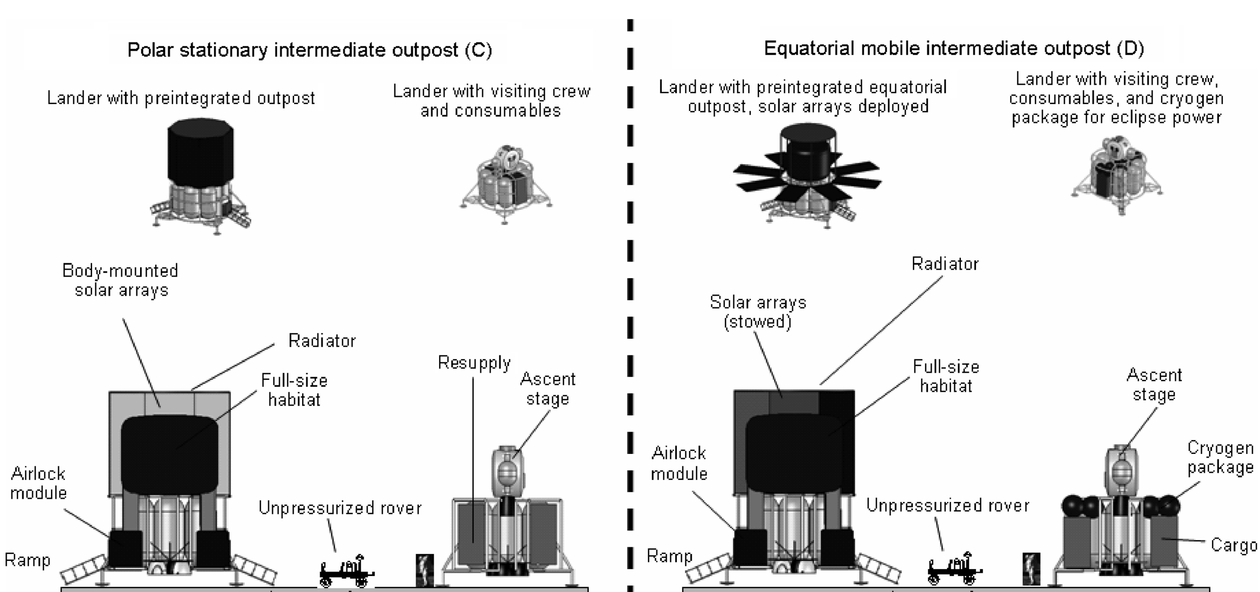

Fig. 8 Stationary (C) and mobile (D) intermediate outpost concepts based on full-size habitat (type 2).

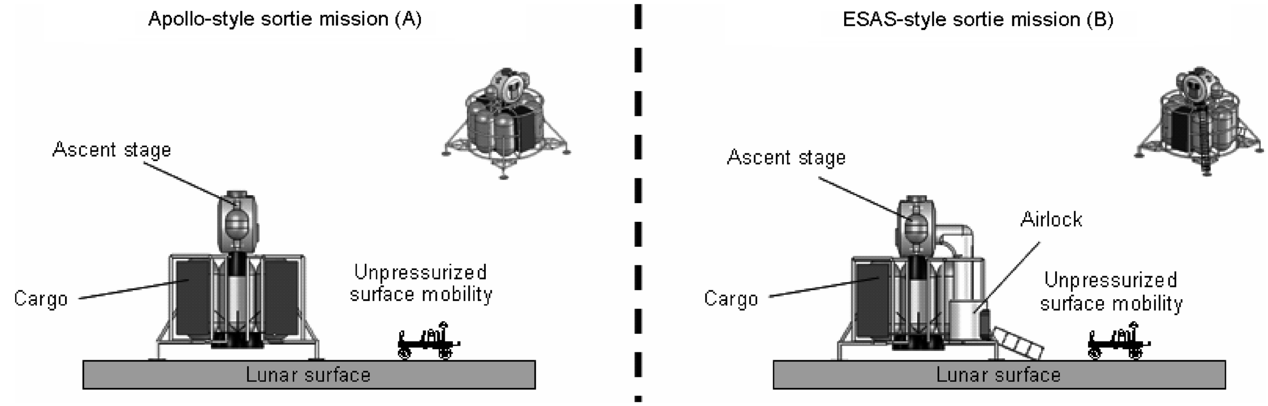

Fig. 9 Sortie lander concepts (campaign elements A and B) using type 2 assets.

campaign [26]. The number of different sites visited is impacted by the overall campaign design, that is, by the mix of campaign elements chosen (see Sec. II). The total cumulative surface time is expected to be impacted by the campaign design as well as the technical architecture (i.e., type 1 vs type 2). Both performance metrics will be assessed for the type 1 and type 2 architecture concepts described in the preceding section.

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: four dedicated cargo flights). Given the number of dedicated cargo flights and the number of crewed flights, the logistics requirement for resupply and spares, and the total infrastructure mass delivered to the lunar surface, the calculation of the stay-time capability is straightforward: it is the difference of the total mass delivered to the lunar surface and the infrastructure mass divided by the logistics requirement (tare and packaging mass for surface elements must be included in both the infrastructure and the logistics mass requirements when using the diagram to assess a concept's cumulative stay capability). Note that the diagrams in Fig. 10 are intended as a tool for comparing the surface stay-time capabilities of different outpost architectures and do not require information about the details of the infrastructure design. It is assumed that the total number of Ares V flights is fixed to 20 over the course of a 10-year campaign, that is, an increased number of cargo flights leads to a reduced number of crewed flights for a fixed number of total flights.

For a long-term outpost of about 50 mt infrastructure mass (including tare and packaging mass), results indicate that 28 crew years on the lunar surface are achievable if two dedicated cargo flights are used, that is, 7 years per crew for a 4-person crew (see diagram on left-hand side). In terms of duration per crew, this is equivalent to more than four conjunction class Mars mission surface stay durations (~1.5 years per crew) or more than two entire conjunction class Mars mission durations (~2.5 years per crew). Each additional dedicated cargo flight buys another four crew years, 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 [26]: if three intermediate outposts are deployed (i.e., three dedicated cargo flights, infrastructure mass ~45 mt), then a cumulative surface stay time of 26 crew years can be achieved, that is, 6.5 years with four 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 prestored on the outpost and consumables resupplied with the crew; as the packaging for consumables prestored in the outpost would be lower than that for resupply, the actual surface duration capabilities would be somewhat higher than shown for an intermediate outpost.

Figures 11 and 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

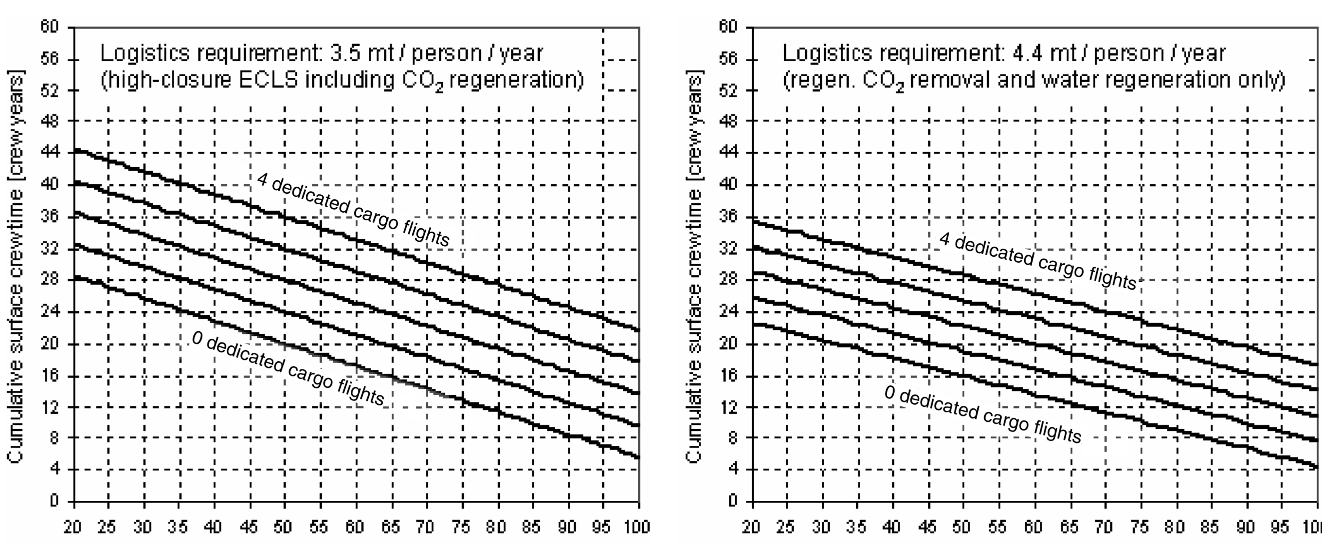

Fig. 10 Logistics diagrams for the long-term outposts (left) and intermediate outposts (right); ECLS: environmental control and life support.

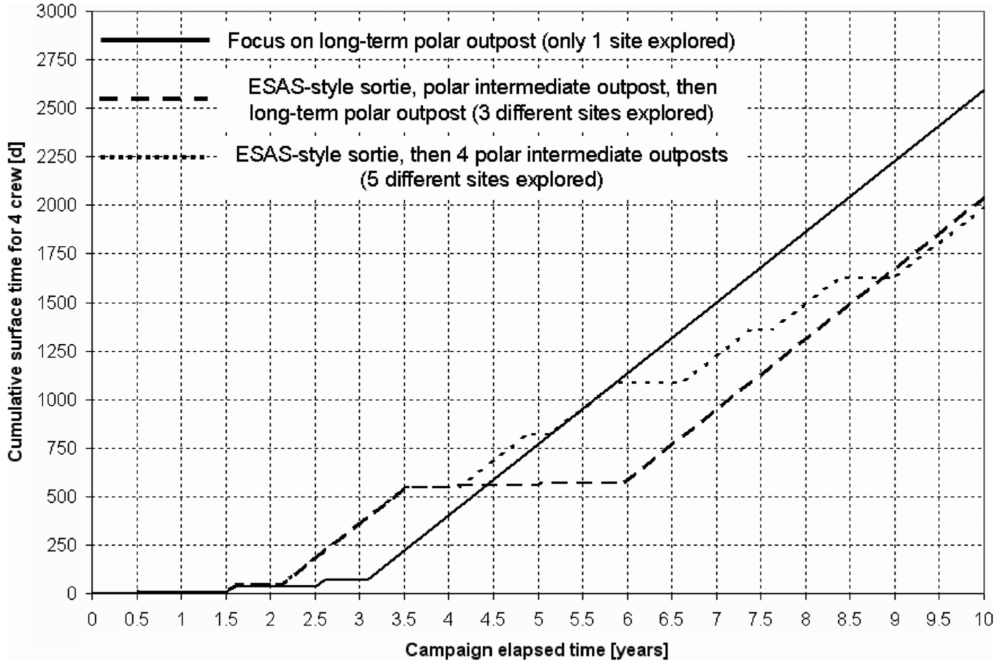

Fig. 11 Comparison of example campaign performance for the type 1 architecture (see Fig. 3).

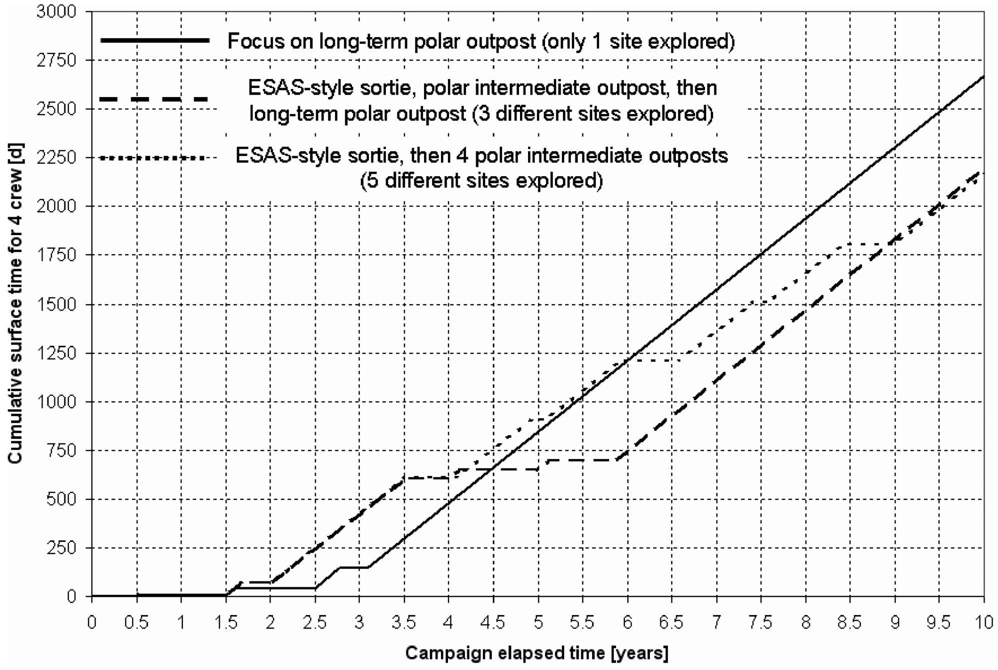

Fig. 12 Comparison of example campaign performance for the type 2 architecture (see Fig. 3).

surface stay time to date is plotted over the campaign elapsed time, enabling a direct comparison of value delivery over time for the campaigns.

Some major insights can be gained from the results shown in Figs. 11 and 12 as follows:

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 (one for long-term outpost focus, five for intermediate outposts only, three for intermediate and long-term outposts).

V. Sensitivity to Changes in Payload Delivery Capabilities

The analysis described in this paper so far was based on the assumption of specific payload delivery capabilities on crewed flights (6 mt) and on dedicated cargo flights (20 mt) [2,4]. To assess the robustness of the surface architectures, a sensitivity analysis was carried out with regard to changes in the 1.5-launch translunar

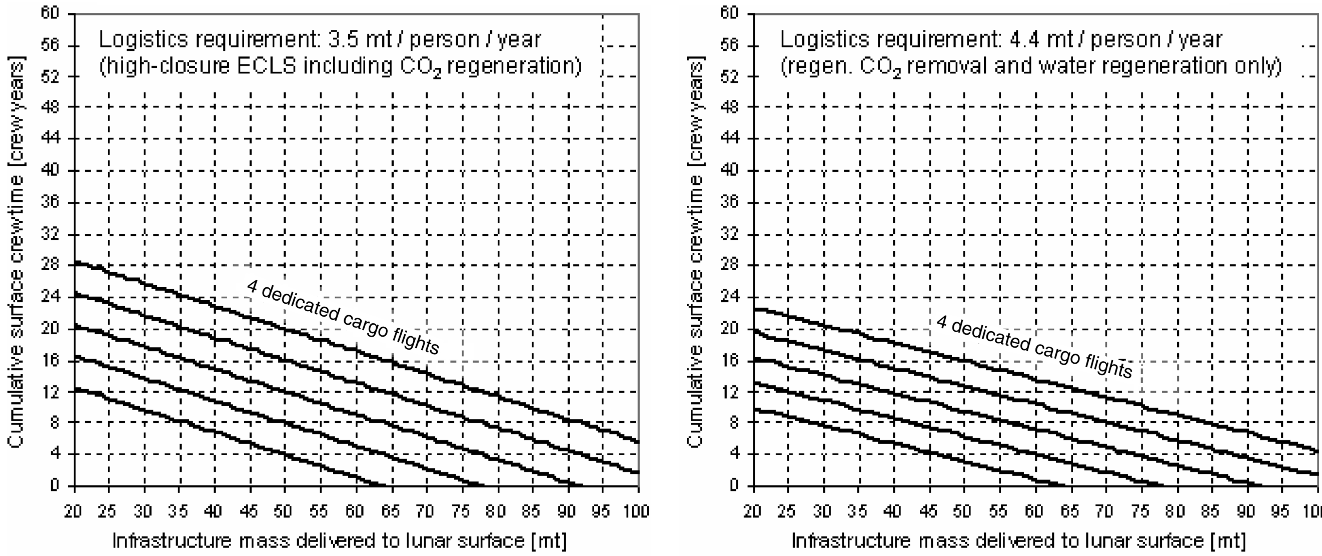

Fig. 13 Logistics diagrams for degraded TLI capability for the long-term stationary outposts (left) and intermediate outposts (right).

injection (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 on crewed flights (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 on crewed flights (to 8.8 mt) and on dedicated cargo flights (to 22.8 mt).

We analyze the impact of degraded TLI capability first; Fig. 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 four (infrastructure mass in the 50 mt range) could still provide at minimum 12 crew years on the lunar surface if two dedicated cargo flights are used. For an average crew size of four, this translates into the equivalent of two Mars surface durations [7,8] (conjunction class, about 1.5 years). Per additional dedicated cargo flight, about four 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 Fig. 13, right-hand side): the emplacement of three intermediate outposts (~45 mt infrastructure mass) leads to a cumulative surface stay capability of ca. 14 crew years or more than the equivalent of two Mars surface durations with four crew.

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 [2] for both architecture options. Apollo-

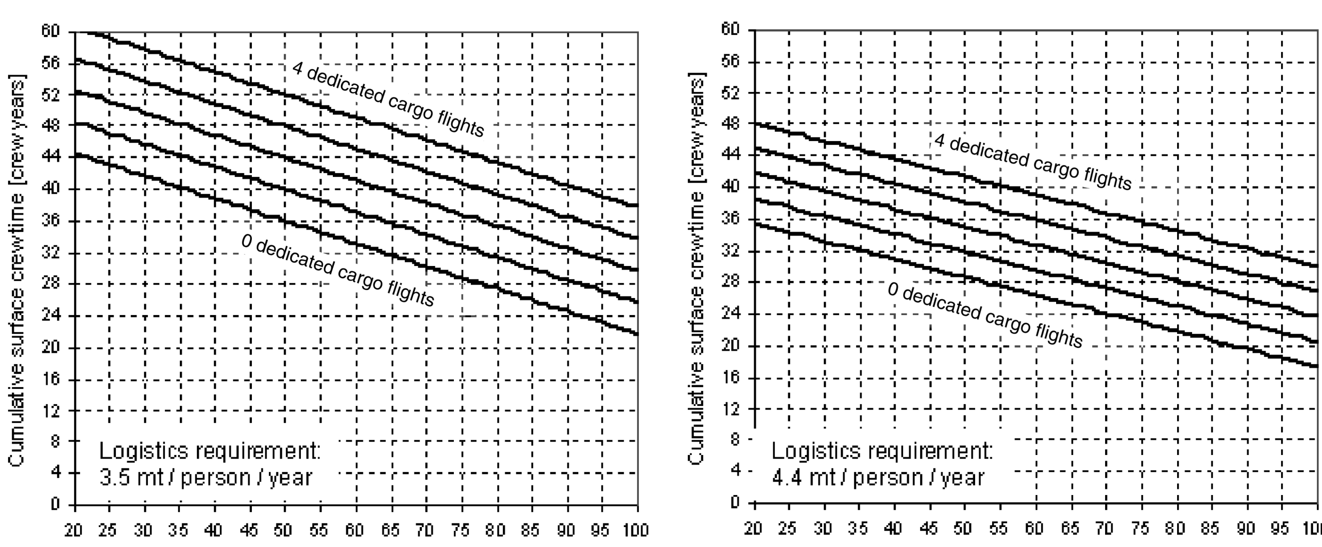

Fig. 14 Logistics diagrams for improved TLI capability for the long-term stationary outposts (left) and intermediate outposts (right).

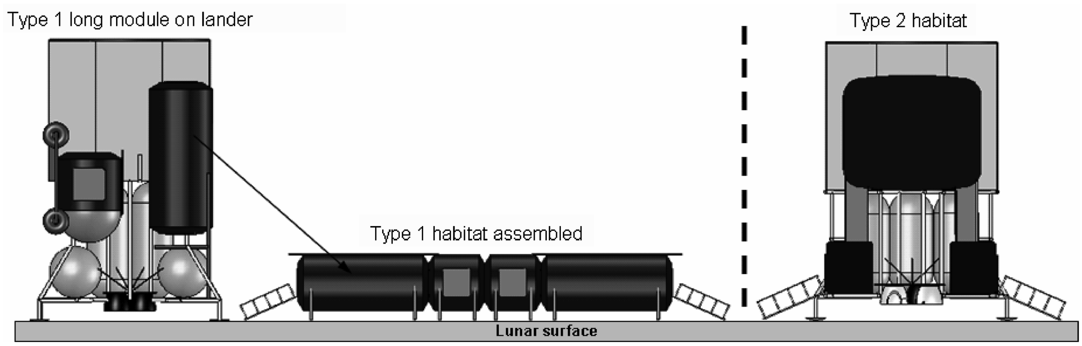

Fig. 15 Comparison of long-term outpost habitats for type 1 and 2 architectures.

style sorties would still be possible albeit with decreased cargo capability relative to 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 Fig. 14). For a campaign with a 50-mt long-term stationary outpost and one dedicated cargo launch, and for an alternative campaign with three stationary intermediate outposts ($\sim$45 mt infrastructure), $\sim$40 crew years in the surface are achievable, that is, a near-continuous presence of four crew on the lunar surface for the duration of the entire campaign.

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. The following criteria were selected as proximate metrics for cost and risk to carry out a high-level comparison of the architecture types: 1) number and complexity of required elements (proxy for development cost and risk); 2) required technical and operational capabilities (proxy for development cost and risk); 3) number of operational configurations and operational complexity (proxy for operational cost and risk); 4) 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 in the following sections.

A. Comparison of Required Architecture Elements

As mentioned previously, the two type 1 and type 2 architectures are 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 four modules delivered to the lunar surface on four separate flights (see Fig. 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 two airlock modules. Although 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 an 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.

A number of advanced technical and operational capabilities such as high-closure life support, habitat resupply 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.

B. Comparison of Required Advanced Technical and Operational Capabilities

A number of advanced technical and operational capabilities such as high-closure life support, habitat resupply 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; rows 1–6 in Table 1 provide an overview of these capabilities.

However, the type 1 architecture requires a number of capabilities which are not crucial or required for a type 2 architecture (rows 7–9 in Table 1):

1) 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. Although 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.

2) Surface transportation of large cargo elements: this is required 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.

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
Resupply 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 (habitat module)	——
Pressurized connection of modules	Required (habitat module)	Desired/optional

3) 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.

It should be noted that the offloading of large cargo elements could be made significantly easier by choosing a lander configuration which has underslung cargo; however, in this case the need to develop a surface transportation and in situ assembly/connection capabilities remains.

C. Comparison of Required Operational Configurations

Experience with the International Space Station 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 four modules necessitates a minimum of three operational configurations, possibly more (see Figs. 7 and 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 two dedicated cargo landers (see Fig. 7). The crewed deployment flight brings unpressurized rovers and science equipment that is offloaded from the lander but not assembled (see rows 10 and 11 in Table 1).

D. 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 toward 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:

1) Long-range roving using pressurized rovers: during the long surface stay of conjunction class human Mars missions ($\sim$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.

2) 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 (see rows 1–6 in Table 1).

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 and surface habitat, a Mars surface habitat, or a landing and surface habitat. In the case of the transfer and surface habitat, the crew lands on Mars in the habitat, that is, the habitat needs to provide full volume and capability before ever touching the surface. In the case of a prepositioned 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 [7,8] are also all based on full-size habitats (see row 12 in Table 1).

VII. Conclusions

In this paper a novel approach to the architecting of surface systems for human lunar exploration has been presented. The approach is based on the enumeration of a set of six discrete campaign elements which represent groups of operationally coherent missions with clear mission objectives. The campaign elements contain all the possible types of missions that could be conducted during a lunar campaign and can therefore be used to derive the envelope of requirements for a lunar campaign. By designing a flexible lunar exploration architecture around this envelope of requirements, it is possible to decouple the architecture from the specific objectives of the lunar campaign which may not be known for years and therefore increase programmatic robustness.

The feasibility and application of this approach was demonstrated through a comparative analysis of two families of lunar surface architectures. These two families were distinguished primarily by the design of the lunar surface habitat: a habitat assembled out of modular components on the surface, or a habitat that is assembled on Earth and delivered to the lunar surface fully integrated. This analysis indicated that the performance of a lunar campaign, as measured by the total cumulative crew time on the surface, the number of sites and area explored on the lunar surface, and the science and exploration capabilities provided, is largely independent of the technical characteristics of the surface architecture used for the campaign. However, the analysis also showed that developmental and operational cost and risk properties of the campaign as well as technical and operational extensibility to human Mars exploration are strongly impacted by the technical characteristics of the surface architecture, specifically by the degree to which assembly and associated offloading and transportation operations are required on the lunar surface. The areas of assembly and lunar surface logistics were identified as the major distinguishers between the lunar surface architecture families. Although lunar lander designs could be chosen that facilitate the offloading of large cargo elements (e.g. by having underslung cargo), these lander concepts do not mitigate the cost and risk of in situ surface assembly of major outpost infrastructure elements.

The campaign-element-based approach presented in this paper is generally applicable to planetary surface exploration architecting problems, including terrestrial campaigns such as in analog environments.

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