Extending NASA's Exploration Systems Architecture towards Long-term Crewed Moon and Mars Operations

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This paper presents a baseline strategy for extending lunar crew transportation system operations as outlined in NASA's Exploration Systems Architecture Study (ESAS) report towards longer-stay lunar surface operations and conjunction class Mars missions. The analysis of options for commonality between initial lunar sortie operations and later Moon and Mars exploration missions is essential for reducing life-cycle cost and providing low-investment / high-return options for extending exploration capabilities soon after the 7th human lunar landing. The analysis is also intended to inform the development of the human lunar lander and other exploration system elements by identifying enabling requirements for extension of the lunar crew transportation system. The baseline strategy outlined in this paper was generated using a three-step process: the analysis of exploration objectives and scenarios, identification of functional and operational extension options, and the conceptual design of a set of preferred extension options. Extension options include (but are not limited to) the use of the human lunar lander as outpost for extended stays, and Mars crew transportation using evolved Crew Exploration Vehicle (CEV) and human lander crew compartments. Although the results presented in this paper are based on the ESAS elements, the conclusions drawn in this paper are generally applicable provided the same lunar transportation mode (lunar orbit rendezvous) is used.

Nomenclature

d_{max}	=	maximum distance from outpost that can be reached on traverse
$v_{Average}$	=	average driving speed on the lunar and Mars surface
$v_{Walk\text{-}Back}$	=	walk-back speed of crew in case of mobility system failure
$\Delta t_{Transportation}$	=	time available on traverse for transportation from outpost and back
$R_{Traverse}$	=	ratio of traverse length to maximum distance from outpost during traverse

I. Introduction

THE human exploration of the Moon and Mars is one of the core goals of the Vision for Space Exploration initiated in 2004[1]. Initial human lunar surface exploration activities are intended to restore exploration capabilities given up with the termination of the Apollo program. Later lunar operations are regarded as essential preparation for human Mars surface exploration. In order to carry out human Moon and Mars missions, complex new exploration systems with unprecedented capabilities are required[2].

A. The Case for Commonality

The traditional approach to the acquisition of these systems would be to carry out independent development programs for each mission type. While these programs would yield systems with optimized performance, they will also require large investments in the form of Design, Development, Test, and Evaluation (DDT&E) cost and fixed recurring cost for production lines for each new element. Also, independent development programs cannot directly leverage the development and operational experience from previous missions in order to reduce risks for loss of

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mission and loss of crew, necessitating more extensive and costly test programs in order to achieve operational readiness. Common (identical) or cousin (close derivative) systems on the other hand leverage both the DDT&E investment and operational experience of previous systems, albeit at a somewhat reduced performance compared to an optimized system, and at somewhat higher development cost for the first set of elements. The trade between the traditional approach and an approach with a high degree of commonality is usually between increased near-term investment and development risk because of increased complexity due to additional requirements introduced by commonality on the one hand, and significantly reduced lifecycle cost and operational risk on the other. In a project environment with milestones and budget pressure, few decision makers will opt for commonality (i.e. take a life-cycle view of the system they are developing and of its context) if the additional resource requirement exceeds a low threshold. Sustainability, on the other hand, is fundamentally a function of life-cycle cost and risk. In this paper, we make a case for an integrated, program-spanning commonality strategy as a crucial means for reducing life-cycle cost and risk, and thereby for ensuring sustainability[3].

The lunar exploration architecture outlined in the NASA ESAS report is explicitly designed with consideration for commonality / extensibility: the ESAS CEV is intended to be evolvable from a Block I ISS CEV to a Block II lunar CEV, and later to a Mars return CEV (for Earth launch and entry only). The Cargo Launch Vehicle (CaLV) and its Earth Departure Stage (EDS) deliberately provide the launch capability required to stage Mars exploration missions. Also, the ESAS Lunar Surface Access Module (LSAM) descent stage is intended to be extensible to an uncrewed cargo lander for outpost pre-deployment and re-supply[2]. While these extensibility options are crucial for enabling affordable lunar outpost missions and Mars exploration, the ESAS architecture does not address the extensibility of LSAM and CEV habitation and propulsion elements towards lunar outpost and Mars exploration applications. This paper is intended to provide a reference strategy as a starting point for future commonality analysis.

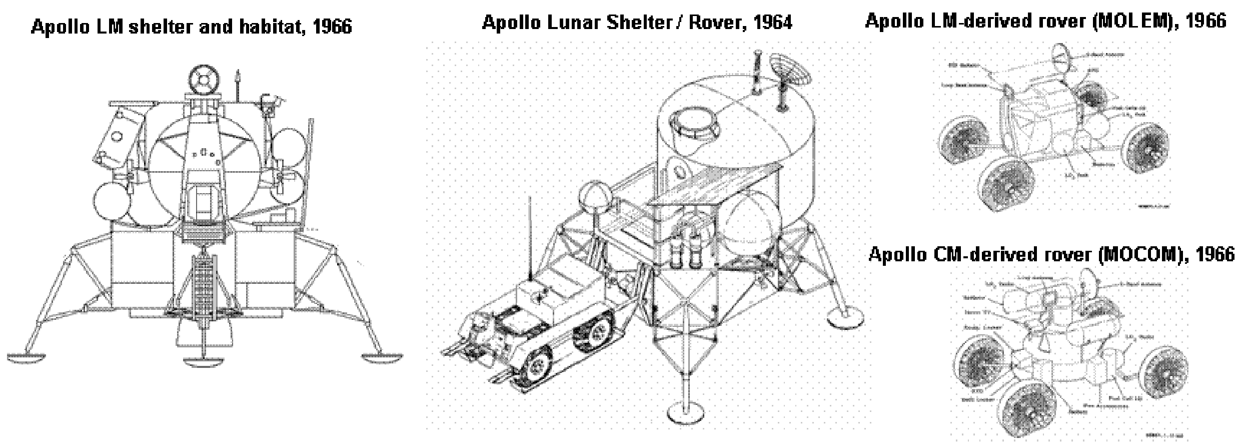


Figure 1: Lunar surface operations hardware concepts designed for the Apollo Applications Program (AAP); all concepts use elements derived from the Apollo lunar sortie hardware.

B. Extensibility in Apollo Applications Program (AAP) Studies

It should be noted that the idea of extending lunar sortie mission elements towards more stressing missions is not entirely new: during the development phase of the Apollo program, numerous design studies of extended lunar surface mission hardware were carried out by Apollo contractors. Many design concepts produced involved the use of Apollo lunar sortie hardware for alternate purposes, such as cargo landing, habitation, and surface mobility. Figure 1 provides an overview of selected concepts[4-7]:

- A Lunar Module (LM)-derived lunar surface habitat and solar storm shelter, which would be used for extended, several-week long lunar surface exploration missions. The ascent propulsion system (excluding the reaction control system [RCS]) was substituted with consumables and additional equipment required for the extended surface stay. This concept would have required moderate re-development of the LM, including the capability to carry out a descent maneuver that would have been remotely controlled from a crewed Command/Service Module (CSM) in lunar orbit. No major new development program would have been required.

- A small lunar outpost including a combined shelter / lab / habitat element and an unpressurized rover. The outpost would have been delivered to the lunar surface using a modified LM descent stage called the "LM truck". This concept would have necessitated a new development program for the habitat / lab element and the rover, as well as an upgrade of the LM descent stage with RCS and GN&C equipment to enable a landing remotely-controlled from lunar orbit.
- The third and fourth concepts presented above show pressurized lunar surface rovers based on the LM and Command Module (CM) crew compartments. In both cases, modifications to the crew compartments would have been required, as well as the development of a chassis, surface power generation, and thermal control equipment.

The designs shown here do not represent an exhaustive list of options considered for AAP, but they clearly illustrate the drive to leverage DDT&E and production line investments made for previous programs in order to make extended lunar operations more affordable and safer, and make extended capabilities available shortly after initial sortie missions. This paper provides a corresponding analysis for the ESAS elements, extending from lunar sortie to conjunction class Mars missions.

C. Analysis Process

The results shown in this paper were obtained using a three-stage process:

- An analysis of exploration requirements focused on Mars preparation objectives and activities for lunar missions, Moon and Mars surface mobility requirements, and overall exploration scenarios capturing the succession of different mission types. The intent of this step is to provide reference objectives and a reference scenario for the subsequent analysis of extension options.
- The generation of extension concepts for the ESAS architecture elements based on different design and operational options. The concepts address all mission types and operations included in the reference scenario.
- The evaluation of these options and the selection of preferred concepts, which are described in detail below.

Results from step 1 are shown in Section II of this paper, and the results from steps 2 and 3 are provided in Sections III and IV (separately for Moon and Mars).

II. Exploration Requirements Analysis

A. Mars Preparation Activities on the Moon

In the Vision for Space Exploration, the use of the lunar surface as a "training ground" for future Mars missions is explicitly listed as one of the driving motivations for returning to the Moon[1]. This goal will be considered as the primary (not exclusive) goal for all lunar mission operations for the remainder of this analysis.

The lunar surface environment offers unique characteristics which make it suitable as a high-fidelity Mars analog: partial gravity, a dust environment in some ways similar to that on Mars, a hard vacuum, surface temperatures approximately equal to Mars daytime temperatures (at certain locations on the lunar surface). Also, the lunar surface requires complex propulsive operations to access, which also provides operational experience for Mars missions. Specific Mars preparation activities that could be carried out at an analog site on the lunar surface include[2]:

- long-duration stays of crew in a partial gravity field
- long-duration operations and maintenance of habitation, EVA suits and mobility elements in a partial gravity and dust environment
- long-duration continuous operations of habitation equipment
- surface exploration traverses on foot or using pressurized / unpressurized mobility
- use of exploration equipment such as drills and other science tools on EVA
- in-situ science analysis of lunar samples
- simulation of Earth-Mars communications, evaluation of communications strategies
- real-time planning of exploration activities (as opposed to activities preplanned by ground operators)

Of these activities, the simulation of Earth-Mars communications, long-duration continuous operation of habitation equipment and real-time planning of exploration activities could readily be carried out on Earth, potentially at significantly lower cost. The rest of the activities, however, would have unique benefits from being carried out on the lunar surface and should therefore be considered as core objectives for long-term Mars preparation activities on the lunar surface.

B. Surface Mobility Operations

Effective surface exploration on both Moon and Mars is strongly dependent on crew mobility. Surface mobility enables access to unexplored territory and transport of equipment on the surface. Surface mobility equipment is also a major contributor to the cargo mass that needs to be transported to the lunar and Mars surface. For the analysis of extension options it is therefore necessary to provide a mobility strategy in order to determine cargo requirements, especially with regard to pressurized surface mobility.

The Apollo sortie missions used three types of surface mobility concepts: walking on foot in Apollo 11 and 12, the MET (Modularized Equipment Transporter) on Apollo 14, and the LRV (Lunar Roving vehicle) on Apollo 15-17[11]. With the MET and walking on foot, the maximum distance from the LM achieved was almost 1.5 km. With one LRV, the crew was able to extend traverse distances to almost 8 km from the LM (over the horizon, utilizing independent communications with Earth / mission control). The maximum distance achievable was determined by walk-back and consumables constraints in case of failure of the LRV and of one EVA suit.

With two vehicles it is possible to further extend the reach of the crew beyond 8 km, provided that each vehicle is capable of carrying the full set of crew on a traverse in the event of an emergency for driving back to the outpost. Equation 1 provides the simple relationship for the maximum achievable range as a function of the average driving speed, the total time available for transportation ("driving") on traverse, and the ratio of total distance traveled along the traverse route and maximum distance achieved ($R_{Traverse}$, 2 in an ideal case).This ratio was assumed to be 3 based on analysis of Apollo LRV traverses (see Figure 12 in the Appendix); this is a conservative estimate and allows for considerable detours from a straight line traverse[8-10]:

$$d_{\max} = \frac{v_{Average} \cdot \Delta t_{Transportation}}{R_{Traverse}} \qquad \textbf{Equation 1}$$

Equation 1 is also based on the worst case that all science operations occur at the farthest point of the traverse, and one vehicle breaks down at the end of the science operations. It is assumed that in this case that any cargo on the good vehicle is offloaded and substituted with crew; the average speed of the vehicle would remain the same as before the contingency occurred. Figure 2 shows results using Equation 1 for different transportation times (black lines). The red lines indicate the maximum distance achievable if a drive-back constraint in case of a Solar Particle Event (SPE) applies. Maximum achievable distances are shown for drive-back times of 1-3 h after the crew is informed of the SPE. This is based on the assumption that for a SPE which exhibits very little time between the arrival of electromagnetic and of particle radiation, the crew could be exposed to the particle radiation for a limited amount of time.

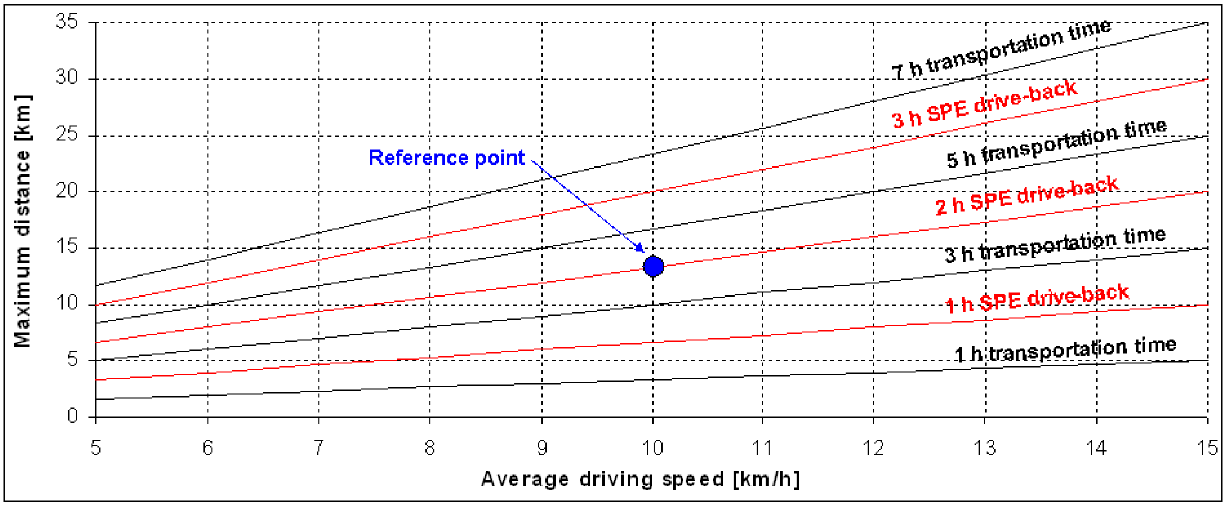


Figure 2: Maximum straight-line distance from outpost (Moon / Mars) for a traverse configuration involving two pressurized vehicles. Black lines represent different times available for transportation along the traverse and red lines represent different drive-back time requirements in case of a Solar Particle Event (SPE). The reference point is based on the assumption that the crew has to be back at the outpost 2 hours after information of the SPE has been received.

Figure 2 shows that for an SPE drive-back time of 2 h and an average speed of 10 km/h (somewhat faster than the Apollo LRV on Apollo 15-17[11]) a maximum distance of about 13 km can be achieved (as denoted by the reference point). This is more than a 60 % improvement over Apollo, and extends the area accessible to the crew by 164 %. Once SPE prediction technology is developed to a level that allows forecasting of flare-free days, the maximum distance would no longer be determined by the SPE drive-back constraint, but instead by the maximum transportation time available based on human factors, science time, and EVA suit consumables. For a maximum transportation time of 5 h, the maximum distance could be increased to 17 km, resulting in a 351 % increase in exploration area accessible to the crew compared to Apollo.

If the crew becomes more familiar with the vicinity of the landing site, the speed could potentially be increased to 15 km/h, resulting in a maximum exploration distance of 25 km and an increase in accessible area of 876 %. This exploration range is comparable to that suggested for NASA's 1992 First Lunar Outpost[12].

Based on these results, it appears that pressurized surface mobility to further extend the exploration range is not required for extended sortie and initial outpost missions, because there is enough area to explore thoroughly for multiple weeks at each landing site provided two unpressurized surface vehicles are available. Pressurized mobility should be delivered after a long-term outpost has been built up; this would enable the crew to significantly extend the exploration reach once the vicinity of the outpost has been sufficiently explored.

C. Exploration Scenarios

The basis for the analysis of extension options is the definition of a set of mission types that need to be carried out, i.e. a scenario of use cases. 5 distinct use cases were considered:

- Lunar sortie missions as described in the ESAS report (up to 7 days stay on the lunar surface)[2]; the initial test missions of the crew transportation are subsumed into this category, too.
- Extended sorties that exceed 7 days surface duration, but do not require any pre-deployment of surface assets (i.e. they feature the same launch operations as sorties).
- Intermediate outpost missions that feature one uncrewed pre-deployment launch (using the CaLV) to the lunar surface before one or a series of crewed missions to the pre-deployed asset.
- Long-term outpost missions that feature more than one launch (using the CaLV) for uncrewed pre-deployment of assets and multiple crewed visits to the pre-deployed assets. The long-term outpost is intended for permanent habitation.
- Crewed Mars missions of conjunction class type.

All lunar use cases require 4 crew, Mars missions 4 to 6 crew. For the extended sortie, the intermediate outpost, and the long-term outpost missions, only polar and equatorial sites are possible due to the lunar orbit rendezvous mission mode, the anytime abort constraint, and the ESAS element designs[2] (the CEV remains in a staging orbit which would be unreachable without significant plane changes for part of the mission duration from landing sites other than polar or equatorial). Figure 3 shows these options arranged into a scenario tree:

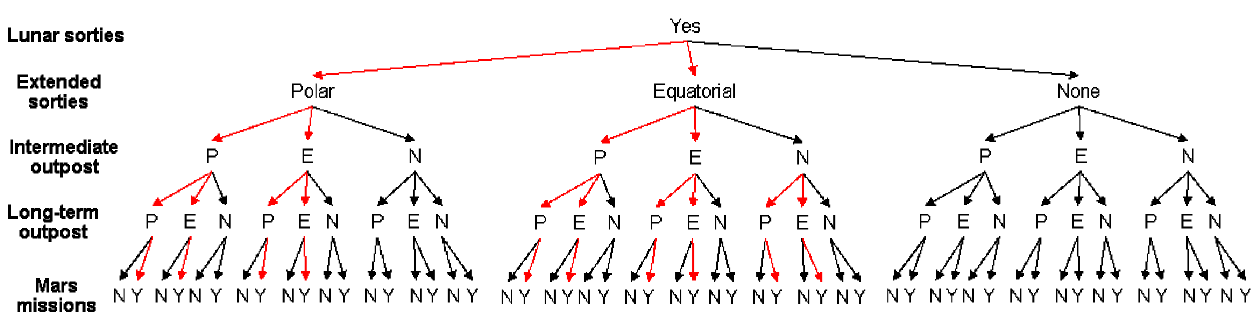


Figure 3: Mission type scenarios for crewed Moon and Mars exploration capturing five different mission types. The four lunar mission types exhibit increasing levels of duration on the surface and of complexity; for Mars missions, conjunction class missions were assumed.

A comprehensive evaluation of all 54 options was beyond the scope of the work presented in this paper and are considered part of future work; however, a bounding set of use cases including all scenario branches marked in red was chosen to provide challenging requirements for system extension. It should be noted that scenarios involving only lunar sortie missions or only sorties and extended sorties are likely unsustainable because they do not involve any permanent assets on the lunar surface.

III. Lunar Extension Strategy

This section describes concepts for extending the lunar crew transportation assets defined in ESAS[2] towards extended sortie, intermediate outpost, and long-term outpost missions. All three mission types can only be carried out at equatorial or polar landing sites because of anytime return constraints[2] (see above). One polar and one equatorial site were chosen from the "top 10 Science Sites"[2] in the ESAS report. Table 1 provides the velocity changes assumed for these landing sites based on the ESAS report and ESAS element capabilities:

Table 1: Polar and equatorial landing site velocity change requirements[2, 13]

South Pole landing site (89.9 S, 180 W)	
LOI delta-v	835 m/s
Descent delta-v	1911 m/s
Pre-rendezvous plane change for CEV	0 m/s
Post-rendezvous plane change, TEI and MCC delta-v	1616 m/s
Mare Tranquilitatis landing site (8 N, 21 E)	
LOI delta-v	852 m/s
Descent delta-v	1911 m/s
Pre-rendezvous plane change for CEV	50 m/s
Post-rendezvous plane change, TEI and MCC delta-v	1053 m/s

In order to calculate the mass of additional consumables and associated storage mass, assumptions were made concerning the consumables required per crewmember per day, and the hydrogen / oxygen requirements for power generation using fuel cells. Table 2 provides an overview of the assumptions made:

Table 2: Consumables requirements including EVA cooling water; one EVA every two days assumed for each crewmember [14, 15, 16]

Consumable	Specific mass
Food	2.3 [kg/p/d]
Waste management	0.28 [kg/p/d]
Hygiene supplies	0.075 [kg/p/d]
Housekeeping	0.35 [kg/p/d]
EVA cooling water	2.5 [kg/p/d]
Clothing	0.5 [kg/p/d]
LiOH for CO2 removal	1.75 [kg/p/d]
Wash water	10 [kg/p/d]
Drinking water	3 [kg/p/d]
Oxygen and nitrogen (pressurization)	1 [kg/p/d]
Fuel cell H2 and O2	0.45 [kg/kWh]

Including a mass overhead for storage of consumables and associated secondary structure, these assumptions lead to a mass requirement of 24 kg/p/d (excluding mass required for power generation); this is in close agreement with mass requirements from previous studies[15]. It was assumed that the water generated in the fuel cells is used as drinking water, wash water, and EVA cooling water. It was also assumed that the LSAM has a closed-loop thermal control system that only requires power and no other consumables while on the lunar surface.

Various options for reducing the mass requirements were analyzed (see below), including:

- Use of solar panels for total or partial power generation (i.e. reduction of hydrogen and oxygen requirements for power generation). Solar panels were sized using a specific power generation capability of 45 W/kg, and an overhead of 100 % for solar panel structure and attachment.
- Use of water regeneration equipment based on a water regeneration plant design and built for ISS[17]; this design was downsized linearly in mass and power to estimate the additional equipment mass and power required. Only the wash water is regenerated, drinking water is provided fresh. Wash water regeneration for 4 crew adds approximately 160 W of continuous power demand, and 116 kg mass.
- Use of regenerative CO2 removal systems instead of expendable LiOH canisters. A 4 bed molecular sieve system design was assumed, which requires 1200 W of continuous power and 120 kg mass for 4 crew[16].

In the figures below, the baseline option (fuel cells for power generation, mass requirements according to Table 2) is shown in black, the solar panel option in red, the solar panel and wash water regeneration option in blue, and the solar panel & wash water regeneration & regenerative CO2 removal option in blue. It should be noted that the technology for all options is currently available.

A. Extended Lunar Sorties

Based on the delta-v requirements in Table 1, a 1.5-launch mission based on the ESAS elements can deliver about 3700 kg of cargo to the polar landing site, and 4800 kg to the equatorial landing site. Assuming about 500 kg for each of two unpressurized vehicles and 500 kg of experiments and science equipment (i.e. a total of 1500 kg of surface mobility and science cargo), an additional *2200* kg of consumables can be delivered to the polar landing site, and an additional *3300* kg to the equatorial landing site.

Figure 4 shows the consumables mass required for extending the crewed duration of the LSAM by a certain amount of days. The colors code the different system design choices described above, and the contours represent different continuous power levels for the LSAM. The lowest line in a family is for 5 kW continuous power and the highest for 20 kW; the intermediate ones are for 10 and 15 kW (due to space constraint not all contours are marked in the figures). For the polar landing site, the contours are simple straight lines, as is to be expected due to the continuous insolation. All options except the baseline involve and increase in equipment mass which manifests itself as an offset for the straight lines.

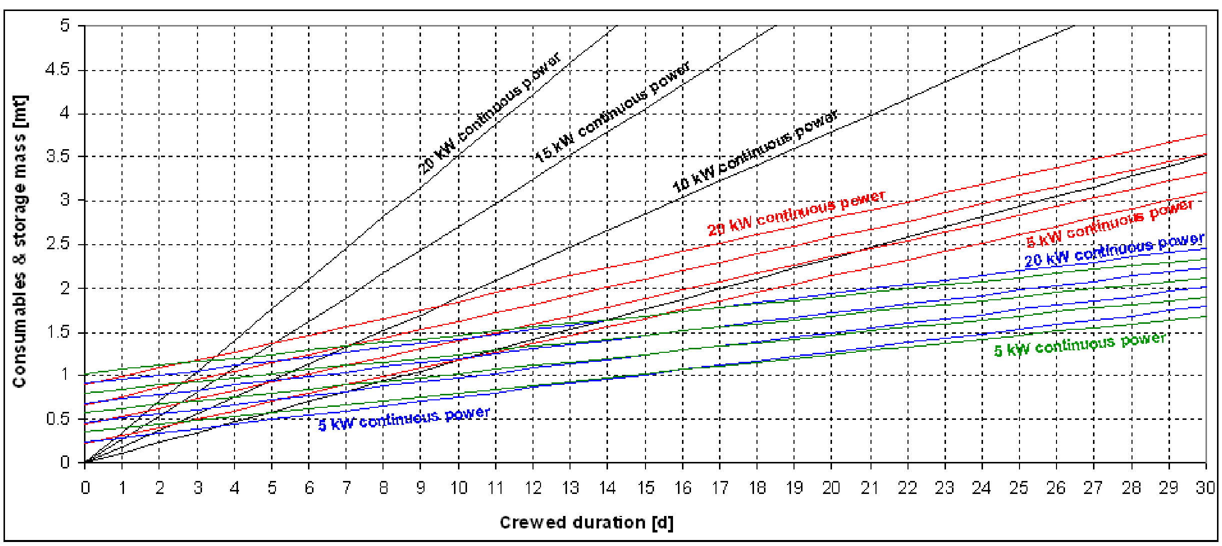


Figure 4: Mass requirements for extending a polar sortie mission. Black lines represent baseline configuration (fuel cells, LiOH, no regeneration), red lines represent baseline configuration plus solar panels, blue lines represent red configuration plus wash water regeneration, green lines represent blue configuration plus regenerative CO2 removal. Contours represent different power levels, highest 20 kW, lowest 5 kW.

The introduction of solar panels is clearly beneficial, as is water regeneration in addition to solar power generation. The substitution of LiOH with regenerative CO2 removal does not appear to be attractive from a mass point of view; however, volume constraints within the crew compartment could require the switch to regenerative CO2 removal. Based on the cargo mass indicated above, and an average power level of 10 kW the polar stay of the LSAM on the lunar surface could be extended to at least 16 days (red option), and potentially up to 30 days (blue / green option). 10 kW of continuous power are assumed to be sufficient for a powered down LSAM and regenerative CO2 removal and water regeneration.

The ESAS LSAM design has a total pressurized volume of 31.8 m^3, which is partially consumed by equipment and space suits[2]. It is therefore likely that volume will be the driving constraint for extension of the stay rather than mass: while there is enough cargo capacity to sustain the crew for more than two weeks, it is unclear whether the crew compartment will be big enough to do so. There are several possible solutions for providing more pressurized volume per crewmember without significantly increasing the mass of the ascent crew compartment that needs to be brought back to lunar orbit:

- Tailoring of the crew activity periods so that sleeping periods for 2 crew overlap with EVA periods for the other 2 crew members
- Provision of additional pressurized volume in the form of inflatable crew compartments, a 2-module LSAM crew compartment (one module left on the surface), or empty propellant tank(s) from LOI & descent
- Reduction of the crew size to 2 or 3 crewmembers; Figure 13 in the Appendix provides an overview of the mass requirements for 2 crewmembers at a polar location.

Figure 5 provides the corresponding mass requirements as a function of extended stay time for an equatorial landing site. For this analysis it is assumed that the lunar day starts at 0 days extension time. Initially the consumables requirements are also linear; however, after the onset of lunar night (after day 14) solar power generation is no longer possible, and fuel cells are used. The change in slopes of each curve are caused by the assumption that fuel cell water is used as wash water, drinking water, and EVA water. Depending on whether the crew water demand or the water generated by the fuel cells dominates is greater, the slopes of the straight line segments change.

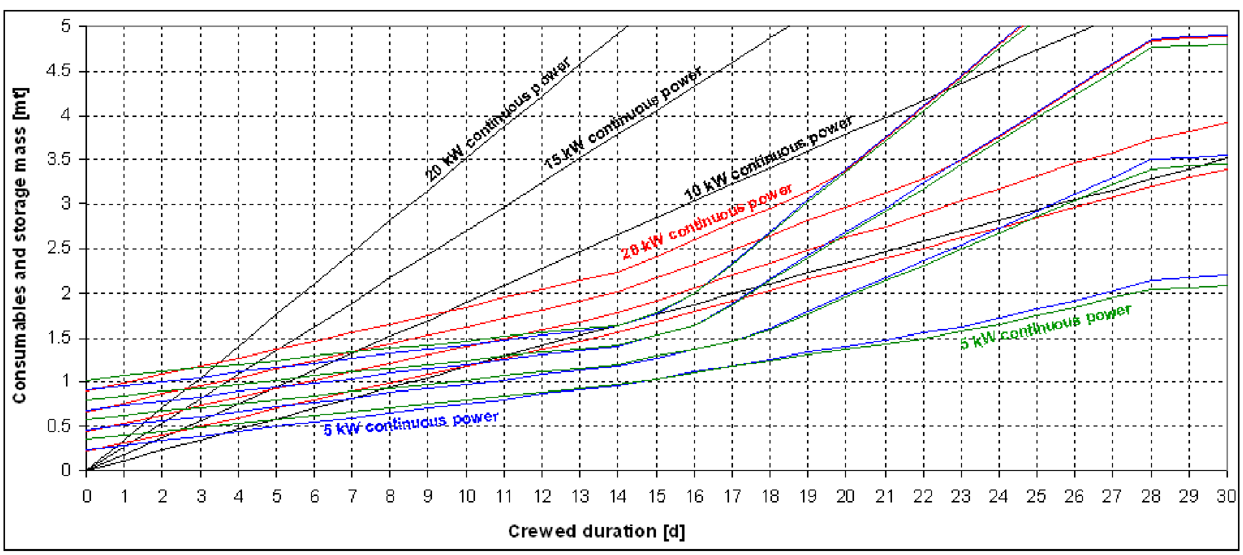


Figure 5: Mass requirements for extending an equatorial sortie mission. Black lines represent baseline configuration (fuel cells, LiOH, no regeneration), red lines represent baseline configuration plus solar panels, blue lines represent red configuration plus wash water regeneration, green lines represent blue configuration plus regenerative CO2 removal. Contours represent different power levels, highest 20 kW, lowest 5 kW.

Based on the cargo capability provided above, equatorial stays could be extended to about 25 days for a 10 kW LSAM with solar panels (red), and to about 27 days for a 10 kW LSAM with water regeneration and regenerative CO2 removal (green). It should be noted that EVA operations are possible during the lunar night provided there is sufficient Earthshine. For the First Lunar Outpost mission[12], it was estimated that EVA would not be possible for 5 days around lunar noon due to surface relief washout, and for 5 days after "sunset" due to insufficient Earthshine at an equatorial landing site. The volume constraints for the crew apply to equatorial missions in the same way as for polar missions.

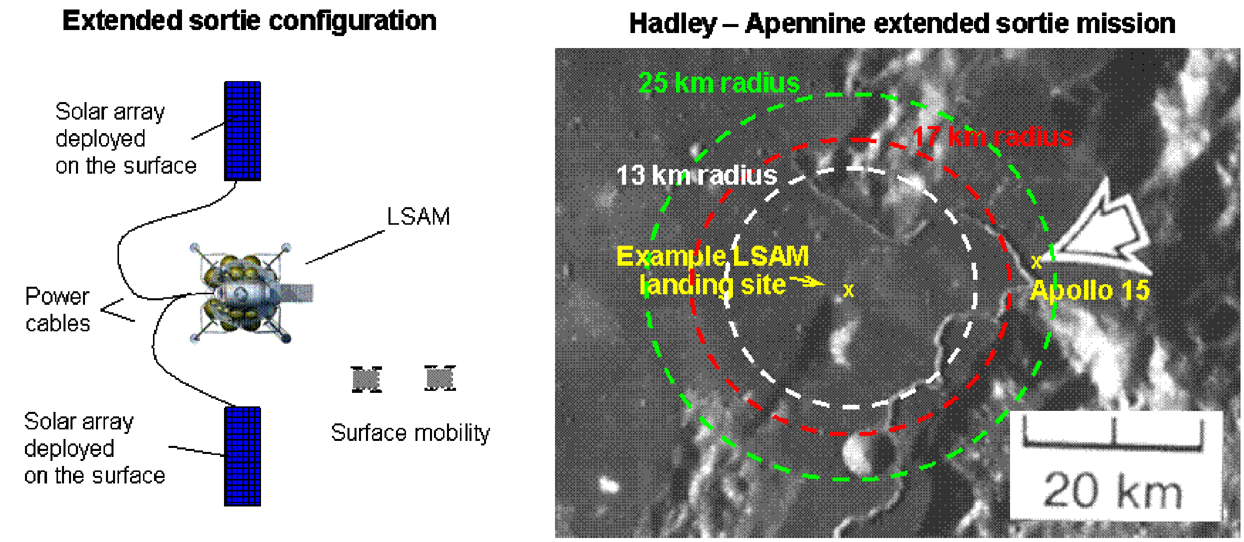


Figure 6: Extended sortie LSAM configuration and surface mobility capabilities as outlined in Section II. Sortie LSAM is augmented by solar panels which are stored as cargo and deployed once on the surface. Additional consumables are stored on the descent stage; crew compartment is regularly re-supplied with pressurized consumables stored on the descent stage. – White circle represents distance limit in case of a 2h SPE drive-back constraint, red circle due to 5 h transportation time constraint at 10 km/h average speed, and green circle represent 5 h transportation time at 15 km/h.

Figure 6 provides an overview of the LSAM extended sortie configuration and a visualization of the surface mobility capabilities for different safety constraints for a hypothetical mission to the Hadley-Apennine region visited by Apollo 15.

In summary, both polar and equatorial stays can be extended by several weeks, the limiting factor likely being the pressurized volume available for the crew. Solar panels are crucial to extending these stays and would be cargo items delivered to and deployed on the lunar surface before being connected to the LSAM power system. Water regeneration is desirable, but not absolutely necessary to extend the stays. The extended stays can be utilized to carry out more extensive exploration of the landing site vicinity both for geological surveys and in-depth study of individual sites of interest. Also, the physiological effects of longer exposure to partial gravity can be analyzed in situ. These capabilities could be provided almost immediately after the initial test missions of the crew transportation system.

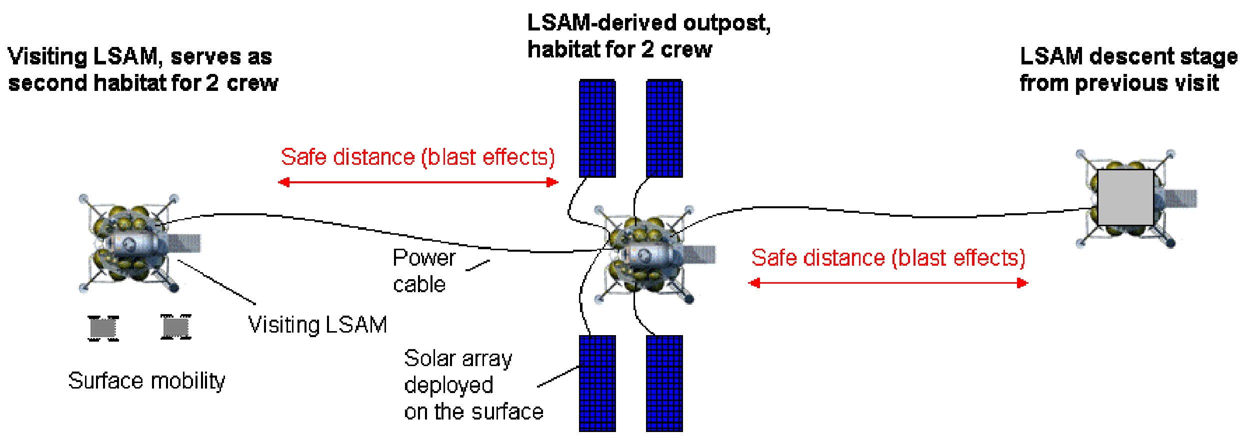
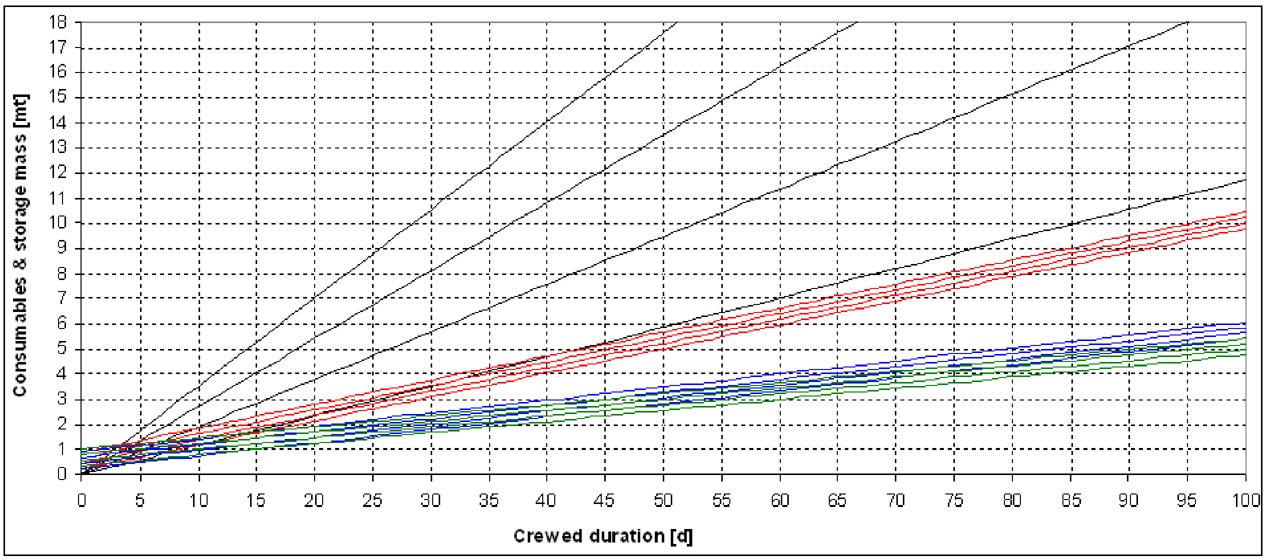


Figure 7: Intermediate outpost configuration on the lunar surface. Middle LSAM lander is pre-deployed uncrewed and carries consumables and equipment instead of ascent propulsion. LSAM lander to the left is a visiting LSAM that brings the crew and serves as habitat for 2 crewmembers during the surface stay. Landers are connected by cable; re-supply of the visiting LSAM is achieved using the surface mobility assets.

B. Intermediate Outpost

The intermediate outpost mission involves a dedicated uncrewed CaLV launch for pre-deployment of equipment and assets before one or multiple visits of the crew. The extension concept selected for this mission type is to pre-deploy a full LSAM without ascent main propulsion (engine & propellant + tanks, but with RCS) which serves as a habitat for 2 crew on the lunar surface, and provides power and consumables. This pre-deployed "outpost" is then visited by a crewed LSAM which delivers 4 crew. 2 crew stay in the visiting LSAM, the other 2 crewmembers inhabit the pre-deployed LSAM. Consumables for the crew are mostly pre-deployed; the visiting LSAM brings surface mobility assets, equipment and experiments. Re-supply of the visiting LSAM is required in regular intervals and is accomplished using a consumables transfer unit (a set of tanks for oxygen and water; other pressurized items like food would be transported in a pressurized "suitcase" to the visiting LSAM) that can be mounted on one of the surface mobility vehicles. The two landers are connected with a power cable to transfer power to the visiting LSAM; the power cable is landed on the visiting LSAM. Figure 7 provides a visualization of the intermediate outpost and additional information.



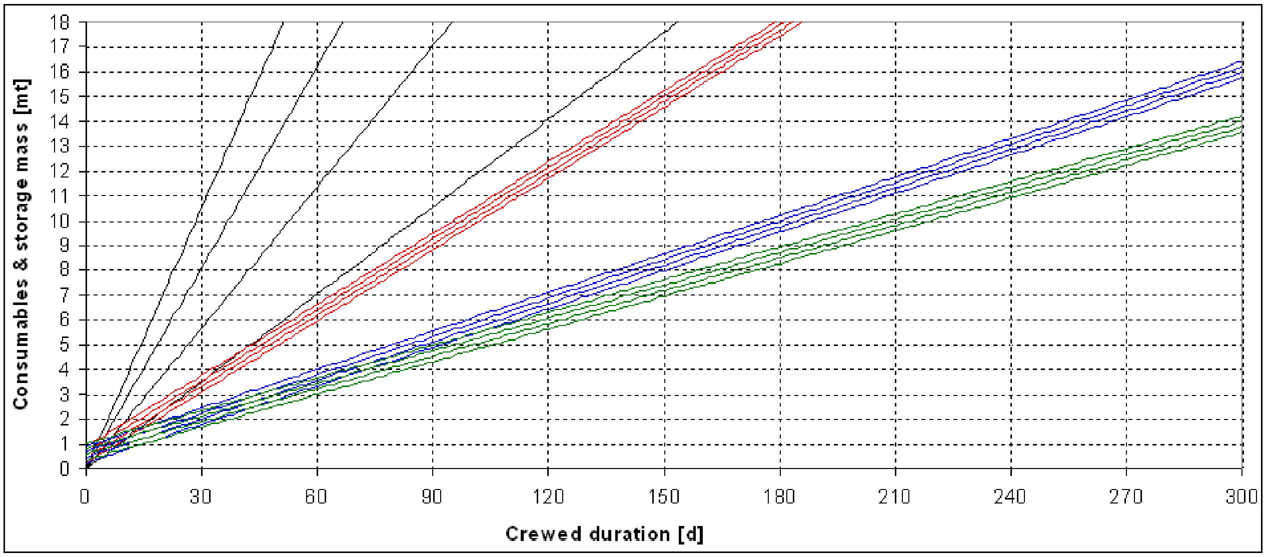


Figure 8: Mass requirements for a polar intermediate outpost mission. Black lines represent baseline configuration (fuel cells, LiOH, no regeneration), red lines represent baseline configuration plus solar panels, blue lines represent red configuration plus wash water regeneration, green lines represent blue configuration plus regenerative CO2 removal. Contours represent different power levels, highest 20 kW, lowest 5 kW. – Top diagram represents zoomed-in version of bottom diagram.

As the visiting LSAM lands surface mobility vehicles, re-supply equipment, experiments, and the power cable(s) for connecting the two landers on the surface, the cargo capacity of the pre-deployed LSAM can be utilized solely to extend the crewed lifetime on the surface. Using the delta-v information provided in Table 1, the amount of additional cargo that can be delivered with an uncrewed LSAM ascent stage without main propulsion (estimated to be 3900 kg) can be calculated as 17.6 mt for a polar landing location, and 17.5 mt for an equatorial landing location. The cargo mass is constrained by the CaLV TLI capability which was assumed to be 53.6 mt[2]. This cargo mass is not entirely available for consumables and equipment, because the pre-deployed LSAM needs extra thermal protection and power generation equipment (RTGs) for the dormant period between crewed visits. 1 mt is provided for this additional power generation and thermal control hardware, reducing the cargo capacity available for consumables and associated equipment to 16.6 and 16.5 mt for polar and equatorial landing sites.

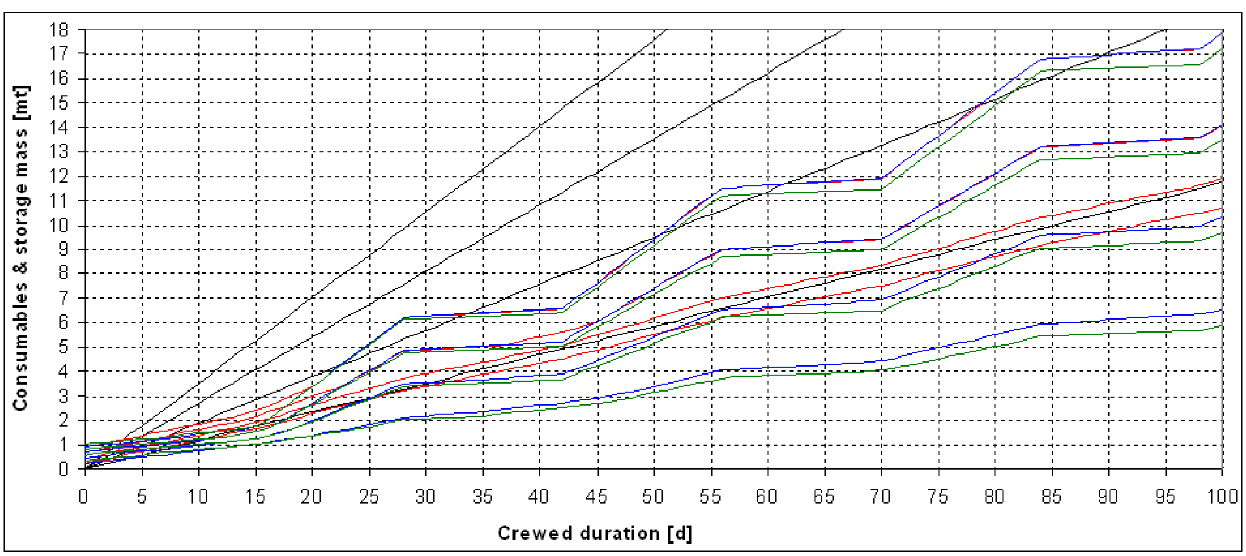


Figure 9: Mass requirements for an equatorial intermediate outpost mission. Black lines represent baseline configuration (fuel cells, LiOH, no regeneration), red lines represent baseline configuration plus solar panels, blue lines represent red configuration plus wash water regeneration, green lines represent blue configuration plus regenerative CO2 removal. Contours represent different power levels, highest 20 kW, lowest 5 kW.

Figure 8 and Figure 9 provide an overview of the consumables and equipment mass required for intermediate outpost missions at the pole and the equator as a function of duration; for polar landing missions it is assumed that the outpost site is illuminated for each crewed day (this does not exclude periods of darkness in-between crewed stays; for these periods the RTGs mentioned above are required).

As both LSAM landers need to be powered while the crew is present, a conservative power assumption of 20 kW was used here (i.e. the top contour applies for each configuration/ color). The results are:

- For a polar site and the use of solar arrays, about 160 days of surface duration for 4 crew can be provided with the one pre-deployment launch. If water regeneration is added to the polar outpost with solar arrays, then over 270 days can be provided on the surface. Use of regenerative CO2 removal technology will increase this even further, and will likely be desired due to the volume requirements of LiOH.
- For an equatorial outpost, just over 80 days of surface duration can be provided due to the hydrogen and oxygen requirements for power generation during lunar night.
- The significant difference between polar and equatorial intermediate outpost capabilities would likely lead to the selection of a polar outpost site for this mission type.
- The up to 270 days at a polar site could be used to carry out two 135 days stays or three 90-day stays (or any other combination of shorter stays); if the landing site was located in an area continuously lit for 270 days, it could even be one long stay. Stays of this duration could be used to provide significant Mars preparation, potentially eliminating the need for a long-term outpost if several different intermediate outposts are deployed sequentially.

C. Long-term Outpost

A long-term outpost was defined above as an outpost that required more than one uncrewed launch to be pre-deployed and sustained and that is intended for permanent inhabitation. Two potential concepts for a long-term outpost are:

- Extension of the intermediate outpost into a long-term outpost by delivery of re-supply consumables using dedicated CaLV launches and addition of an additional power generation unit (for crewed stays during lunar night) and pressurized surface mobility. This concept would still have the crew split up into two pairs, one living in the visiting LSAM, and one in the intermediate outpost LSAM (see above).
- Development of a dedicated outpost habitat solely intended for use as part of the long-term outpost. The development of a dedicated habitat for long-duration stays also represents an opportunity for commonality with crewed Mars surface assets. A number of designs for dedicated lunar surface habitats have been carried out in the past[2, 3, 7, 12, 15].

IV. Mars Extension Strategy

A. Overview of Required Mars Mission Elements and Options for Lunar Extensibility

In considering extending the use of the ESAS elements from lunar operations towards Mars operations, it is useful to first examine the elements that are required in order to perform Mars missions. Many studies have been performed to identify architecture and design options for Mars missions. A number of potential elements could be used to make up a Mars mission, however for the purposes of this paper we will assume that the following list is the minimum required.

Minimum Set of Required Mars Elements:

1. Earth Launch and Entry Crew Cabin(s)
2. Heavy Lift Launch and Earth Departure Systems
3. Long-duration Habitat(s) and Mars Ascent/Descent Crew Cabin(s)
4. Mars Aeroentry and Descent System
5. Mars Landing Propulsion System
6. Mars Ascent Propulsion System
7. Earth Return Propulsion System

8. Surface Exploration Systems
9. Surface Power Systems
10. In-Situ Resource Utilization Systems (while not strictly necessary, provide significant leverage for Mars missions)

The intent in developing the CEV, as described in ESAS, is for it to serve as the Earth Launch and Entry Crew Cabin for Mars missions[2]. Depending upon the mission architecture, the same CEV may be used for both legs in a given mission, or two distinct CEVs employed. In terms of what is required to enable the CEV to perform this functionality, the greatest change relative to the lunar CEV is in terms of its entry velocity capability and dormancy duration requirements. This paper will not focus on these aspects of extending the CEV, although they are of high importance in developing the CEV such that it is extensible towards Mars. Another factor worthy of consideration in terms of extending the CEV towards Mars is that if the only functionality it provides is crew accommodations during Earth launch and entry, it will effectively represent a large parasitic mass upon the overall Mars crew transportation system, as it is transferred from Earth to Mars (either orbit or surface) and back without providing any useful functionality along the way. Options to allow the CEV to provide additional functionality thus are of interest to decrease the overall cost of Mars missions. One such option is presented towards the end of this section in the discussion of a potential ESAS lunar element-derived Mars architecture.

Applicability of the ESAS Cargo Launch Vehicle (CaLV) towards the heavy lift requirements inherent in a Mars mission has been suggested as one of the major linkages between the current lunar program and eventual Mars missions[2]. The following subsection of this paper thus looks in depth at the capability of the ESAS launch vehicles towards providing heavy lift launch along with Earth departure capability for human Mars missions.

The requirements on the long duration habitats making up a Mars mission include supporting the crew during the approximately 180-day transfer from Earth to Mars, the 500-600-day stay on the surface of Mars, and the approximately 180-day return transfer from Mars to Earth. Short-duration crew cabins are also required during Mars landing and ascent. While it is highly unlikely (and undesirable from a design perspective) that all of these mission phases will be accomplished using a single instance of a habitat, it is possible that a single habitat/crew compartment could take on multiple phases and/or the same habitat/crew compartment design could be employed (using multiple instances) to accomplish distinct sets of mission phases. Taking the NASA JSC Mars Design Reference Mission 1.0 and 3.0 architecture as an example, a single habitat would be used for Earth-Mars transfer, Mars descent, and Mars surface operations, while another habitat of a similar design is used during the Mars-Earth return transfer[18, 19]. Two examples of a habitat/crew compartment being used across multiple phases include having a single crew compartment used for both Mars ascent and descent, or a single habitat used for the in-space Earth-Mars and Mars-Earth transfers. In terms of examining the capability of the ESAS elements for providing this functionality, it would appear that the LSAM crew compartment would be well suited for the Mars ascent and descent roles. The LSAM crew compartment conceivably could also be extended for use as an in-space habitation on either the Earth-Mars or Mars-Earth legs (or both), provided that modifications are made to the life support and power systems to enable significantly longer occupation. The CEV crew compartment could also be pressed into service as a Mars habitat, particularly for transfers to and from Mars. In relation to providing surface habitation on Mars, the LSAM crew compartment as presented in the ESAS report does not appear to provide sufficient volume for the expected activities, even if the life support could be extended for a sufficient duration. If extensibility from the LSAM crew compartment is desired, multiple LSAM crew compartments could perhaps be used for Mars habitation, or inflatable extensions developed to increase the volume available. Another possibly more reasonable option would be the development of a large, long duration surface habitat for use in these missions. With proper design, such a habitat could also be used on the Moon to provide long duration outpost capabilities beyond those available with LSAM derived habitats only (see long-term lunar outpost above).

In terms of the propulsion and aeroentry systems required for the major post-Earth departure maneuvers of a Mars mission, the Mars aeroentry systems in particular clearly have no parallel in the lunar exploration elements. As such, these systems would need to be developed specifically for Mars, and it is recommended that advanced development work on them be initiated such that they can be made available for Mars missions in a timely manner. It is worth noting that in creating the minimal set of Mars mission elements listed above, the Mars aeroentry systems were also considered to provide aerocapture into Mars orbit, for which an additional set of technological challenges exist. If aerocapture is not used, the Mars orbit capture maneuver could either be provided by an additional dedicated propulsion system, or by the same system that provided Earth departure, particularly in the case of a nuclear thermal Earth departure system. Our analysis however indicates that aerocapture is the most preferred of these options. The propulsion systems used for the maneuvers near Mars are required to operate after significant durations in space, ranging from 6 months to several years; boil-off considerations thus likely eliminate hydrogen fuel as an option[15]. Methane-oxygen propellants have frequently been proposed for Mars missions due to their more benign boil-off characteristics, relatively high performance, and in-situ propellant production potential. If methane-oxygen propellants are used in the lunar systems (as proposed by ESAS), the engines and other propulsion technologies may thus be applicable towards the propulsion functionality required near Mars. If hypergolics are selected for lunar missions, they could potentially also be extended to Mars missions, although at the cost of decreased performance and ruling out in-situ propellant production (and thus certain architecture options such as those employing direct return from the Martian surface). Alternatively, hypergolics could be employed for the moon while methane-oxygen propulsion systems are developed for use on Mars missions. In terms of the designs of the stages themselves, it does not appear that the ESAS stage designs can be directly used in Mars mission applications, although options to provide multiple copies of ESAS stage elements (engines, tanks) in the Mars systems may be feasible.

The surface exploration systems, such as crew mobility and EVA equipment, offer many potential opportunities for extensibility between lunar and Mars missions. The drivers for Mars missions are very similar to those for lunar missions, possibly with some modifications primarily in the thermal arena; as such the discussion provided in the lunar portion of this paper applies here as well. Power systems for lunar missions also can be extended towards Mars operations. In the case of solar power systems, an increase in collection area would be required due to the decreased solar flux, although storage requirements would be significantly decreased relative to a non-polar lunar outpost. A modular design could be employed to allow the system to be increased in collection area and decreased in storage capacity in an effective manner as it is extended from lunar operations towards Mars operations. While not assumed in the baselines presented in this paper, nuclear power systems could also be designed for use on both the Moon and Mars, possibly with considerations given to a modular heat rejection system to tailor the system to the particular operating environments.

Note that while not strictly required, In-Situ Resource Utilization (ISRU) can provide significant leverage for Mars missions. Major uses of ISRU products include consumables for crew support, EVA, and surface mobility as well as ascent and potentially trans-Earth injection propellants. This being the case, however, the potential for extensibility of lunar ISRU systems towards Mars is quite limited. At present, it is unclear if lunar ISRU will be employed or is even advantageous to lunar operations. If it is used though, the technologies involved for lunar resource utilization are quite different from those used on Mars. Mars ISRU would most likely entail utilization of carbon dioxide extracted from the atmosphere through relatively simple means in a variety of chemical processes. By contrast, lunar ISRU involves extensive infrastructure for extraction of useful chemicals (primarily oxygen) from regolith or the extraction of lunar ice from extremely low temperature, permanently shadowed polar deposits. As Mars ISRU is in fact much simpler than lunar ISRU, requiring demonstrations of lunar ISRU in order to allow the use of Mars ISRU could be quite detrimental to the progress of human Mars exploration. While some of the downstream chemical processing may be similar between lunar and Mars ISRU systems, this is relatively minor when compared with the vast differences between the overall technology required in the lunar ISRU case relative to the Mars ISRU case. In addition, as a number of the Mars ISRU chemical processes are similar to those employed in regenerative life support systems, focusing on commonality and extensibility in those areas may be more beneficial.

B. Applicability of ESAS Launch Vehicles to Mars Missions

The launch systems provided by the ESAS lunar architecture serve as a major cornerstone for future missions to Mars. Figure 10 below provides an overview for a variety of launch configurations for transfer of payloads to a Trans-Mars Injection (TMI) trajectory consistent with a Low Earth Orbit (LEO) delta-V of 4,050 m/s (sufficient for both cargo and human Mars transfer trajectories). The payload mass which can be sent towards TMI is shown based upon the existing Cargo Launch Vehicle (CaLV), Crew Launch Vehicle (CLV), and Earth Departure Stage (EDS) designs as presented in the ESAS report[2]. No modifications are made to the vehicles or stages and no advanced technology (such as nuclear thermal propulsion) is included. While advanced propulsion technology could lead to increased TMI payloads, in terms of extending the ESAS elements for Mars exploration it is useful to understand the capability utilizing the existing hydrogen-oxygen earth departure system.

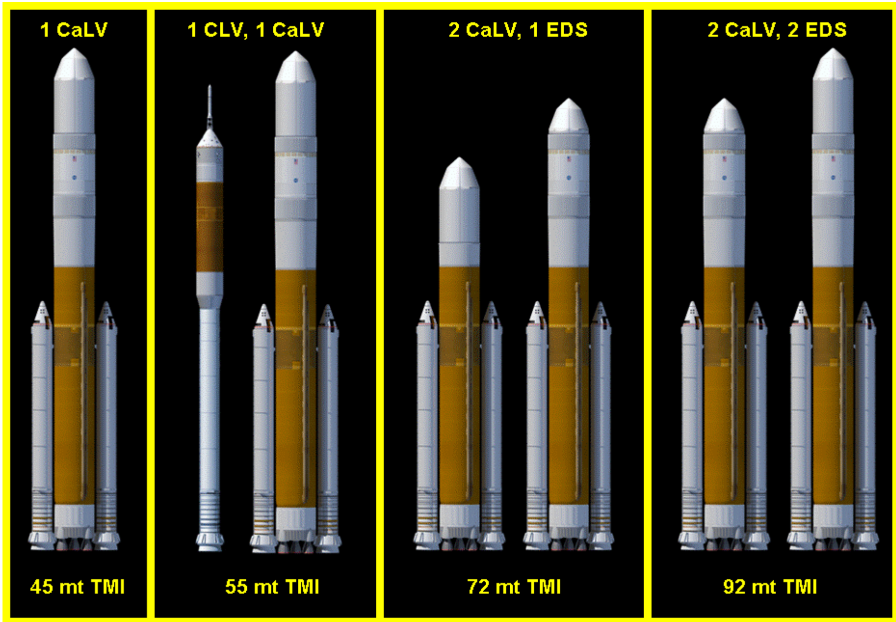


Figure 10: Overview of ESAS CaLV and CLV derived Mars launch options showing Trans-Mars Injection (TMI) capability for 4,050 m/s burn from 400 km low Earth orbit. Dual launch options include rendezvous in Earth orbit prior to TMI.

The first case presented in Figure 10 includes a single, direct launch of a CaLV towards Mars. As no Earth orbit rendezvous is required, this case is the simplest operationally, and results in a 45 mt TMI payload. By docking the 25 mt payload of a CLV to the payload and EDS of a CaLV, the total payload to TMI is increased to 55 mt. This launch architecture is operationally similar to that employed in the ESAS recommended lunar architecture. The third case presented involves two CaLVs, one with an EDS onboard (which performs a partial burn to reach orbit) and the second with a payload but no EDS. Once these elements are docked in LEO, the EDS can launch up to 72 mt payloads towards Mars. The fourth case involves two CaLVs, each with an EDS and one with the TMI payload. Both EDSes are burned suborbitally, with the EDS on the CaLV with the TMI payload burning most of its propellant in order to reach orbit. Once the elements have docked, the almost empty EDS launched with the TMI payload burns its remaining propellant to move the stack into an elliptic orbit and is then staged. The EDS that was launched without the TMI payload then completes the remainder of the burn required to inject the payload towards Mars. While this launch configuration is the most complex operationally, it allows payloads of approximately 92 mt to be launched towards Mars, a significant figure given that this does not include any advanced propulsion technologies for Earth departure.

Based upon these launch configurations, the various vehicles that make up the overall Mars architecture can then be examined. While modifications to the launch systems may be possible, exploring the capability of Mars systems that can fit within these constraints will be instructive to understand the possibilities of extending the ESAS lunar elements towards Mars. The useful payload delivered to Mars is of particular interest for this purpose. Table 3 presents capabilities of the launch options described in terms of useful mass aerocaptured into Mars orbit or delivered to the surface through aerodynamic and propulsive deceleration. In Table 3, Mars orbit mass is calculated as 75% of the TMI mass and Mars surface mass is 50% of TMI mass, with any fractions rounded down. These mass fractions are representative of aerocapture and aeroentry systems combined with either methane-oxygen or hypergolic propulsion systems.

Table 3: Equivalent Mars orbit and Mars surface payloads delivered for the launch options investigated.

	Case 1	**Case 2**	**Case 3**	**Case 4**
Total TMI Mass	45 mt	55 mt	72 mt	92 mt
Equivalent Mars Orbit Mass	33 mt	41 mt	54 mt	69 mt
Equivalent Mars Surface Mass	22 mt	27 mt	36 mt	46 mt

It is interesting to note that the case of a single CaLV launch towards Mars provides effectively equivalent payload mass on the surface of Mars as a single CaLV launch to the Moon provides in terms of surface payload there. This may be an attractive feature in terms of utilizing similar surface elements on both the Moon and Mars.

C. Baseline ESAS-derived Mars Exploration Architecture

Based upon the capabilities of the ESAS launch vehicles, a baseline human Mars exploration architecture was created that maximizes the use of other ESAS elements (CEV, LSAM). The baseline architecture is presented in Figure 11.

In this architecture, the surface habitat is sent uncrewed to the surface of Mars prior to the arrival of the crew. Additional logistics flights are also sent to provide power, consumables, and surface exploration systems for use once the crew arrives. Each of these uncrewed flights is performed using a single CaLV launch, simplifying launch operations considerably, as well as decreasing the burden on Mars aerocapture/entry systems through decreased system mass. The payload capacity to the surface for each of these flights is approximately 22 mt as outlined in the previous section. The particular number of logistics flights required per mission depends upon whether in-situ resource utilization is employed, the degree of life support closure, the crew size, and the amount of surface exploration cargo desired. The habitat could potentially be an extended version of the LSAM crew compartment augmented with additional inflatable volumes, or be of a dedicated design. If multiple sequential missions are flown to the same location across multiple opportunities, significant infrastructure can be used from one mission to the next, decreasing the number of uncrewed flights which are needed to support the mission. Assuming that ISRU is used with a crew of six, it appears that two logistics flights (in addition to the surface habitat flight) would be sufficient for the first human mission, followed by one logistics flight (and no additional habitat flight) for subsequent missions.

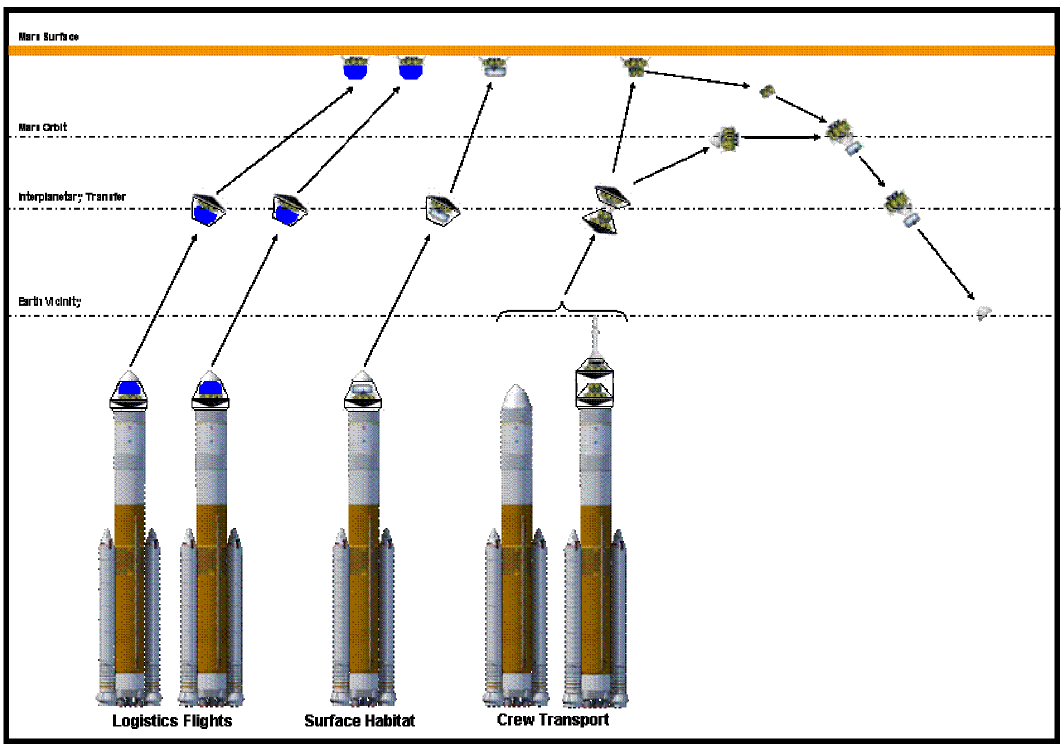


Figure 11: Baseline ESAS-derived human Mars exploration architecture. Logistics flights and a surface habitat are sent to Mars prior to the arrival of the crew, each on a single dedicated CaLV. Crew transportation involves two CaLVs and two EDSes, which rendezvous in LEO prior to sending the crew to Mars. The crew travels to and from Mars in a vehicle composed of an extended duration CEV and an LSAM derived Mars ascent-descent vehicle crew compartment. Propulsion systems derived from the LSAM ascent stage are used for maneuvers in the Mars vicinity.

The Mars crew transportation system employs two ESAS CaLV launches, each one with an EDS. One of the launches also contains a CEV with a trans-Earth injection stage and a LSAM crew compartment-derived Mars ascent-descent vehicle, along with two heatshields (one for the ascent-descent vehicle, one for the CEV and TEI stage.) During transit to and from Mars, the crew lives in the combined volume of the ascent-descent crew compartment and the CEV. The CEV would be modified to provide life support for the approximately one-year combined duration of the outbound and inbound transfer. The service module would have its independent propulsion capability removed as part of this modification. The LSAM-derived ascent-descent crew compartment would not provide life support during the inbound and outbound legs, but would provide additional volume for crew activities. Combined, the ESAS CEV and LSAM provide 40 cubic meters of habitable volume. While additional volume per crew member may be desirable, based upon tolerable volumes for the 6-month transfer duration, this configuration could support a crew of up to six. Rather than volume, the mass impacts of various crew sizes scaled through the selected propulsion systems has a larger impact on the potential crew sizes for these ESAS-derived Mars crew transportation system elements. In particular, using a life support model based upon systems developed for the International Space Station, the crew transportation system could transfer 2 crew with hypergolic propellants, 3 crew with methane-oxygen propellants and no in-situ propellant production, or 4 crew with methane-oxygen propellants and in-situ propellant production. Given that minimum crew sizes from 4-6 are likely to be desired for early Mars missions, multiple instances of the crew transportation system could be used to transport crew in independent groups to Mars, where they would subsequently meet up on the surface.

Based upon this overall architecture, a basic traffic model can be created to determine the number of cargo launch vehicles required per Earth-Mars transfer opportunity (once every 27 months) to both setup and support a series of human missions to a Mars outpost. The results are presented in Table 4 for both a low demand and a high demand scenario. The low demand scenario would be representative of a crew size of 4 employing in-situ resources for both consumables on the surface and for ascent propulsion. The high demand scenario would be representative of between 4 and 6 crew with either hypergolic or methane-oxygen propulsion without in-situ propellant production and with limited to no in-situ consumables production. The traffic model does not account for replacement habitats or the position of additional infrastructure to significantly build up the base capabilities, although this clearly would be an option. Overall it appears that the number of launches required for a sustainable series of Mars missions using ESAS-derived elements is quite achievable.

Table 4: Number of Cargo Launch Vehicles required for initial and subsequent transfer opportunities for series of Mars missions to single site, under low and high demand scenarios.

	Low Demand			High Demand	
	Initial Opportunity	**Subsequent Opportunities**		**Initial Opportunity**	**Subsequent Opportunities**
Logistics and Infrastructure	3	1		4	2
Crew Transport		2			4
Total # CaLVs	**3**	**3**		**4**	**6**

V. Conclusions and Recommendations

This paper provides an initial analysis of Moon and Mars exploration program strategies with special focus on extending capabilities in an incremental fashion based on the lunar crew transportation system. The quantitative analysis was based on data from the ESAS report; the following qualitative results, however, are generally applicable:

- An integrated approach to the development and operations of human Moon and Mars exploration systems offers significant benefits with regard to life-cycle cost and mission and crew safety due to the introduction of common systems and operations.
- For a program of exploration that includes human Mars missions, the primary goal of human lunar exploration should be preparation for Mars exploration. Major Mars preparation objectives include: study of physiological response to long-duration partial-g exposure, EVA and mobility operations in a dusty, partial-g environment, and re-supply of habitation equipment and assets on the surface.

- The option to extend sortie missions soon after the 7th human lunar landing (1st post-Apollo) would significantly contribute to the sustainability of the overall program because capabilities unprecedented by Apollo could be provided quite rapidly.
- Quantitative analysis indicates that with the addition of a photovoltaic power generation element to the fuel cell system currently planned for the human lander, sortie surface stays could be extended to several weeks both at the equator and the pole. The limiting factor for these stays is likely to be the pressurized volume of the crew compartment rather than the cargo capability of the lander.
- With one uncrewed launch using a CaLV, consumables, equipment and a crew compartment can be pre-positioned that enable a succession of longer-stay missions in a polar or equatorial environment. The pre-deployed asset would be visited by crews using the sortie crew transportation system. Once on the surface, the sortie lander is connected to the pre-deployed lander for power supply, and two of the four crewmembers transfer to the pre-deployed crew compartment for habitation. This "intermediate outpost" will likely require water regeneration and regenerative CO_2 removal in addition to a photovoltaic power system. This additional functionality can be provided with add-on modules that are deployed once the crew is at the outpost site.
- Several of the above intermediate outposts in a polar environment would provide the capability to carry out a series of long-duration (longer than 180 days) stays at the lunar South Pole which would arguably provide sufficient experience and Mars preparation to mount Mars missions. In this scenario no permanent long-term lunar outpost would have to be developed.
- Should a long-term lunar outpost be desired, it could be based on the intermediate outpost with re-supply and additional power and mobility equipment, or a dedicated habitat could be developed with a high degree of commonality with Mars.
- Unpressurized surface mobility is likely going to provide access to sufficient exploration area for initial long-duration missions; pressurized surface mobility will not be required until a long-term outpost has been established.
- The ESAS CaLV provides significant capability for Mars exploration, in both single- and dual-launch modes, without resorting to the use of advanced propulsion.
- The ESAS LSAM crew compartment and CEV can be extended for use in transit to and from the Earth and Mars, and for Mars ascent and descent.
- A dedicated long duration habitat would be beneficial for Mars surface crew support due to the volume required for such missions.
- The ESAS elements can be combined with existing or near-term propulsion technology in order to enable human Mars missions within a reasonable number of CaLV launches.

Based on the above conclusions, the following recommendations can be derived for the design and operations of the lunar crew transportation system:

- The human lunar lander should be equipped with or provide an interface for a lunar surface closed-loop thermal control system that provides the capability of operating the lander through lunar noon. This is crucial to enable the extended stays without a significant development effort.
- The human lunar lander should be capable of carrying out trans-lunar coast, LOI, and descent in an uncrewed, teleoperated mode.
- The human lander should be equipped with appropriate interfaces to enable photovoltaic power generation, water regeneration, and regenerative CO_2 removal while on the lunar surface. Also, interfaces for additional consumables storage units need to be provided.
- The human lunar lander main ascent propulsion system should be removable without impairing the RCS system used for lunar descent.
- The development of the CaLV should include considerations for its use as a Mars heavy lift launch vehicle, including potentially in a crewed launch mode.
- The development of the CEV and LSAM crew compartment should consider possible extension towards Mars, including use as the in-space crew transfer vehicle, as opposed to simply a parasitic Earth entry vehicle (in the case of the CEV) and as a Mars ascent-descent vehicle crew compartment (in the case of the LSAM crew compartment).

Future work will be focused on more in-depth analysis and design of the baseline concepts presented here and an adaptation of the concepts to other lunar crew transportation system designs and launch architectures.

VI. Appendix

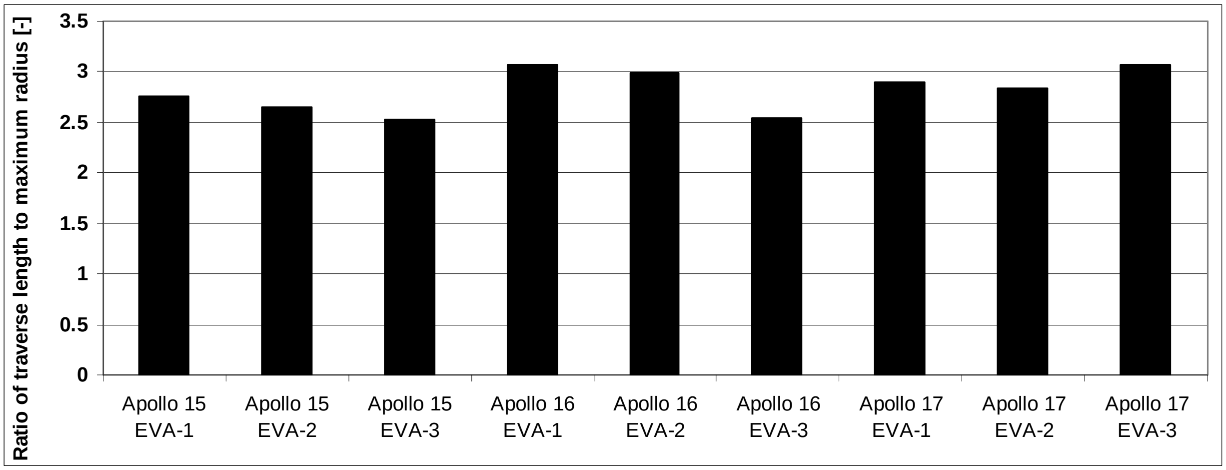


Figure 12: Ratio of traverse length (as measured by LRV odometer) over maximum traverse radius for the Apollo 15, 16, and 17 LRV traverses[8-9]

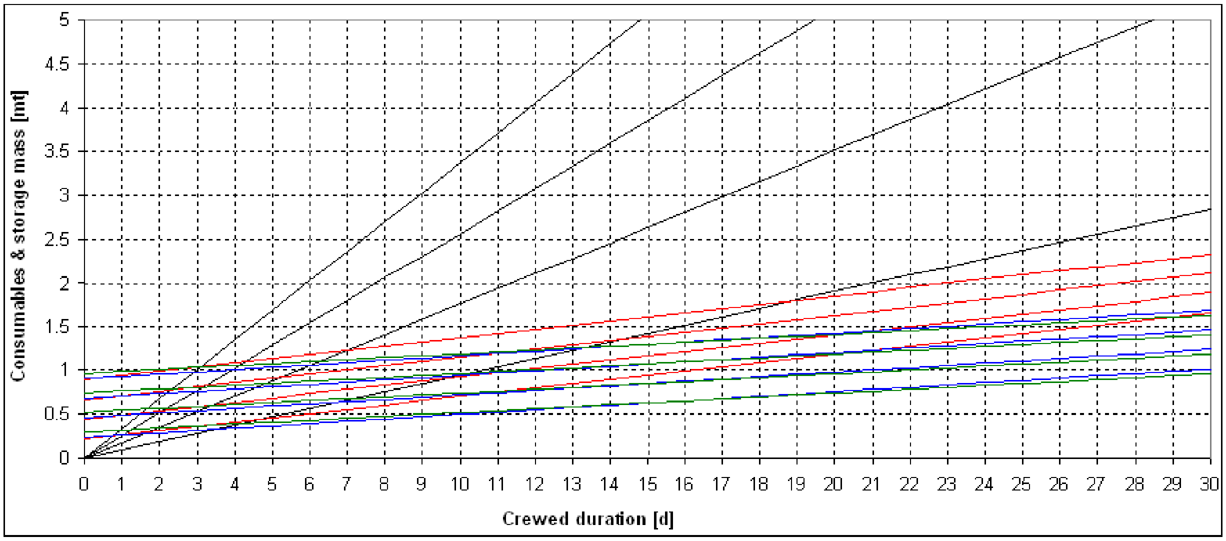


Figure 13: Mass requirements for extended polar LSAM stays of 2 crewmembers. Black lines represent baseline configuration (fuel cells, LiOH, no regeneration), red lines represent baseline configuration plus solar panels, blue lines represent red configuration plus wash water regeneration, green lines represent blue configuration plus regenerative CO2 removal. Contours represent different power levels, highest 20 kW, lowest 5 kW.

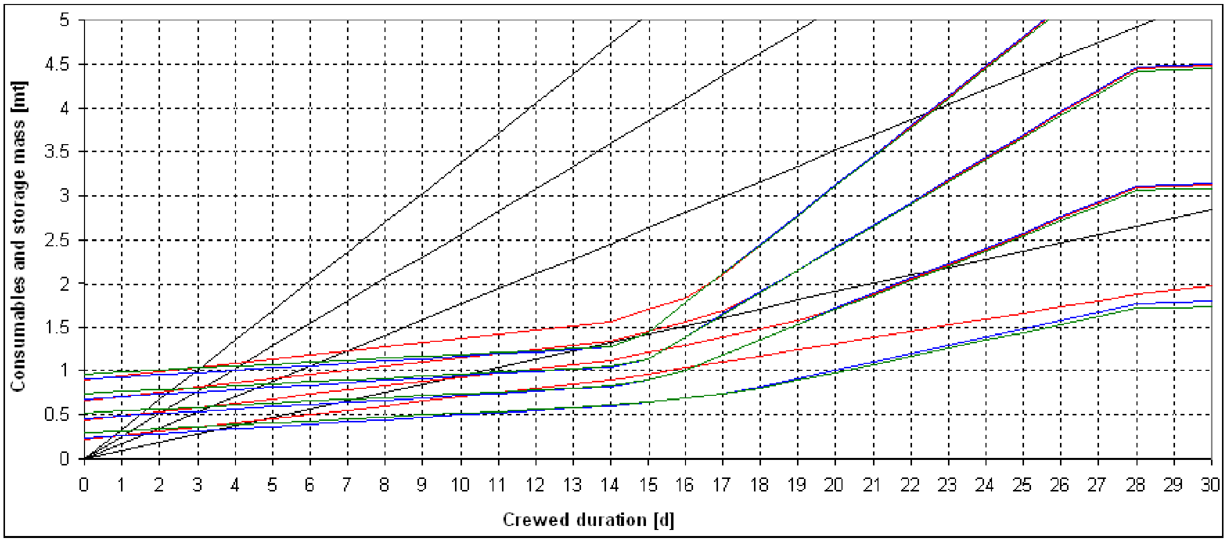


Figure 14: Mass requirements for extended polar LSAM stays of 2 crewmembers. Black lines represent baseline configuration (fuel cells, LiOH, no regeneration), red lines represent baseline configuration plus solar panels, blue lines represent red configuration plus wash water regeneration, green lines represent blue configuration plus regenerative CO2 removal. Contours represent different power levels, highest 20 kW, lowest 5 kW.

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