

The Mars-back Approach to Moon-Mars Exploration System Commonality

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ABSTRACT

The Mars-back approach entails the development of a common system for the exploration of Moon and Mars by first looking at the requirements placed upon the system by the Mars exploration case and then projecting the system capabilities back to the Moon. By developing a common system for the exploration of both destinations, overall development cost is decreased and any gap between Moon and Mars is either eliminated or significantly reduced. As elements needed for lunar exploration are a subset of those utilized in Mars exploration, lunar exploration directly demonstrates and validates the elements prior to Mars exploration and lunar exploration can continue during the exploration of Mars. Through directly linking lunar exploration to the exploration of Mars, Mars exploration can be significantly accelerated and greater public support can be maintained in order to sustain the Vision for Space Exploration. In designing elements for a common Moon-Mars exploration system, our analysis indicates that through proper upfront systems engineering and appropriate use of platforming and modularity, the performance overheads associated with each particular use case can be kept low while the affordability of the overall system can be significantly improved.

1.0 Introduction

This paper provides a high-level overview of the Mars-back approach to developing common Moon-Mars exploration systems. The work presented in this paper was developed as part of a NASA Concept Exploration and Refinement (CE&R) study conducted by MIT and Draper Laboratory. Further detail regarding the work presented herein is available in the referenced papers.

1.1 Motivation for a Common Moon-Mars Exploration System

The Mars-back approach is a method for the development of Moon and Mars exploration systems, wherein the requirements for Mars missions are first analyzed, and then the capabilities resulting from such missions are projected back to see how they could be used to also enable lunar exploration. As such, the Mars-back approach aims to develop a common exploration system for exploring both the Moon and Mars, wherein the lunar exploration systems are a sub-set of those required for Mars missions.

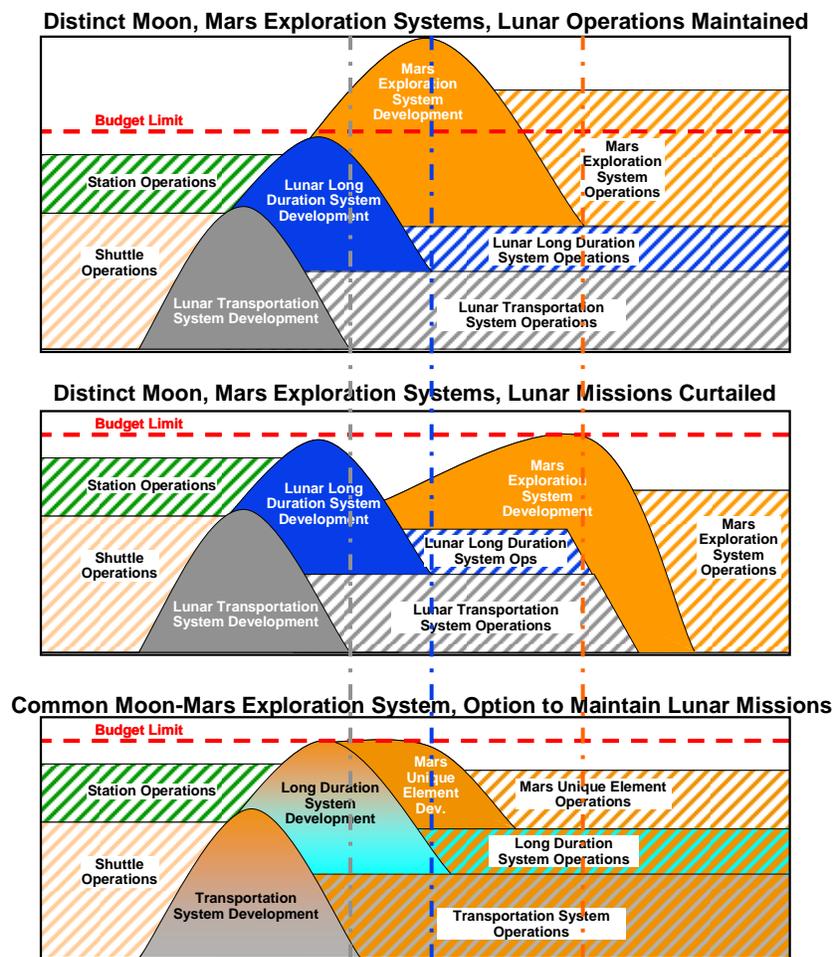


Figure 1. Notional funding profiles for Moon and Mars exploration system development and operation. Initial operating capabilities of the first approach are shown with vertical lines for comparing across approaches.

A major motivator for the development of a common Moon-Mars exploration lies in the cost and schedule profiles that are required to develop and test a new human exploration system. Figure 1 shows

notional funding profiles for a series of development approaches for human Moon and Mars exploration. When Moon and Mars exploration systems are developed independently, it is extremely difficult if not impossible to adequately fund the development of the Mars exploration system once lunar exploration is underway. While it may be feasible to eventually curtail lunar operations in order to open a funding wedge for Mars exploration system development, doing so entails both a significant delay in initial Mars mission capability and the need for a potentially unsustainable cutback in lunar operations. Just as difficulties are currently being encountered in efforts to curtail space shuttle and space shuttle operations to enable lunar exploration, similar confrontations could arise in cutting lunar operations to enable Mars exploration. By contrast, with the third approach shown, the development of a common Moon-Mars exploration system allows the lunar systems to be directly applicable to the exploration of Mars, thus obviating the need for their curtailment for Mars operations and greatly decreasing the development necessary for Mars missions to take place. While building Mars capabilities into the lunar exploration systems may slightly increase their cost and possibly delay their implementation, our analysis indicates that through proper up-front systems engineering, these impacts on the lunar system can be quite modest and will be offset by the overall benefit derived from the Mars-back approach. By using this approach Mars exploration can be significantly accelerated.^{1,2}

Beyond the significant cost and schedule benefits associated with developing a common Moon-Mars exploration system, a number of other benefits exist. From an operational perspective, the use of a subset of Mars exploration hardware in lunar exploration will allow that hardware to be directly validated and additional operational experience with it gained, prior to committing to significantly longer duration Mars missions. While testing of technologies and sub-systems on the Moon can have some benefits towards Mars exploration, the use of the same systems will have an increased impact in terms of decreasing risk for Mars missions. Looking at production, the continuity of the workforce across Moon and Mars exploration programs will not only have political benefits but will also allow all of the learning curves benefits from the production of lunar systems to be carried forward to Mars exploration. This will thus further reduce the overall life cycle cost of Moon and Mars exploration. In addition, because the lunar production lines will remain in operation during Mars exploration, the option exists to conduct lunar exploration in parallel with Mars exploration. Lunar scientific, exploration, and economic objectives can thus be achieved even while Mars missions are underway. The likelihood that such would be the case if distinct systems were produced is remote. Finally, in the eyes of the public and Congress, directly tying lunar exploration to Mars exploration is crucial. While it is easy to discount public opinion in technical matters, it is of the utmost importance that this consideration be included.³ Mars is a world that captivates the imagination and offers answers to questions unanswerable on the Moon. The development of a system which can not only explore the Moon but leads directly to Mars will allow NASA to draw upon the excitement surrounding the novel aspects of exploring Mars.

While options exist for partial commonality between Moon and Mars exploration, such as the use of the same launch vehicle or sub-systems of particular elements, our analysis indicates that commonality of propulsion stages, habitats, and other major exploration elements is quite feasible.⁴ Maximizing the degree of commonality, such that lunar systems are almost entirely applicable towards Mars exploration provides the most overall benefit. The remainder of this paper describes the architecture selection and common system design that arose while applying the Mars-back approach as part of the MIT-Draper CE&R study.

2.0 MIT-Draper Concept Exploration and Refinement Study Overview

The MIT-Draper CE&R study was performed in two phases over a 12-month period between September, 2004 and August, 2005. The purpose of the study was to perform a comprehensive analysis of Moon and Mars exploration options to inform NASA's efforts to enable the sustainable exploration of space. The

study explored the breadth and depth of exploring space considering everything from stakeholder analysis and value delivery to surface exploration, space transportation, and information architectures. The Mars-back approach was a defining element of our overall investigation and was incorporated in all of these areas. The focus of this paper is on the transportation architecture aspects of the CE&R study, although the analysis was informed by and integrated into the overall framework developed throughout the study.

2.1. Moon-Mars Transportation Architecture Evaluation using Object-Process Network

In order to provide a comprehensive analysis of potential transportation architectures for the exploration of the Moon and Mars, an architecture generator based upon the Object-Process Network metalanguage was developed.⁵ Using this generator, 1,162 potential operational sequences were enumerated for missions to either the Moon or Mars. The architectures thus generated were evaluated across a series of technology options using an integration tool that combined the operational sequences with vehicle and sub-system models. Figure 2 shows the Initial Mass in Low-Earth Orbit (IMLEO) sorted from lowest to highest for each of the Moon and Mars architectures, as an example of the types of output available from the tool. As the quantity of mass launched is a driver for the cost of the architecture, IMLEO was used as an initial screening metric to narrow the architectures under investigation.

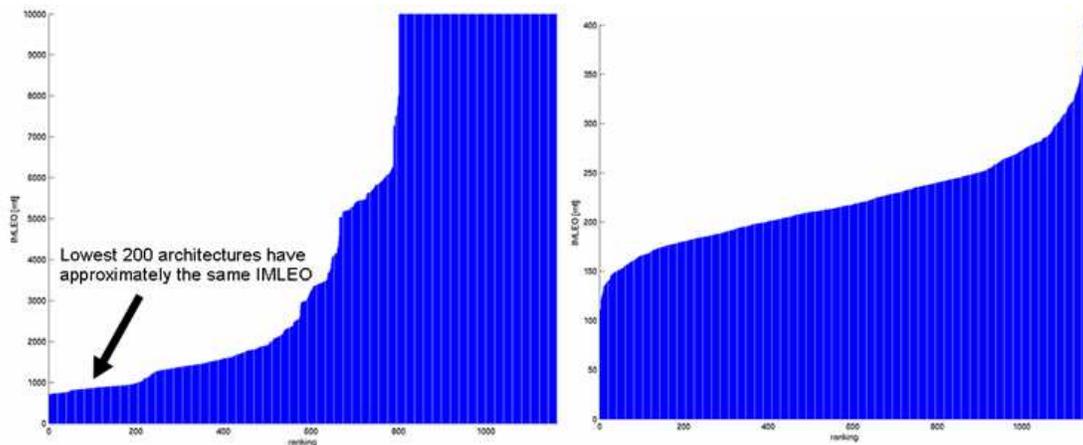


Figure 2. Ranked Initial Mass in LEO (IMLEO) results for 1162 Mars architectures (left), and lunar architectures (right). x-axis: architectures; y-axis: IMLEO; analysis for chemical propulsion, conjunction class Mars mission and short-stay lunar mission (7-day surface stay).

Using this tool, we were able to rapidly evaluate large areas of the Moon and Mars transportation architecture space and determine the benefit to be derived from advanced technologies such as In-Situ Propellant Production, Nuclear and Solar Electric Propulsion, and Nuclear Thermal Propulsion. Based upon this analysis, a small number of architecture options were selected for further analysis using a variety of metrics and screening criteria.⁶

2.2. Moon and Mars Architecture Selection

In order to develop the common Moon-Mars exploration system design presented in this paper, a single Moon transportation architecture and a single Mars transportation architecture were selected. It should be noted that the commonality focus is on the elements that make up the architectures rather than the architectures themselves. As such, distinct Moon and Mars operational architectures are employed, rather

than employing commonality in the operational architecture itself. While some experience may be gained from employing the same operational sequence in both cases, we found focusing on the reuse of element designs and heritage to be more beneficial. In addition, while two architectures are presented here for commonality, the general approach to utilizing common elements across Moon and Mars exploration can be extended beyond the individual pairing presented.

The selected Mars transportation architecture is a Mars-orbit rendezvous architecture similar to that chosen in the NASA Mars Reference Mission studies of the 1990s.^{7, 8} The architecture is depicted in Figure 3. In this architecture a Mars Ascent Vehicle (MAV) and an Earth Return Vehicle (ERV) are prepositioned to Mars one opportunity before crew arrival. The crew travels to Mars, lands, and operates on the surface in the Transfer and Surface Habitat (TSH). At the conclusion of the surface mission, the crew employs the MAV to reach Mars orbit and rendezvous with the ERV, which returns them to Earth. Two Crew Exploration Vehicles (CEV) are used – one as the ascent cabin of the MAV, which also serves as the Earth entry vehicle on return to Earth; the other for crew launch at Earth and contingency crew return in case of Mars propulsive swing-by abort. In our analysis, this architecture was found to offer a good balance between cost, operational risk, and development risk.

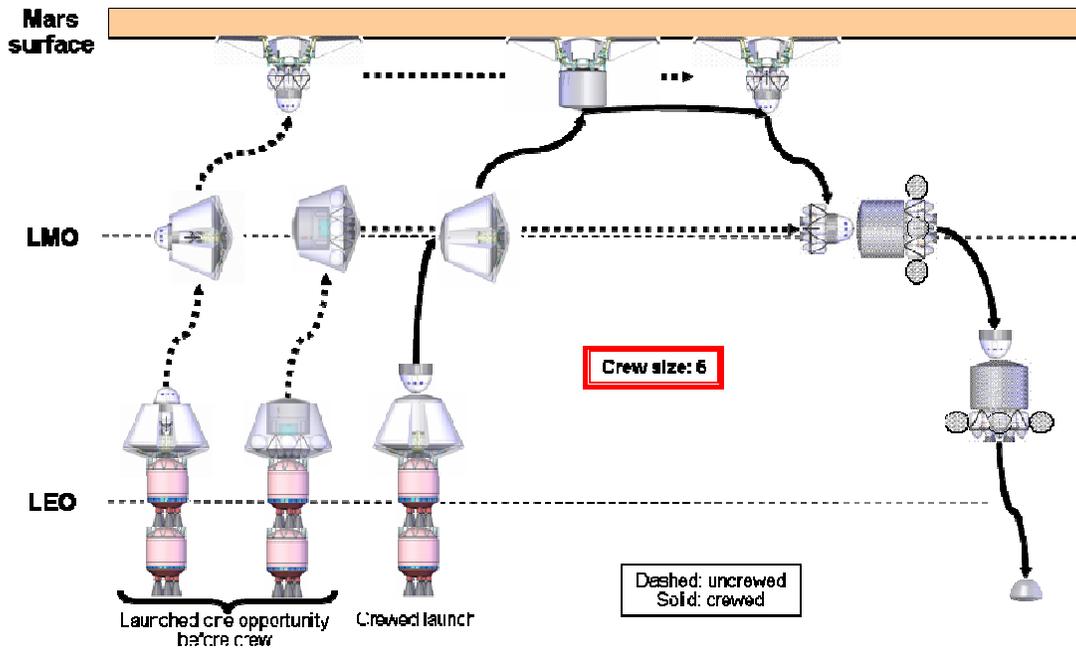


Figure 3. Selected human Mars exploration transportation architecture.

For the lunar transportation architecture, a direct return architecture was chosen in which the CEV travels to the lunar surface and then returns directly to Earth without rendezvous in lunar orbit. This architecture would thus be operationally similar to that proposed as part of the NASA First Lunar Outpost study.⁹ While lunar direct return architectures are typically considered to be considerably more massive than lunar orbit rendezvous architectures, our analysis indicates that with present-day propulsion technology, and global-lunar access and anytime return requirements, this is not the case.¹⁰

Figure 4 shows the mass of three architectures across a series of technology and operational options to illustrate this. The architecture in red, Arch 67 (the Object-Process Network architecture index), is a standard Lunar Orbit Rendezvous architecture similar to that employed during the Apollo program; in this architecture, a CEV carries the crew to lunar orbit, and a separate Lunar Surface Access Module (LSAM) carries the crew to and from the surface. The architecture in blue, Arch 1, is a Lunar Direct Return architecture; in this architecture, the CEV carries the crew to and from the surface, without any

rendezvous during the return. The architecture in gray, Arch 12, is effectively a hybrid of the other two, with the CEV transporting the crew to and from the surface, but rendezvousing with a propulsion stage in lunar orbit in order to propel itself to Earth. With modern methane-oxygen and/or hydrogen-oxygen propulsion for descent and ascent, it becomes clear that mass is no longer a major discriminator between these architectures.

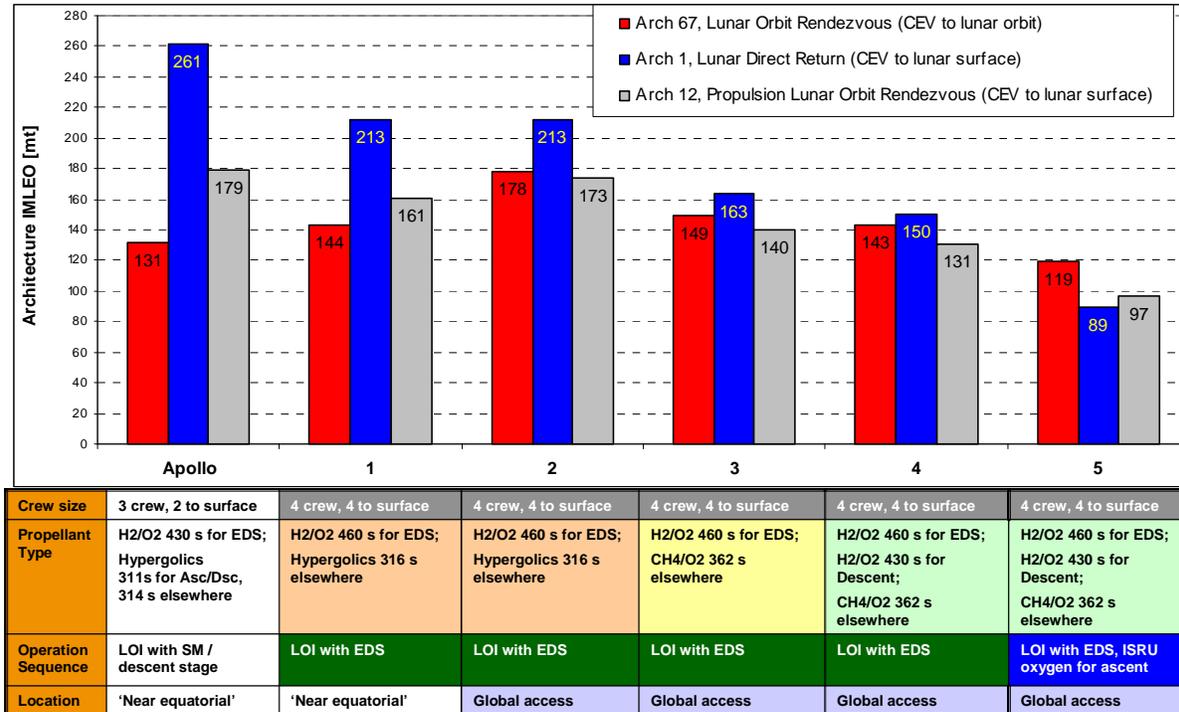


Figure 4. Initial Mass in Low Earth Orbit of standard Lunar Orbit Rendezvous, Lunar Direct Return, and Propulsion Lunar Orbit Rendezvous across a series of operational and technology options.

With mass no longer distinguishing the architectures, we examined a series of other options including launch considerations, crew safety and mission risk, and development and operational cost in order to select a lunar architecture for the commonality analysis. We found the direct return architecture fared best overall and as such selected it for the common-system design presented herein.¹⁰ Initial analysis outside of the scope of this paper has also determined that a number of similar commonality options exist for the Lunar Orbit Rendezvous architecture.

Figure 5 shows the operational sequence for the selected lunar exploration transportation architecture both for crew transport and for the delivery of large cargo elements such as habitats and smaller cargo elements such as surface logistics or other smaller assets to the lunar surface.

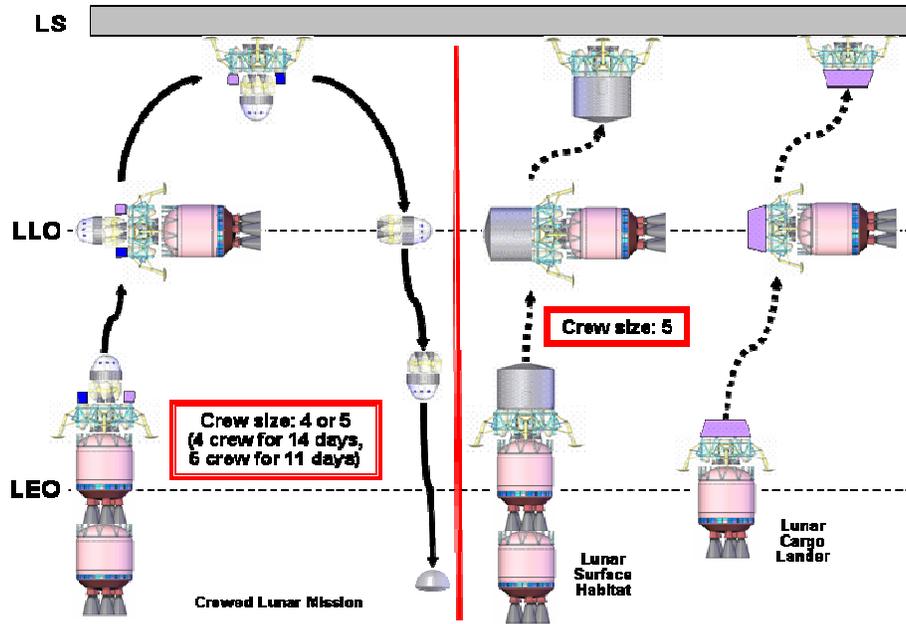


Figure 5. Selected human Moon exploration transportation architecture and associated cargo delivery options.

3.0 Common Moon-Mars Exploration System Design

Once a pair of Moon and Mars architectures has been selected, options for high-level commonality between them can be investigated. The selected high-level commonality design is evident in the architecture figures presented above (Figure 3 and Figure 5). The propulsion stages presented in red represent common hydrogen-oxygen Earth departure stages. Similarly the habitats and CEVs across both architectures are each of the same design, with varying consumables loads in the cases of the habitats, and an additional inflatable surface “tent” in the Mars Transfer and Surface Habitat case. The Mars aeroentry system used for Mars aerocapture, entry, and descent represents a Mars unique element. It is useful to note that in the design of the common exploration system, we included not only commonality between Moon and Mars transportation architectures but also within each of the Moon and Mars architectures.¹ For example, within the Mars architecture, the same core habitat design is used both for crew transfer to and operation on the surface as for Earth return.

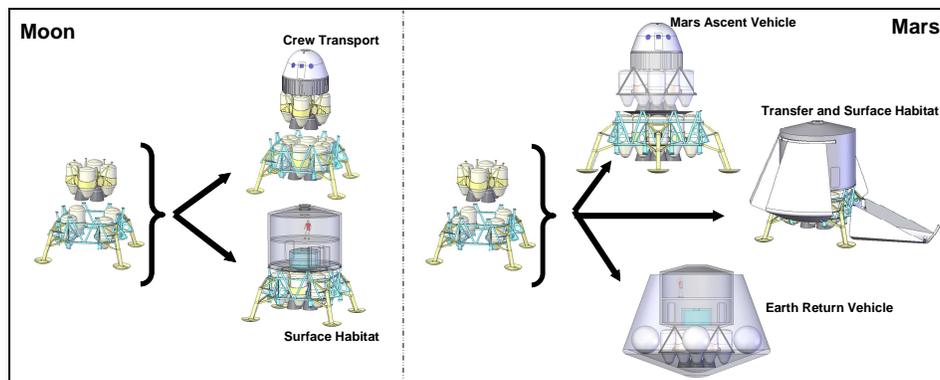


Figure 6. Modular methane-oxygen Surface Access Module configurations.

A common methane-oxygen propulsion system was selected to perform all of the planetary landing, ascent, and Earth return maneuvers. Due to the wide variety of requirements placed upon this system, a modular approach was selected for this element. Figure 6 shows the various configurations of this modular system. The system includes a common propulsion core which is used across all use cases. This core is sized such that it can perform lunar ascent and Earth return of the CEV for lunar crew transportation cases. A core augmented by a duplicate set of tanks, additional structure, and landing gear serves as the lunar descent stage for both crew transport and the emplacement of other elements such as a surface habitat. Using a larger gauge landing gear, the core augmented with a duplicate set of tanks is also used to land large elements on the surface of Mars. For the Mars Ascent Vehicle use case, after being landed by a core with a duplicate set of tanks, a second core and duplicate set of tanks is used for Mars ascent of the CEV. Once the CEV docks with the Earth Return Vehicle, a core propulsion stage augmented with an “extra-large” set of tanks is used to perform trans-Earth injection from Mars orbit. By using a modular, platformed approach for this element the objectives of commonality can be achieved without unduly hindering the performance of the system across multiple use cases.²

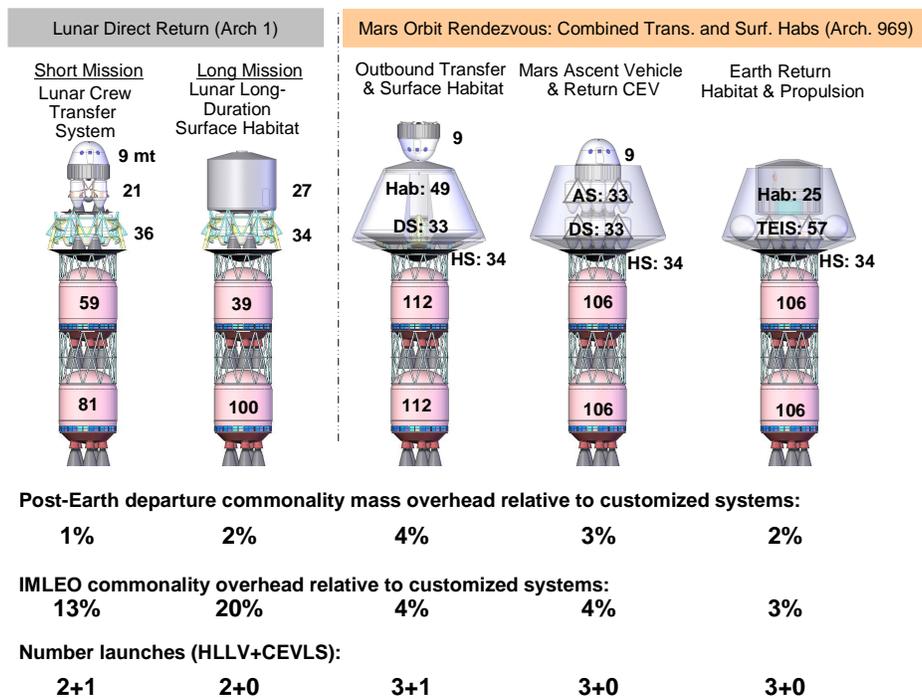


Figure 7. Full system configurations for Moon and Mars missions with associated commonality overhead and launch solution. The numbers by each of the common elements represents the mass of that element in metric tonnes.

Figure 7 shows an integrated view of the resulting vehicle stacks as they would be configured post- rendezvous and docking in low Earth orbit. The number of launches assumes a 30 mt capacity CEV Launch System (CEVLS), a 100 mt Heavy-Lift Launch Vehicle (HLLV) for lunar missions, and a 125 mt HLLV for Mars missions. It can be seen that the mass overhead of the common system relative to a point designed system for each case is small when compared post-Earth departure. The higher overhead pre-Earth departure in the lunar cases is due to the Earth departure stage being only partially filled in these cases. While this results in a larger total mass launched, it was determined that for the given launch vehicle size (100 mt), the number of launches was not impacted.¹ The overheads presented in the above chart are offset by a 63% decrease in dry mass of unique elements required for the common system

relative to the point designed system. Dry mass is frequently used as a surrogate for development cost, as such this, combined with a related reduction in the number of unique elements, is representative of massive savings in development cost. This savings will also carry forward into production, as fewer production lines will be required.

Figure 8 shows the overall system development roadmap that this approach would thus entail. It can be seen that while the elements required for short lunar and ISS missions are similar to those required by any direct return architecture, there is a significant reduction in the number of elements required to enable long duration lunar missions and Mars missions. In particular, the ability to achieve Mars missions with upgrades to the HLLV and landing gear, and the introduction of Mars aeroentry systems is very attractive, and represents a significant decrease relative to traditional development approaches.

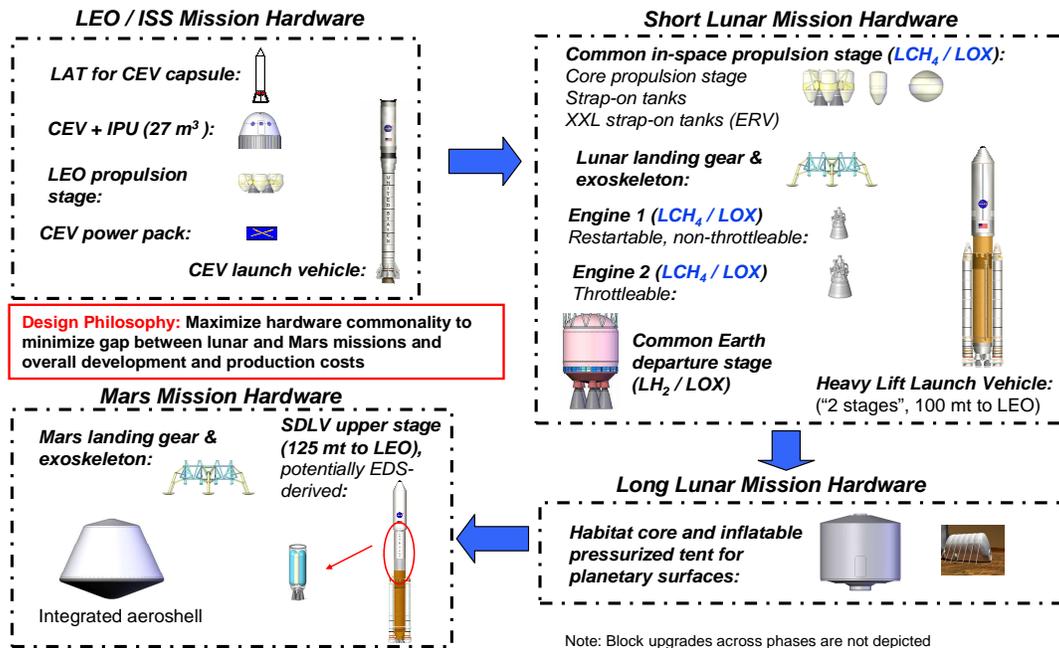


Figure 8. Integrated transportation system development roadmap to achieve ISS, lunar, and Mars mission objectives.

4.0 Summary

The development of a common Moon-Mars exploration system appears to be quite feasible. While resulting in a modest overhead for the upfront development of a lunar exploration capability, this approach enables significant benefits including greatly decreasing the overall life cycle cost, substantially accelerating the onset of Mars exploration, eliminating the need to curtail lunar operations to enable Mars missions, and directly validating and gaining operational experience with a sub-set of the hardware required for Mars exploration. In addition, by directly tying the lunar exploration system to the exploration of Mars, additional support from the public and Congress can be gained.

While presented in this paper for a single set of Moon and Mars exploration architectures, the same approach can be applied in the context of other architecture pairings. We recommend the development of common Moon-Mars exploration systems be pursued in the execution of the Vision for Space Exploration.

5.0 References

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