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THE MARS-BACK APPROACH: AFFORDABLE AND SUSTAINABLE EXPLORATION OF THE MOON, MARS, AND BEYOND USING COMMON SYSTEMS

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ABSTRACT

The Mars-back approach involves the development of a common system for the exploration of the Moon and Mars by first investigating the requirements for missions to Mars and then projecting the ensuing capabilities back to lunar missions. This enables both Mars and Moon mission objectives to be more rapidly and cost effectively met than through designing unique systems for each objective. As element designs are the same for both Moon and Mars missions, the early Moon missions enable direct testing of Mars exploration systems in an environment close to Earth, prior to committing to a long-duration mission to more distant Mars. Finally, as production lines for the Moon and Mars hardware are the same, there is neither an incentive nor a need to stand-down Moon operations prior to and during Mars missions. This can help keep policy-makers and the public interested in the program and therefore help reduce the risk of program cancellation. In this paper we describe the methods by which the Mars-back approach is applied to the design of common Moon-Mars human exploration transportation system designs.

Motivation for the Mars-Back Approach

Mars exploration is the ultimate objective of human space exploration for the foreseeable future. Lunar exploration is intended to build up the capabilities and allow us to prepare for the exploration of Mars[1]. As such, the Mars-back approach states that the design of lunar exploration systems should directly enable Mars exploration to the fullest possible extent. Through the use of a common system design taking into account the requirements of both lunar and Martian exploration, this objective can be achieved. Moreover, we feel that such an approach is essential to ensure the sustainability of the Vision for Space Exploration.

As shown in Fig. 1, multiple approaches to the development of the systems for the exploration of the Moon and Mars exist[2]. In the first approach shown, sequential development of independent lunar and Mars exploration systems is undertaken, with lunar exploration capabilities maintained during the build-up and operation of the Mars system. While, in principle, this approach could accomplish the exploration mission objectives, it is unlikely that the development and operation of Mars system would be affordable with lunar operations underway.

In the second approach, the affordability of the vision is maintained by curtailing lunar operations in order to enable the build-up for Mars. While this does meet budget constraints, Mars missions are significantly delayed in the process. In addition, the need to curtail lunar operations and suffer a gap in exploration missions may be fatal for the sustainability of the overall Vision for Space Exploration. Just as we are currently faced with political and institutional difficulties in retiring the space shuttle, we will likely encounter difficulties in curtailing lunar missions, particularly if done after only a small number of missions, given the large investment required to conduct those missions in the first place. In addition, this approach would abandon the capability for lunar exploration, ruling out future missions which may be of interest to the scientific and space exploration communities.

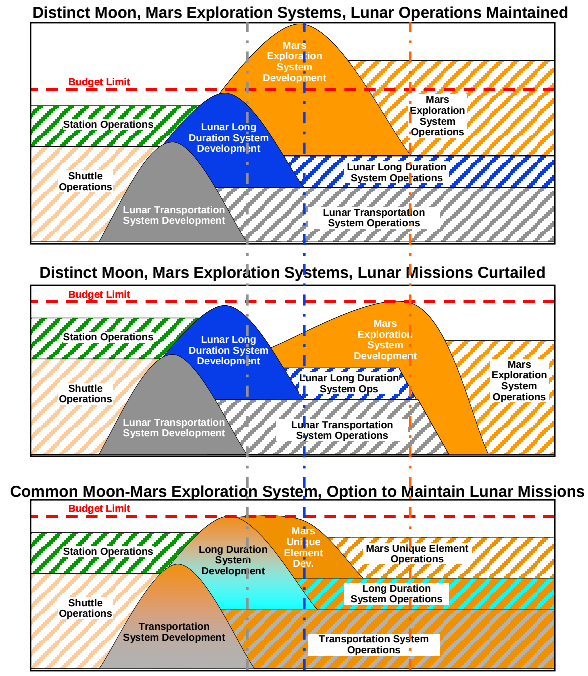

Fig. 1: Notional funding profiles for Moon and Mars exploration system development and operation. Initial operating capabilities of the first approach are shown with vertical lines for comparing across approaches.

In contrast, the Mars-back approach of developing common systems for the Moon and Mars is highlighted in the final funding profile. In this case, the development of systems for lunar exploration is not focused exclusively on the lunar missions but also takes into account the requirements necessary to support Mars missions in the future. By using common systems for the exploration of the Moon and Mars, the development required to commence Mars missions will be greatly decreased. The development of the Mars-specific elements can thus be quickly completed. Mars missions will be significantly accelerated and can commence without the need to curtail lunar operations.

In addition, by using the Mars-back approach, a significant sub-set of the Mars elements will be directly validated during lunar operations. By itself, this will significantly decrease risk and improve crew safety for missions to Mars. Unlike lunar missions, where anytime return to Earth is possible, the elements making up a Mars missions must work reliably for a considerable period of time without the option of an early return. Retiring the risk of equipment failure during the lunar campaign will thus provide a much higher confidence in our ability to mount a successful Mars campaign. This approach also will allow the exploration of the Moon to be directly linked to the exploration of Mars in the eyes of the public and Congress, thus enhancing the support for lunar missions.

Acquiring Common Systems

It is important that appropriate attention be given to the development of requirements for common exploration systems. The traditional approach to space system development includes the creation of high-level mission requirements outlining what the system is to achieve, the development of a system architecture to meet the mission requirements, and then the flow down of requirements to each of the elements that make up the system. Each element is then developed based upon the requirements specific to the single scenario in which it operates in the architecture. The scenario in which an element operates is termed a "use case" in common system development. While in traditional system development one element is typically limited to a single use case, in common system development one element will typically have several distinct use cases. For example, a common descent system could be used for a series of use cases involving landing a variety of cargoes on both the Moon and Mars. The use cases for a common element can also extend beyond direct operational similarity to include operations for which the system design is similar, such as the case of including commonality between ascent, descent, and Earth return propulsion systems.

Fig. 2 shows a decomposition of a common Moon-Mars exploration system to support a series of use cases. This system decomposition differs significantly from the traditional method of decomposing the system along the lines of particular use cases, such as the Crew Transportation System or Cargo Delivery System. Instead, the figure shows the relationships which arise between the elements of the overall common system in supporting the required use cases. The arrows represent the flow of mass and volume requirements from one element to the next. In the design of a common exploration system feedback loops are included, although these are not shown in the diagram.

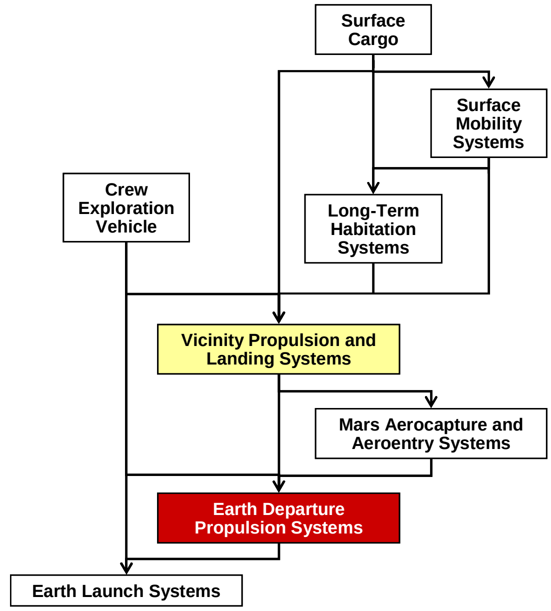

Fig. 2: Common exploration system decomposition and system dependencies (feedback-loops not shown).

In developing a common system design, operational architectures for the exploration of the Moon and Mars must be chosen. It is important to note that the use of commonality in the system design does not necessitate the use of the same operational architecture for both missions. Instead, the focus is on using the same elements to achieve distinct missions with different operational architectures. The operational architectures used in the discussion of this paper are derived from the work of the Draper/MIT Concept Exploration and Refinement (CE&R) team in investigating options for human lunar and Mars exploration. They were derived based upon a comprehensive analysis of thousands of operational architectures and technology options, using an Object-Process Network based architectural meta-language[3].

The following figures both describe the operational sequence for the two architectures and visualize the high level of commonality possible between them. Fig. 3 shows the operational architecture for Mars exploration; it is a Mars orbit rendezvous architecture similar to that employed in the NASA Mars Design Reference missions of the 1990s[4,5,6]. Fig. 4 shows the lunar mission architecture; it is a direct return architecture similar to that chosen in the NASA First Lunar Outpost study[7]. Our analysis indicates that this architecture offers a good balance of cost, risk, and safety for lunar missions[8].

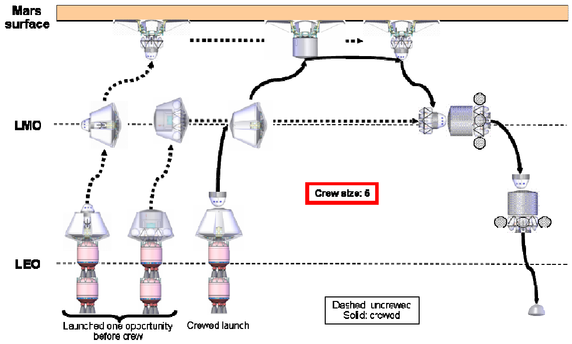

Fig. 3: Human Mars exploration architecture. Mars Ascent Vehicle (MAV) and Earth Return Vehicle (ERV) are prepositioned to Mars one opportunity before crew arrival. Crew travels to Mars, lands, and operates on surface in Transfer and Surface Habitat (TSH). At the conclusion of the surface mission, the 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.

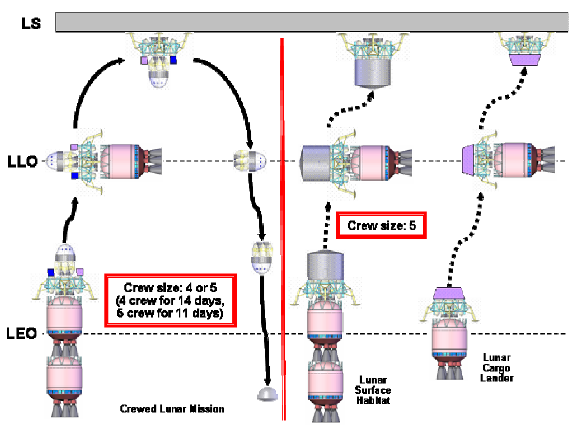

Fig. 4: Human lunar exploration architecture. Lunar crew transportation is performed using a direct return architecture in which the CEV proceeds all the way to the lunar surface and is used by the crew to return directly to Earth (without lunar orbit rendezvous.) The crew transportation elements can also be used to emplace lunar surface habitats and large cargo manifests, enabling long duration lunar missions.

Note that while the specific pair of architectures shown above is used as an example in this paper, the general concepts presented herein can be used across other operational architectures in order to enable the sustainable exploration of the Moon and Mars.

Propulsion Stage Commonality[9]

In developing a design for a common system, it is important to consider the driving or characteristic requirements placed upon the system due to the series of use cases it must support. In the case of a propulsion stage, these characteristic requirements include delta-v, payload, and thrust. Due to the interrelations of these requirements, it is necessary to consider all three of them simultaneously: two use cases with identical delta-v requirements but different payloads would drive a propulsion stage differently, whereas two use cases with high and low delta-v's and low and high payloads, respectively, could result in very similar propulsion stage designs.

In order to meet the requirements placed upon propulsion stages, a number of approaches can be taken[10]. These include:

1. A single propulsion stage design for all use cases. Variable quantities of propellant can be loaded into the stage depending upon the needs of a particular use case.

2. A platform approach in which optional elements of the propulsion system can be included to meet the needs of a given use case.

3. A "stretchable" design, in which the volume of the propulsion tanks can be changed by adding additional segments. The remainder of the stage would either be identical across use cases, or could make use of the platforming approach described above.

4. Unique designs for each of the use cases or for particular sets of use cases. This would not provide complete commonality, but should be considered in the design of these systems and traded on the base of life-cycle cost and risk.

The first approach, namely a single design with variable propellant filling, was selected for the Rocket for Earth Departure (RED) stage which meets the requirements of the Earth Departure System in Fig. 2. Given that the requirements were quite similar for each use case, this appeared to be a reasonable approach. While the fourth approach of using variable sized tanks could have resulted in a reduced mass in Low Earth Orbit (LEO) for the Earth Departure System, it was believed that the savings from only needing to development and manufacture a single design would offset the added launch cost.

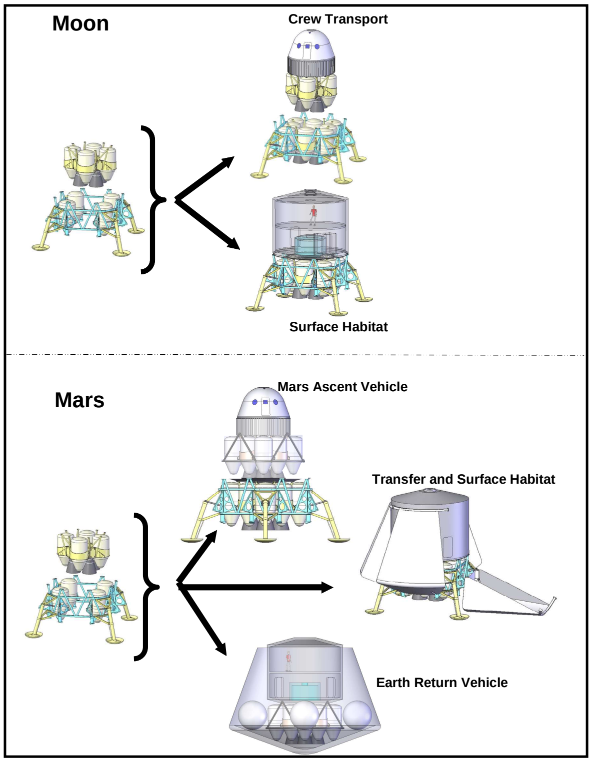

Fig. 5: Modular methane-oxygen Surface Access Module configurations for the multiple vicinity propulsion and landing system use cases.

In the case of meeting the requirements of the Vicinity Propulsion and Landing System, the modular Surface Access Module (SAM) design covers the required use cases. These use cases have more varied requirements than those for Earth departure. As such, the second approach of using a modular, platform design was chosen to better meet the requirements of the individual use cases without unduly burdening the overall system. Fig. 5 shows the way the modular elements of the SAM fit together to accomplish a variety of use cases. The core propulsion stage is sized by lunar ascent and Trans-Earth Injection (TEI) of the CEV, and is employed in all configurations. To become a descent stage, an additional set of tanks duplicating the core's propellant volume, additional structure, and a set of landing gear are added to the core. While the configuration is similar for both Moon and Mars, the Mars landing gear and structure is able to carry additional load (and is thus heavier) than the lunar landing gear and structure. In order to provide the Mars ascent propulsive functionality, the core is augmented by an additional set of tanks as in the descent case, although without the associated landing gear. For TEI of the Earth Return Vehicle (ERV) from Mars, an additional set of extended strap-on tanks are included. In this manner, the common system design can perform each of the use cases required of it.

Crew Exploration Vehicle Commonality[9]

In developing a common design for the CEV, a number of driving requirements across the series of supported use cases must be considered. In our CE&R analysis, six use cases were analyzed for the CEV, with requirements defined for each. In designing the CEV, a number of methods were then used to accommodate the requirements. In some cases, such as pressurized volume, the CEV was developed so as to envelope all of the requirements in a single design. In other cases, such as providing thermal control in different environments or providing power for different durations, a modular approach was employed in which a use case specific system could be added to the CEV.

Fig. 6 shows the high-level design of the CEV with an Earth entry capsule which holds the crew (similar to the Apollo CM) and an integrated power unit that contains elements of the power, thermal control, and life support subsystems which support the entry capsule (i.e., similar to the Apollo Service Module but without propulsive functionality).

Fig. 6: Crew Exploration Vehicle (CEV) design with Entry Capsule and Integrated Power Unit modules.

In general, given the highly integrated nature of the CEV entry capsule and the high performance demands associated with hypersonic reentry, we included an additional goal of keeping the capsule itself as constant as possible across use cases. As the design of the integrated power unit was less constrained, it could be modified more easily than the capsule. An extension power pack was also included to augment the powered duration capability of the CEV. This allowed the additional mass of the extension power pack to be jettisoned prior to performing lunar ascent & TEI. In considering the rapid development of the CEV, a LEO-only CEV heatshield for early ISS missions was included. This would later be upgraded using a different material to enable hyperbolic reentry for return from the Moon and Mars. This is an example of introducing modularity to improve the development schedule of a system, as opposed to optimizing its performance or total cost.

One decision that was specifically made to improve the commonality of the CEV was to not include any major translational propulsive functionality. As the propulsive functionality required varies by use case, keeping this functionality external to the CEV prevents the system from being saddled with a sub-optimal propulsive system overall. This approach differs from the traditional approach of optimizing for a single use case, in which a propulsion stage integrated with the CEV would likely be chosen, perhaps to perform TEI from lunar orbit. Beyond providing flexibility across use cases, this approach also decreases the up-front development cost of the CEV and provides flexibility across architectures – allowing final architecture selection to be conducted after CEV development is initiated without unduly impacting the CEV[8].

Habitat Commonality[9]

The characteristic requirements for a habitation system include the supported crew size and activities, mission duration, and operational environments. Geometrical aspects such as packing into aeroshells in the Mars use cases and providing access to the surface for surface habitats are also important in the design of the system. The use cases our habitats must support include providing long-term crew support and laboratory facilities on the lunar surface (Lunar Surface Habitat), providing habitation during the outbound transfer to Mars and crew support and laboratory facilities on the surface of Mars (Transfer and Surface Habitat), and providing crew habitation during the return from Mars orbit to Earth (Earth Return Vehicle.)

In designing a common system to support these use cases, potential approaches include providing modularity in the habitat sub-systems to support varying crew sizes or mission duration and varying the volume of the habitat through either “stretching” the habitat with additional “plugs” positioned between “end-caps” or by adding additional modular elements to the exterior of the habitat. The approach of using modular sub-systems could also be used to enable commonality between the sub-systems of the CEV, long-duration habitats, and pressurized rovers, although this was not investigated during the course of our study. The use of common sub-systems could also be employed if the design of the habitats themselves were different across use cases, although we decided against this approach.

Originally, the concept we utilized for varying the habitat volume configuration for differing crew activities and mission durations was by designing the habitat to be made up of a set of modular plugs, effectively equivalent to floors of the habitat, which could be connected in series and terminated on both ends by end-caps. This approach is similar to the method by which airliners are fabricated with differing lengths and would have been integrated on the ground in a similar fashion to minimize any interface overhead from the approach. While this served well the needs of varying pressurized volume, when we began to investigate vehicle packaging in further detail, we found it was difficult to maintain this configuration within the constraints we had placed upon the vehicle design. As an alternative, we settled on a configuration in which a core habitat was used across all use cases. This core habitat was augmented by an inflatable surface tent which would be stowed while the packaging dimensions were constrained (Earth launch, Mars entry), and then deployed once the habitat was emplaced on the surface. This would thus increase the pressurized volume when it was needed – during the surface operations phase – without unduly impacting the configuration during other phases. The additional inflatable module would be included at minimum in the Mars Transfer and Surface Habitat, and could potentially be added to the Lunar Surface Habitat to increase the Mars analog fidelity, although it would not be strictly necessary given the shorter mission duration. The inflatable module would not be included in the Mars Earth Return Vehicle, as the core habitat provides sufficient volume for in-space use.

Enabling Alternate Missions

We developed the systems described in this paper for the specific purposes of enabling LEO/ISS mission, short and long duration lunar missions, and Mars missions. However, the approaches used to investigate capabilities of the systems described above can also be used in determining the inherent capability of these systems to perform missions other than those for which they were initially intended.

The analysis of a system's capability to enable alternate missions differs from the design of the system to meet Moon and Mars mission requirements. When designing a system to support Moon and Mars missions, the requirements from the missions directly drive the design of the elements. In analysis of the capabilities a designed system, the objective is to identify what additional missions the as-built system can support without modifying the design. Any modifications required would likely be added as upgrades for those specific missions such that they do not impact the design of the systems for their primary mission of exploring the Moon and Mars.

We have specifically investigated and found our system designs to be capable of conducting Earth-Moon and Earth-Sun libration point missions, missions to near-Earth asteroids, and Apollo 8/10-class missions to Lunar Orbit. By providing this flexibility, mission planners can conduct alternate missions either to meet specific goals inherent in the missions themselves or as a demonstration of the capabilities of the system prior to attempting more challenging endeavors.

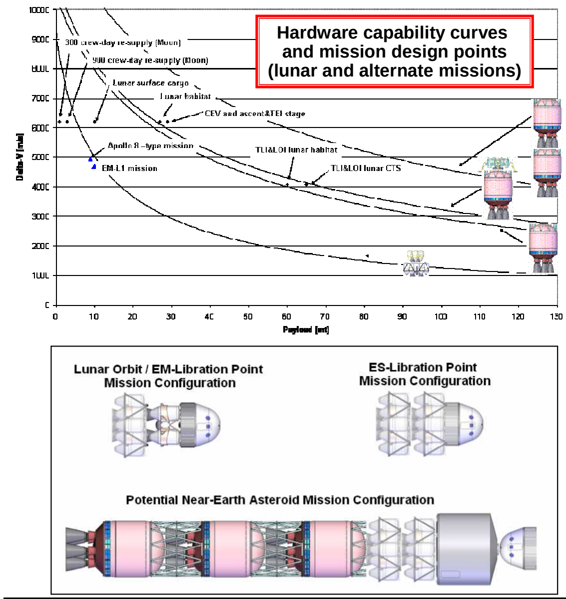

Fig. 7: Capability curves of common Moon-Mars exploration system design and hardware configurations to enable alternate missions.

Fig. 7 shows both the capability curves used to investigate alternate missions and the configuration of transportation elements required to enable these missions. The capability curves represent the delta-v vs. payload space of propulsion stages within the common Moon-Mars exploration system. As missions can be represented as a combination of delta-v and payload, missions supported by various hardware configurations can be investigated. As seen in the figure, a propulsion stage equivalent to the Mars ascent stage, coupled with a propulsion stage equivalent to the Lunar Ascent/TEI stage and a CEV is sufficient to enable missions to either lunar orbit or to any of the Earth-Moon libration points. A single extension power unit would be included as in the short lunar mission hardware manifest. No RED stages are required; as such, these missions could be used prior to the RED stage coming online to test the CEV and SAM (propulsive but not landing functionality) outside of LEO. With an additional set of tanks in the second stage to make it equivalent to the Mars ascent stage, and an additional extension power unit, the common elements could also be used to accomplish missions to the Earth-Sun L1 or L2 points. These missions may be desirable for telescope installation or servicing. The final configuration presented is one of a number of possible configurations for Near Earth Asteroid missions. An analysis was conducted over a large series of Near Earth Asteroids (>3,000) from the JPL Near Earth Asteroid Database[11] to identify asteroid missions which could be completed with the common elements in the baseline design. In this analysis, it was identified that the existing system design could enable many asteroid flight opportunities, allowing flexibility in mission scheduling. The configuration presented at the bottom of the figure is the maximal configuration required for the possible missions, including three RED stages for Earth departure and two SAM propulsion stages for near-asteroid operations and Earth return. A habitat core is used for crew support, and a CEV is used for crew launch and Earth reentry, i.e. it would be possible to carry out the mission with long-duration lunar exploration hardware. These missions would require a unique set of surface exploration equipment, due to the distinct differences in operating in the near micro-gravity environment of an asteroid relative to operating in the partial gravity environment of the surface of the Moon or Mars. Beyond the benefit from exploring the asteroid itself, a mission of this sort would both serve to offer a high-visibility event for the public and provide operational use experience of the habitat in a deep-space, micro-gravity environment similar to that encountered during transits to and from Mars.

Integrated View and Impact of Commonality

Fig. 8 shows the vehicle configurations which result from the common system design for Moon and Mars exploration. In the figure, each of the Rocket for Earth Departure (RED) stages, uses the same design and has a dry mass of 11 mt. The differing wet masses represent different levels of tank filling in each case, up to the maximum wet mass of 112 mt in the Mars Outbound Transfer and Surface Habitat stack. The launch solution for each of the vehicle stacks is also noted in the figure. A 30 mt CEV launch system is used for launching the crew into orbit. The lunar use cases also utilize a 100 mt Shuttle-derived Heavy Lift Launch Vehicle (HLLV). For the Mars use cases, the HLLV is upgraded to a 125 mt to LEO capacity through the addition of an upper stage. While not shown, a single lunar HLLV using one RED and one lunar descent stage can deliver 10 mt directly to the lunar surface.

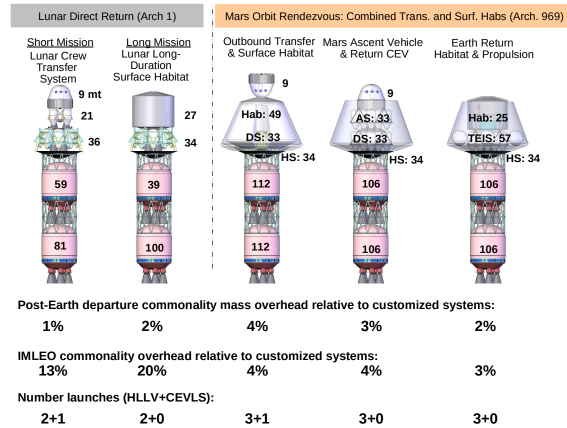

Fig. 8: Full system configurations for Moon and Mars missions with associated commonality overhead and launch solution. The numbers by each of the common elements represents the mass of that element in metric tonnes.

As can be seen in the post-Earth departure commonality mass overhead, the impact of using commonality in the destination vicinity propulsion system (i.e., Surface Access Module), habitats, and heatshields is quite small. The overhead is calculated as the increase in mass of the common system design relative to a point design not including any benefits of commonality. The overhead is low in this case due to the effective use of modularity, which allows the common system design to closely match the requirements of each use case without a large surplus capability. When moving to the Initial Mass in Low Earth Orbit (IMLEO) impact, we can see the overhead is much larger, particular for the lunar use cases. This results from the fact that the same RED stage design is used across all the lunar and Mars use cases. An additional (smaller) RED stage variant could be introduced to reduce the IMLEO overheads. This could perhaps be accomplished through a stretchable propulsion stage in which the length of the tanks could be varied to accommodate varying propellant quantities. While this would decrease the IMLEO of the system, we found that it would not decrease the number of launches required for the assumed maximum launch vehicle size available. As such, the decrease in IMLEO would result in a decreased launch vehicle size instead. As the 100 mt launch vehicle could likely be upgraded to a 125 mt launch vehicle through the addition of an upper stage, we found the use of a wholly common RED stage to be a reasonable approach to balancing the cost of lunar missions relative to providing an effective upgrade path towards Mars.

While a modest overhead is incurred through the use of a common system, significant benefits also exist. For the vehicle stacks described above, there is a 63% decrease in the dry mass of the unique elements in the common system design relative to the customized design used for evaluating the overheads. Dry mass is typically used as a metric for the development cost of a particular element, so this can begin to show the reduction in the development cost necessary for this approach. Beyond the total unique dry mass, the number of elements to be developed is also significantly decreased.

Figure 9 shows the transportation hardware development roadmap for the baseline common exploration system design. The system design for LEO/ISS missions is comparable to the standard design of a system for such needs. A unique LEO propulsion module was selected for this phase in order to minimize the up-front development cost and accelerate the fielding of the CEV for ISS missions. The short duration lunar missions begin to already demonstrate the benefits of commonality as distinct descent and ascent stage developments do not need to be undertaken; instead, a single development of the common vicinity propulsion system and lunar landing gear and structure is needed. While not directly related to commonality, further benefit arises in the short duration lunar mission through the selection of the lunar direct return architecture, as in a lunar orbit rendezvous architecture an additional crew compartment and propulsion stage would also be required at this point.

The long duration lunar missions are also provided a large benefit from the common system design approach, because at this point a separate cargo delivery system does not need to be developed, but instead the development focus would simply be on the things that need to be delivered to the Moon – primarily habitation and surface power systems. The development benefits are clearly visible for Mars exploration in that now the development is limited to only those systems unique to Mars – in this case the development of the aerocapture/aeroentry system and upgrades to the landing gear and HLLV. By limiting the development necessary to transition from short lunar to long lunar to Mars missions, the onset of Mars missions will be greatly accelerated. Beyond the development cost and schedule benefits of this approach, the use of the Mars exploration systems during lunar operations will both directly validate the systems and provide additional experience in their manufacture

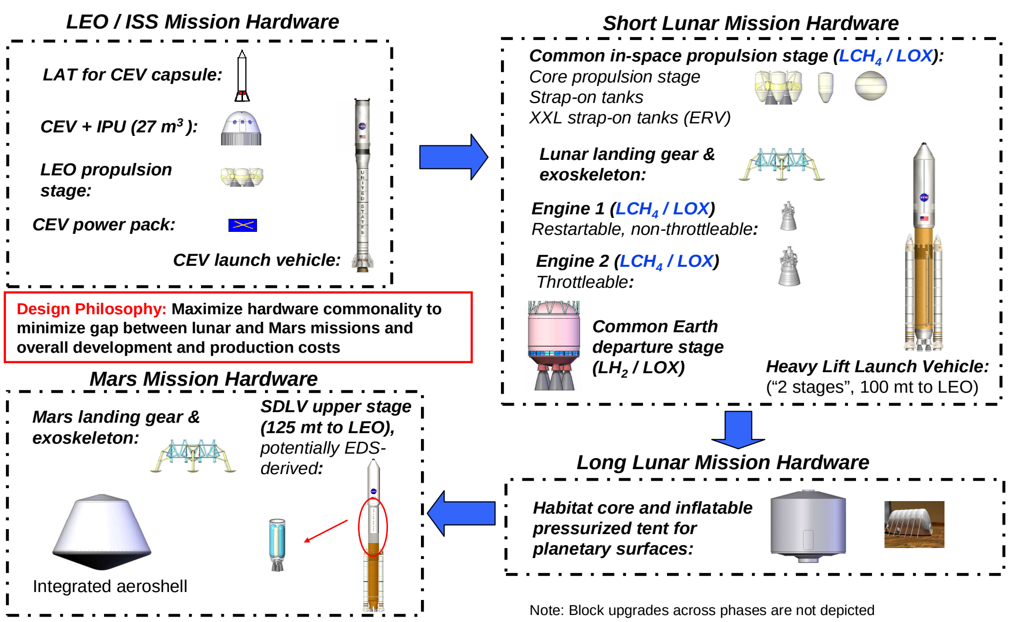

Fig. 9: Integrated transportation hardware development roadmap shows the significant advantages of the Mars-back approach in terms of incrementally building up capabilities that enable both Moon and Mars exploration missions.

and operations, which will provide risk and safety benefits during Mars exploration.

Also, as the number of unique elements is decreased, the number of production lines required will also be concomitantly decreased, resulting in a decrease in the fixed recurring costs associated with maintaining that production capability. In addition, as the lunar exploration production lines will not need to be shutdown in order to enable Mars exploration (as they are being used to produce the Mars exploration elements), lunar missions could be conducted in parallel with Mars missions, if so desired. The fact that the production lines will continue through both lunar and Mars operations will also remove the workforce transition issues associated with closing production lines.

It should also be noted that while the same elements developed for early missions are used for much later missions, technology insertion can still proceed apace both through the addition of block upgrades or the complete replacement of an element. The introduction of advanced propulsion such as nuclear thermal or solar electric propulsion could lead to the replacement of the hydrogen-oxygen Rocket for Earth Departure stage with an advanced propulsion stage to perform the same function. The modular nature of the vehicle stacks would allow this introduction to be performed in a reasonably straightforward manner and result in an appropriate reduction of heavy lifter launches to accomplish the missions (e.g., transition from 9 to 6 HLLV launches per Mars mission).

International participation

The Vision for Space Exploration explicitly calls for international participation in human and robotic exploration of space[1]. In this section, we discuss several options for international participation in the US human lunar exploration program based on the commonality analysis and system design philosophy outlined above.

Beyond political and foreign policy considerations, the primary motivation for international participation is that the participants contribute different elements or capabilities to the program (and thus program cost is shared), while all partners have access to the overall capabilities provided by the program. An example for this type of participation would be the Space Shuttle / SpaceLab program between NASA and ESA.

For human lunar exploration, it is likely that NASA would initially focus on the crew transportation capability, which represents the "critical path" to human lunar exploration, and is represented in our design by the short lunar mission hardware. Based on this assumption, potential areas for international participation could be:

1. A lunar surface habitat that provides significantly increased surface-stay capability compared to that of the crew transportation system (i.e. durations from several weeks to several months). The habitat could be delivered by the transportation infrastructure used for crewed missions, and could be developed mostly independently as long as it satisfies the basic constraints of the transportation system. As international partners have built up experience in developing habitation capability for ISS, the lunar surface habitat could be based on ISS module designs (the 1992 NASA First Lunar Outpost design included a space-station-derived lunar surface habitat design[12]). A long-duration lunar surface habitat would provide significant added value for all human lunar exploration activities, and could potentially be the cornerstone of a permanent lunar base.

2. A lunar logistics lander for the delivery of supplies and equipment for long-duration surface missions. A logistics lander would enable the reuse of existing habitation assets on the lunar surface by providing consumables and spare parts re-supply and additional equipment for each new mission, not unlike Progress spacecraft or other re-supply vehicles do for ISS (the lander would, however, remain on the lunar surface at the end of the mission). A logistics lander could greatly reduce the operating cost of a long-duration / permanently crewed lunar outpost, and also provide international partners with a unique capability for delivering payloads to the lunar surface. In that latter function it could also be used before and / or independently of the human exploration

program for the delivery of rovers and scientific payloads to the lunar surface. In order to provide maximum flexibility in terms of launch, the logistics lander could be sized and designed to fit on various 20 mt to LEO–class launch vehicles (such as Ariane V, Proton, Delta IV heavy, etc.), potentially for direct launch to the Moon. A Mars logistics lander could offer similar benefits for human mars exploration.

3. Lunar surface mobility assets such as unpressurized / pressurized rovers, “campers”, etc. Extended-range surface mobility is crucial to the delivery of value in human lunar and mars exploration, both from a scientific and an exploration point of view, because it enables flexible exploration of a large area of terrain. As mobility equipment is a pure surface payload, it could be developed somewhat independently of the transportation system while taking into account basic constraints such as weight and geometrical limitations, and could be delivered by the US transportation system in the same manner as a lunar surface habitat. Surface mobility equipment could also be of interest for international participation in US human mars exploration.

It should be noted that the options for international participation described here are largely independent of the transportation architecture type chosen for crew transportation to the lunar surface, as long as basic weight and volume constraints are taken into consideration. As such, they are not only relevant in the context of the Moon and Mars exploration system design presented herein, but remain valid also for the recently presented NASA Exploration Systems Architecture Study (ESAS) lunar transportation architecture concept.

Conclusions

In summary, we have found that the common exploration system design approach is both feasible and offers significant benefits in terms of development and production cost, crew safety and mission risk, and achieving Mars missions in a timely manner. While presented for a particular pairing of lunar and Mars exploration architectures, the commonality approach described here is not exclusive to that one pairing. Through proper upfront systems engineering, a common Moon-Mars exploration system design can lead to the safe, affordable, and sustainable exploration of the Moon, Mars, and beyond.

A key enabling factor for common exploration system design appears to be a modular design approach that allows for the addition of elements and capabilities to an existing system over time (e.g. addition of tanks, engines, habitats, etc.). Successful implementation of this approach necessitates rigorous definition and control of element interfaces. Options for customization (e.g. a dedicated descent engine design) have to be traded on the basis of life-cycle cost and overall system impact (risk, performance) rather than performance alone.

Being focused on capabilities rather than solely on individual mission design points, the Mars-back approach facilitates taking into account alternate missions (e.g. to near-Earth asteroids) that might otherwise be precluded by specific design choices for “optimal” point designs.

The Mars-back approach also provides realistic opportunities for significant international participation in the form of a lunar surface habitat, Moon and Mars logistics lander, or Moon and Mars surface mobility assets. In addition, the direct tie between lunar and Mars missions will yield additional public and congressional support for lunar activities.

We recommend the Mars-back approach for the design of systems for the Vision for Space Exploration.

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