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# Small Habitat Commonality Reduces Cost for Human Mars Missions

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**Most view the Apollo Program as expensive. It was. But, a human mission to Mars will be orders of magnitude more difficult and costly. Recently, NASA's Evolvable Mars Campaign (EMC) mapped out a step-wise approach for exploring Mars and the Mars-moon system. It is early in the planning process but because approximately 80% of the total life cycle cost is committed during preliminary design, there is an effort to emphasize cost reduction methods up front. Amongst the options, commonality across small habitat elements shows promise for consolidating the high bow-wave costs of Design, Development, Test and Evaluation (DDT&E) while still accommodating each end-item's functionality. In addition to DDT&E, there are other cost and operations benefits to commonality such as reduced logistics, simplified infrastructure integration and with inter-operability, improved safety and simplified training. These benefits are not without a cost. Some habitats are sub-optimized giving up unique attributes for the benefit of the overall architecture and because the first item sets the course for those to follow, rapidly developing technology may be excluded. The small habitats within the EMC include the pressurized crew cabins for the ascent vehicle,**

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**rover, Mars-moon taxi and exploration vehicle. In addition, the scope of commonality is broadened to include a precursor cis-lunar Exploration Augmentation Module (EAM) and the logistic elements supporting both the EAM and Mars surface operations. Together, these amount to over 20 flight vehicles. The approach to maximizing commonality combines not only the physical and functional characteristics of the habitats, but also methods of acquisition and management spanning the multi-decade exploration campaign. The paper presents a method of quantifying the cost benefits of developing common habitats. First, based on the campaign schedule, the time for developing individual habitat is identified. Then this is compared to strategy that combines all habitat requirements into a core for a single DDT&E with follow-on delta development for each end item. The savings as a result of overall program schedule compression is measured using analogous DDT&E and recurring costs escalated to a common year dollar. In order to demonstrate a workable common solution, three design/analysis products are shown. These include a commonality analysis tool derived from the master equipment list for each habitat, a cost analysis tool and representative configurations that validate the initial common core tailored to each vehicle.**

## Nomenclature

*CBM* = Common Berthing Mechanism
*CDR* = Critical Design Review
CSM = Command Service Module
*DDT&E* = Design Development Test and Evaluation
*EAM* = Exploration Augmentation Module
*EMC* = Evolvable Mars Campaign
*EMU* = Extravehicular Mobility Unit
*HAT* = Human Spaceflight Architecture Team
*ISS* = International Space Station
*LEM* = Lunar Excursion Module
*LCC* = Life Cycle Cost
*LEO* = Low Earth Orbit
*MACES* = Mars Advanced Crew Escape Suit
*MAV* = Mars Ascent Vehicle
*MEL* = Master Equipment List
*MMEV* = Mars Moon Exploration Vehicle
*NDS* = NASA Docking System
*PLSS* = Portable Life Support System
*PNP* = Probability of No Penetration
*RCS* = Reaction Control System
*SLS* = Space Launch System
*SME* = Subject Matter Expert
*TRL* = Technology Readiness Level

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## I. Introduction

INITIALLY, the small habitats within the Evolvable Mars Campaign (EMC) and near-earth Proving Ground Exploration Augmentation Module (EAM)) were at significantly different levels of design maturity and only coincidentally similar. Realizing this, the EMC management offered a challenge to "maximize small habitat commonality" with the objective of reducing program cost. The following description presents a summary of work performed by a team of engineers and contractors at four NASA centers. In addition, it draws on eleven Subject Matter Experts (SMEs) for providing the detailed subsystem information necessary to conduct the commonality analyses.

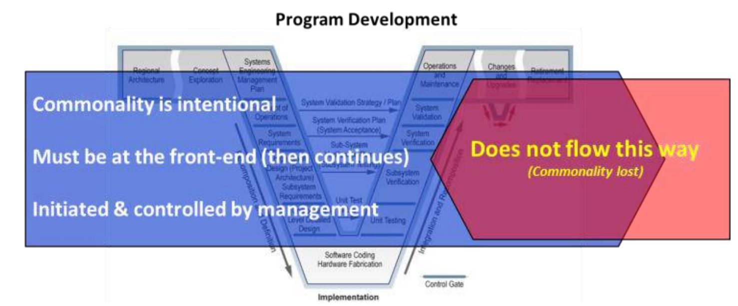



**Figure 1. Commonality must start early in the program.**

It may be misconstrued that because the architecture, mission definition, and habitats are ill-defined that it is too early to address commonality. The opposite is true. Commonality must be considered at the beginning otherwise as concepts and organizations mature, it will be disruptive and costly to impose common solutions. In this way, it is much like mass properties. It is necessary at the beginning and continues throughout the program. Figure 1 overlays a commonality flow on the program development "V" diagram stressing early management involvement.

## II. EMC Small Habitats

Before the commonality study, small habitats in the EMC were on different design paths. Figure 2 shows images of these vehicles along with the key design characteristics. For the EMC analysis, analysis was focused on small habitats or crew cabins for the Mars vicinity vehicles and the precursor cis-lunar modules. Specifically, they include the EAM and its pressurized logistics modules, the Mars Moon Exploration Vehicle, the Mars Moon Crew Taxi, the

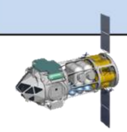
| | Mars Ascent Vehicle | Mars Moon Taxi | Mars Moon Exploration Vehicle | Mars Rover | Mars Logistics Module | EAM | EAM Logistics |
|---|---|---|---|---|---|---|---|
| **Before EMC Commonality** |  |  |  |  |  | **Not Included** | **Not Included** |
| **Crew Size** | 4 | 4 | 2 | 2 | 0 | 2-4 | 0 |
| **Duration** | 1.8 da (44 hrs) | 3.2 da (77 hrs ) 1 Sol-Phobos-Deimos-1Sol | 14 days (max) | 14 days (max) | Temporary access | 14 days (max) | Temporary access |
| **Reuse** | Disposable | Disposable | Disposable | Reusable | Disposable/Repurpose | Reusable | Disposable/Repurpose |
| **Environment** | Mars surface, Mars Orbit | Mars Orbit | Mars Moon | Mars surface | Mars surface (possible orbit) | Cis lunar orbit | Cis lunar orbit |
| **EVA** | No EVA | One way transport 4 suits to Mars moon | Micro-g (suitport) | Mars surface (suitport) | No EVA | Attached Micro-g Airlock | No EVA |

**Figure 3. Before EMC the small habitats were on different (uncommon) design paths.**

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Mars Ascent Vehicle, the Mars Pressurized Rover and Mars Pressurized Logistics Module. See Fig. 2. Some are used for two days then discarded while others offer recurring two week excursions over multiple human missions. Some habitats operate solely in weightless vacuum, others on the dusty surface of Mars and the MAV transitions between the two. Some are designed for extravehicular activity (EVA) and others without EVA. Maximizing commonality means accommodating the differences by creating a light-weight solution of the highest level of integrated systems that can satisfy vehicle requirement without significantly compromising performance

## III. Benefits/Challenges of Commonality

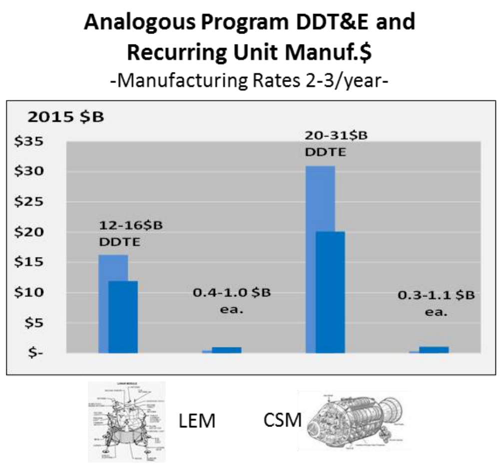


**Figure 3. Similar historical vehicles show the cost benefits of a common DDT&E.**

With all products, and to a much greater degree with human spacecraft, there is a significant up front cost associated with the Design, Development, Test and Evaluation (DDT&E) of the first flight unit. Some of this expense is engineering, but there are costs associated with acquisition, documentation, international participation, training, sparing and other aspects of large government programs. For space, commonality is not new, just elusive. The International Space Station (ISS) was founded on a common module with common racks. For the EMC small habitats, a commercial model was adopted with the intent of incurring the greatest (DDT&E) costs in the development of a common core thus reducing costs in each recurring element. A benefit of a common core approach is the avoidance of potentially large DDT&E costs associated with many independent vehicles having similar habitats or pressurized containers. Figure 3 provides a historical example of the magnitude of DDT&E costs and their significance relative to recurring costs for the Apollo Command Service Module (CSM) and Lunar Excursion Module (LEM).

In addition to cost savings, there are other compelling benefits to commonality. These include improved safety because of common configuration and operations; interoperability allows the crew to use different vehicles with the same controls; logistics are reduced because the same spare can be used in different vehicles; standardized interfaces simplify physical and functional connections across the EMC infrastructure; and commonality simplifies training for nominal, maintenance, and contingency operations.

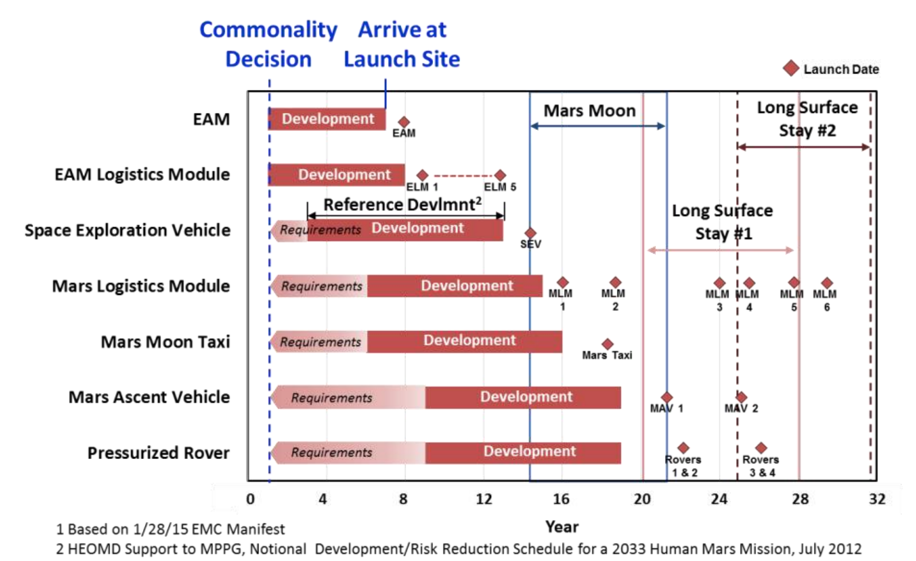


**Figure 4. Few deliverables over a long period of time challenges acqusition.**

True commonality is intended to benefit a higher level architecture and there is a cost to achieve this goal. To the end-user this means sub-optimization. In other words, the habitat is not uniquely designed for that specific application. Another disadvantage is keeping pace with technology advancements. Because of infrequent orbital opportunities and pre-deployed assets, there can be up to five years after launch before a habitat is used. Add to this the fact that most technologies are to be

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mature (Technology Readiness Level (TRL) 6) by program Critical Design Review (CDR). This means that commonality will likely preclude inclusion of the latest technology into the flight vehicle.

Two significant challenges to EMC small habitat commonality are the low numbers of units and the length of time between need-dates. (See Fig. 4) Including EAM, a Phobos mission and two Mars surface missions there are only 9 habitats and 11 logistics modules required. The need dates for these units span 20 years. By comparison, there were 15 Apollo Lunar Excursion Modules built over a span of 4 years.

A Common Building Block approach presented in A.C. Wicht's thesis, Acquisition Strategies for Commonality Across Complex Aerospace Systems-of-Systems, has the best chance of structuring procurement with few units over many years. This approach focuses on the high value elements employing either a "build to print" or "supply as government furnished equipment" acquisition strategy. It stresses both strong systems engineering with vision and authority to force projects into performance-cost compromises and strong management with the authority to compel projects to take action in the interest of the higher level architecture. Added to this are life cycle incentive payments and commonality award fees.

## IV. Early Results

Early analysis shows that a high level of commonality is possible yielding between $3-4 billion ($FY15) savings by having a combined DDT&E. However, to be realized, commonality must start now by becoming culturally ingrained and incentivized throughout the entire development and implementation process. These claims of commonality and cost savings are based on a three-step process. (See Fig. 5) The steps are: 1. master equipment list

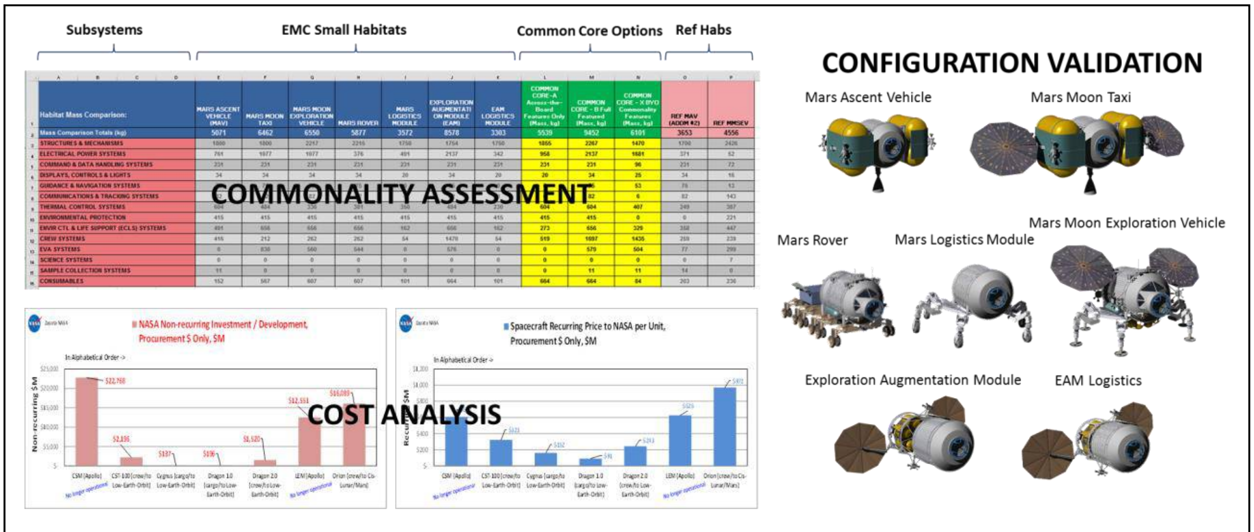


**Figure 5. Three key elements of the commonality assessment.**

commonality tool, 2. a cost estimating tool and 3. an iterative configuration process for validating the physical commonality across all habitats. These tools and the process have been developed, demonstrated and exposed to an early sanity check.

## V. Approach

To assess the potential for commonality to improve the life cycle characteristics of the EMC small habitats, a process was implemented, built around creating a "common core." The objective was to use a structured approach to ultimately define a core of common subsystem equipment that would become the initial development basis for all of the individual small habitat designs. Unique components and subassemblies could then be added, or subtracted from, this common core for creating any given unique small habitat to be fielded. (See Fig. 6)

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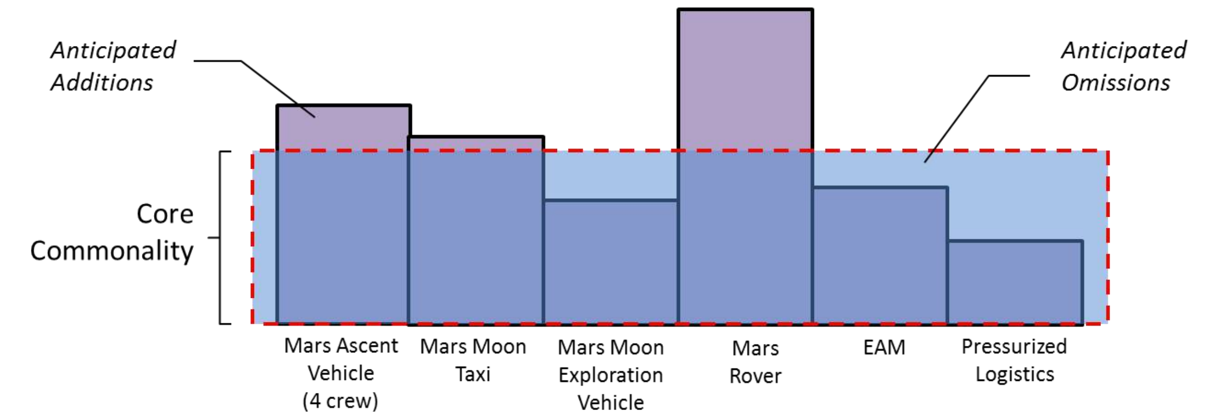


**Figure 6. Common core allow tailoring while reducing cost through a single DDT&E.**

### Evaluate Unique Small Habitat Applications

A structured approach emerged where each unique design concept was analyzed in terms of generic subsystem discipline functions (such as structures, power, thermal control, etc.) and generic subsystem equipment groups defined to accomplish the functions. Each equipment group was then broken down by component/subassembly types. Weight statements and Master Equipment Lists (MELs) were used to quantify each space habitat. The team compiled a set of MELs by system discipline function, generic equipment groups, and unique components/subassemblies, to provide a consistent level of concept definition and discern which areas in these designs had the greatest potential for commonality. A MEL Commonality Assessment Tool (or *MEL Tool*) was developed and is described in more detail in Section VI.

### Create and Explore "Common Core" Scenarios and Assign Commonality Indexes

The development of a MEL Tool allows the team to rapidly create *common core* design scenarios directly from available concept definitions. A common core is made up of common system equipment to which a smaller, confined set of unique components and subassemblies could then be added to, or outfitted with, in order to create any given unique small habitat application, such as an ascent vehicle, surface rover, or a pressurized logistics module. The team approached this task by soliciting the contribution of SMEs that cross-cut the many different applications to explore the potential for common equipment groups and components, and to help understand the underlying state of the assumed technology types.

To better assess the similarity across the different habitats, the concept of a *commonality index* was introduced. The index is a set of normalized values (0.0 to 1.0) assigned by the MEL Tool to provide a rough order comparison of how potentially "common" each common core scenario is against the set of unique habitat concepts. The Common Core analysis and use of the indexes are described in Section VI.

### Compare Life Cycle Characteristics

The next step in the approach is to assess cost savings of the commonality scenarios in a life cycle context. These are run with two major categories of estimation assumptions: technical characteristics of the architecture under comparison (which are provided by the MEL Tool); and also non-technical assumptions accounting for different business case scenarios, such as different government program-based, or, commercial/market-based business operations. Each scenario is compared to unique life cycle stages (both recurring and non-recurring) to estimate costs. The life cycle analysis portion of the effort is described in Section VII.

### Validate Commonality Assumptions with Configuration

The final step even though it is iterative, is to validate the commonality assumptions by developing configurations. For this, the habitats are tested for each stage of delivery and operation against each of the 7 vehicles. The purpose is to create a common structure that accommodates solar arrays, propellant tanks, radiators, windows, hatches, etc. The configuration validation portion of the effort is described in Section IX.

## VI. Master Equipment List Commonality Tool

The Master Equipment List (MEL) Commonality Assessment Tool was developed as an aid for assessing the potential for commonality among small crew habitats and pressurized logistics containers that are part of EMC architecture elements or vehicles. The tool tabulates a MEL for each habitat, allowing comparisons between habitat concepts at the equipment and component levels of detail. At a higher-level of concept definition, the comparisons help to identify equipment within habitat subsystems with the potential to be common. The content of the MEL was defined with input from Agency subject matter experts in each subsystem area and is inclusive of equipment options applicable to each habitat, representing a "superset of selections". This feature allows the flexibility to select the degree of commonality to be assumed among habitats and the investigation of various commonality scenarios. This is a useful capability for defining options for a common core habitat.

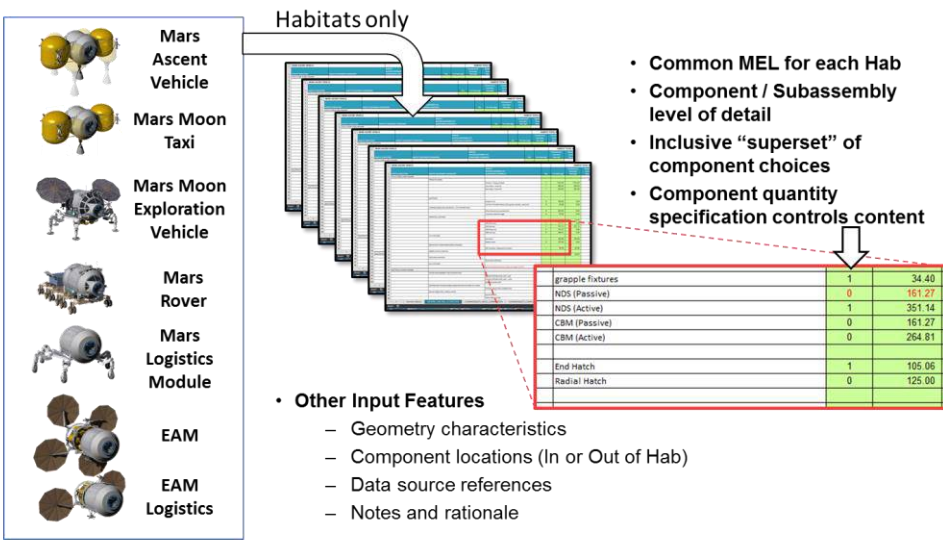

**Figure 7. Master Equipment List for each habitat starts commonality assessments.**

The tool is an Excel workbook with a spreadsheet tab for each habitat MEL, as well as other tabs for auxiliary calculation sheets and output tables. Outputs of the tool includes commonality indicators, potential common core definitions, commonality scenario mass impacts, subsystem commonality measures as input to costing analysis, and habitat summary "baseball" cards.

A MEL is defined for each small habitat in the Split Chemical-SEP architecture of the EMC, as illustrated in Figure 7. Only the habitat portion of each element or vehicle is included in the breakdowns. Each MEL consists of three levels of breakdown: Subsystem, Equipment Summary, and the Master Equipment List. The Master Equipment List is equivalent to a component or subassembly-level of detail and is defined by the subsystem subject matter experts. Each MEL consists of a superset of components, with associated masses, representing the expected range of possible choices for all habitats in the current set. For any particular habitat MEL, content is controlled by specifying the component quantity.

| | A | B | C | D | E | F | G | H | I | J |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | | | FUNCTIONALLY NEEDED IN SMALL HAB? | | | | | | | |
| 2 | HABITAT SUBSYSTEM | HABITAT EQUIPMENT SUMMARIES | MARS ASCENT VEHICLE (MAV) | MARS MOON TAXI | MARS MOON EXPLORATION VEHICLE | MARS ROVER | MARS LOGISTICS MODULE | EXPLORATION AUGMENTATION MODULE (EAM) | EAM LOGISTICS MODULE | NORMALIZED COMMONALITY INDICATOR (STRONG = 1.0, OR 7 OUT OF 7) |
| 3 | STRUCTURES & MECHANISMS | | | | | | | | | 0.59 |
| 4 | | PRESSURE VESSEL | X | X | X | X | X | X | X | 1.00 |
| 5 | | SUITPORTS | | | X | X | | | | 0.29 |
| 6 | | UNPRESSURIZED ENCLOSURE (E.G., SUIT PROTECTION) | | | X | X | | | | 0.29 |
| 7 | | INTERFACE, DOCKING | X | X | X | X | X | X | X | 1.00 |
| 8 | | HATCHES | X | X | X | X | X | X | X | 1.00 |
| 9 | | SEPARATION COMPONENTS/MECHANISM(S) | X | X | | | | | | 0.29 |
| 10 | | WINDOWS | | | X | X | | | | 0.29 |
| 11 | ELECTRICAL POWER SYSTEMS | | | | | | | | | 0.95 |
| 12 | | POWER MANAGEMENT AND DISTRIBUTION | X | X | X | X | X | X | X | 1.00 |
| 13 | | DISTRIBUTED POWER BUSSES/CABLES (POWER SOURCES TO LOADS) | X | X | X | X | X | X | X | 1.00 |
| 14 | | POWER GENERATION EQUIPMENT INCL. INSTALLATION | X | X | X | X | | X | X | 0.86 |

**Figure 8. Assessment of functional commonality for each habitat.**

In addition to the mass input cells on the spreadsheets, there are cells for inputting approximate component geometry characteristics, component locations (inside of



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habitat, attached externally, or externally interfaced), data source references, and notes/rationale.

One spreadsheet in the assessment tool provides a high-level means for indicating the potential for commonality among the habitats. The spreadsheet, partially shown in Figure 8, consists of the MEL breakdown at the Equipment Summary level (one up from component level). A column for each habitat is provided next to the breakdown and is used to indicate if a particular equipment summary is functionally needed. X's are placed in the cells where the equipment is assumed to be needed. The number of X's is simply added up for each equipment summary row and divided by the total number of habitats to compute a normalized value from 0 – 1. The equipment summary values are then averaged to provide an overall value for each subsystem. Values closest to 1.0 indicate the greatest potential for commonality. This is only a high-level indicator of the potential, since a more accurate assessment of commonality requires understanding at a more detailed level, at least to the component/subassembly level.

To support investigation of a Common Core implementation strategy, a commonality scoring process was also developed. This process determined an index of the level of commonality for each habitat relative to a common core as an input to a life cycle cost analysis tool. The index is defined per subsystem as the fraction of the equipment groups within the subsystem that are common with the common core. A value of 1.0 for a subsystem means that all of the equipment in that particular subsystem is assumed to be part of the common core.

There are three Common Core modeling scenarios currently available in the tool. The first one assumes that only the equipment identified as being functionally needed by all habitats (see commonality indicator) makes up the common core. This is referred to as the "Natural Commonality" scenario. This scenario defines a common core with the least amount of common equipment. The second scenario is where equipment needed by any habitat is universally selected for all of them. This is referred to as the "Full-Featured" scenario. It defines the highest-mass common core. Both of these scenarios are unrealistic, but establish the lower and upper bounds for a common core. The third scenario allows a customized selection of equipment for the common core. Figure 9 shows a sample output of index values for one of the common core scenarios.

| Habitat Commonality Comparison CORE-A (Natural, "Across-the-Board) | COMMON CORE-A | MARS ASCENT VEHICLE (MAV) | MARS MOON TAXI | MARS MOON EXPLORATION VEHICLE | MARS ROVER | MARS LOGISTICS MODULE | EXPLORATION AUGMENTATION MODULE (EAM) | EAM LOGISTICS MODULE |
|---|---|---|---|---|---|---|---|---|
| COMPOSITE | 0.52 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 | 0.50 |
| STRUCTURES & MECHANISMS | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 | 0.38 |
| ELECTRICAL POWER SYSTEMS | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 | 0.33 |
| AVIONICS | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 | 0.48 |
| THERMAL CONTROL SYSTEMS | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| ENVIRONMENTAL PROTECTION | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |
| ENVIR CTL & LIFE SUPPORT (ECLS) SYSTEMS | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 | 0.60 |
| CREW SYSTEMS | 0.80 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 | 0.57 |
| EVA SYSTEMS | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 |
| RESEARCH & UTILIZATION SYSTEMS | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |

**Figure 9. Commonality scores for each habitat by subsystem.**

## VII. Life Cycle Cost Assessment

Estimating the life cycle cost effects of a common small habitat design applied across assorted applications (a Mars taxi, a Mars ascent stage, an in-space augmentation module, etc.) can be an exercise fraught with uncertainty. Analogous commonality efforts provide encouraging (automotive industry[i]) and discouraging (Joint Strike Fighter[ii]) data points. Addressing uncertainties informed the effort of assessing the Life Cycle Cost (LCC) effects of small habitat commonality applied across different user applications. Historical data, sensitivity analysis (3-point estimate), and the prior MEL generating a measure (index) of potential commonality were merged into a structured process for relating technical and non-technical factors to cost effects.

| Scenario | LCC (Procurement Only) Development, Manufacturing, Ground Ops FY 15 $ | Savings Over the Life Cycle (Phobos, Long Stay #1, & Long Stay #2) FY 15 $ |
|---|---|---|
| No commonality | $11.0 - $16.8B | n/a |
| Baseline Scenario Commonality LO – HI (Technical) | $9.5 - $14.5B | **$1.5 - $2.3B** |
| Baseline Scenario Commonality + 25% LO – HI (Technical) | $9.3 - $14.1B | **$1.7 - $2.7B** |
| Baseline Scenario Commonality LO – HI (+ Further Non-technical Factors) | $8.7 – $13.2 B | **$2.3 – $3.6 B** |
| Mission Ops | Additional TBD; Savings not Calculated | |
| Gov't Program/Project Management | Additional 5 – 12% per Approach | |

**Figure 10. LCC Assessment of Small-Habitat Commonality across Diverse Applications.**

Historical data was especially important in determining the results as these set the points of departure from which later extrapolations are derived. Historical data for spacecraft stretched from LEO to cis-lunar applications, from older to recent projects, from cost-plus to commercial acquisition approaches, from in-space spacecraft to landers, and from cargo to crew applications. This was all joined into a model suitable for an assessment consistent with the level of detail available in this phase of defining the space system elements.

The tabulated preliminary LCC results (Figure 10), even on the low end of potential savings, provide compelling evidence that commonality as assessed should be further pursued.

The graphical results (Figure 11) are a comparison of the case where wholly independent efforts and designs have costs for development and unit manufacturing versus the case where the small habitat portion of these efforts are common. Intermediate cases were also assessed. Notably, further savings not yet estimated are likely from including Mission Operations and Government Project & Program Management effects. Changes in the mission tempo would also affect the LCC savings, offering more or less savings from unit manufacturing and operations. As racked and stacked (Figure 11) the LCC results reflect a specific manifest going only through a 2nd Long Stay Mars mission.

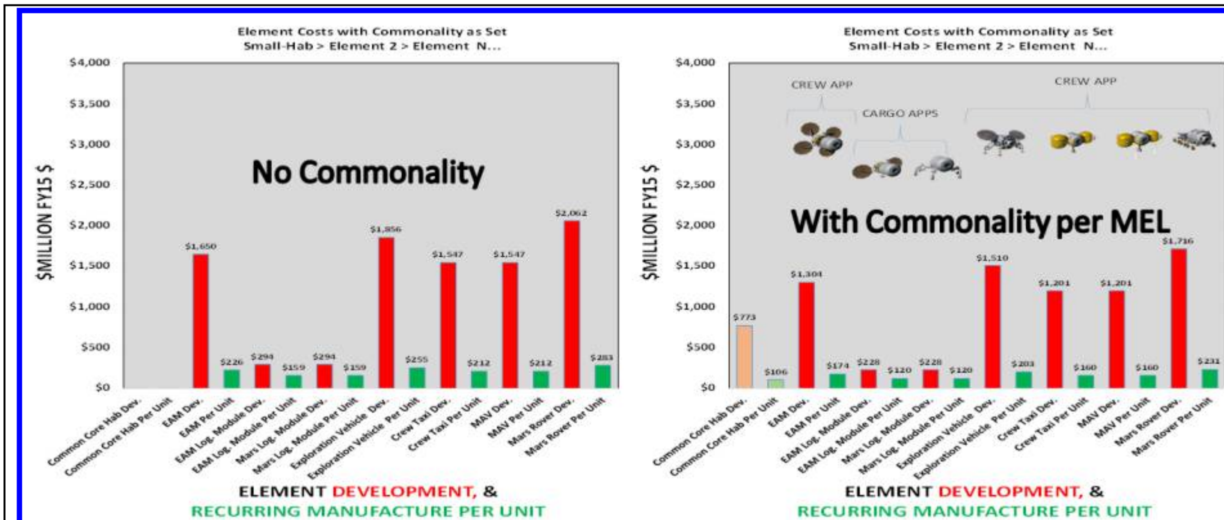


**Figure 11. Independent Development & Unit Manufacturing Commonality vs. without Commonality.**
(Costs are for the whole element, including systems (propulsion, etc.) beyond the habitat portion. All 2015 $)

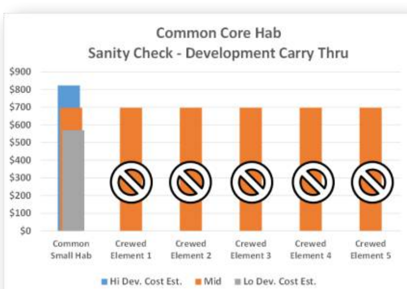


**Figure 12. A Notional Mental Model of Small-Habitat Commonality Saving Across User Applications.**

As a sanity check, a notional mental model of the potential for commonality cost savings would have expected significant savings from development alone (Figure 12). Merging the mental model with the estimated development cost alone of the small-habitat would lead to an expected savings of $3-$4B across 5 elements - the "sanity check" proving consistent with the more refined model assessment results.

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The LCC assessment supports a decision to further define potential small habitat commonality across Mars space system elements. Maturing from an assessment to an analysis would emphasize (1) refining the understanding of diverse acquisition approaches and characteristics while integrating a commonality strategy, (2) base-lining an acquisition approach and (3) iterating as required with a more fully integrated LCC, performance, reliability/safety and campaign level set of tools and capabilities.

## VIII. Habitat Design

**Interfaces**

In order to better determine how commonality could be applied to the various small habitats in the architecture, a preliminary effort was initiated to define habitat interfaces and identify those with the potential to be common. The habitat portion of a vehicle will have a number of required external interfaces. Definition of the interfaces is derived from design assumptions associated with habitat-to-vehicle or vehicle-to-vehicle integration, surface systems support infrastructure, subsystem functional allocations, and the conduct of crew ingress/egress operations. Some of these interfaces can be significant drivers of habitat design. For instance, structural design will be affected by integration loads and selected crew hatch sizes. The subsystem makeup of a habitat will depend on what services to the habitat (e.g., power, thermal, etc.) are assumed to be supplied from external sources and, in some cases, what services the habitat itself supplies to other parts of the vehicle or even to other vehicles/elements.

Interfaces can consist of a number of different basic types. These can be further decomposed into more specific lower-level constituents. Given that design of the EMC architecture elements is in the early concept phase, the definition of interfaces are currently at a high level. Figure 13 shows interface diagrams for the habitats of Mars vehicles used to create a common interface diagram that applies to all vehicles. Similarly, preliminary definitions have been assembled for most of the other small habitats as part of this fiscal year's effort. For next year, it is intended that the interfaces be defined in more detail and opportunities for commonality identified as common core options are investigated.

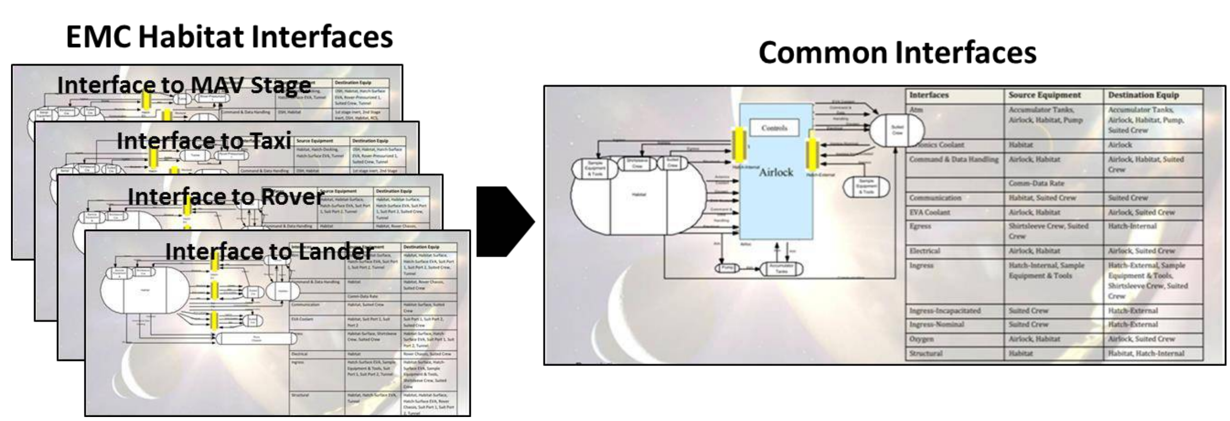


**Figure 13. Interfaces to EMC elements for each habitat are used to create a common interface diagram.**

**Environments and Loads**

To achieve a common core cabin design, loads and environments for all applicable missions and applications must be considered given that the cabin functions as the core backbone in each case. For the small habitats under consideration in this study, there is a significant range of environments and loads that must be accommodated for missions ranging from pressurized rovers to Mars ascent vehicles to Mars taxis. Each application has multiple driving loading events (load cases) across the mission operations as shown in Figure 14. Each of these primary load cases are represented as equivalent steady state loads that envelope dispersions and also include an unsteady dynamic load amplification factor covering low frequency vibration environments.

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| Mission Phase | Acceleration Loads | Mars Ascent Vehicle | Mars Moon Taxi | Mars Moon Explor Vehicle | Mars Rover | EAM | EAM Log Mod | Mars Log Mod |
|---|---|---|---|---|---|---|---|---|
| SLS launch<br>1 – Transonic<br>2 – Max accel | 1) 2.75 g's axial, 1.5 g's lateral[1]<br>2) 5 g's axial, 0.25 g's lateral[1] | X[a] | X[b] | X | X | X | X | X |
| Transit burns | 0.5 g's axial | X[a] | X[b] | X | X | | | |
| Mars entry/descent | 4.5 g's axial, 0.5 g's lateral[2] | X[a] | | | X | | | X |
| Mars landing | 2.75 m/s sink rate 1.0 m/s lateral[3] | X[a] | | | X | | | |
| Mars ascent | 1.3 g's[2] axial, 0.5 g's lateral[4] | X[b] | | | | | | |

1. 12-15-2014, Bart Fowler (MSFC EV31) via Sam Yunis (LaRC) 2. 2-3-2015, Alicia M. Dwyer Cianciolo (LaRC) 3. Mars DRA 5 addendum 2 4. 3-24-2015, Herbert D. Thomas (MSFC ED04) a. LCH4 tanks full b. LCH4 tanks and LOX tanks full

**Figure 14. Design loads by element and mission phase.**

Additional environment considerations for each of these cabin designs include cabin atmosphere, thermal (internal and external,) and external atmospheric loading (Mars entry, ascent, and surface winds,) for all operating phases of each mission. Figure 15 shows external cabin environment considerations for Mars surface operations as a sample. All of the small habitats in this study will be designed to a standard one atm. equivalent to a shirt-sleeve environment.

| External Environment | Value | Comments | Source |
|---|---|---|---|
| Thermal<br>-Direct Solar Flux<br>-Surface Temperature<br>-IR Sky Temp | <br>700 w/m$^2$<br>35/-90/15 C<br>-100/-180/-70 | <br>Worst Hot Case<br>Worst Hot/Cold/Night Hot<br>Worst Hot/Cold/Night Hot | MSL-223-0301, Rev D, May 18, 2011<br>(note: values picked from plots) |
| Surface Atmosphere<br>-Pressure<br>-Density | <br>0.56 kPa<br>0.013 kg/m$^3$ | <br>0 MOLA, nominal<br>0 MOLA, nominal | MSL-223-0301, Rev D, May 18, 2011 |
| Acceleration due to Mars Gravity | 3.72 m/s$^2$ | Nominal | MSL-223-0301, Rev D, May 18, 2011 |
| Max Atmospheric Surface Wind Speed | 95 m/s | Gust | MSL-223-0301, Rev D, May 18, 2011 |

**Figure 15. Mars surface external environments.**

### Crew Accommodations

Creating a common cabin for operations in very different environments is a challenging proposition. For example, with the Mars Rover, windows are positioned to accommodate the eye position of a seated astronaut. However, there is no requirement for MAV windows during the automated, short-duration ride from the Mars surface to the orbiting transit habitat. A common cabin requires understanding the full range of postures for crew operations in all vehicles. At worst, such a cabin can be kitted for each spaceflight application, but the theoretical ideal is for the cabin to be capable of being used with equal and

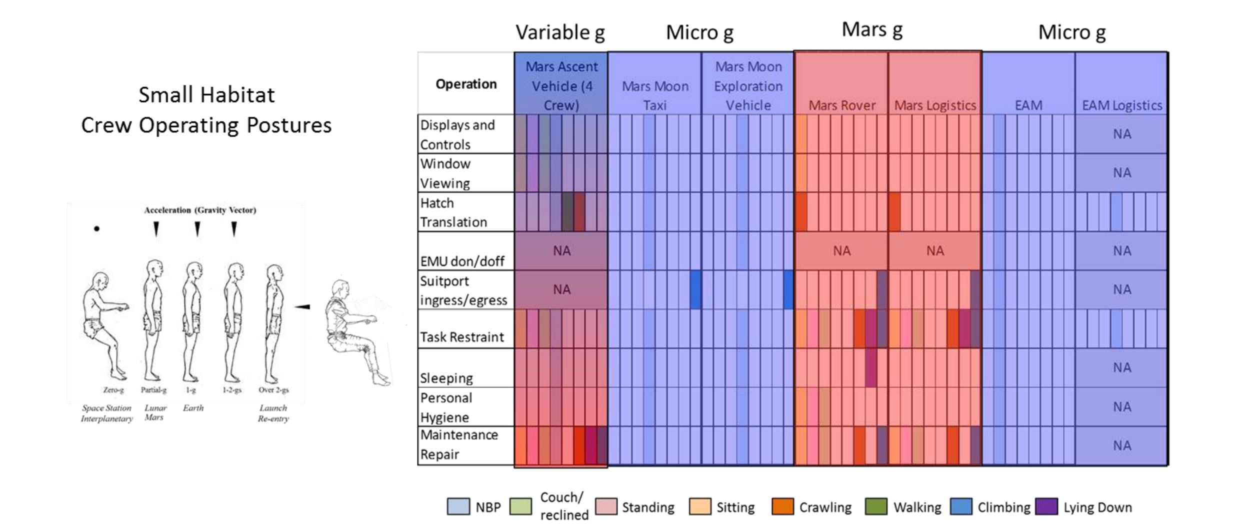


**Figure 16. A common habitat considers a range of space environments and crew operating postures.**

sufficient efficiency across all gravitational environments and mission applications. Figure 16 compares a broad range of postures against the EMC small habitats and their operating environments.

Vehicle weight drives most spacecraft decisions. This is why it was important to understand not only the overall dry mass, but the incremental increase in consumable mass required to support the crew. For the assumed maximum 14 day excursion, a "light-weight" open-loop ECLSS is preferred for the small habitats. Thus, there is a sensitivity not only for accommodating the consumables over the entire mission, but for the increased mass of crew systems based on duration. Crew accommodations are often represented in terms of mass per crew member per day, which implies the existence of a linear relationship, but it is actually more complex. Some items, such as food, for instance, can be represented with a linear relationship. However, there are significant step functions driven by the addition of various crew support equipment that the crew can do without in shorter durations and few standards that guide the exact break points where such items should be included. As an example, Figure 17 shows the consumables per day with step-function increases for a commode at 5 days and exercise device at 9 days. Five days for a toilet, however, is not a standardized rule, but is instead a design trade.

The EMC small habitats lend themselves to grouping according to similar attributes. The two-person, 14-day rover and the Mars-moon exploration vehicle are almost virtually the same cabin. They have very similar visibility requirements, the same crew size and mission duration, and very similar general mission objectives. They will need virtually identical crew accommodations equipment.

There is also a potential similarity between the four-person MAV and the Mars-moon Taxi. Both vehicles are

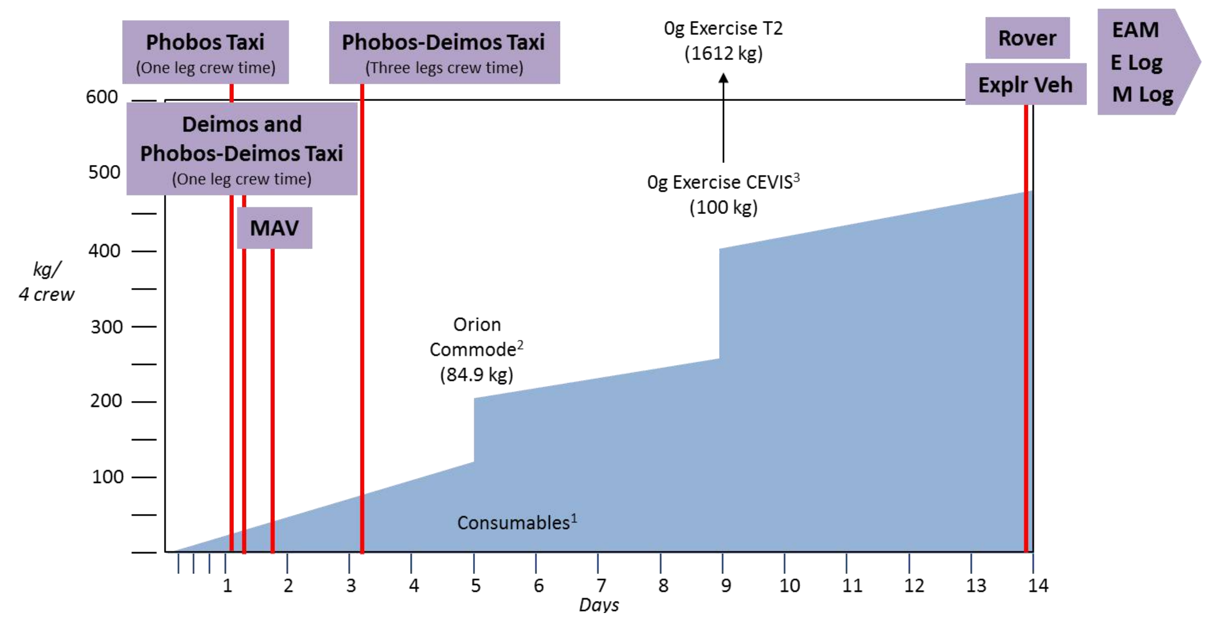


**Figure 17. Crew accommodation per day including possible step functions.**

transport craft – the MAV carrying four people from the surface of Mars to the deep space habitat and the Taxi carrying four people between the deep space habitat and Phobos/Deimos. If the MAV can be held to a 1-3 day mission (launch to docking), then it will have similar requirements as the Mars-moon Taxi.

The next small habitats that bear similarity to one another with respect to crew systems are the EAM and Mars surface logistics modules. While one operates in a gravitational environment and the other in microgravity, their function remains virtually identical. The act of transferring supplies in microgravity is different from that in a planetary environment and if unconstrained, such differences could lead to different hatch sizes, anchoring systems, etc., but if constrained, it is likely they can be brought to a point of identical commonality. Reconciliation might require one vessel be constructed of multiple copies of the other, just as intermodal shipping containers are transported together on Earth. This may in turn allow the logistics modules to share the same pressure vessel as the rover, exploration vehicle, MAV, and taxi. The final small habitat studied, the EAM, is arguably the least defined so there is a greater deal of uncertainty regarding its potential commonality with the other small habitats.



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**EVA**

The EVA System allows crewmembers in space suits to perform autonomous and robotically assisted extravehicular exploration, research, construction, servicing, and repair operations in pressure and thermal environments that exceed human capability. The EVA System also includes support hardware, such as don/doff stands, umbilicals for pre- and post-EVA operations, and hardware needed to maintain and resize suits during both ground and flight environments. While EVAs and suit maintenance will be performed from large habitats on the surface of Mars Moons and Mars surface, there are small habitats that also include EVA capability. In order to look at commonality from an EVA perspective, a high level assessment of EVA hardware and functionality per small habitat was performed to look at the number and types of suits in each, hardware, logistics, potential ingress/egress methods, and to gain a better understanding of the masses in each small habitat.

In the current EMC operational concepts, EVA functionality exists on small habitats such as the Mars Moon Exploration Vehicle, the Mars Rover and the EAM. EVAs can be performed using long umbilicals or Portable Life Support Systems (PLSS). A short high level mass and consumables study was performed to determine which method would be preferred. Consistent with findings of previous single vehicle architectures, it was found that performing EVAs with a PLSS would trade better if performing more than a few EVAs. EVA operational drivers such as having readily available, high-frequency EVA capability with dust mitigation and shorter prebreathes drive cabin atmosphere to an alternative atmosphere of 8.2 psi, 34% O2 in conjunction with the suitport concept (reference AIAA 2013-3399). This alternative atmosphere in turn impacts materials selection, suit mass, etc., while potentially saving on vehicle consumables and power. This is beneficial for the Mars Moon Exploration Vehicle and the Mars Rover. For other vehicles, such as the EAM, high-frequency EVAs are not necessary unless used for testing purposes to ensure the alternative atmosphere and suitport operations are vetted prior to use for the first time in the Mars vicinity. Currently, the EAM concept utilizes a sea-level atmosphere. Forward work should assess cabin atmosphere commonality and ingress/egress commonality with a large habitat. Dust mitigation and planetary protection are also factors to consider, which can drive ingress/egress concept design. While not all small habitats should be common by including EVA

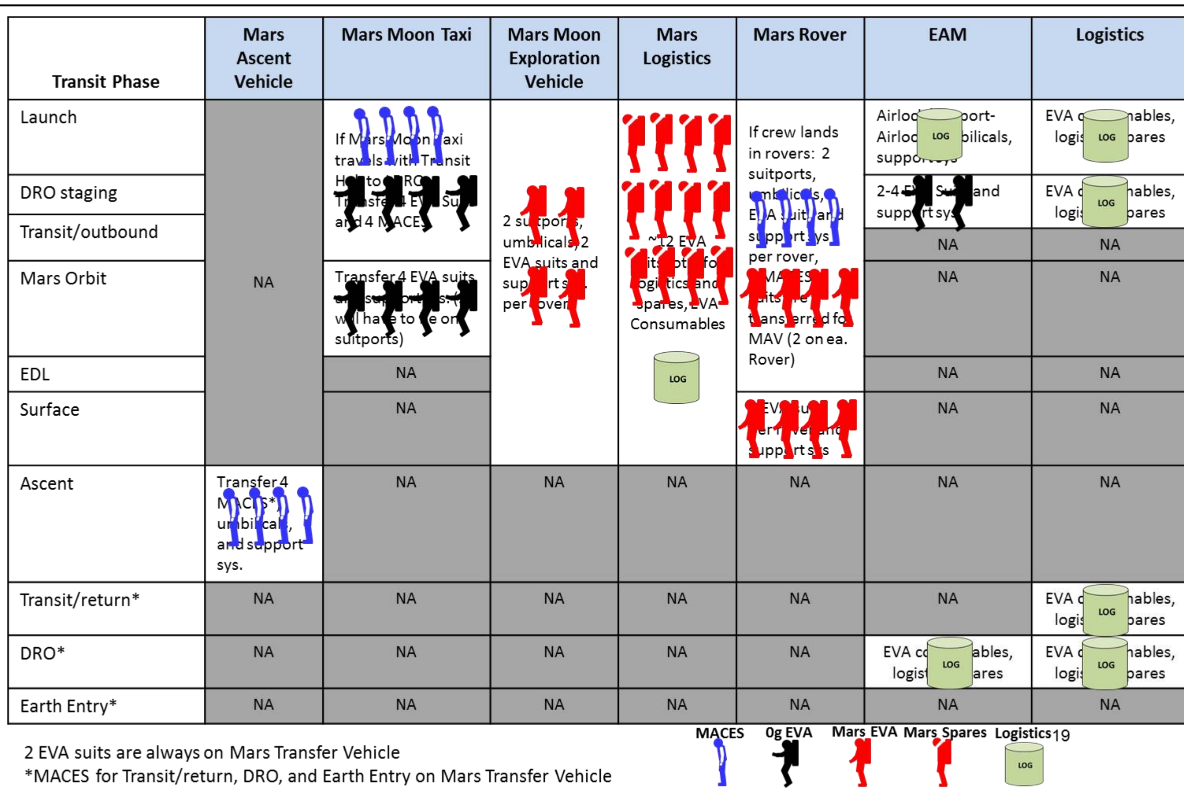


**Figure 18. Crew suits and spares for habitats by mission phases.**

functionality, those that do include EVA could all have common methods of ingress/egress. For example, the Mars Moon Exploration Vehicle, Mars Rover, EAM, and the Mars Taxi could all include suitports, suitport-airlocks, or suitlocks (possible commonality with the large habitat); however, past studies have shown that mobile elements (Mars Moon Exploration Vehicle and Mars Rover) should have an unpressurized enclosure (suitports) to cut down on mass and increase excursion range. The amount of ingress/egress architectures used across the EMC should be reduced as much as possible. Assuming the baseline for pressurized rovers is the suitport concept, and a large habitat includes the suitport-airlock (which has a pressurizable enclosure and is common with the suitport at a sub-system level), the rest of the elements/vehicles throughout the campaign could be reduced to two. Suitports, suitport-airlocks, and suitlocks all include a different hatch size through which the crewmember dons/doffs their suits through a vestibule hatch on a bulkhead. This helps mitigate dust inclusion into the habitat by preventing the crewmember from walking through the dust and keeps the dusty suit on the other side of the bulkhead. Dust could also be present near the EAM for potential asteroid missions. In addition to the suitport vestibule hatch, a larger hatch size (potentially 40" x 40") must be utilized on any habitat with EVA capability to allow a suited, pressurized crewmember to pass through for EVAs and contingency cases. Due to the different hatch sizes necessary to facilitate EVA capability, all hatches cannot be common across small habitats; however number of different hatches could be reduced to a suitport hatch, a 40" x 40" hatch, and a NASA Docking System hatch (not used for EVA).

The other small habitats in this study may include transfer of the EVA suits, but not the functionality to support EVAs. EVA equipment is transferred in the Mars Moon Taxi, MAV, and logistics modules. The Mars Moon Taxi can be common with the MAV, or it can be common with the Mars Moon Exploration Vehicle. The EVA suits must be checked out on-orbit prior to descent. Discussion is taking place on how 4 EVA suits and 4 crewmembers can fit on a Mars Moon Taxi common with a MAV. If the Mars Moon Taxi is common with the Mars Moon Exploration Vehicle, which includes suitports, two suits can be stowed on the suitports during descent to the moons, thus saving volume and potentially addressing this issue. This would also drive the atmosphere to an alternative atmosphere common with the Mars Moon Exploration Vehicles and Mars Rover.

Ingress/egress trades should be further reviewed as architecture and operational concepts are better defined. Commonality with other ingress/egress methods (large habitats) should also be considered. While not all small habitats should be made common by including EVA capability, elements/vehicle with EVA capability can include common EVA subsystems (PLSS recharge), common hatches (suitport, 40" x 40"), and common ingress/egress methods to the extent possible (suitports, suitport-airlock).

### Micrometeoroid Orbital Debris Protection

Different EMC spacecraft may require protection against micrometeoroid or orbital debris impacts, which can degrade performance, shorten operational life, or cause catastrophic failure (Christiansen, 2009). Protection needs will vary depending on how long each craft remains in a particular environment. For example, spacecraft loitering more than a few weeks in Earth vicinity during operation, staging, or assembly will be exposed to both naturally occurring micrometeoroids and human-generated orbital debris, whereas a vehicle

| Element | Exposure Duration (Days) | | | | Do We Need Shields? | Rationale |
|---|---|---|---|---|---|---|
| | Cis-Lunar Aggregation | Transit | Destination | | | |
| | | | Orbit | Surface | | |
| EAM | - | 365 | 270-300 | - | Yes | Long exposure duration |
| Mars Transit Habitat | 183 | 183 | 365-1095+ | - | Yes | Near-Earth orbital debris exposure + long Mars orbit exposure |
| Phobos Taxi | 183-365 | 365 | 365 - 548 | - | Yes | Near-Earth orbital debris exposure + long Mars orbit exposure |
| Phobos Hab | - | 365 - 1204 | 730 | 365-1095+ | Yes | Very long exposure durations |
| Mars Surface Hab | - | 1351 | - | 500+ | Probably in transit | Trade shield mass vs. risk of repair in Mars orbit before landing |
| Mars Pressurized Rover | - | 1351 | - | 500+ | In transit | Depends on whether it's exposed or encapsulated in transit |
| Mars Ascent Vehicle | - | 1351 | - | 730 | In transit | Possibly remove shields for ascent, if ascent is short and MAV is not re-used |

**Figure 19. Estimated duration for small habitat considering delivery and long periods of dormancy.**



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operating primarily in Mars orbit will only have to contend with the micrometeoroid environment. Spacecraft that can rely on other elements for protection--such as inside a Mars entry aeroshell or shielded behind other elements in a vehicle stack—may need little additional protection.

Where additional protection is required, a common micrometeoroid/orbital debris shield is desired—though that may not be entirely practical. In fact, different parts of the *same* spacecraft may have different shielding requirements. Micrometeoroid/orbital debris shields are typically designed to meet a protection requirement, set by the Program, and usually specified as a Probability of No Penetration (PNP) over a given period of time. For example, critical elements of the International Space Station (ISS) are shielded to 0.98 to 0.998 PNP over 10 years (Christiansen, TP-2003-210788, Meteoroid/Debris Shielding, 2003). Typical micrometeoroid/orbital debris protection is provided by one or more layers of protective material placed at a precise separation distance from the critical item. Choice of shield material, number of layers, and spacing between layers is optimized for a given environment and PNP requirement, but must also accommodate vehicle-specific needs, such as hull curvature or thermal control.

Micrometeoroid shielding can be retrofit to existing spacecraft, but the most cost-effective approach is to include—or at least scar for—shielding early in the design process. Although it may not be possible to design a common shield assembly for all EMC elements, shield materials and attachment mechanisms could likely be standardized. A conservative mass estimate for current materials of construction is about 20 kg per square meter of shielding, not including the stand-offs that provide separation. See Fig. 19 for estimated duration times. Pending more detailed design work, a 10 cm stand-off distance is assumed for EMC elements; note that this effectively increases the diameter of each EMC element by up to 20 cm and must be accounted for when integrating with a launch shroud.

## IX. Configuration Validation

The transportation "intermodal" cargo container system (Fig. 20) provides a common structural interface that allows many options for stacking, handling and transporting a great variety of cargo. Part of our commonality approach was modeled after the intermodal system in order to provide the same benefits from launch packaging to operations in space. Initial studies assumed a 3m diameter pressure vessel as a common cabin cylinder among all small-volume functions in the Evolvable Mars Campaign. This dimension provided a reasonable starting point for accommodating the internal outfitting for a crew of four in both weightless or Mars gravity. Furthermore, this diameter provided the necessary surface area and adjacent volume to allow side-by-side suitports for EVA operations (Fig. 21). The initial "strawman" cabin dimensions provide a reasonable starting point for commonality assessments; they are neither arbitrary nor optimized. With the goal of maximizing commonality, not only was a common pressure vessel geometry established, but so was the orientation. Because habitats like the Mars rover and logistics elements have a strong preference for a horizontal orientation and


**Figure 20. Standardized interfaces served as a model for the common core structural system.**

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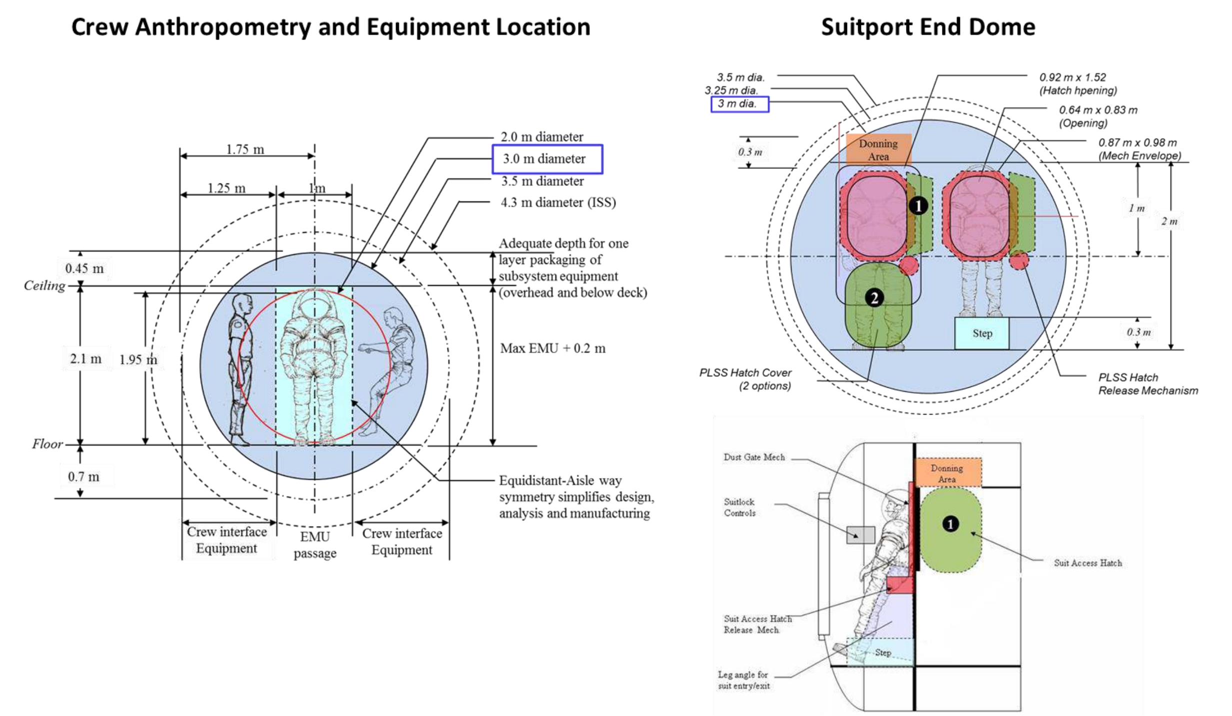


**Figure 21. Initial diameter accommodates 4 crew all postures and side-by-side suitports.**

others do not, this orientation was selected as a baseline. (See Fig. 22) Another factor in selecting the horizontal over vertical is that changes in the vertical orientation often require a change in diameter. Even the smallest change in diameter has a significant impact to manufacturing whereas there are minimal changes with stretching the barrel length.

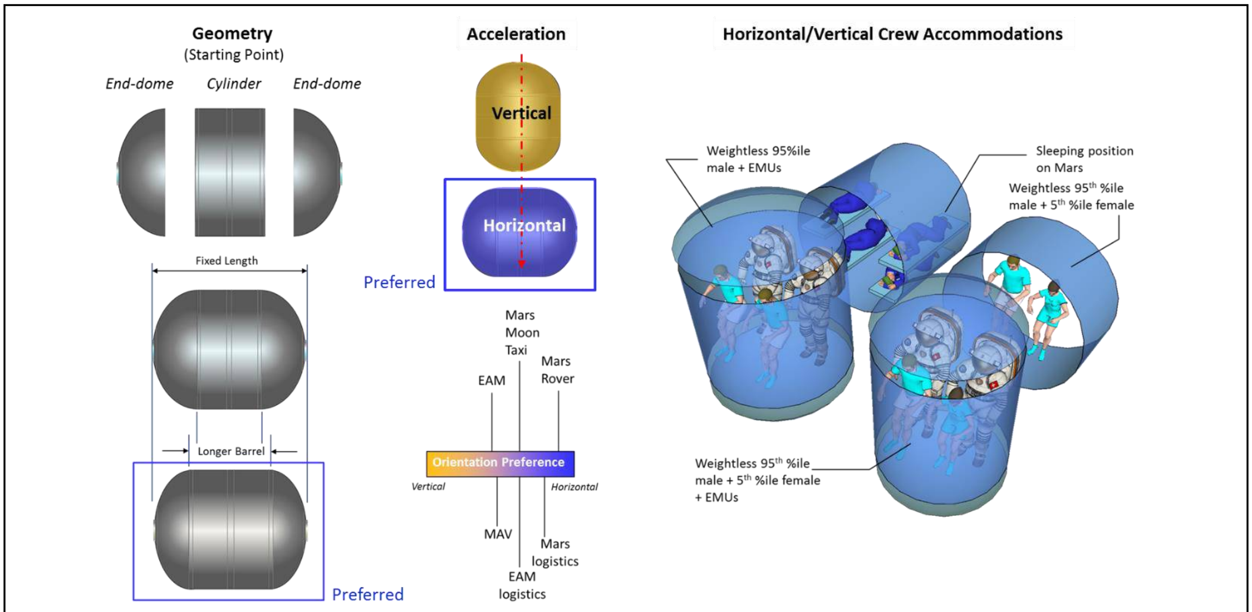


**Figure 22. Horizontal orientation preferred for common habitat geometry.**

The EMC small habitat concept for "intermodal" operations incorporates a structural channel ring frame joining the cylinder to the endcones. The channel legs protrude above the skin and have equally spaced holes allowing structural attachment to transportation stages, propellant tanks, mobility systems, radiators, solar arrays and other external hardware. The pressure vessel skin uses an external iso-grid providing node points for attaching thermal insulation and micrometeoroid debris paneling as well as a smooth interior surface for cleaning. (See Fig. 23)

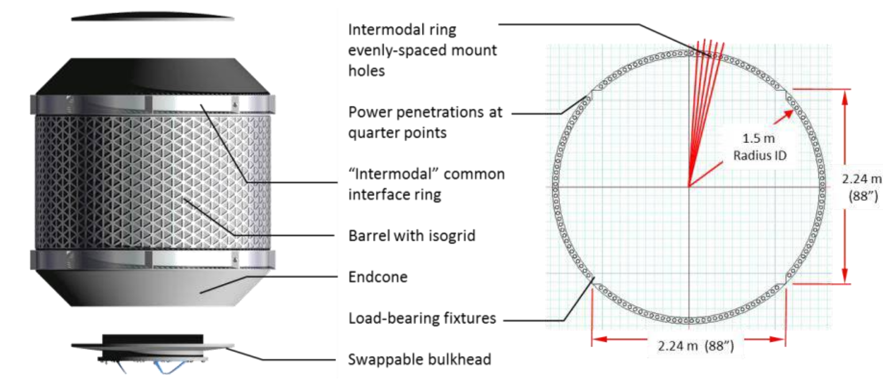


**Figure 23. Common pressure vessel with channel ring frame attachment.**

Module diameter is the result of a calculated balance between internal and external accommodations. For external, there is an incentive to make it small for reduced mass as well as launch packaging on the lander deck. For internal outfitting, the 3m diameter allows for both weightless and gravity operations using a 2m spacing between decks shown in Figure 24. This allows an efficient use of the cylinder geometry while reserving adequate depth above and below decks for subsystem packaging.

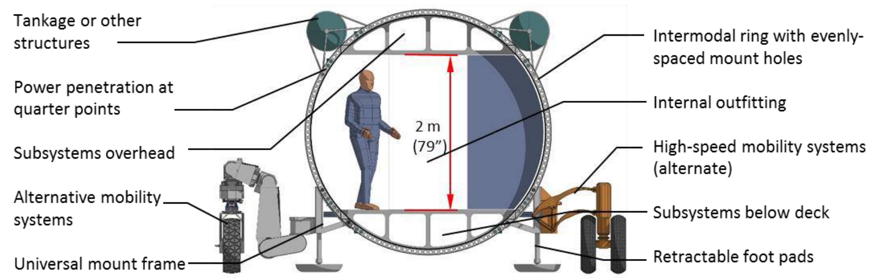


**Figure. 24. Common deck spacing for weightless and gravity operations.**

In addition, a system of swappable bulkheads has been established to allow for identical pressure vessels to be tailored with unique endcones. Swappable bulkheads have been sized to accommodate a variety of heritage docking systems, such as an exploration bulkhead and NASA Docking System (NDS).

Using the swappable bulkhead method, a cockpit for a variety of space and surface vehicles can use the common cabin and allow for a pilot station with windows and clear visibility (Figure 25). Identical small cabin vehicles that have been designed include Exploration Augmentation Module (EAM), EAM Logistics Module, Crew Taxi, Mars Moon Exploration Vehicle (MMEV), Mars Rover, and Mars surface pressurized logistics (Figure 26).

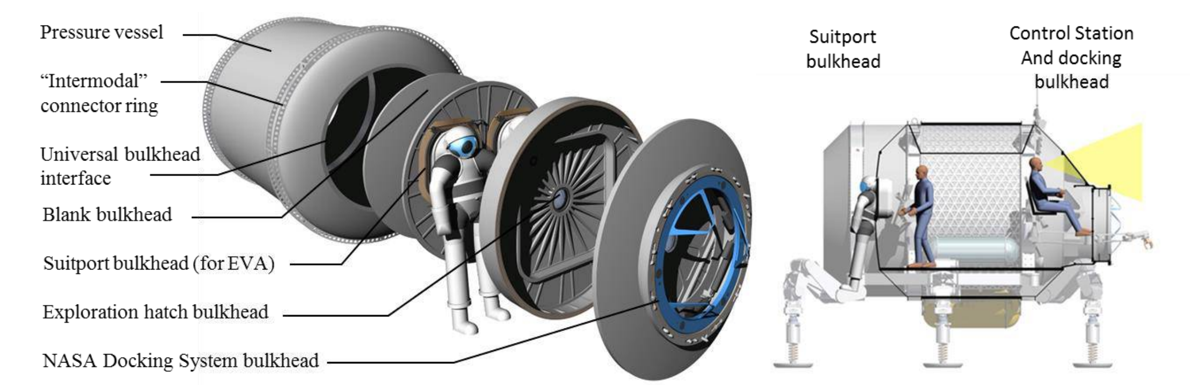


**Figure 25. Swappable bulkheads establish common interface for tailoring each habitat.**



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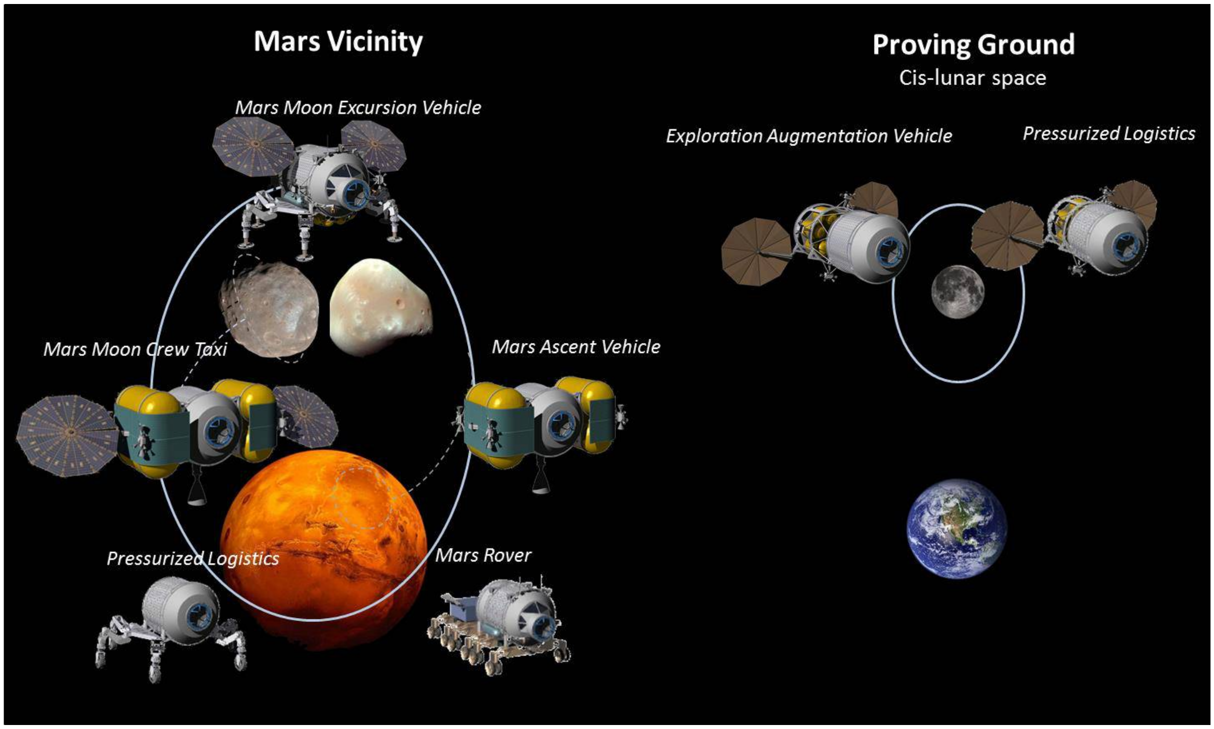


**Figure 26. Notional configurations showing maximized EMC small habitat commonality.**

## X. Conclusions

For the EMC, new analytical tools have been created offering an early and on-going objective measure of cost savings using commonality. This is significant because human Mars missions must identify and demonstrate cost savings early in an environment where traditional cost estimating models are designed for more mature designs. It is no surprise that commonality will reduce cost; this is standard practice in the commercial world. The challenge for NASA will be procurement. The number and pace of deliverables calls for a creative solution that is front loaded for core commonality allowing changes and upgrades without diminishing the benefits of consolidated DDT&E.

## XI. Acknowledgements

The team would like to recognize the participation of the SMEs for design guidance and their essential contribution to the MEL. There is no commonality assessment without their input. These are the SMEs that supported maximizing commonality for the EMC Small Habitats: Jeff Cerro, Jack Chapman, Steve Chappell, Leo Fabisinski, Robert Howard, Ruthan Lewis, Natalie Mary, Michelle Rucker, Imelda Stambaugh and Steve Sutherlin.

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