Design and Development of a Methane Cryogenic Propulsion Stage for Human Mars Exploration

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NASA is currently working on the Evolvabe Mars Campaign (EMC) study to outline transportation and mission options for human exploration of Mars. One of the key aspects of the EMC is leveraging current and planned near-term technology investments to build an affordable and evolvable approach to Mars exploration. This leveraging of investments includes the use of high-power Solar Electric Propulsion (SEP) systems evolved from those currently under development in support of the Asteroid Redirect Mission to deliver payloads to Mars. The EMC is considering several transportation options that combine solar electric and chemical propulsion technologies to deliver crew and cargo to Mars. In one primary architecture option, the SEP propulsion system is used to pre-deploy mission elements to Mars while a high-thrust chemical propulsion system is used to send crew on faster ballistic transfers between Earth and Mars. This high-thrust chemical system uses liquid oxygen – liquid methane main propulsion and reaction control systems integrated into the Methane Cryogenic Propulsion Stage (MCPS). Over the past year, there have been several studies completed to provide critical design and development information related to the MCPS. This paper is intended to provide a summary of these efforts. A summary of the current point of departure design for the MCPS is provided as well as an overview of the mission architecture and concept of operations that the MCPS is intended to support. To leverage the capabilities of solar electric propulsion to the greatest extent possible, the EMC architecture pre-deploys the required stages for returning crew from Mars. While this changes the risk posture of the architecture, it provides mass savings by using higher-efficiency systems for interplanetary transfer. However, this does introduce significantly longer flight times to Mars which, in turn, increases the overall lifetime of the stages to as long as 3000 days. This unique aspect to the concept of operations introduces several challenges, specifically related to propellant storage and engine reliability. These challenges and some potential solutions are discussed. Specific focus is provided on two key technology areas; propulsion and cryogenic fluid management. In the area of propulsion development, the development of an integrated methane propulsion system that combines both main propulsion and reaction control is discussed. This includes an overview of potential development paths, areas where development for Mars applications are complementary to development efforts underway in other parts of the aerospace industry, and commonality between the MCPS methane propulsion applications and other Mars elements, including the Mars lander systems. This commonality is a key affordability aspect of the Evolvable Mars Campaign. A similar discussion is provided for cryogenic fluid management technologies including a discussion of how using cryo propulsion in the Mars transportation application not only provides performance benefits but also leverages decades of technology development investments made by NASA and its aerospace contractor community.

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Nomenclature

ΔV	=	Propulsive Delta Velocity (m/s)
ARM		Asteroid Redirect Mission
AR&D		Approach, Rendezvous & Docking
CFM		Cryogenic Fluid Management
EMC		Evolvable Mars Campaign
EOI		Earth Orbit Insertion
GN&C		Guidance, Navigation & Control
LDHEO		Lunar Distant High Earth Orbit
LDRO		Lunar Distant Retrograde Orbit
LEO		Low Earth Orbit
MAV		Mars Ascent Vehicle
MCPS		Methane Cryogenic Propulsion Stage
MDV		Mars Descent Vehicle
MOI		Mars Orbit Insertion
MPCV		Multi-Purpose Crew Vehicle
MPS		Main Propulsion System
RCS		Reaction Control System
SEP		Solar Electric Propulsion
SLS		Space Launch System
TEI		Trans Earth Injection
TLI		Trans Lunar Injection
TMI		Trans Mars Injection
TRL		Technology Readiness Level

I. Introduction

NASA is currently developing a new long-term strategy to expand human exploration of space beyond the confines of low Earth orbit and into the solar system. This Pioneering Space strategy focuses on evolving space exploration capabilities from our current Earth Reliant state, through a cis-lunar Proving Ground of technology demonstrations and incrementally more challenging human space flights, to an Earth Independent state where crews of astronauts live and work on the surface of Mars. To provide the context for identifying and prioritizing technology investments along that path to Mars, the Evolvable Mars Campaign (EMC) is supporting an ongoing series of architectural trade analyses. The EMC is integrating teams from across NASA to investigate common capability needs across three broad areas; transportation, habitation, and destination systems. At its core, the EMC is not a study to define the next Mars design reference mission, but rather a series of ongoing studies designed to understand the potential future paths for human Mars exploration within the context of the Pioneering Space strategy, placing emphasis on affordability, sustainability, and reusability.

The Pioneering Space strategy is built on a set of key principles for a sustainable and affordable space program that help ensure NASA's investments efficiently and effectively achieve the nation's space exploration goals. These principles include:

- Implementable in the ***near-term with the buying power of current budgets*** and in the longer term with budgets commensurate with economic growth;
- ***Exploration enables science and science enables exploration***, leveraging robotic expertise for human exploration of the solar system;
- Application of ***high Technology Readiness Level*** (TRL) technologies for near term missions, while focusing sustained investments on ***technologies and capabilities*** to address challenges of future missions;
- ***Near-term mission opportunities*** with a defined cadence of compelling and integrated human and robotic missions providing for an incremental buildup of capabilities for more complex missions over time;
- Opportunities for ***U.S. commercial business*** to further enhance the experience and business base;
- ***Multi-use, evolvable*** space infrastructure, minimizing unique major developments, with each mission leaving something behind to support subsequent missions; and

- Substantial ***new international and commercial partnerships***, leveraging the current International Space Station partnership while building new cooperative ventures.

The EMC team has been working to identify and evaluate a suite of potential mission architectures, integrating transportation, habitation, and destination systems in a mission construct that supports successful human Mars exploration within the guidelines of the Pioneering Space strategy. Several papers are being published at the AIAA Space 2016 conference by these various teams to provide an overall picture of the breadth and depth of the ongoing EMC work.

A key component of the Mars exploration plan is liquid oxygen – liquid methane propulsion. This capability is leveraged not only for the Mars Descent Vehicle (MDV) and Mars Ascent Vehicle (MAV), but also for in-space transportation of crew to and from the Martian system using a mission element known as the Methane Cryogenic Propulsion Stage (MCPS). The common use of this methane propulsion system across many elements of the architecture offers a potential reduction in development and production costs by limiting the number of engine development programs, and increasing the number of flight units required for the execution of the overall campaign. Reliability of the MDV and MAV is also increased by accumulating operational time on the engine design through the use of multiple MCPS in the initial Mars orbital mission of the campaign. Finally, the use of methane propulsion for Mars dovetails with past, current, and planned technology investments, expanding on previous work, leveraging current work within and outside of NASA, and laying the groundwork for future, improved in-space transportation technologies.

This paper provides an overview of the recent work completed in the design and planning of the MCPS and the methane propulsion system at its core. The EMC split Solar Electric Propulsion (SEP)-Chemical campaign and key mission attributes are discussed to provide context for the requirements used to design the MCPS. The most recent round of bottoms-up MCPS design work is outlined including performance sensitivity analyses. Finally, an overview of the potential development path for key technologies of the integrated methane propulsion system is provided, including technology needs and projected timelines for development.

II. A Brief Overview of the Evolvable Mars Campaign

The EMC does not seek to prescribe a particular path for exploring Mars, but rather seeks to better clarify and understand the various paths available to help guide the next 20 years of technology developments as NASA moves closer to its long-term goal of sending humans to Mars. A small set of ground rules and constraints guide the various trade analyses and design studies being performed. These ground rules include:

- Humans to the Mars System by mid-2030's
- Propulsion technology will utilize solar-electric systems extensible from the Asteroid Redirect Vehicle spacecraft bus
- Earth-to-Orbit SLS Block 2 launch vehicle and Orion spacecraft will be available
- Vehicle checkout and assembly (aggregation) in a lunar distant retrograde orbit (LDRO) to leverage infrastructure established during Proving Ground phase
- Crew of four to Mars system
- Crewed vehicle reusability for sustainability and potential cost advantages where reasonable

Several different general transportation architecture approaches are being investigated as part of the ongoing EMC study. These options leverage the investments in high-power SEP being made to support the Asteroid Redirect Mission. One such transportation architecture approach currently being investigated is referred to as the SEP-Chemical approach. This family of architecture options splits the functions of crew and cargo delivery into two distinct transportation approaches. High-efficiency SEP is used to deliver all cargo to Mars, including Phobos exploration elements, Mars landers, and crew Earth return stages. These cargo delivery flights, while longer in duration, can be achieved in single launches using the Space Launch System (SLS) Block 2 vehicle. Flight time reductions can be realized by increasing the number of SLS launches used to emplace these elements, or by increasing the power of the SEP vehicle.

While slower trajectories may be acceptable for cargo elements, the crew flight duration must be significantly shorter to minimize the impacts of zero gravity and prolonged radiation exposure. The SEP-Chemical architectures employ the MCPS for these crew flights, using more traditional high-thrust, conjunction-class trajectories. Previous Mars exploration studies have not considered methane propulsion as a means for interplanetary flight because the specific impulse of such a systems is approximately 100 seconds lower than that of the liquid oxygen – liquid hydrogen systems considered in many of the past Mars architecture studies, including NASA's Design Reference Mission 5.0[1]. However, some unique aspects of the SEP-Chemical architecture enable the use of these lower-performing methane stages which allows mission designers to side-step some of the technical challenges associated with long duration liquid hydrogen storage.

III. The SEP-Chemical Architecture

While there are several architecture options currently under investigation in the EMC, the MCPS is primarily being considered for use in the SEP-Chemical architecture. The SEP-Chemical architecture uses a traditional chemical propulsion approach to crew delivery and places technology development focus on long-duration cryo fluid management. Cargo, including Earth return propulsion, landers, and exploration equipment, is pre-deployed using high-efficiency SEP stages. The following section provides an overview of the current baseline SEP-Chemical transportation architecture and provides insight into the functional requirements of the MCPS.

A. Mission Sequence of the Campaign

The baseline EMC SEP-Chemical campaign consists of three, progressively more challenging human Mars exploration missions. In 2033, a crew of 4 will depart on the first human mission to Mars and will explore the Martian moon Phobos. This mission will be followed in 2039 by the first human landing on Mars. The crew of 4 will spend the bulk of their stay living, working, and exploring on the surface of Mars. In 2043, a new crew will return to the same landing site to continue Mars surface exploration, building on the infrastructure remaining after the first surface mission. After these three initial missions a steady cadence of surface missions would continue but the steady-state phase of Mars surface exploration is beyond the scope of the emplacement phase being studied by the EMC teams.

For each of the three missions, several elements are pre-deployed to Mars using a high-power SEP vehicle. The Phobos mission requires a Phobos habitat for the crew to work out of during their stay in the Martian system. Each surface mission requires multiple Mars Descent Vehicles to land surface equipment and crew on Mars. All three missions pre-deploy the Earth return propulsion systems to Mars where the crew will rendezvous with them upon arrival in the Martian system. Pre-deployment of the Earth return stages greatly reduces the stack size for crew flights to Mars. However, due to the relatively low power levels of the current SEP vehicle design, these stages are launched into space up to 7 years prior to being used, setting a requirement for these stages to operate after very long periods of dormancy.

Each SEP pre-deployment flight is launched by a single SLS Block 2 launch vehicle to an elliptical Earth orbit with an apogee determined by the total wet stack mass of the SEP vehicle and its payload. The SEP vehicle then performs a slow spiral trajectory to climb towards Earth escape. All crew flight stacks are launched piece-by-piece to the LDRO where they are assembled. The completed crew flight stack is then transferred to a Lunar Distant High Earth Orbit (LDHEO) where the crew meets the stack, transfers into the transit habitat, and departs for Mars. An overview of the flights that make up the current baseline 3-mission campaign is provided in Figure 1. A more complete overview of the SEP-Chemical campaign can be found in Reference 2.

B. Derived Requirements for Flight Regimes of the Methane Cryogenic Propulsion Stage

The unique combination of long-duration SEP flights and LDRO aggregation brings with it a diverse set of operational requirements for the MCPS. In order to set the stage for the design update performed earlier this year, a complete review of the concept of operations was performed identifying the key driving requirements for the MCPS. Among the goals of this effort was the identification of operating environments and operational lifetime requirements. General functional requirements identified include the ability to operate as a free-flying, autonomous spacecraft and the ability to dock with various mission elements including other MCPS and habitation modules. The ability to store cryogenic liquid propellants for long durations at very low loss rates led to a requirement for active cryogenic fluid management (CFM) and the ability to produce the associated power required to run those systems. Analysis of functional requirements focused on the two different flight regimes experienced by the MCPS in the architecture; that of a pre-deployed mission element and that of an active crew flight element.

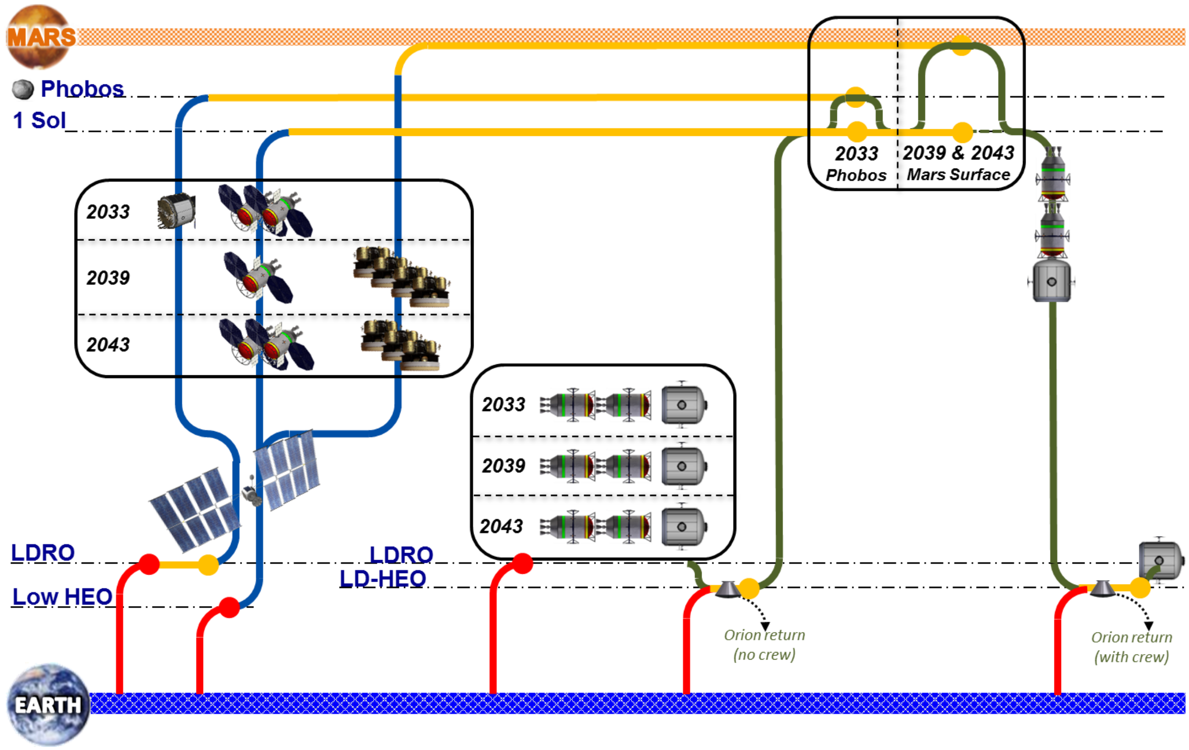

Figure 1. Overview of the Baseline SEP-Chemical Architecture for the Evolvable Mars Campaign. *The SEP-Chemical architecture consists of a series of pre-deployment flights using a 150 kW SEP vehicle followed by crew flights to Mars using traditional high-thrust conjunction-class trajectories with methane propulsion systems. Pre-deployed elements are launched with their SEP vehicles while crew elements are stacked in LDRO prior to Earth departure.*

1. Pre-Deployed Mission

The pre-deployment of MCPS involves five phases; low-thrust Earth escape, low-thrust interplanetary flight, Mars Orbit Insertion (MOI), loiter in Mars orbit, and rendezvous and dock with crew elements. Many of these phases are driven by the mass of the MCPS being delivered, a value that can range from 20t to 50t depending on the flight opportunity and burn allocation. As the mass of the MCPS increases, the low-thrust portions of the pre-deployment will be extended and the propellant required for MOI will also increase. During the Earth escape phase of pre-deployment, the MCPS and SEP vehicle are launched by an SLS Block 2 launch vehicle to an elliptical orbit with an apogee that is driven by the combined weight of the Mars elements. With a perigee fixed at 200 km altitude, the apogee of the initial parking orbit can vary from 6,000 km to 105,000 km altitude for the range of MCPS sizes required for the architecture. The slow spiral trajectory is longer for lower initial apogees and spiral times can range from 4 months to 3 years. Two typical altitude profiles are provided in Figure 2. Spiral profiles provide insight into the operational environments experienced by the MCPS, specifically the thermal environments that contribute to the design of the CFM system required to store the cryogenic propellants.

Once the SEP vehicle stack has escaped from Earth, the interplanetary flight phase begins. While steadily increasing the distance from the Sun, the low-thrust interplanetary trajectories still take from 435 – 865 days to complete. The end destination for the pre-deployed MCPS is a 10 Sol Mars parking orbit. It is here that these pre-deployed stages will meet with the crew transit habitat to support Mars departure and Earth arrival for the crew return trip. The current SEP vehicle design does not provide adequate power to support a propulsive capture using the SEP thrusters at Mars due to the size of the solar arrays and the distance from the Sun. This necessitates a propulsive capture using the MCPS. In order to minimize the impact to the size of the MCPS, the ΔV for the MOI maneuver is minimized using a combination of two techniques. First, the 10 Sol parking orbit at Mars provides a

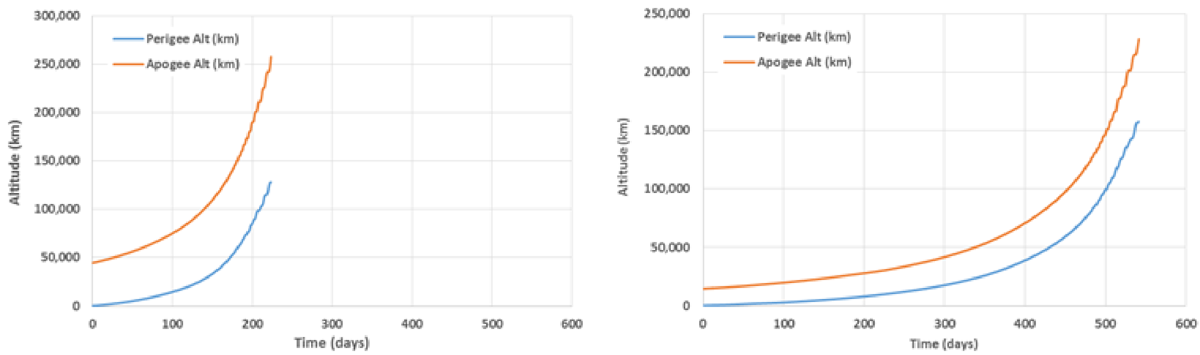

Figure 2. Earth Escape Spiral Profiles. *Several of the MCPS in the SEP-Chemical architecture are pre-deployed to Mars using SEP vehicles. These pre-deployment flights begin with an Earth escape spiral maneuver during which the Earth parking orbit is slowly raised. These two graphs show two typical perigee and apogee altitude time profiles. The graph on the right represents a larger MCPS stack with a lower initial apogee and a longer spiral while the graph on the left represents a lighter MCPS stack with a higher initial apogee a shorter spiral.*

very high periapse velocity to close the velocity gap between the incoming hyperbolic trajectory and the parking orbit. This gap is further reduced by using the high-efficiency SEP propulsion during interplanetary flight to reduce the Mars arrival velocity to 0.5 km/s. The total MOI phase ΔV budget includes the initial orbit insertion burn and additional accomodations for orbit maintenance and alignment.

After completing the MOI phase of the pre-deployment, each MCPS will spend time loitering in the 10 Sol orbit while awaiting the arrival of the crew transit habitat. This loiter duration is highly dependent on the launch phasing of elements, but can be as long as 2 years. When the crew stack does arrive at Mars, the pre-deployed stages will perform rendezvous and dock maneuvers to attach to the crew transit habitat. Once stage capture has been completed, the remainder of the mission will be carried out. The pre-deployed stages will complete the transfer to a 1 Sol orbit and perform orbit maintenance while the crew is on the surface of Mars. Upon completion of the surface mission, the pre-deployed stages will provide the Trans Earth Injection (TEI) and Earth Orbit Insertion (EOI) burns for the crew transit habitat. Mars stay times range from 350 to 530 days for the opportunities being considered and Earth return flight times range from 200 to 350 days. Looking at the duration requirement for each individual stage for the specific opportunities investigated, it was determined that the maximum in-space duration for an MCPS will be the nearly 3000 day lifetime of the pre-deployed TEI/EOI stage used in the 2039 crew mission.

2. Active Crew Flight

The second flight regime, the active crew flight regime, yields a different set of functional requirements. The active crew flight regime encompasses time spent aggregating with and actively flying the crew transit habitat to and from Mars. This flight regime consists of 4 phases; aggregation, planetary departure, active flight, and planetary arrival. The active crew flight elements perform all propulsive maneuvers connected with the transfer of crew to and from Mars. The MCPS for Trans Mars Injection (TMI) and MOI are connected to the transit habitat at Earth, while the TEI and EOI stages are pre-deployed to Mars and connected with the transit habitat in Mars orbit as described above. Aggregation at Earth takes place in the LDRO around the Moon. The stages must be capable of performing automated rendezvous and docking with other elements in LDRO, and will be required to loiter in LDRO until the crew stack is completed. Once complete, the crew stack is moved from LDRO to a LDHEO through a series of small propulsive and lunar gravity assist maneuvers. Once in LDHEO, the crew will meet the transit habitat in an Orion Multi-Purpose Crew Vehicle (MCPV), transfer into the habitat, undock Orion and target an Earth departure burn at perigee of the LDHEO. The TMI MCPS performs the TMI maneuver and is jettisoned. The MOI MCPS performs any trajectory corrections required during the active flight phase to Mars, and then performs the MOI maneuver to capture into a 10 Sol orbit upon arrival at Mars. The MOI MCPS then guides the habitat through rendezvous and docking with the pre-deployed stages and is jettisoned once the docking is completed.

Operations in the 10 Sol orbit very closely resemble the rendezvous and dock operations of an aggregation phase and mark the beginning of the active crew flight regime for the pre-deployed stages. Most crew flight opportunities will pre-deploy two MCPS, one for Mars departure and one for Earth arrival. However, in the 2039 flight opportunity, these two functions are combined into one MCPS. Whether one or two stages, the pre-deployed elements must perform rendezvous and dock maneuvers with the transit habitat in the 10 sol orbit and then transfer the stack to the 1 Sol Mars parking orbit. While in that orbit, the stages perform station keeping and orbital realignment while the crew explores the surface of Mars. When the crew is ready to return to Earth, the MCPS will perform a sequence of maneuvers to raise the Mars parking orbit and align for TEI. The Mars departure and Earth arrival burns are performed in much the same way as the TMI and MOI burns on the outbound leg of the crew mission. Upon Earth arrival, the crew transfers into an Orion MPCV to return to Earth's surface, and the EOI MCPS returns the transit habitat to LDRO for refurbishment and reuse on the next crew flight to Mars.

C. Derived Requirements of the Methane Cryogenic Propulsion Stage

A review of the two flight regimes identifies several functional requirements for the MCPS. The requirement for automated rendezvous and docking requires the MCPS to be capable of operating as a free-flying spacecraft. A suite of sensors, including a full complement of guidance, navigation, and control systems, and docking hardware must be provided and the stage must be capable of independently determining its state. The periods of free flight, in transit to the LDRO as well as loitering in both LDRO and Mars orbit, require some limited communications capability to transmit housekeeping data. Independent flight also implies that the stage must be capable of providing its own power. Additionally, the requirements for active CFM drive the required power levels beyond the capability of batteries, implying the need to include solar arrays in any MCPS design.

Flight environments and durations are key metrics for determining what is required of the CFM systems. Thermal environments for this mission are most extreme in orbit around Earth, the moon, and Mars. As the SEP vehicle slowly spirals up through Earth's gravity field, the albedo effect of the Earth is slowly reduced. The LDRO orbits the Moon at approximately 80,000 km altitude, somewhat diminishing the Moon albedo effect. The distance of Mars from the Sun reduces the overall thermal environment challenges of long duration Martian orbit. However, a detailed thermal analysis was required, accounting for environment and duration as well as orientation to the Sun, to fully understand which phases are the thermal drivers for CFM. This analysis is detailed in the following section.

Several propulsion requirements are also derived from the functional view of the concept of operations. Many applications of the MCPS require at least one main engine restart during the course of the mission. In the case of the 2039 Earth return stage, the main engines must be started twice with nearly 300 days of interplanetary flight between those two starts, necessitating the inclusion of a robust main propulsion system (MPS) purge system to ensure survival of the dormancy period. There are also several instances of burns which are relatively low ΔV but require steady state operation of a propulsion system. These maneuvers include the MOI burns for the pre-deployed stages as well as powered lunar gravity assist maneuvers during the transit to LDRO both during aggregation and during repositioning of the transit habitat after Earth return. These burns, if completed with the MPS, would be very short in duration, many less than 1 minute. In order to minimize the impact to the main propulsion system and reduce the number of main engine starts, it was decided that the requirement to perform these burns would be absorbed by the reaction control system (RCS), leading to a unique RCS design. Additionally, the duration of the MCPS operations (up to 3000 days) led to the requirement for very low leakage valves to minimize propellant loss.

IV. Design of the Methane Cryo Propulsion Stage

The general concept of a methane-based in-space transportation stage has been considered for human Mars missions for several years now. While chemical in-space propulsion for larger missions has often led to the assumption of the higher performing hydrogen-based systems, there are several technical challenges associated with the long term storage of hydrogen in space. By comparison, liquid-oxygen / liquid-hydrogen stage concepts typically assume specific impulse values around 460 seconds, while a typical liquid-oxygen / liquid-methane engine may provide somewhere between 340 and 375 seconds of specific impulse, depending on the selection of an engine cycle. However, the storage temperatures of methane are considerably higher than hydrogen and much closer to those temperatures required for oxygen. The storage density of methane also provides additional design benefits. The challenge, then, is to find a way to overcome the reduction in specific impulse in order to take advantage of the technology and design benefits of methane.

When the Evolvable Mars Campaign study began, investigators looked for operational opportunities to reduce the energy requirements of in-space transportation systems to find ways around requiring the extreme performance of hydrogen-based stages. Previous Mars architectures have limited aggregation to Low Earth Orbit (LEO) to maximize the mass lofted to orbit, but this greatly increases the Earth departure energy requirement. By taking advantage of the SLS lift capacity to Trans Lunar Injection (TLI), the EMC mission profiles aggregate in cis-Lunar space and depart from LDHEO. Departure from LDHEO greatly reduces the energy requirement for the TMI burn, where the crew transit stack is its heaviest. Pre-deployment of the Earth return stages also reduces the crew transit stack mass at Earth departure which also reduces the amount of propellant required for both Earth departure and Mars arrival. The SEP vehicle efficiently performs this pre-deployment. While this does introduce a new risk to the mission concept of operations, this pre-deployment in concert with departure from high Earth orbits, enables the use of the methane propulsion systems and avails program managers of the technical and design benefits of the higher temperature, higher density propellant choice.

While the EMC study teams had been leveraging older concepts for methane transportation stages in the early architecture work, this past year the study teams decided a refresh of the design was in order. In addition to reaffirming some of the design selections previously baselined, this design effort served to add fidelity in two specific technical disciplines; the integrated methane propulsion system and the CFM system. Structural mass was updated based on the latest set of structural requirements and the power system was updated to meet the latest power generation requirements. This bottoms-up design effort not only provided higher fidelity mass estimates of the stage for use in transportation architecture analyses, but also served as the backbone for the technology development plan discussed in Section VI of this paper. A concept drawing of the MCPS identifying the main areas of focus for this design study is provided in Figure 3.

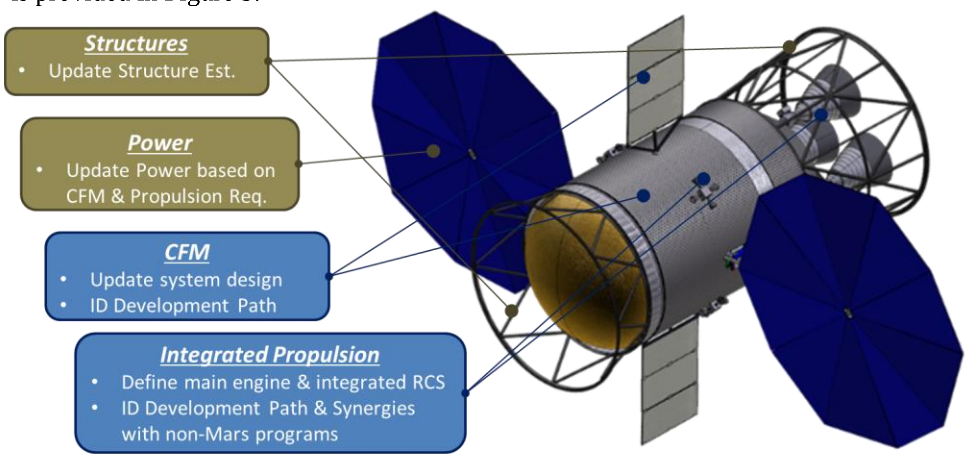

Figure 3. The Methane Cryogenic Propulsion Stage. *The MCPS design update primarily focused on increasing the fidelity of the integrated propulsion and CFM sub-system designs as well as updating the power and structures designs to absorb any additional requirements resulting from the refinement.*

A. Propulsion

The integrated propulsion system consists of three 22,500 lbf main engines and four sets of reaction control thrusters. The main engines at the heart of this system are the same main engines being assumed by the EMC Mars Lander team for both the MAV and the MDV. An independent assessment of engine requirements was conducted reviewing mission requirements for all three of these Mars elements, and it was determined that the packaging and performance requirements of the Mars lander systems will drive the design of the main engine itself. In order to maintain commonality across the various elements and build a Mars program that requires only one main engine development program, it was assumed that the same engine would be used for the MCPS. The mass of the engine, is comparable to the mass of an RL-10 engine. Helium purge gasses are used to ensure that feed lines are clear of any residual propellants after main engine firings and prior to long duration periods of dormancy.

The stage configuration consists of two in-line propellant tanks. Constructed from aluminum, these tanks are held at 50 psia tank pressure and have a diameter of 4 meters. Tank pressurization is provided by an ambient gaseous helium system with a tank pressure of 4500 psia. One technology investment area identified for the integrated propulsion system specifically related to the feed system is low leakage valves. These valves must be capable of cycling through multiple burns, sometimes with several hundred days between them, while maintaining leak rates less than 0.0053 kg/day. This leak rate represents a 100*x* improvement over current state of the art valves, however, work is currently underway investigating various methods for improving leak rate. This is discussed further in the technology development section below. A schematic of the MPS and tanks is provided in Figure 4.

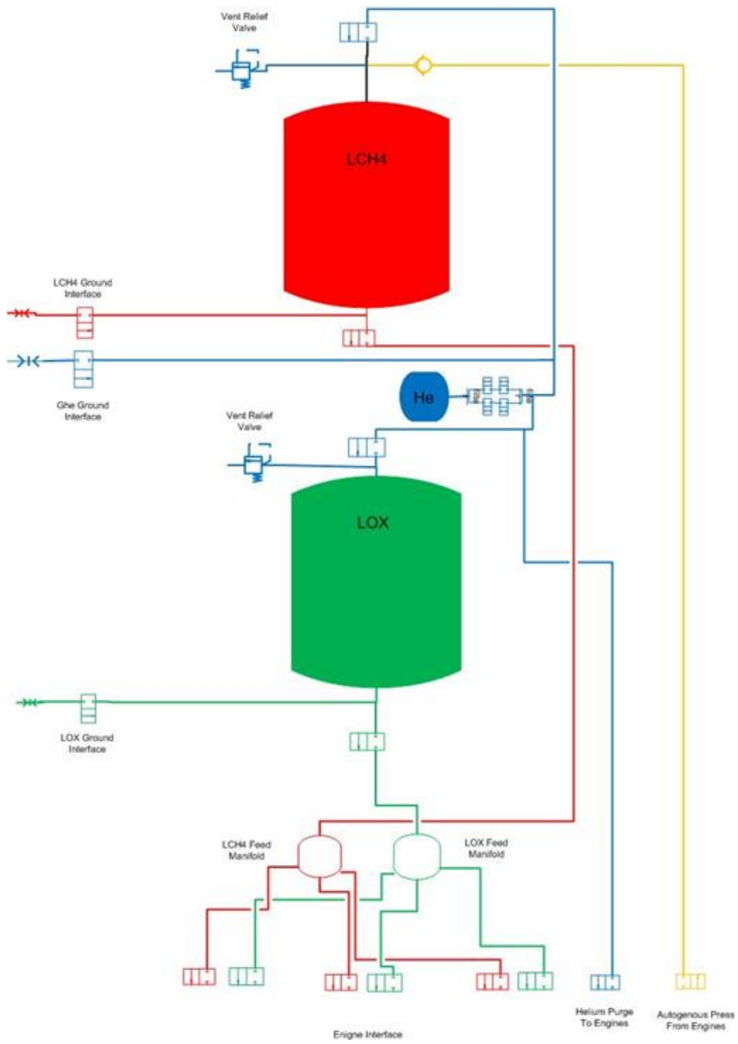

Figure 4. Methane Main Propulsion Systems. *The methane MPS consists of two in-line cylindrical propellant tanks and a small helium pressurization system to feed three 22,500 lbf pump-fed oxygen-methane engines.*

There are two unique aspects to the design of the RCS system of the MCPS. Like most traditional reaction control systems, the MCPS RCS system consists of four thruster pods each containing four thrusters. However, in order to support the series of smaller steady-state burns required for LDRO operations and MOI of the pre-deployed stages, each thruster pod uses a 1000 lbf thruster pointed in the aft axial direction. The remaining three thrusters in each pod are 100 lbf thrusters. The combined axial 4000 lbf of thrust is capable of performing all smaller translational burns for which the MPS would be overkill. With the RCS system absorbing this extra work load for each stage, the RCS propellant loads can quickly grow to several thousand kilograms. In a traditional pressure-fed RCS system, this would translate to very large propellant tanks and significant helium loads. To reduce the impact of this additional work and increase the overall stage operational flexibility, the RCS system for the MCPS uses liquid-oxygen / liquid-methane thrusters that are fed from the main propellant tanks. A notional schematic of this system is provided in Figure 5.

The integrated RCS system uses accumulator tanks which are sized to hold the propellant required for a single translational maneuver. These accumulator tanks are fed from the main propellant tanks by a set of electric pumps which draw in the appropriate propellant load and provide tank pressurization for operations. This pressurization is supplemented by a gaseous helium system, however, the helium load is greatly reduced due to the smaller accumulator tanks and the electric pumps employed to feed the tanks. From the accumulator tanks to the thruster, the RCS system operates as a traditional regulated pressure-fed system. Propellant flow to the electric pumps is tapped off the flow system used by the CFM circulators which minimizes the number of penetrations into the main propellant tanks.

There are several operational benefits to using this type of RCS system. First, the use of methane-based RCS thruster increases the specific impulse from 325 seconds to 340 seconds. The use of accumulator tanks rather than packaging all of the required RCS propellant into a separate system from the main propellant tanks not only reduces the size of the relatively high pressure RCS propellant tanks, but also provides additional propellant inventory flexibility. This flexibility adds an additional set of contingency operational modes where translational ΔV can be provided by two separate systems. The central storage of all propellants in the main tanks also allows a single set of CFM systems to maintain liquid propellant storage conditions reducing the complexity of the CFM system while maintaining the higher performing methane-based RCS.

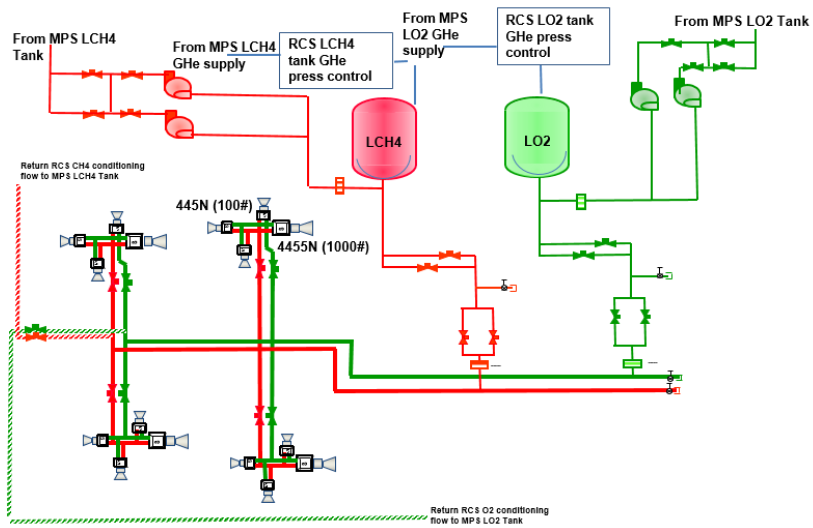

Figure 5. Integrated Methane RCS. *The integrated RCS system for the MCPS consists of electric-pump-fed accumulator tanks tied to pods of RCS thrusters. Each pod consists of three 100 lbf thrusters and one 1000 lbf axial thruster for translational maneuvering.*

B. Thermal Control

The primary focus of the thermal control system design analysis was the CFM system. To fully understand the requirements of the CFM system, specifically the passive elements and the cryocooler, a broad evaluation of the various thermal environments experienced by the MCPS was completed. Reviewing the concept of operations in both flight regimes (pre-deployed and active flight), environments include long duration slow-climbing elliptical orbits around Earth, and long duration assembly in LDRO, interplanetary space, and long duration loiter in Martian orbit. Thermal Desktop was used to evaluate the heat load in these environments with different spacecraft orientations. Table 1 shows the heat load results from the environmental analysis. All heat loads include a 25% margin. Two main results should be noted from this analysis. First, it should be noted that orientation is a powerful means to reduce heat load into the propellant tanks. A comparison of the heat loads in LDRO shows that by pointing the engines towards the sun, the heat load can be reduced from a nominal 79 W to 28 W. The second finding in this analysis is that none of the scenarios investigated result in a heat load into the MPS tanks in excess of 100 W.

Table 1. Thermal Loads. *The MPS storage tank total heat load was calculated using Thermal Desktop for a variety of environments and vehicle orientations.*

MCPS Thermal Environments	***Vehicle Orientation***	***MPS Storage Tanks Total Heat Load (W)***
Delivery to aggregation		
SEP Early Spiral, Arg. Periapsis 180°	+XVV	38
SEP Early Spiral, Arg. Periapsis 270°	+XVV	43
SEP 30000 km Circular	+XVV	51
Chemical Lunar Transit	+XSI	80
Chemical Lunar Transit Broadside	+ZSI	39
Aggregation and beyond		
Low HEO	+XSI	76
LDRO	+XSI	79
LDRO Engines-to-Sun	-XSI	28
LDRO Broadside	+ZSI	40
LDHEO	+XSI	80
Mars Transit	+XSI	34
1Sol	+XSI	28

The design of the thermal control system is divided into two main functions. The first is the thermal conditioning of various sub-systems including avionics and propulsion. This system consists of a state-of-the-art cold plate and evaporator system tied into deployable radiators using an ammonia coolant loop. The second main function is the removal of heat energy from the main propellant tanks to maintain cryogenic storage conditions. The cooling approach for the tanks consists of a single 90K reverse turbo-Brayton cryocooler based on work completed by Zagarola, et al.[3] A tube-on-tank-wall broad area cooling network is used to cycle cooling fluids over the tanks and into the cryocooler. From there, the cryocooler ties directly into the deployable radiators using an ammonia cooling heat exchange loop similar to the coldplate system. The active cryocooling systems are supplemented by multilayer tank insulation. The reverse turbo-Brayton cryocooler has a total lift of 100 W which is more than sufficient to handle even the most extreme heat loads anticipated. The cryocooler and supporting subsystems are estimated to weigh 89 kg and require 1.1 kW of input power, which includes a 15% power margin.[4] As with the engine system, the cryocooler technology is assumed to be the same for all elements in the Mars campaign that require methane propulsion, including the MAV and MDV used for Mars surface access.

C. Power

The power sub-system on the MCPS is designed to drive all electrical systems at Mars according to a mission-phased power profile. Power requirements were gathered for the various avionics and propulsion components, as well as the thermal control system, most notably the CFM system. Additionally, the power requirements for the electric pumps that drive the RCS accumulator tank filling were accounted. The power profile assumption by phase is provided in Table 2. Batteries are included in the power system design to accommodate power requirements during various mission phases. Because orientation during docking may preclude arrays from seeing sunlight, battery power must be available during certain times in the docking and assembly process. Main propulsion will not be used during these times, so 2 hours of avionics and CFM power have been ground-ruled. Battery power is also used to supplement solar array power production for peak loading from the avionics and propulsion system during propulsive maneuvers. Battery power is sized to provide full power to essential systems for 2 hours and supplemental power for peak power draw applications for 1 hour. Due to the large number of battery cycles assumed during the course of the MCPS mission, 40% is the max depth of discharge for the batteries. Depth of discharge can be increased to as much as 80% for end of life operations where the stage will not be required to function after that discharge.

Table 2. Power Profile. *The solar power system power production requirements were evaluated for various mission phases to determine the peak power production required for the MCPS mission.*

	Mission Operation Mode Power Requirement (W)			
Subsystem	**Standby**	**Propulsion**	**AR&D**	**Attitude Control**
Avionics	671	671	671	671
Thermal	1150	1150	1150	1150
Propulsion	345	1563	345	345
RCS Pumps	93	0	0	93
Subtotal	2259	3384	2166	2259
+30% Margin	677.7	1015.2	649.8	677.7
Design Power	***2936.7***	***4399.2***	***2815.8***	***2936.7***

The design of the power system assumes the use of UltraFlex solar arrays. These arrays are sized to provide the maximum power load, 4.4 kW, at end of life at Mars. Accounting for array cell degradation and Martian solar distance, this requirement results in two UltraFlex arrays of 23.5 m^2 each assuming 70% cell coverage. Each array wing has a diameter of 5.6 m, a mass of 46.8 kg, and a maximum acceleration limit of 2.5 g.

D. Structures

A structures analysis was completed to provide updates to all of the structural members of the MCPS. The MCPS consists of two propellant tanks, an intertank segment between them, and forward and aft skirts at either end of the tank assembly which connect to thrust structure and adapters. Figure 6 shows the FEA model of all structural elements in the MCPS design. All panel structural elements, including tanks, are made of 2219-T87 aluminum, while all truss structures are made of composite materials. A finite element model was made of the structural elements of the MCPS and the structures were optimized using a combination of MSC Patran and Hypersizer. Assessments included strength and stability checks for launch, ascent, and in-space operations. The driving operational case for loads analysis was the launch of an MCPS with a SEP vehicle, the launch configuration of all pre-deployed MCPS. The SEP vehicle was modeled as a block mass above the MCPS. Axial loads of 3.5g and lateral loads of 1.5g were assumed. The focus of the structures analysis in this effort was the refinement of the primary structures mass incorporating changes to the design resulting from refined analysis of other sub-systems. As such, the secondary structures were not explicitly evaluated and a 20% mass increase was assumed to account for all secondary structures in the MCPS. A multiplyer was added to the mass estimate of all truss structures to account for joints and fittings.

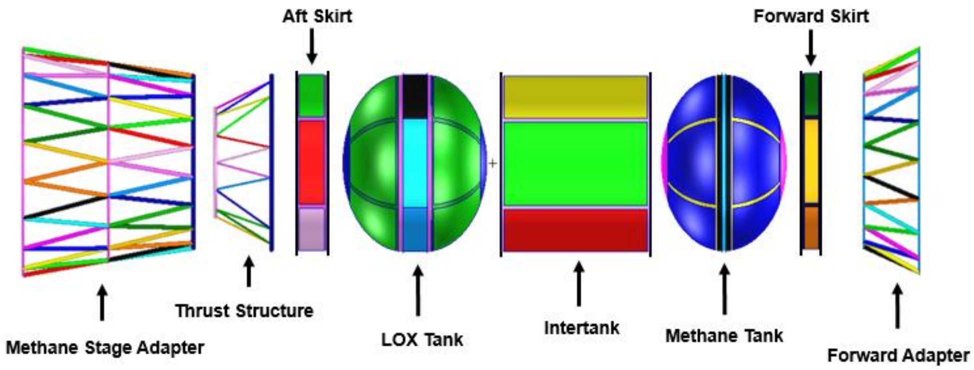

Figure 6. Structures Modeling. *The finite element model of all structural components of the MCPS was evaluated using a combination of MSC Patran and Hypersizer*.

E. Avionics

The avionics system design for the MCPS was driven primarily by the requirement for free-flying and automated rendezvous and docking operations. Each stage in the architecture must provide its own guidance, navigation, and control (GN&C) system and be capable of determining its own state at all phases of the mission. The stages must also be capable of transmitting housekeeping data to Earth to support system health monitoring. Stages also provide command and data links to all other stages in the stack. The avionics architecture for the stage is designed to be single-fault tolerant for critical systems needed for mission success and to maintain long term GN&C fault tolerance. The attitude and control system includes sun sensors, star trackers, and inertial measurement units. The command and data system include independent computers (using a triple-voting scheme), data acquisition units and solid state data recorders. The systems designed to support rendezvous and docking includes long range and short range approach, rendezvous, & docking (AR&D) systems. A suite of system controllers support general vehicle systems such as CFM controllers, propulsion controllers (MPS, RCS, Thrust Vector Control), and jettison controllers. Each stage is also equipped with instrumentation, which includes pressure sensors, temperature sensors, strain sensors, and video monitoring cameras (for health and status). Finally, the avionics suite on each stage includes a communications system which consists of a Ka-band high gain system (for a high data rate link between Earth and Mars), an S-band medium gain system (for ground link in low Earth and Mars orbits), and a low gain system (for in-space inter-stage communications and AR&D).

F. New Mass Estimate and Comparison

One main result of the design refresh effort was to produce a new MCPS mass estimate for use in architecture analysis trades going forward. The mass estimates for each subsystem described above were assembled to complete an update to the MCPS dry mass estimate. These estimates were based on a combination of analysis and off-the-shelf component selection. The AIAA standard for mass growth allowance was applied to each item in the mass breakdown commensurate with the technology readiness level of the component and the level of fidelity of the analysis that produced the mass estimate.[5] This resulted in a composite contingency mass of 20.94%. Table 3 provides a complete summary of the MCPS point design mass estimate.

In addition to the dry mass estimate, the MCPS propellant inventory was also evaluated and updated. The MCPS must carry not only the propellant required to complete all main propulsion and RCS burns but also the propellant to cover various loss sources throughout the mission. Start up and shut down propellant loads were estimated for each main engine operation based on the liquid oxygen transient losses of current state-of-the-art boost engines. Propellant required to chill the feed lines prior to engine start was also estimated based on currently fielded engines. While the CFM system is designed to maintain cryogenic propellant storage temperatures throughout the mission, it is acknowledged that a small amount of propellant will be lost during initial stage ascent on the SLS, while the CFM system is inoperable. Another small amount of propellant will be lost to ullage gases as the tanks move towards steady-state operations. Propellant leakage was also accounted based on the 100*x* improvement over current state of the art cryogenic valves as discussed in the propulsion subsection above. A residual percentage of 1% was assumed to account for trapped propellants. The design team assumed that the RCS system would be used to settle tanks when a propellant load measurement was required in order to baseline settled mass gauging technologies rather than the still experimental zero-g mass gauging technologies currently under investigation. This reduced the assumed mass gauging error to 0.6%, a value in line with current in-space stages. An additional 1.4% reserve propellant load brought the overall unusable propellant estimate to 3% plus the measureable or estimated values discussed above. Mission and operational contingencies were added through finite burn analyses and ΔV margins which lead to an initial calculated burned propellant value that accounts for mission-level variability related to trajectory and timing issues. Therefore, these contingencies do not manifest as individual margins within the propellant inventory. The full propellant inventory for the MCPS design point is included in the Table 3 mass estimate summary. Table 4 provides a summary of the basis of estimate for the unusable propellant inventory.

Table 3. MCPS Mass Estimate Summary. *The mass estimate of the MCPS is broken down by sub-system and includes a contingency mass growth consistent with the AIAA standard. The dry mass is provided as well as the unusable propellant inventory.*

MEL - MCPS				Basic Mass (kg)	Contingency (%)	Contingency (kg)	Predicted Mass (kg)
Mass Breakdown Structure							
1.0	Structures			2582.28	20.72%	535.03	3117.31
2.0	Propulsion			2313.57	22.61%	522.99	2836.55
3.0	Power			565.40	15.00%	84.81	650.21
4.0	Avionics			748.25	17.62%	131.85	880.10
5.0	Thermal			634.06	24.94%	158.17	792.23
Dry Mass				6843.56	20.94%	1432.84	8276.40
6.0	Non-Prop Fluids			2238.35			2238.35
	6.1	MPS Engine Start/Stop Propellant		*636.00*			*636.00*
		6.1.1	Fuel	141.33			141.33
		6.1.2	Oxidizer	494.67			494.67
	6.2	MPS Vapor Loss		*150.00*			*150.00*
		6.2.1	Ullage Vapor	100.00			100.00
		6.2.2	Ascent Heating	50.00			50.00
	6.3	Propellant Reserves & Residuals		*1044.00*			*1044.00*
		6.3.1	Fuel	232.00			232.00
		6.3.2	Oxidizer	812.00			812.00
	6.4	Propellant Leakage		*272.00*			*272.00*
		6.4.1	Fuel	136.00			136.00
		6.4.2	Oxidizer	136.00			136.00
	6.5	Fuel Bias		*77.35*			*77.35*
		6.5.1	Fuel	77.35			77.35
	6.6	Propellant Pressurant		*59.00*			*59.00*
		6.5.1	MPS GHe	59.00			59.00
Inert Mass				2238.35			2238.35
Total Less Propellant				9081.91			10514.75
7.0	Usable Propellant			34805.80			34805.80
Total Stage Gross Mass				43887.71			45320.55

Table 4. Unusable Propellant Inventory Basis of Estimate. *Various sources of unusable propellant are accounted for in the estimate of the MCPS inert mass. These unusable propellant loads are partially based on historical data and partially based on industry standard practices.*

Unusable Source	Estimated Amount	Comment
Loss overboard due to heat leaks	~50 kg	Loss during ascent prior to CFM system start
Loss to ullage due to operations	~100 kg	Predictable amount lost to ullage vapor
Residuals & Trapped Propellant	1%	Based on industry best practices
Main Engine Start/stop transients	65 kg/engine	Based on RL-10 transients
Engine and feed line chill	41 kg/engine	Based on Lox chill for RL-10
Valve leakage	~300 kg for 3000 day stage	Based on est. result of initial dev. program
Loading / Mass Gauging Uncertainty	0.6%	Based on SOA settled mass gauging (Centaur)
Additional Reserves	1.4%	Brings total unusable to 3% + measurable sources

The point estimate for the MCPS provides several insights into the design constraints and requirements for technology development which are discussed later in this paper. However, as part of an integrated mission architecture analysis effort, the MCPS point design must inform a flexible method of estimating the mass of the MCPS given a wide range of potential mission constraints. Architecture analyses completed for the EMC study account for variations in payload masses as the design of various payload elements, including the crew transit habitat. Different flight opportunities are investigated as are different trajectories and contingency operations. In the context of these architecture analyses the design of the MCPS is more valuable as a mass estimating relationship that supports flexible stage sizing over a wide range of mission scenarios. Past design efforts had been leveraged to develop such a mass estimating relationship for architecture analysis. Figure 7 shows this mass estimating relationship between total loaded propellant and stage dry mass. Superimposed on this curve is the latest MCPS design point, represented by a blue diamond. While the new point design shows small increases in mass for the structures and RCS systems, an equivalent reduction in MPS tank mass and power systems was also noted. As the graphic shows, the refinement of the MCPS design lies within 1% of the previous dry mass prediction, further validating the relationship for use in architecture studies.

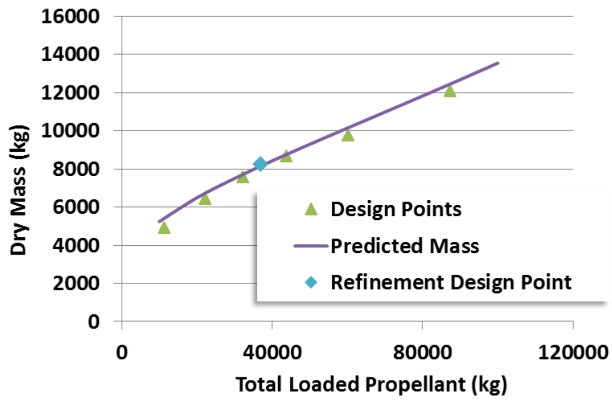

Figure 7. The MCPS Mass Estimating Relationship. *This mass estimation curve is based on previous design points and is used to provide flexible MCPS sizing for architecture analyses. The current Refinement Design Point is very consistent with the mass estimating curve.*

A comparison between the mass fraction of the current MCPS design and other fielded stages was also performed. The S-IVB stage on the Saturn V launch vehicle had a loaded propellant mass fraction of 0.867. The Delta IV upper stage, DCSS, has a loaded propellant mass fraction of 0.882, while the Centaur upper stage comes in at 0.900. The current point design for the MCPS has a loaded propellant mass fraction of 0.817. Several functional requirements add dry mass to the MCPS above and beyond what is required of any previous or currently flying upper stage. Duration is one major factor, with all previous stages having lifetimes on the order of several hours as compared to the 3000 day life requirement of MCPS. MCPS also carries micrometeoroid and orbital debris protection, adapter truss structures at both ends, and CFM systems and the associated solar power production systems. Simply removing those equipment line items from the mass estimate and recalculating the mass fraction increases it from 0.817 to 0.852, a value which aligns well with the class of stages normally associated with large in-space transportation functions. While this comparison indicates that the MCPS may be conservatively sized at this point, the comparison does show that the MCPS is generally in good agreement with the current body of knowledge relating to stage design.

V. Performance Sensitivities and Trades

Several architecture-level trade and sensitivity analyses were completed using the results of the latest MCPS design exercise. These analyses leveraged the greater understanding of MCPS design to quantify the architecture-level impacts of variations on mission design and MCPS design and performance. The trades also helped to determine the impacts of technology development assumptions related to the various technology gaps to be filled in the MCPS development strategy.

A. Impacts of Common Stage Sizing

One overarching architecture assumption relating to programmatics and cost is the assumption of common stage sizing for the MCPS. In every architecture trade performed, the mass estimating relationship is used to size the appropriate MCPS for the missions to be performed in that architecture. In order to save money on element production and increase reliability by limiting the number of unique elements in the architecture, the MCPS has traditionally been sized to meet the needs of the largest propellant load in the architecture. All other MCPS in the architecture have the same dry mass and propellant is offloaded to carry only what each individual stage requires. While this ensures that all MCPS in the architecture are carbon copies of one another, this assumption also introduces several potential issues. Some stages have considerable propellant offload, with 5 of the required 12 stages for the current EMC SEP-Chemical architecture having a propellant offload greater than 40%. Propellant slosh is one potential issue for these high-offload stages but this can be mitigated with a relatively lightweight slosh baffle system.

The other issue of concern with the single common stage size is that many of the stages in the architecture are significantly less mass efficient than they could be. All offloaded stages are carrying the excess inert mass of partially filled tanks. This additional mass can drive the size of other elements if the penalty is high enough. To investigate the impact of this assumption, an alternative architecture was sized using two common stages, a large stage and a small stage. In the baseline single common stage architecture, the common MCPS had a dry mass of 8.6t based on a maximum propellant load of 42.3t. Switching to a dual common stage approach, 4 of the required 12 stages fell into the smaller category of MCPS with a dry mass of only 6.7t. The other 8 stages in the architecture remained at the baseline size of 8.6t

Several impacts of this stage size reduction were observed. First, the overall mass launched into space to support the architecture was reduced by 3%. While not a large percentage, this does lead to an increase in individual launch margin when compared to the baseline approach. Some of the stages that fell into the smaller stage category were EOI stages that are pre-deployed with SEP vehicles. The 2-3t mass savings on these stages will result in shorter flight times for SEP pre-deployment. In terms of offloaded propellant, the dual common stage approach reduces the number of stages with propellant offload greater than 40% from 5 to 2.

B. Sensitivity to Specific Impulse

The assumption of common engine design for all methane-propulsion elements in the architecture drives the MCPS to inherit the performance of the methane main engine that is driven by the design of the Mars lander systems. Throttling requirements and packaging constraints on the MDV and MAV drive the selection of engine cycle and set the performance metrics such as specific impulse and thrust for the engine. The baseline design point for the methane main engine that is used by the MCPS is a thrust of 22,500 lbf. At this thrust level, three engines on the MCPS will support short burn times and minimize gravity losses in all main burns while still maintaining the ability to complete the mission with engine out. However, the length of the methane engine nozzle is not as constrained for the MCPS as it is for the Mars lander systems. Therefore, a sensitivity to increase in specific impulse was evaluated.

Increasing the specific impulse of the MCPS will reduce the overall propellant load required for the mission. In the context of the baseline EMC campaign mission set, the sensitivity shows approximately 0.25% reduction in total launch mass for every 1 second increase in specific impulse. This equates to approximately 10 kg reduction in stage dry mass for every 1 second increase in specific impulse. While not a significant reduction in mission mass, this does increase the launch margin for each individual element. This increase in performance also shows potential for changing the burn allocations to reduce the total number of MCPS required for the campaign. The current campaign combines the TEI and EOI maneuvers into a single MCPS for the 2039 crew flight opportunity. At the current performance levels, this is the only flight opportunity where this options exists while still maintaining reasonable pre-deployment flight times. With a 10 second increase in specific impulse, it may be possible to combine these Earth return maneuvers in the 2033 flight opportunity as well, thus eliminating an MCPS and high-power SEP vehicle from the campaign manifest. While more integrated analysis is required to determine the full benefit, this does point to an example of increased margin opening alternative mission scenarios that impact metrics such as number of launches and number of mission elements that directly impact operations and production costs.

C. Impact of Non-Integrated RCS

One of the more non-traditional aspects of the MCPS design is the integrated RCS system. Typical stages carry independent RCS systems with their own propellant tanks and pressurization systems. The integrated methane RCS baselined for the MCPS stores all propellant in the main propellant tanks and uses electric pumps to fill accumulator tanks for individual RCS maneuvers on an as needed basis. This integrated system enables the use of methane RCS thrusters at improved specific impulse and eliminates most of the helium pressurization system mass associated with self-contained RCS systems. Furthermore, by adding 1000 lbf axial thrusters to the RCS pods, small but significant translational maneuvers can be performed using RCS rather than the significantly over-thrusted MPS. This option is exercised not only for MOI on pre-deployed MCPS, but also for LDRO insertion and maneuvering for aggregated MCPS for the crew flights from Earth. In many cases these maneuvers required as much as 7t of total propellant. When storing that propellant in the main tanks and pressurizing only a fraction of that overall propellant load on a burn-by-burn basis, the impact to the stage dry mass is minimized.

A valuable point of comparison for program planning purposes is the equivalent stage designed with a self-contained storable propellant RCS system. Several factors, including overall system reliability and technology development funding, could reduce the likelihood of developing and fielding the integrated methane RCS system in the current baseline design. Therefore, analysts investigated the stage design with a more traditional RCS system. Two scenarios were assessed. In the first scenario, all translational maneuvers were allocated back to the MPS and the RCS was only required to carry 2500 kg of storable propellant for attitude control, orbit station keeping, and trajectory correction maneuvers. This resulted in an RCS system mass that was equivalent to the integrated methane

RCS mass and no significant dry mass penalties were incurred. This operational scenario would, however, impact the operations of the MPS, increasing the number of engine starts required. Many of the smaller translational maneuvers will also experience very high accelerations and burn time could be as short as 30 seconds.

The second scenario was one where all of the currently integrated methane RCS system maneuvers were absorbed by a self-contained storable RCS system. In this scenario, the RCS system propellant load can be as high as 7-9t, depending on the performance of the RCS thrusters. This propellant load translates to a 200 – 300 kg increase in the RCS system dry mass, as compared to the integrated methane RCS system. For the campaign, this results in a 3% increase in the total launched mass and brings several of the MCPS very near the current launch mass limit for aggregation in LDRO. While it appears that a storable RCS system may be a viable fallback position in the design of the MCPS, reduction in launch margins and increased pre-deployment flight times must be considered as well as the loss of propellant inventory flexibility that an integrated methane RCS system provides.

VI. Development of Methane Propulsion System Technologies for MCPS

Using the baseline design of the MCPS discussed above, an evaluation of the technology development requirements for the stage was performed. Subject matter experts in propulsion system design, engine and thruster development, and CFM technology development reviewed the MCPS design and identified the key areas of research and development required to make the MCPS a reality. The technology needs were divided into three categories; MPS, CFM, and reaction control systems. A notional technology development roadmap outlining the timing of development in each of these three categories is provided in Figure 8.

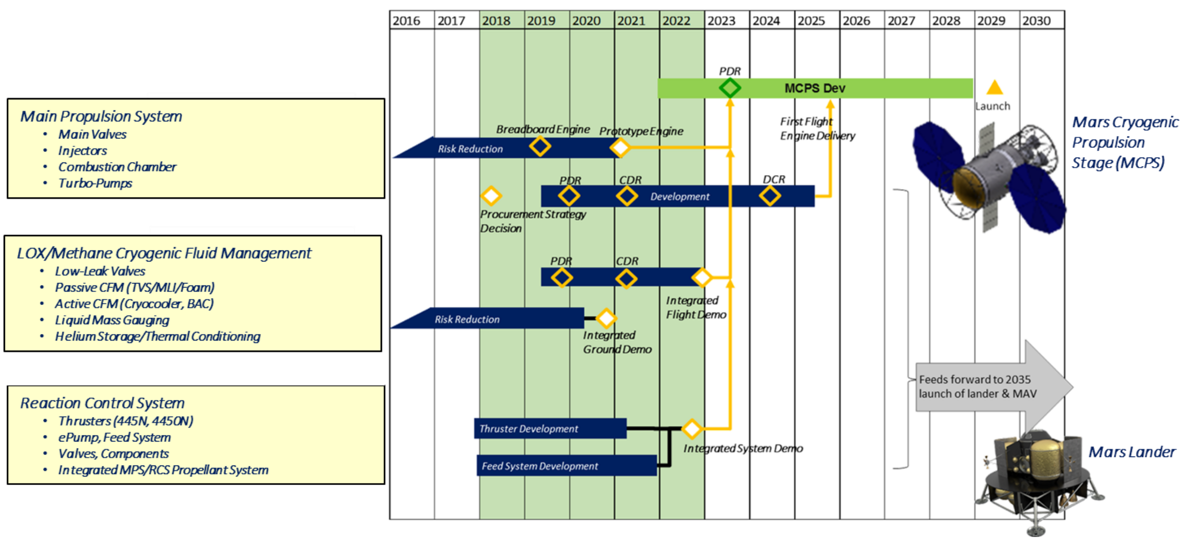

Figure 8. MCPS Technology Roadmap. *This notional technology development roadmap shows the three general categories of development required to support the methane elements of the EMC. Timelines are current best estimates from subject matter experts and are intended to show interdependencies.*

Three key findings came out of the evaluation of the technology development strategy for the MCPS. First is the fact that, while several development efforts are required, they leverage heavily the technology investments made by NASA over its history. Cryogenic in-space main engines of the thrust class currently being considered for the MCPS are not new to NASA. NASA has been continuously funding research in CFM for decades with steady progress being made in the area of cryocooler design and thermal modeling. The second key finding is that much of the required development is engineering development rather than pure technology development. Many of the technologies in question are understood and the main hurdle in their further development is the demonstration of operations in an integrated system in a relevant environment. In short, many of the technologies identified sit at the technology development valley of death between TRL 5 and 6. Others, while not fully demonstrated with the working fluids required for the MCPS, have been demonstrated many times in the past with alternate propellant combinations. While there is development work still to be done, much of it is engineering and systems integration related rather than pure technology development. The third key finding, as is exhibited by the timeline shown in Figure 8, is that this development work must start today to ensure these systems are ready for integration into the MCPS to support the initial flight date of 2029 required by the current EMC campaign.

A. Main Propulsion System Development

The technology of a pump-fed liquid rocket engine of the thrust class currently under consideration for the MCPS is not new. Many liquid propellant engines exist in this thrust class, several for in-space transportation applications. The engine development effort for a new pump-fed engine for Mars largely comes down to two main areas, risk reduction and engineering development. A technology risk reduction effort will seek to test components, specifically, turbomachinery and injectors, for operations with methane fuels. Work in this area is already underway at NASA's Marshall Space Flight Center, where engineers in the propulsion engineering group have run several tests with bread-board turbopump assemblies using methane.[6] Two things make this latest round of risk reduction testing unique. First is the use of methane rather than hydrogen as the fuel. The second is the use of additive manufacturing in the development of components for this turbo-pump assembly. It is believed that additive manufacturing, or 3D printing, will reduce lead time for engine component manufacturing, reduce part counts, and reduce production and testing costs. However, risk reduction efforts must be conducted to bring this new capability to the point where it is ready to contribute to a production engine.

Engineering development of a new pump-fed methane engine will follow a standard engineering development lifecycle, with component design and refinement followed by the development of a prototype engine for test and design refinement. Once the design has been finalized, production can begin with the first few units being dedicated to more testing prior to flight in a space environment. While the TRL of the engine components is high, great care must be taken in the design and test of a new engine, regardless of propellant selection. The process of developing a bread-board and prototype engine is expected to overlap the development of a flight engine with the two processes combining to take approximately 8 years. Assuming a 7 year development for the MCPS and an anticipated first flight of the MCPS in 2029, the MCPS preliminary design review is estimated to take place around 2023. By this date, the prototype engine should be complete and the production engine development should be well into Phase B. With all of these time constraints accounted for, development of this critical component of the Mars campaign must begin within the next year or two in order to support overall program success. Even with high TRL, there is still much work to be done to fully develop an engine ready to fly humans to Mars.

The development of the methane engine offers unique opportunities for collaborations with entities outside of NASA. Several commercial companies and other government programs are considering methane engines in this same thrust class for inclusion on new vehicle concepts. This opens up the potential for data sharing relationships where lessons learned in the overall development of these engines can be leveraged to make all of these engine programs more successful. For instance, by developing a set of engine requirements and prototype designs early in the process, NASA can identify opportunities for overlap in test programs where test data may be available without having to duplicate test events. If nothing else, any instance where a methane-based pump fed engine is used in either a test or operational scenario will build flight data and confidence that will serve to reduce future risk and increase overall system reliability.

In addition to work on the main engine of the MPS, work continues in the area of low leakage valves. The current MCPS design assumes a 100*x* improvement in leak rate over current cryogenic valves. While some internal research and development is already underway within NASA, it is anticipated that the closure of this gap will require a combination of engineering and technology development. A significant contributor to the fact that the leak rates of current valves are as high as they are is simply because requirements have not dictated that they be improved. Typical applications for these types of valves last only minutes to hours and are largely disposable. The creation of a specification for leak rate compliant with the needs of a long duration, mass-sensitive application such as flying humans to Mars will lead to engineering solutions, mostly related to manufacturing and tolerances, which will begin to close the gap. Researchers believe that the gap will not be fully closed without some technology development in the areas of materials and manufacturing, but given current progress in the area, it is anticipated that the 100*x* reduction is an achievable goal.

B. Cryogenic Fluid Management Development

CFM encompasses a broad range of components and functions. It extends far beyond the thermal management of cryogenic propellants, although this is a significant area of continued research and importance, to functions that include mass gauging, liquid propellant acquisition, and leak detection. A complete CFM system will be required for all propulsive elements in the SEP-Chemical Mars architecture. CFM also represents an area of significant research and development investment within NASA for the past five decades. The use of cryogenic propellants for space applications stretches all the way back to Apollo and, while Mars represents durations that have never been achieved, many of the same fundamental heat transfer and physics phenomena drive the design of these new CFM systems.

There are two important things to note about the CFM systems required for a methane-based propulsion system. The first is that methane is not hydrogen. Many of the previous CFM technology programs, both within and outside of NASA, have focused on the task of liquid hydrogen storage. This is because hydrogen-based systems are much higher performers and hydrogen storage applies not only to chemical propulsion applications, including several that would leverage currently existing engines, but also to more advanced propulsion systems such as nuclear thermal rockets. The extreme cold associated with the storage of liquid hydrogen has presented significant challenges in the advancement of the 20K-class cryocooler technology required to enable such applications. However, liquid methane storage temperatures are much closer to those required for liquid oxygen and the 90K-class cryocooler technology required for oxygen and methane storage is much more mature. Many hydrogen cryocooler concepts begin with a first stage cryocooler in the 90K temperature range. Therefore, the development of a 90K cryocooler is able to leverage the decades of investments spent on hydrogen storage to tackle a somewhat less technically strenuous case.

The second item of note is that the MCPS is not seeking to maintain “zero boil off” storage conditions. The term “zero boil off” or ZBO is a bit of a misnomer. While reduction of boil-off has always been a goal of the CFM community, the ZBO program specifically sought to reduce propellant boiling to zero at steady state storage in tanks in space. In reality, it is understood that total elimination of propellant boiling in all phases of a flight mission is an unnecessarily lofty goal. The true intent of a good CFM system is to maintain liquid propellants in their required states and to properly account for all unusable propellant, regardless of its phase state. Therefore, while ZBO has become a term synonymous with CFM, the real goal of the CFM systems required for a stage such as the MCPS is not zero boil off, but rather full accounting and accuracy in the propellant inventory with the ability to anticipate minor propellant losses and plan propellant budgets accordingly.

The primary challenge facing the CFM community in general is a lack of flight experiments and data. While technology work has progressed and is continuing to move forward towards flight weight 90K cryocoolers such as the reverse turbo Brayton cycle cryocooler in the MCPS design, budget instability and a lack of true technology pull from mission applications has made funding for a flight demonstration scarce. Many flight demonstration concepts have been proposed and shelved over the years. With the long term investments at the component level, knowledge of the physics and technologies required for a CFM system has advanced in the laboratory setting, and many of the component technologies required are at a TRL of 4 or 5. The flight demonstration will be the key to raising the TRL to 6 and above as it will seek to demonstrate the integrated system in a relevant environment. This is true not only of the cryocooler technology but also of supporting equipment required to round out the complete CFM system, including liquid acquisition devices, leak detection sensors, tank mixers, and broad area cooling tank wall tubing.

To achieve the CFM system required for the MCPS and Mars lander applications, component and sub-system level technology maturation must continue in the laboratory environment. The development road map anticipates an integrated ground demonstration of the CFM system in the 2021-22 timeframe followed by an integrated flight demonstration in 2023. The flight demonstration will provide critical data about the effects of zero gravity on heat transfer physics, liquid acquisition devices, and mass gauging systems that cannot be recreated in a 1-g lab environment. Unlike past CFM technology flight demonstrations, the methane-based flight demonstration for Mars applications would restrict investigations to only those technologies relevant to the mission pull of a Mars program, eliminating investigations into hydrogen storage and transfer that have historically increased the cost of flight demonstration missions. While much is known about the technology needs and the solutions required to make long term storage of oxygen and methane a reality for Mars the true engineering challenge will be providing a relevant, in-space flight demonstration to help carry the integrated system across the TRL valley of death.

C. Reaction Control System Development

The development of the integrated methane RCS in the current baseline MCPS design is largely an engineering and integration problem. Many of the components required to build such a system exist and can be integrated into a flight vehicle. Research underway in the area of integrated vehicle fluids will further support the development of such a concept.[7] However, the integration of an electric pump system with accumulator tanks to support the operation of small pressure-fed thrusters has not yet been demonstrated. Risk reduction efforts must be completed to demonstrate this concept, first on the ground and then in a space environment. Engineering development is also required in the areas of flight weight electric pumps and methane RCS thrusters. Several breadboard thruster designs for 100 lbf and 1000 lbf methane thrusters currently exist and are in various states of test and development. It is anticipated that a full system demonstration will be required to prove the integrated system will work as desired, and this demonstration should be completed in time to inform the design of the MCPS.

VII. Summary

The intent of the EMC study is to understand the architecture trade space of options for sending people to Mars and returning them safely to Earth. Transportation alternatives are one area of focus for this study as analysts try to identify the long-lead technology items required for such a bold endeavor and try to guide investment strategies in the near term. The evaluation of the MCPS in the SEP-Chemical architecture alternative has provided valuable information for those technology investment decisions. Over this past year, a team of experts from across NASA has worked to design a conceptual MCPS for Mars that provides the context for technology investment discussions. The latest iteration of this MCPS design has provided insights into the MPS requirements, including the performance and reliability requirement for a new pump-fed methane engine. The MCPS design effort has also added fidelity to the concept of an integrated methane RCS system and shown the benefits and challenges of such a system in the Mars application. The needs of the CFM system have also been clarified through this design effort.

The MCPS has the potential to provide a reliable and cost effective transportation alternative for crew flights to Mars. In its current design, a crew flight would require 3 – 4 such stages for each round trip. The application of methane to this problem is made feasible through a combination of selected aggregation orbits and the pre-deployment of Earth return stages using a high-efficiency SEP vehicle. While these selections bring with them unique challenges in terms of environments and operational life time, they also bring within reach a chemical propulsion solution that is more readily achievable than the higher performing hydrogen-based chemical propulsion systems of traditional Mars architectures. Indeed, many of the development challenges associated with the MCPS are engineering and not technological in nature. While there are some technology development requirements within this program, the majority of the work is anticipated to be in the design and integration of systems comprised of components and operating within the realm of physics already well understood. As shown by the technology development roadmap associated with the current MCPS design, the true challenge will be developing these systems in time to meet the needs of the Mars program. By leveraging the wide array of past technology investments and building on the ongoing risk reduction efforts already underway in many of these technology areas, the MCPS offers an achievable solution for expanding human presence in the solar system.

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