AIAA 2015-4611

SPACE Conferences & Exposition

31 Aug-2 Sep 2015, Pasadena, California

AIAA SPACE 2015 Conference and Exposition

A Conceptual Mars Exploration Vehicle Architecture with Chemical Propulsion, Near-Term Technology, and High Modularity to Enable Near-Term Human Missions to Mars

Mark G. Benton, Sr.*

The Boeing Company, El Segundo, CA 90009-2919, USA

[Abstract] The Mars Exploration Vehicle (MEV) Architecture was first presented in January, 2012. It describes a possible method to accomplish a long-stay conjunction class Mars surface exploration mission, for 2033 or 2035 opportunities, with a four-person crew and using chemical propulsion, existing or near-term technology, and common modular elements to minimize development costs. It utilizes a common Cryogenic Propulsion Stage (CPS) that can be configured as an Earth Departure Stage (EDS) or Mars Transfer Stage (MTS). It satisfies mission requirements using a combination of Earth orbit rendezvous, aerobraking of unmanned landers, Mars orbit rendezvous, and Mars surface rendezvous. The purpose of this paper is to present major enhancements to the architecture and provide additional design details. The MEV architecture is assembled in low Earth orbit (LEO) from subassemblies launched by Space Launch System rockets and includes a Mars Crew Transfer Vehicle (MCTV) with a crew of four, two redundant unmanned Mars Lander Transfer Vehicles (MLTVs), and four redundant Booster Refueling Vehicles which top off CPS LH_2 propellants before Trans-Mars Injection (TMI). The MCTV and its assembly sequence were redesigned to reduce mechanical complexity, enhance design commonality, simplify LEO assembly, and improve mission reliability. Each MLTV utilizes one EDS and one MTS and carries three landers as payload: The Mars Personnel Lander (MPL) provides two-way transport for four crew members between low Mars orbit (LMO) and surface. Two unmanned Mars Cargo Landers, a habitat variant (MCL-H) and a rover variant (MCL-R), provide one-way cargo delivery to the surface. Additional MCL-R design details will be presented in this paper. The MLTVs escape from LEO, transit to Mars, and propulsively brake into a highly elliptical orbit. The landers separate, aerobrake, circularize their orbits, and rendezvous with the MCTV in LMO. Additional aerobraking design details will be presented in this paper. The MCTV utilizes three EDS, one MTS, and: (1) The Orion Multi-Purpose Crew Vehicle transports the crew from Earth to LEO, provides propulsion, and returns the crew to Earth using a direct entry at the nominal mission end or after aborts. (2) Three Deep Space Vehicles (DSVs), modified MCL-H landers, provide crew habitation space, life support consumables, passive biological radiation shielding, and propulsion. (3) An Artificial Gravity Module permits the MCTV to vary its geometry and rotate to generate artificial gravity for the crew and provides photo-voltaic power generation and deep space communications. The MCTV escapes from LEO, transits to Mars, propulsively brakes into LMO, and docks the six landers from the MLTVs. Cargo and crew landers perform Mars entry, descent, and landing, and rendezvous and dock on the surface to form an exploration base camp. After completion of surface exploration, the crew returns to LMO in the MPL, docking with the MCTV for the return trip to Earth. With inherent modularity, the MEV architecture could enable an economical "flexible path" approach to achieve progressively more ambitious "stepping stone" human solar system exploration missions: starting with flights in Earth and lunar orbit, progressing through missions to near-Earth asteroids and the moons of Mars, and culminating in the Mars surface exploration mission.

* Boeing Company, Mail Code W-S50-X403, POB 92919, Los Angeles, CA 90009-2919. Senior Member of AIAA.

Nomenclature

AGM	Artificial Gravity Module
BRV	Booster Refueling Vehicle (BRV1-4)
CA-C1	CPS Adaptor, MCTV 1 (CPS to DSV1)
CA-C2	CPS Adaptor, MCTV 2 (CPS to DSV2)
CA-C3	CPS Adaptor, MCTV 3 (CPS to DSV3)
CA-L	CPS Adaptor, MLTV (CPS to Landers)
CPS	Cryogenic Propulsion Stage (EDS, MTS)
DSV1	Deep Space Vehicle 1
DSV2	Deep Space Vehicle 2
DSV3	Deep Space Vehicle 3
EDA	EDS Docking Assembly (EDS3-5, Forward)
EDS-C	Earth Departure Stage, MCTV (EDS3-5)
EDS-L	Earth Departure Stage, MLTV (EDS1,2)
ILA	Inter-Lander Adaptor (MCL-R to MCL-H)
LBA	Lander-BRV Adaptor (MPL1,2 to BRV1,2)
LDA1	LIDS Docking Adaptor-Single (DSV)
LDA2	LIDS Docking Adaptor-Dual (MPL)
LDS	LIDS Docking Structure (DSV3, Aft)
LIDS	Low Impact Docking System
MCL-H	Mars Cargo Lander, Habitat Variant
MCL-R	Mars Cargo Lander, Rover Variant
MDA	MPCV-DSV3 Adaptor
MPCV	Orion Multi-Purpose Crew Vehicle
MPL	Mars Personnel Lander
MTS-C	Mars Transfer Stage, MCTV (MTS3)
MTS-L	Mars Transfer Stage, MLTV (MTS1,2)
SLS	Space Launch System
TBA	TMI Booster Assembly (EDS3-5 & CA-C1)

I. Introduction

THE conceptual Mars Exploration Vehicle (MEV) architecture was first presented in January, 2012[1]. Subsequent design iterations were presented later in 2012[2,3] and in 2014.[4] This MEV architecture study presents a possible method to accomplish a long-stay conjunction class Mars Surface Exploration (MSE) mission, for the low energy 2033 or 2035 opportunities, with a four-person crew, chemical propulsion, existing or near-term technology, and common modular elements to minimize development costs. It satisfies mission requirements by utilizing a combination of Earth orbit rendezvous (EOR), Mars orbit rendezvous (MOR), aerobraking for unmanned landers, and Mars surface rendezvous (MSR). The design iteration in this paper presents major architectural enhancements to (1) reduce the number and complexity of architectural elements to enhance reliability and improve standardization, (2) simplify Low Earth Orbit (LEO) assembly and Trans-Mars Injection (TMI) mission phases, and (3) presents additional design details for the Mars Cargo Lander, Rover Variant (MCL-R). Earlier architectures[1,2,3,5] incorporated an active crew biological radiation shield (the Mini-Magnetosphere[6], or "Mini-Mag"), a potential key enabler for human interplanetary exploration. It has the potential to protect the crew from hazardous interplanetary radiation in a more mass-efficient way than using passive shielding materials alone. The architecture presented in Ref. 4 and this paper omits the Mini-Mag and incorporates additional passive shielding.

The MEV architecture is assembled in LEO from subassemblies launched by Space Launch System (SLS) rockets and includes a Mars Crew Transfer Vehicle (MCTV) with a crew of four, two redundant unmanned Mars Lander Transfer Vehicles (MLTVs), and four redundant unmanned Booster Refueling Vehicles (BRVs) to top off CPS LH_2 propellants before TMI to compensate for LEO assembly boil-off. Each MLTV utilizes an EDS-L and an MTS-L and carries three landers as payload: The Mars Personnel Lander (MPL) provides two-way transport for four crew members between LMO and the surface. Two unmanned Mars Cargo Landers, a habitat variant (MCL-H) and a rover variant (MCL-R), provide one-way cargo delivery to the surface. The MLTVs are launched to Mars ahead of the MCTV. They each autonomously escape from the LEO assembly/parking orbit, transit to Mars, and transport three Mars landers on a one-way trip, propulsively braking into a highly elliptical Mars capture orbit. The MLTVs release the landers, which aerobrake, circularize their orbits, and rendezvous and dock with the MCTV in the 500 km circular Low Mars Orbit (LMO) parking orbit. The MCTV transports the four person crew on a round trip between Earth and Mars, from the Earth assembly/parking orbit to the Mars parking orbit, and back to a direct Earth entry. The MCTV utilizes three EDS-C, one MTS-C, and the following: (1) The Orion Multi-Purpose Crew Vehicle (MPCV) transports the crew from Earth to LEO, provides propulsion, and returns the crew to Earth using a direct entry at the end of the nominal mission or after an abort. (2) Three Deep Space Vehicles (DSVs), modified MCL-H landers, provide crew habitation space, Life Support System (LSS), LSS consumables, passive biological radiation shielding, and propulsion. (3) An Artificial Gravity Module (AGM) permits the MCTV to vary its geometry and rotate to generate artificial gravity for the crew and provides photo-voltaic power generation and deep space communications. The MCTV escapes from LEO, transits to Mars, propulsively brakes into LMO, and docks the six landers from the MLTVs. One MPL and the four cargo landers perform the MSE mission. The 2nd MPL is kept in orbit as a rescue vehicle. Landers perform Mars entry, descent, and landing, and rendezvous and dock on the surface to form an exploration base camp. After completion of the MSE mission, the crew returns to LMO in the MPL and rendezvous and dock with the MCTV for the return trip to Earth. In a nominal mission, the crew will remain on the surface for 450 of the 480 day Mars stay time. In the event of a loss of landers, the MCTV carries sufficient LSS consumables to sustain the crew during the Mars stay time as well as the outbound and inbound transits. In the event of a casualty to the MCTV, the landers provide backup propulsion and 480 days of LSS consumables. MEV design is discussed below in sections II and III. MEV mission profiles are discussed below in sections IV, V, and IV.

The MCTV has key features that will be needed to keep the crew healthy and safe during a 30 month duration round-trip mission to Mars: sufficient human habitation volume, artificial gravity (AG) to prevent deterioration of the human body caused by prolonged zero-g periods, and effective cosmic/solar radiation shielding. The MEV architecture is based on many existing or near-term technologies, is flexible and modular, and could enable an economical “flexible path" approach to achieve progressively more ambitious “stepping stone” missions for human exploration of the solar system: starting with test flights in Earth and lunar orbit and progressing through missions to near-Earth asteroids and the moons of Mars, and culminating in the Mars Surface Exploration (MSE) mission. Its use on shorter-duration precursor missions will demonstrate key technologies for the longer duration missions.

II. Overview of the MEV Architecture

A. MEV Design Reference Mission (DRM) Requirements

Reference 7 describes a human exploration mission to Phobos and Deimos for 2033 and 2035 opportunities. It provided the requirements for velocity change (δV) and mission duration of Table 1, Col. 2 & 3. The DRM outlined in this paper assumed δVs of 3,700 m/s for TMI, 1,800 m/s for Mars Orbit Insertion (MOI), and 2,150 m/s for TEI to cover requirements for both 2033 and 2035 mission opportunities. 3,700 m/s was estimated to provide a 30d launch window for MLTV or MCTV TMI. The unmanned MLTVs utilize both propulsive braking and aerobraking for MOI, hence the lower MOI δV shown in Table 1 for MLTV. δVs assumed for course corrections and Flight Performance Reserve (FPR) are also shown in Table 1. δV for Entry Corridor Control (ECC) burns and Mission Performance Reserve (MPR) is shown in Section VI.E, below. Ref. 8 provided representative orbital alignments for a 2033 long-stay conjunction class mission shown in Fig. 1. For vehicle sizing, this paper assumed a 905d duration: 210d outbound and inbound transits; 480d at Mars (MOI to TEI), 2d for crew launch, LEO injection, docking, and assembly, and 3d for end of mission Earth entry. MLTVs depart Earth orbit 30 days earlier than the MCTV. MEV architectural considerations are outlined in Sect. II.B, below, and the MSE mission is outlined in Sect. VI.D, below.

Table 1. Mission δVs, 2033 and 2035 Opportunities.

Mars Mission Opportunity	2033	2035	Design	MLTV	MCTV
Trans-Mars Injection (TMI) [1, 2]	3,520	3,620	3,700	3,774	3,774
Mars Orbit Insertion (MOI) [1, 3, 4, 5]	1,800	1,360	1,800	842	1,862
Trans-Earth Injection (TEI) [1, 6, 7]	1,620	2,150	2,150	N/A	2,219

[1] Burns include 2% Flight Perf. Reserve (FPR) on δV.
[2] TMI δV estimated at 3,700 m/s for 30 day launch window: 3,700 m/s + 2% FPR = 3,774 m/s.
[3] MOI includes 25 m/s Outbound Course Corrections.
[4] MLTV only: Aerobraking circularizes highly elliptic post-MOI capture orbit. Compensates for ~1,000m/s δV deficit: 800 m/s + 25 m/s + 2% FPR = 842 m/s.
[5] MCTV: 1,800 m/s + 25 m/s + 2% FPR = 1,862 m/s.
[6] TEI includes 25 m/s Inbound Course Corrections.
[7] TEI: 2,150 m/s + 25 m/s + 2% FPR = 2,219 m/s.

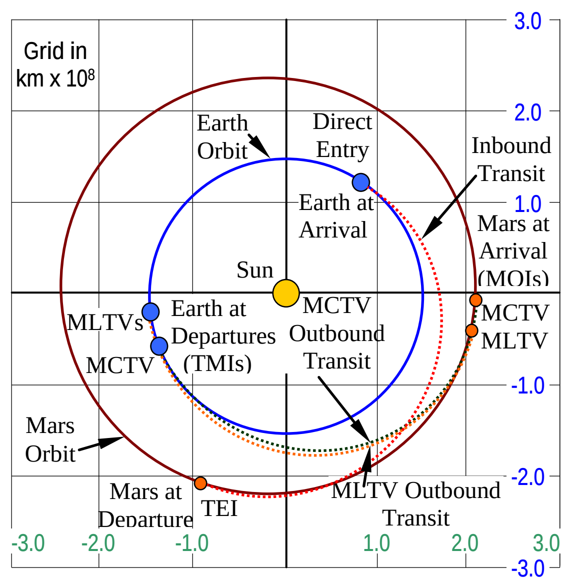


Figure 1. Representative 2033 MEV Mission Opportunity showing Orbital Alignments

B. MEV Architectural Considerations

The significant mission assumptions, design considerations, trade study results, and lessons learned in multiple design iterations that shaped the MEV architecture are shown below in Table 2.

Table 2. Significant Mission Assumptions and Design Considerations that Shaped the MEV architecture.

Vehicle and Crew Sizing	The smallest size and mass architecture needed to accomplish a Mars surface exploration mission was desired: The minimum reasonable crew size was assumed to be four, which sized habitation volume & consumables.
	Existing vehicle designs also supported a crew size of four: The Orion MPCV was designed for crew of four for deep space missions. The MPL design was originally designed to accommodate a maximum crew of four.
Technology Level	Existing or near-term technology was utilized extensively to minimize development cost and risk, e.g.: the Centaur RL10-C-2 rocket engine and the Orion MPCV Service Module thrusters and Ultra-Flex solar Arrays.
TMI, MOI Propellants	Use high performance cryogenic LH_2/LO_2 propellants to meet high mission δV req'mts. for TMI/MOI. Storable hypergolic propellants for MOI produced unacceptably high injected mass to LEO (IMLEO) and were rejected.
I_{SP} of CPS Engines	The RL10-C-2 engine was selected over the J-2X engine based its significantly higher vacuum I_{SP} (465.5s vs. 448s) and resulting reduction in IMLEO. Clustered RL10-C-2 engines (vs. 1xJ-2X) produced a compact CPS.
TEI Propellants	Use storable hypergolic propellants for TEI (which occurs approximately 23 months after TMI) to eliminate the requirement and risk of maintaining very low-loss storage of cryogenic propellants for almost two years.
Launchers & Payload Size	Launch subassemblies sized for SLS. Assume payload maximum mass/ fairing size of 130t/ 36m long x 8.4m diameter. To simplify the architecture, use of other launchers, e.g. the Delta-IV Heavy (D4H), was eliminated.
Launch Rate & Facilities	Launch SLS with reasonable 45 day spacing between launches (30 day centers, with 15 days of contingency). Use the existing capabilities of Kennedy Space Center Space Launch Complex 39 to minimize cost.
Launch Packaging	Divide the launch payloads that are assembled in LEO to form the MLTVs and MCTV into launch subassemblies of roughly the same mass, volume, & form factor to minimize the difference in configurations.
Assembly Orbit	Launch MLTV and MCTV subassemblies from KSC into a vehicle assembly orbit that will be stable for up to one year: 407km (220 nautical mi.) altitude, eastbound, circular orbit inclined 28.5 degrees to the equator.
LEO Assembly	Use simple axial docking, rather than parallel berthing of elements, to assemble MLTVs and MCTV in LEO. Rotate docked elements if they need to be parallel. Minimize number of docking events to increase reliability.
	Enable all MCTV vehicles to be joined, or dock, at either end to enable easy reconfiguration during assembly and mission. Provide DSVs with two additional docking ports (on sides of vehicle) for docking of landers.
Common Elements	Use common vehicle elements: MLTVs and MCTV utilize same EDS & MTS, with only minor modifications; The DSV design is derived from designs for Mars cargo landers (MCL-H) and crew lander (MPL).
Artificial Gravity (AG)	Rotate the MCTV for AG, with the ability to balance vehicle in a dumbbell configuration, with sufficient mass on both sides of the vehicle and variable geometry to compensate for changing masses during the mission.
Mission Duration	Launch all MEV elements during a single Mars low-energy opportunity to minimize requirements for overall mission duration and vehicle and subsystem service life. The 2033 and 2035 opportunities were selected.
Launch Sequencing	Design launch windows and sequence Earth departures and Mars arrivals to enable MLTVs to arrive 30 days before arrival of the MCTV to allow landers time to aerobrake and then rendezvous with the MCTV in LMO.
Aerobraking for MOI	Utilize aerobraking for MOI to the maximum extent practicable to minimize MEV IMLEO. Utilize aerobraking only for MEV unmanned elements (i.e. the six Mars landers) in order to not subject the crew to this risk.
CPS Boiloff Rates	Assume zero boil-off for LO_2 and a very low boil-off rate for LH_2 propellant during LEO assembly & outbound transit in order to minimize the amount of LH_2 required for top-off, and to maximize TMI performance.
Top-off of CPS LH_2	Provide the capability for top-off of CPS LH_2 in LEO, just before TMI, to compensate for LH_2 boil-off during assembly, maximize vehicle performance capabilities, and relax time constraints on assembly launches.
Sizing of CPS	Using three EDS for MCTV enabled using the same EDS design for MLTV, with good thrust/weight for all burns, and enabled using same basic CPS design for both EDS and MTS, with either four or six engines.
MCTV TMI Booster Size	Total IMLEO of the three MCTV EDS is 253.5t, or 51.7% of MCTV IMLEO. This mass is roughly the maximum lift capability of two SLS, and eliminates the possibility of launching a single EDS for the MCTV.
TMI Booster Cross-Feed	TMI Booster propellant cross-feed was eliminated. This resulted in three identical EDS for MCTV which enhanced commonality, reduced mechanical complexity, simplified LEO assembly, and enhanced reliability.
Number of Mars Landers	Earlier MEV designs utilized four landers: 1xMPL, 2xMCL-H, and 1xMCL-R. The resulting lander payload was considered the minimum capability for Mars surface exploration, with no margin or redundancy.
	The current MEV utilizes six: 2xMPL, 2xMCL-H, and 2xMCL-R. The 2nd MPL enables crew rescue from surface or orbit. The 2nd MCL-R provides redundant mobility and enables a nuclear power generator payload.
Mission Redundancy	The MEV design utilizes two identical MLTVs (1xMPL, 1xMCL-H, & 1xMCL-R each). This provides mission redundancy to complete a partial Mars surface exploration mission in the event of complete loss of one MLTV.

C. MEV Architecture Design Description

The MEV architecture is comprised of three major types of vehicles: (1) two unmanned MLTVs, shown in Fig. 2, (2) the MCTV, with a crew of four, shown in Fig. 3, and (3) four Booster Refueling Vehicles (BRV), shown in Fig. 4. The BRVs are used to top-off EDS and MTS LH_2 propellant tanks in LEO prior to MLTV and MCTV TMI.

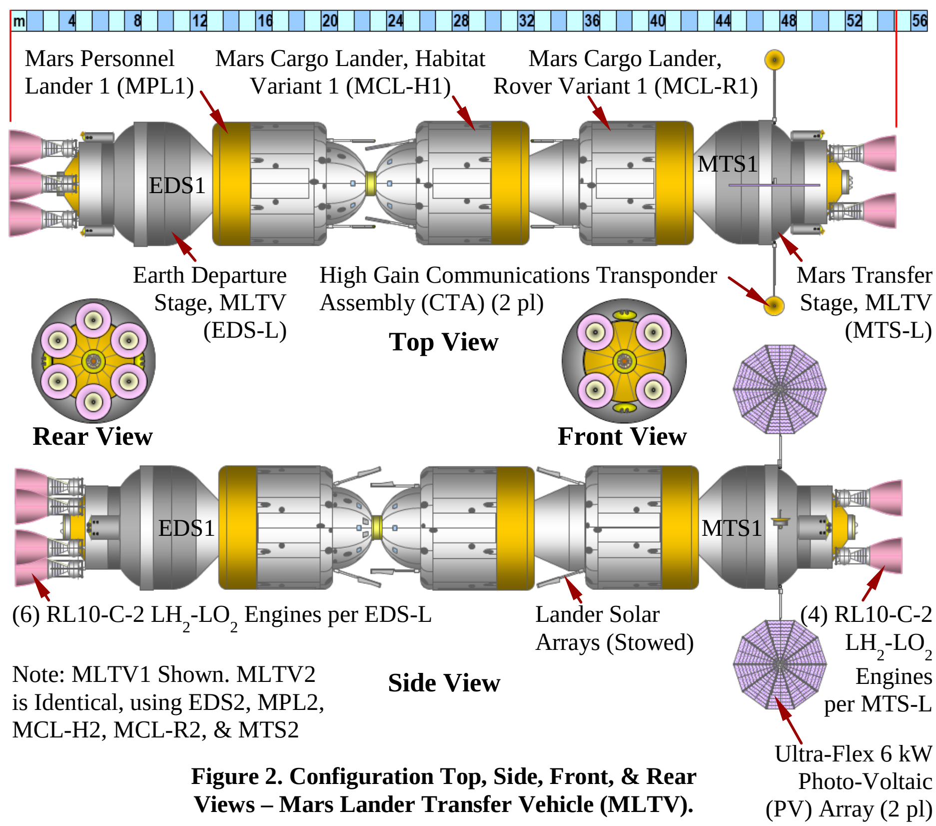


Figure 2. Configuration Top, Side, Front, & Rear Views – Mars Lander Transfer Vehicle (MLTV).

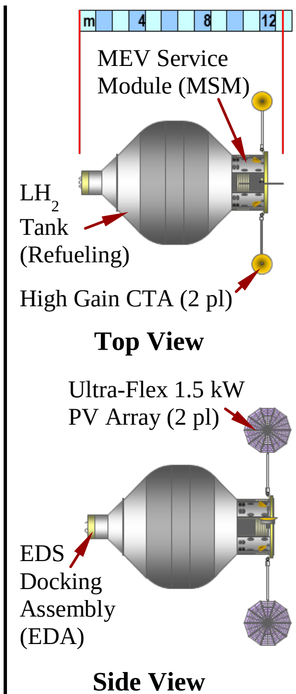


Fig. 4. Config. Top/Side Views – Booster Re-fueling Vehicle (BRV).

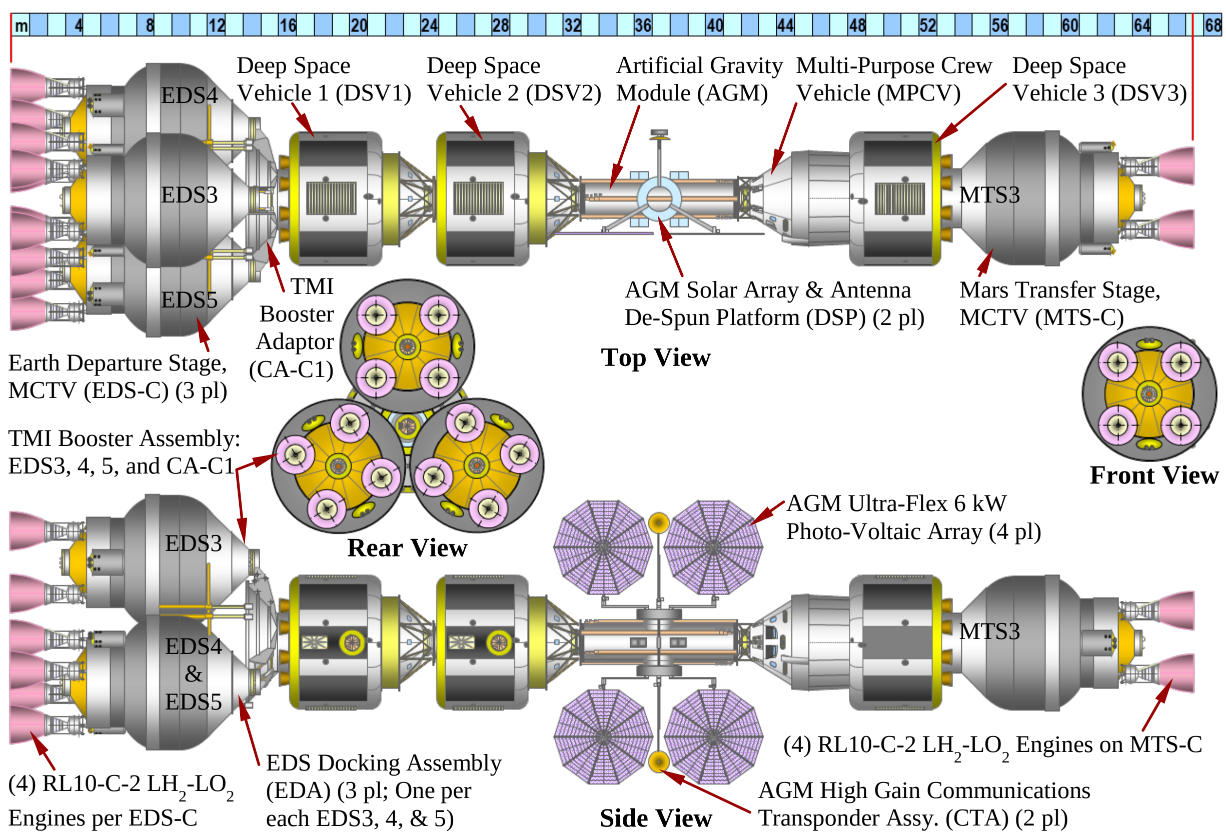


Figure 3. Configuration Top, Side, Front, and Rear Views – Mars Crew Transfer Vehicle (MCTV).

1. MEV Architectural Elements

The MEV Architecture is composed of six major types of modular components and various structural adaptors as shown in Fig. 5. It is designed for launch on SLS rockets with 130t lift capability to LEO as shown in Fig 6. The six modular MEV architectural components are the major “building blocks” of the architecture, and can be assembled in various combinations as needed to satisfy mission requirements. Component designs are discussed in detail below in Section III: Landers, III.A and B, DSVs and MPCV, III.C, AGM, III.D, CPS, III.E, and BRV, III.F.

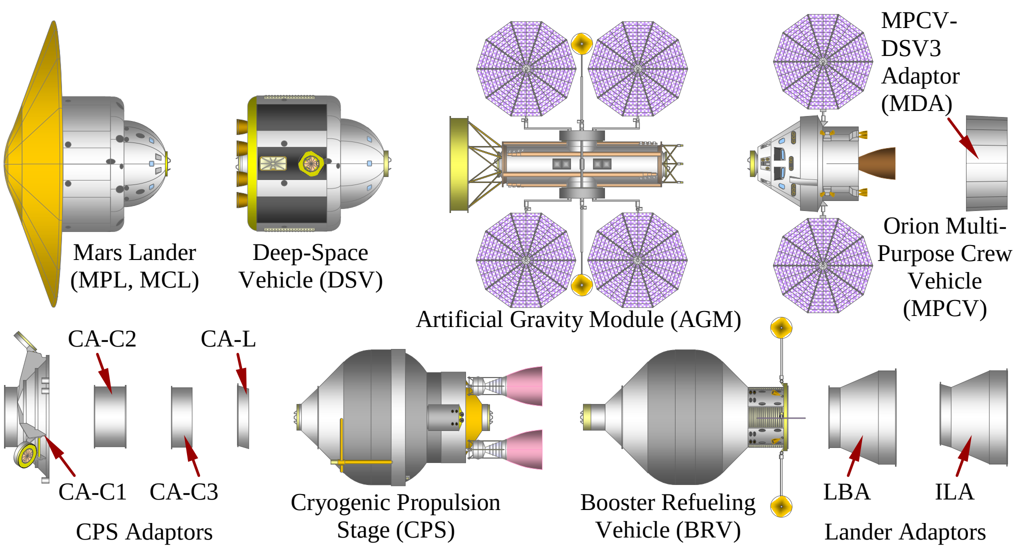


Figure 5. The “Building Block” Components of the MEV Architecture.

Figure 6. SLS - 130t to LEO.

2. Design of Mars Lander Transfer Vehicle

The two MLTVs are identical. Each MLTV is composed of the following major components: an Earth Departure Stage (EDS-L) and a Mars Transfer Stage (MTS-L) both utilizing cryogenic LH_2/LO_2 propellants, and a payload of three Mars landers. Each MLTV carries two Mars Cargo Landers, a Habitat Variant (MCL-H), and a Rover Variant (MCL-H), and a Mars personnel Lander (MPL). In addition to major components: EDS-L, MTS-L, and landers, the MLTV incorporates the following additional components: Adaptor structure CA-L joins EDS/MTS to landers. The ILA joins the MCL-R to the MCL-H, and the LBA joins the MPL to the BRV. Each MPL carries a LIDS Docking Adaptor-Dual (LDA2) to enable the MPL to mate with passive LIDS on MCL-H during MLTV assembly, and later for the MPL to mate with passive LIDS on MCTV DSV1/DSV3 rear docking hatches in Mars orbit. Each MLTV is launched with a dedicated BRV to top off EDS-L and MTS-L LH_2 propellant tanks before TMI. Each MLTV transports its three Mars landers (MCL-H, MCL-R, and MPL) from the LEO assembly/refueling orbit to a highly elliptical Mars capture orbit, where the individual landers are released for aerobraking into the 500km circular parking orbit. The landers utilize aerobraking in Mars’ atmosphere to augment MLTV propulsive braking for MOI, significantly reducing MOI propellant mass and overall IMLEO. Aerobraking is discussed in Section V.B, below.

3. Design of Mars Crew Transfer Vehicle

The MCTV is composed of the following major components: three EDS-C (EDS3-5) and one MTS-C (MTS3) utilizing cryogenic LH_2/LO_2 propellants, an Orion MPCV, three Deep Space Vehicles (DSV1-3) utilizing storable hypergolic mono-methyl hydrazine/nitrogen tetroxide (MMH/N_2O_4) propellants, and an Artificial Gravity Module (AGM). In addition to these major components, the MCTV incorporates the following additional components: Adaptor CA-C1 connects DSV1 to EDS4 for launch. During assembly, EDS3-5 dock to CA-C1 docking fittings and are rotated 90 deg., parallel to the MCTV long axis. The three EDS lock together to form the TMI Booster Assembly (TBA), which operates as a single stage for TMI. EDAs, with active LIDS, are mounted on the nose of EDS3-5 to enable them to dock to the passive LIDS on CA-C1. Adaptor CA-C2 connects EDS3 to DSV2 for launch, and adaptor CA-C3 connects MTS3 to DSV3 for launch through MOI. The MDA adaptor connects the MPCV to DSV3. The MCTV is launched with two dedicated BRVs (3, and 4) to top off the three EDS-C and single MTS-C LH_2 propellant tanks before TMI. The two MLTV BRVs (1, 2) have sufficient remaining LH_2 onboard after topping off MLTV1 and MLTV2. They could provide backup for the two MCTV BRVs (3, 4), enhancing mission redundancy.

The MPCV transports the crew from earth to LEO. It also provides for return of the crew to earth after successful completion of the mission or in abort situations. MPCV design parameters were taken from NASA publications (in Refs. 1, 2, 3, and 5) and were used without any modifications. The MPCV, DSV1, and DSV3 provide propulsion. DSV1 and DSV2 provide habitation volume, life support system (LSS), LSS consumables, and passive biological radiation shielding for four crewmembers during the in-space portion of the mission. The DSV design is derived from the common modular landers used in the Spaceship Discovery vehicle architecture for human exploration of the solar system.[9] The DSV is a modification of Spaceship Discovery LM3 autonomous cargo lander, habitat variant (renamed MCL-H in this paper).[10] The DSV design and MPCV interface are discussed in detail below in Sect. III.C.

The AGM links DSV2/DSV1 and MPCV/DSV3 sides of MCTV mechanically and electrically using telescoping artificial gravity (AG) rails. The rails extend to separate DSV2/DSV1 and MPCV/DSV3 from the AGM to get long radius arms for AG rotation, providing 0.379 g's (Mars surface equivalent) of AG generated by centrifugal force in DSV2 middle level, the lowest living level in the crew cabin, during the three main coast phases of the mission: outbound transfer orbit (OTO), Low Mars orbit (LMO), and inbound transfer orbit (ITO). The MCTV AG concept has the flexibility to vary the length of the radius arms, depending on relative vehicle masses which vary throughout the mission. The MCTV is spun up and spun down using thrusters during OTO, LMO, and ITO mission phases, and has a de-spun platform to facilitate solar array Sun tracking and antenna Earth tracking. The AGM provides a tunnel for pressurized crew access between MPCV and DSV1 when the MCTV is not rotating (zero-g) and the MPCV and DSV1 have been retracted and docked to the AGM. The AGM also provides photovoltaic power generation and deep space communications. The AGM design and AG operations are discussed below in detail in Section III.D.

III. Design of MEV Architecture Components

A. Common Modular Design for MEV Mars Landers and Deep Space Vehicles.

Mars lander and DSV designs utilized in the MEV architecture are based on the Spaceship Discovery landers. The Spaceship Discovery conceptual space vehicle architecture was an independent research study performed by the author to evaluate a range of possible human solar system exploration destinations enabled by the use of advanced nuclear thermal propulsion.[9] Seven design Reference Missions (DRMs), to Earth's Moon, Mars, the asteroid Ceres, and the moons of Jupiter, Ganymede and Callisto were formulated. An eighth DRM to the largest airless moons of Saturn, Rhea and Iapetus, was planned but not completed. Landers were developed to land crew and/or cargo on all of these bodies: Lander Module 1 (LM1) is designed to land on large airless moons Ganymede, Callisto, and Earth's moon[11] and provides two-way transportation for a two-person crew between orbit and the surface and life support for 60 man-days. Lander Module 2 (LM2) is a Mars personnel lander[10] which provides two-way transportation for a three- or four-person crew between LMO and the surface and life support for 81 man-days. Lander Module 3 (LM3) is an autonomous Mars cargo lander[10] which provides one-way transportation of cargo from LMO to the surface and can be configured to carry a mix of consumables and equipment. The LM3 habitat variant (LM3-HAB) incorporates a large pressurized radiation-shielded habitat, and is designed to rendezvous and dock with LM2 on the surface to increase endurance an additional 630 man-days beyond LM2 capability. Lander Module 4 (LM4) is a crew exploration lander designed to land on smaller airless bodies Iapetus, Rhea, and Ceres[12] and provides two-way transportation for a two-person crew between orbit and surface and life support for 60 man-days. All four lander designs are modular and share many design features to maximize commonality and minimize development cost.

The Spaceship Discovery (SSD) architecture numbered the four different landers (LM1, LM2, LM3, and LM4) in concert with the eight numbered Spaceship Discovery DRMs. Later, in developing the MEV architecture, it was realized that the Spaceship Discovery landers could be incorporated into the MEV architecture, or any other solar system exploration architecture that orbited the target planet or moon in the specific low orbit from which these landers were designed to operate. To avoid confusion, these four landers have been given descriptive names in the MEV architecture: The LM1 has been renamed the Lunar Personnel Lander, Large (LPL-L), the LM2 has been renamed the Mars Personnel Lander (MPL), the LM3-HAB has been renamed the Mars Cargo Lander, Habitat Variant (MCL-H), and the LM4 has been renamed the Lunar Personnel Lander, Small (LPL-S). A rover variant of the MCL (MCL-R) was developed as part of the MEV architecture, and is presented for the first time in detail in this paper. The MEV architecture's Deep Space Vehicle (DSV) designs, DSV1, DSV2, and DSV3, are derived from the MCL-H and also share common features with the MPL and MCL-R. The four renamed Spaceship Discovery landers are shown in Fig. 7 along with the MEV architecture's DSVs, highlighting their common modular design. Designs for the MEV architecture's Mars landers and DSV are discussed in sections III.B and III.C, respectively, below. Reference 13 provides additional details on the common modular designs used for MEV Mars landers and DSVs.

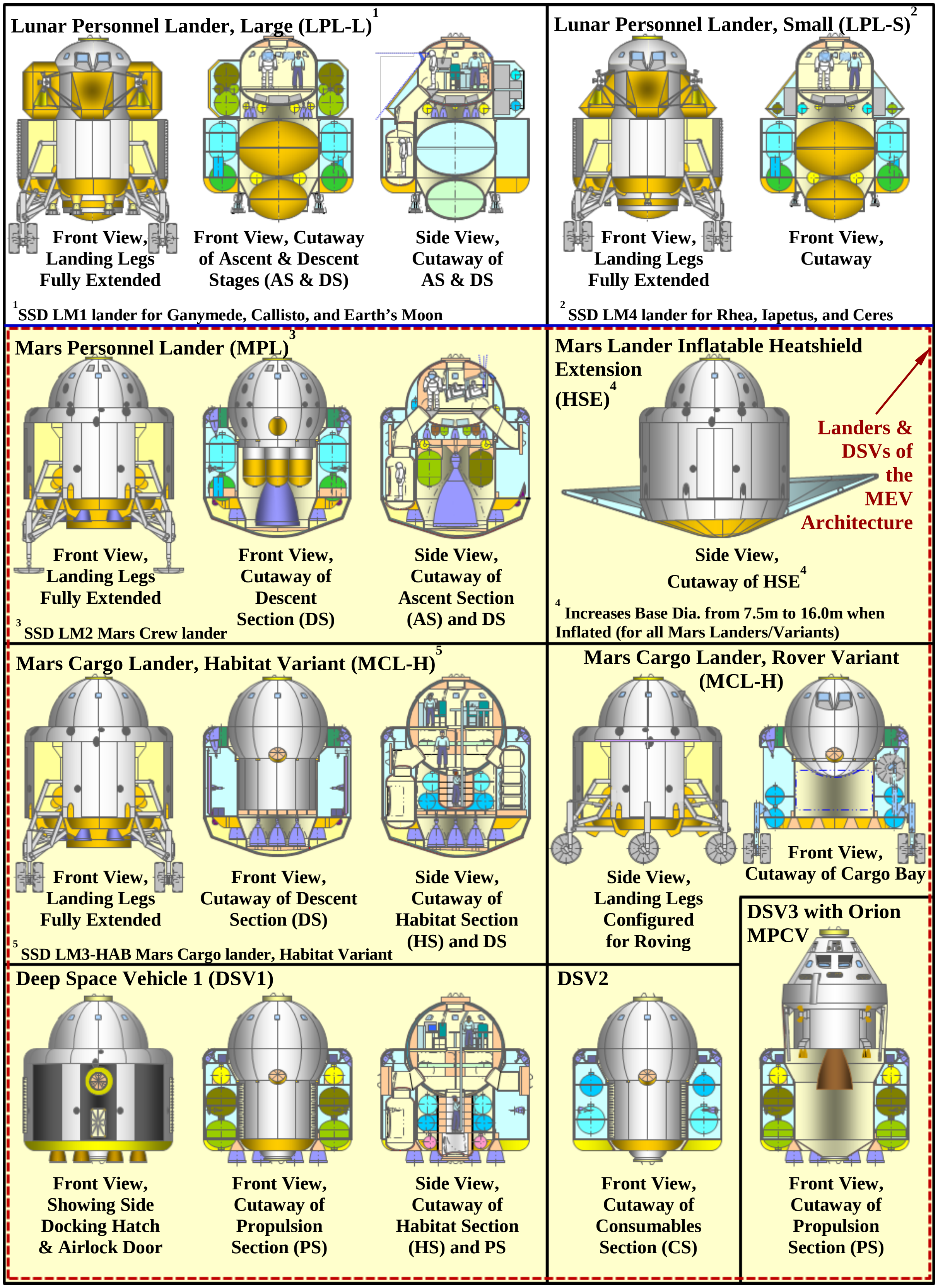


Figure 7. Designs for Common Modular Landers and Deep Space Vehicles for Human Solar System Exploration.

B. Design of Mars Lander Vehicles

1. Design Overview

Reference 10 provides a detailed description of the design rationale, analysis, and trades conducted to develop the Mars landers first utilized in the SSD architecture and later incorporated into the MEV Architecture. It also provides a detailed set of references for the Mars Lander Vehicle design study summarized below. The landers are based on a common design that can be configured to carry either crew or cargo, and assume a Mars orbit rendezvous methodology with initial capture of the crew vehicle and landers into a circular LMO parking orbit. A circular parking orbit was desired to facilitate rendezvous and docking of the Mars ascent vehicle with the crew vehicle. The δV needed to return the crew from the surface of Mars to LMO (4.34 km/s) is the largest single δV increment in the entire Mars mission, and is a significant driver of ascent vehicle size and mass. The parking orbit altitude originally used in the Spaceship Discovery architecture was 556 km (300 naut. mi.). This was later reduced to 500 km for the MEV Architecture. LMO altitude was set to the minimum estimated to remain stable for the full 480 day Mars stay time, in order to minimize Mars ascent vehicle δV. Since the ascent vehicle must be carried in the descending lander, ascent vehicle mass drives the overall lander size and mass. This also influenced the MCL size, mass, and number of MCLs needed for the mission, as the MCL carries cargo mass in place of the MPL's ascent vehicle mass on its one-way mission. The MEV architecture also takes advantage of the facts that: (1) the landers are already designed to withstand significant aerodynamic deceleration and aeroheating during atmospheric entry from the LMO parking orbit, and (2) the MEV architecture delivers the landers to LMO in the MLTV, separate from the crew who arrive in the MCTV. Aerobraking in Mars' atmosphere is a much more benign environment than entry from LMO, and the landers' relatively high hypersonic drag coefficient of 1.55 enables them to rapidly aerobrake into the final LMO parking orbit. This enables utilization of lander aerobraking to augment MLTV propulsive braking for MOI, significantly reducing MLTV MOI propellant mass and overall IMLEO of the MEV architecture.

Aerodynamic braking was selected as the primary method to slow the landers from orbital speed to a soft landing to minimize overall system mass. The Viking-type aerodynamic braking concept offered many advantages: It is well understood, flight proven, provides a low ballistic coefficient, defined as $C_B = m/(C_d * S_{Ref})$, where m is mass, C_d is hypersonic drag coefficient, and S_{Ref} is base area, and sufficient stability to minimize control system usage. The scaled Viking 70-deg sphere cone forebody shape has a broad set of existing aerodynamic performance data and significant heritage to not only Viking, but every other Mars landing mission to date. The Viking lifting entry trajectory provides a tolerable peak deceleration, and can be additionally tailored to limit peak crew deceleration loads. Simulations conducted during the SSD and MEV design studies were able to limit peak deceleration loads to 4.7 Earth g's by modulating angle-of-attack (α) to control lift to drag ratio (L/D). Initial SSD architecture studies indicated a lander mass of 80t or more was needed in order to land sufficient payload plus the ascent vehicle on the surface. Implementing the Viking-type aerodynamic braking concept to soft land a payload of 80t or greater, however, poses many technical difficulties. Viking entry vehicles had a ballistic coefficient (C_B), of 64 kg/m^2 with base diameter of 3.505 m. Holding C_B constant for a Viking forebody shape for an entry mass of 80t would require a base (heatshield) diameter of 32m. This was deemed impractical. As a result, the proposed design divided the 80t into four equally-sized 20t landers. A 20t lander mass requires a more achievable base diameter of 16m, and would be a more reasonable extrapolation from the existing Mars lander databases and analyses than an 80t lander mass with a 32m base dia. Later SSD and MEV architecture studies increased the number of landers from four to six. Lander mass increased from a nominal 20t to 21.5t due to increases in parachute, engine, and propellant masses. The MSE mission utilizes four MCL to increase surface endurance up to 16 months for the 4 person crew in the MPL.

2. Mars Entry, Descent, and Landing (EDL)

The MPL/MCL landers are designed to be identical during the EDL phase from the standpoints of aerodynamic shape, mass properties (center of mass and moments of inertia), propulsion, and guidance, navigation, and control (GN&C). They utilize a combination of an initial deorbit burn, aerodynamic deceleration during atmospheric entry, a parachute, and a final powered descent to decelerate from orbital velocity to a soft landing on the surface of Mars. The MPL/MCL EDL concept is based on flight test-qualified hardware and operations concepts. The MPL/MCL heatshield windward outer moldline (OML), or forebody, is geometrically scaled (4.565 scale factor) from the 3.505m diameter unmanned Viking lander 70 degree sphere-cone forebody OML to enable dynamic flow similarity with wind tunnel test data to keep the aerodynamic design within a well understood database to minimize risk and development cost. The descent mission profile and parachute design are based on Viking heritage and recent design concepts that have been flight tested. The EDL trajectory was initially modeled on a Mars Science Laboratory vehicle EDL parametric analysis, with C_B of 63 kg/m^2 and L/D of 0.18. Two degree-of-freedom simulations were then performed using the NASA standard Mars atmosphere model and a spherical Mars gravitational potential to size the DGB parachute, descent engines, and vehicle, and optimize the trajectory. The MPL/MCL EDL trajectory utilizes Apollo-type guidance, with center of gravity (CG) offset and lifting to enable precision landings. The MPL/MCL forebody/heatshield incorporates an inflatable heatshield extension (HSE) to increase base diameter beyond what can be accommodated in existing or proposed launch fairings (assumed to be 8.0m). The HSE is attached to the rigid, central heatshield, and more than doubles base diameter from 7.5m to 16.0m to keep C_B manageable and close to the nominal Viking 64 kg/m^2. The MPL/MCL C_B is between 66.1 and 73.2 kg/m^2 (at $\alpha = 0$ to 20 degrees). Inflatable aerodynamic decelerators/ heatshields have been the subject of recent studies and experiments and have been considered for many years. The HSE inflation sequence is shown in Fig. 8.

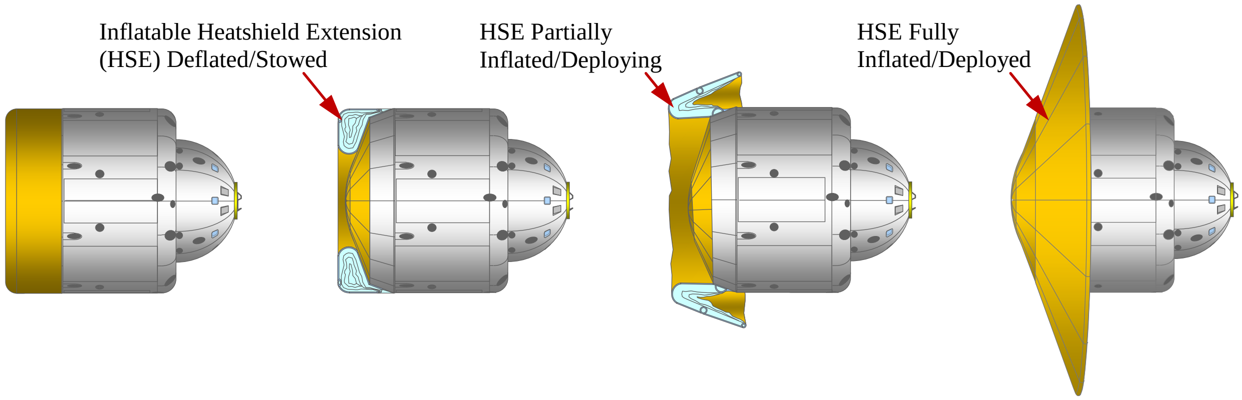


Figure 8. MPL/MCL Inflatable Heatshield Extension Enables a High Mass Lander with a Low Ballistic Coefficient.

The MPL/MCL vehicles are axisymmetric. MPL mass properties are strongly affected by the centrally located, 13.2t Ascent Section (AS). It was not possible to relocate sufficient mass within the vehicle to achieve the 0.28m CG offset required by the scaled Viking OML. The correct 0.28m CG offset was achieved by canting the vehicle 3 degrees within the Viking OML shape as shown in Fig. 9. The rigid portion of the lander heatshield, as well as the inflatable HSE, is asymmetric to the vehicle centerline but the forebody is axisymmetric to the Viking OML shape. This has the effect of causing the vehicle to fly at 3 degrees of incidence to the flight path at forebody $\alpha = 0$. This should not be a concern, as the bulk of the vehicle is shielded by the forebody during reentry, and the vehicle becomes axisymmetric once the heatshield is jettisoned. EDL simulations showed it would be feasible to utilize a single large disk-gap-band (DGB) parachute in combination with propulsive thrust to slow the vehicle to a soft landing. Lander trajectories were simulated for 22m to 30m diameter Viking-style DGB parachutes for a parachute sizing trade study, which selected a 27m DGB parachute that minimized both vehicle mass and developmental risk. The parachute sizing trade study also showed that the vehicle will never decelerate to subsonic speed without an adequately sized parachute that deploys correctly. An abort-to-orbit could not be conducted until the vehicle has slowed to subsonic speed and jettisoned the heatshield to expose rocket engines. A successful supersonic parachute deployment is, therefore, crucial to crew safety and mission success. A separate, redundant DGB parachute and mortar system are included as part of the MPL/MCL design. Sect. VI.D.2 below provides additional EDL details.

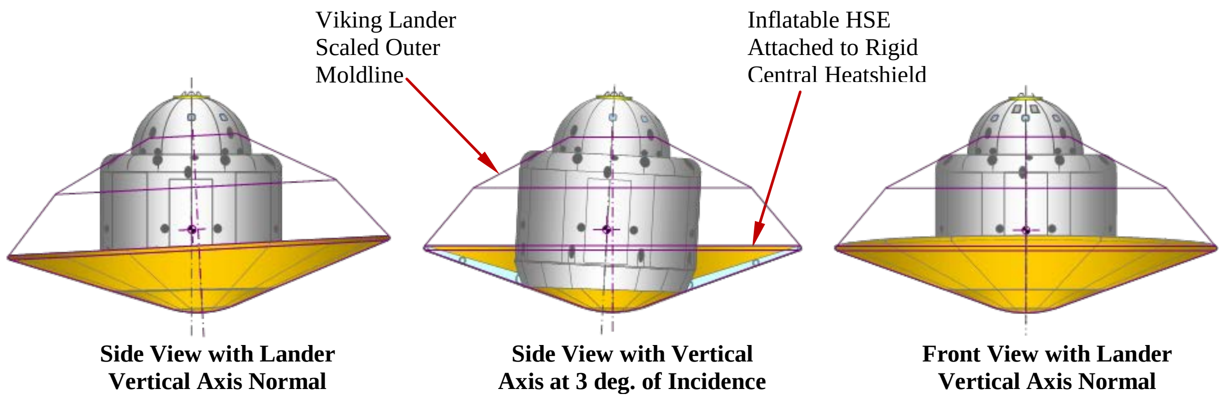


Figure 9. Correct 0.28m CG Offset Achieved by Canting Lander Vertical Axis 3 deg. to Scaled Viking Forebody OML.

3. Ascent to Orbit

The two-stage MPL Ascent Section (AS) is used to return the crew to the parking orbit. The AS Booster stage places the AS into a circular, intermediate 250 km altitude orbit. Ascent performance requirements to the 250 km orbit are based on a design study for an unmanned Mars sample return mission. The intermediate orbit was selected to reduce the stress on the lander design, and the resultant landed mass requirements and EDL issues, that would be present if the AS had to achieve the final parking orbit using a single-stage-to-orbit design. The intermediate orbit should be stable for a week or more and is at a sufficiently high altitude that the crew could be rescued by another MPL in the event they cannot raise their orbit to the parking orbit altitude. The AS Booster is jettisoned and the crew utilizes a Hohmann transfer to raise the AS Orbiter altitude from the 250 km intermediate circular orbit to the 500 km circular parking orbit. Sect. VI.D.4 below provides additional details on MPL Ascent Orbiter flight performance.

4. Common Design Features

The MPL/MCL vehicles have the same outer moldline geometry, overall mass properties, flight characteristics, parachutes, and flight controls. Lightweight composite structures are extensively utilized to maximize performance and minimize overall system mass. It is envisioned that advanced composite materials used for crew habitation areas will be "dual-mode," to provide biological radiation shielding as well as structural integrity. The descent section (DS) is common to the MPL/MCL, with the same four landing legs and basic structural design that utilizes a central thrust cylinder to efficiently carry loads. Minor structural differences exist to account for changes in cargo loading and habitat accommodations. The common DS houses eight 13.6 kN non-gimballed descent engines (throttleable between 38%-100%), eight 2.64 kN deorbit thrusters, and a 6-axis reaction control system (RCS), with sixteen 0.745 kN RCS thrusters for attitude control and translation maneuvers. These engines are sized for single engine-out considerations, and utilize storable, hypergolic monomethyl hydrazine (MMH) and nitrogen tetroxide (N_2O_4) propellants for reliable operation after years of storage. The rigid heatshield, HSE, and four landing gear doors are jettisoned before initiation of powered descent. Eight 6.7 kN solid propellant separation motors are used to jettison the heatshield/HSE/landing gear doors. Rocket engine design parameters are based on design data for Space Shuttle OMS and RCS thrusters and commercial rocket engines. Structure and avionics designs are based on Apollo and Viking designs, with upgrades for advances in materials and subsystems. Fuel cells are based on Apollo fuel cells.

5. Mars Personnel Lander (MPL)

The MPL provides two-way transportation for the four-person crew between Mars orbit and the surface, and provides life support for a 20-day contingency mission. The MPL is designed for abort-to-orbit (ATO) during all parts of the powered descent portion of the EDL profile. The lander utilizes the common DS and has a two-stage ascent section (AS), with Booster and Orbiter stages. The AS Orbiter is designed to achieve parking orbit (with 8.8 deg. plane change) with a crew of four in space suits with emergency life support systems (ELSS), and a minimum sample payload of 20 kg. Additional payload mass could be traded against reduced plane change capability. The AS booster has a single, fixed thrust, gimballed, 98.2 kN thrust main engine that is used for both descent and ascent to save engine mass and facilitate aborts during the powered descent phase. During descent it is cross-fed with propellants from the DS. The AS orbiter has six, fixed thrust, non-gimballed, 1.91 kN main engines that are sized for single-engine-out considerations. Sixteen 0.445 kN RCS thrusters on the AS orbiter provide AS attitude control during the booster ascent phase and provide the orbiter stage with 6-axis control during orbit raising, rendezvous, and docking. Electrical power is provided by LH_2-LO_2 fuel cells in the DS and batteries on the AS orbiter. The MPL DS houses a personnel airlock accessible by tunnel from the ascent section crew cabin. It has a descent payload capacity of 500 kg in a cargo bay on the opposite side of the DS as the airlock. The DS also houses two horizontal surface docking adaptors, accessible by tunnels from the crew cabin. These enable up to two MCLs to mate with the MPL utilizing MCL surface docking systems (SDS), permitting pressurized access to MCL-H habitats or MCL-R rovers. MPL configuration drawings are presented in Figs. 10 and 11 and a mass breakdown is presented in Table 3.

6. Mars Cargo Lander, Habitat Variant (MCL-H)

The MCL-H provides one-way, autonomous transportation of cargo from parking orbit to the surface of Mars. Each MCL-H provides 560 man-days of LSS consumables, greatly extending the crew's surface endurance when mated to the MPL. The MCL-H carries a 9.6t crew habitat in place of the 13.2t ascent section of the MPL, and an additional 4.0t of equipment cargo inside the three DS cargo bays and airlock. It uses the same common DS, descent engines and thrusters, propellants, and avionics. The habitat contains a 5m dia., three-level pressurized crew cabin and 6.7t of water, food, oxygen, and nitrogen. 4.8t of water is stored in a toroidal tank. After landing, 3.6t is pumped into a 5cm spherical shell surrounding the crew cabin, providing 5gm/cm^2 of radiation shielding. The habitat LSS is modeled after the MPCV system, using a partially closed-loop air revitalization system utilizing CO_2 amine scrubbers, and an onboard waste water recovery system to convert gray water and urine into purified water for drinking, washing, and equipment cooling. Waste water recovery of 85% is required to keep the shell filled. The MCL-H utilizes five, fixed thrust, gimbaled, descent engines in place of the single MPL main engine. The MPL main engine was sized for ATO considerations and has excess thrust for the powered descent phase. The smaller MCL-H descent engines integrate better with the cargo lander structure and their support beams provide a flat surface at the bottom of the DS thrust cylinder for cargo loading. The MCL-H has wheels and is designed to rendezvous on the surface with the MPL. It has two, steerable, 5.5m diameter Ultraflex solar arrays that are deployed after landing, each producing up to 5kW. The MCL-H is designed to move at the relatively slow pace of 90m per hour. It can traverse up to 1.0km per day, using 4.5kW for the drive motors. Array and motor drive power calculations are based on Mars Exploration Rover design data. The MCL-H DS houses a personnel airlock and a horizontal surface docking adaptor (SDA) in the airlock bay. It also houses a three degree-of-freedom SDS in the cargo bay on the side opposite to the airlock. These surface docking components permit the MCL-H to mate with an MPL or another MCL in various combinations. The airlock, SDA, and SDS are all accessible by tunnel from the habitat. 500kg of the 4.0t equipment cargo is allocated to the SDS. The equipment cargo also includes a small unpressurized rover, communications equipment, a weather station, and a scientific station. The MCL-H configuration drawings are presented in Figs. 10 and 12 and a mass breakdown is presented in Table 3.

7. Mars Cargo Lander, Rover Variant (MCL-R)

The MCL-R provides one-way, autonomous transportation of cargo from parking orbit to the surface of Mars and functionality of a large pressurized rover. Each MCL-R provides 60 man-d LSS consumables for a 30d roving sortie for a two-person crew. MCL-R1 carries a deployable, 600 man-d consumables payload pallet for recharge each MCL-R for five additional 30d sorties, for a total of 12 30d roving sorties. MCL-R2 carries a deployable, compact nuclear fission-powered electric generator payload pallet to provide power to the base camp. The MCL-R carries a 8.9t crew habitat in place of the 13.2t ascent section of the MPL, and an additional 4.2t of equipment cargo inside a central cargo bay and airlock, plus two EVA suits with portable life support systems (PLSS). It uses the same common DS, descent engines and thrusters, propellants, and avionics. The habitat contains a 5m dia., two-level pressurized crew cabin and 5.4t of water, food, oxygen, and nitrogen. The cabin upper level has rover controls, with two large angled windows providing excellent visibility for roving, and habitation space for the nominal two person crew, with bunks, computer table, kitchen with dining table and chairs, and hygiene facilities including a toilet, sink, and shower. The cabin lower level has an EVA dust cleaning area, scientific and medical stations, and LSS components. The habitat LSS is open-loop, with no onboard water recovery. The MCL-R descent engine layout is the same as MCL-H. The MCL-R descent engine package is jettisoned after landing to allow deployment of the central payload pallet and to permit the vehicle to lower itself into the roving configuration (RC) for more stability when roving over rough surfaces. The MCL-R has four two-wheel main gear bogeys, like MCL-H, and is designed to rendezvous on the surface with MPL/MCL. It has two additional sets of two-wheel bogeys that are deployed when in the RC. It has the same Ultraflex solar arrays as MCL-H, and additional Li-ion batteries for roving. The MCL-H is designed to move up to 1km per hour traversing up to 10 km per day. The MCL-H DS houses a personnel airlock and SDA in the airlock bay. It also houses a 3-DOF SDS in the cargo bay, similar to MCL-H. These surface docking components permit the MCL-R to mate with an MPL or another MCL in various combinations. The MCL-R configuration drawings are presented in Figs. 10 and 13 and a mass breakdown is presented in Table 3.

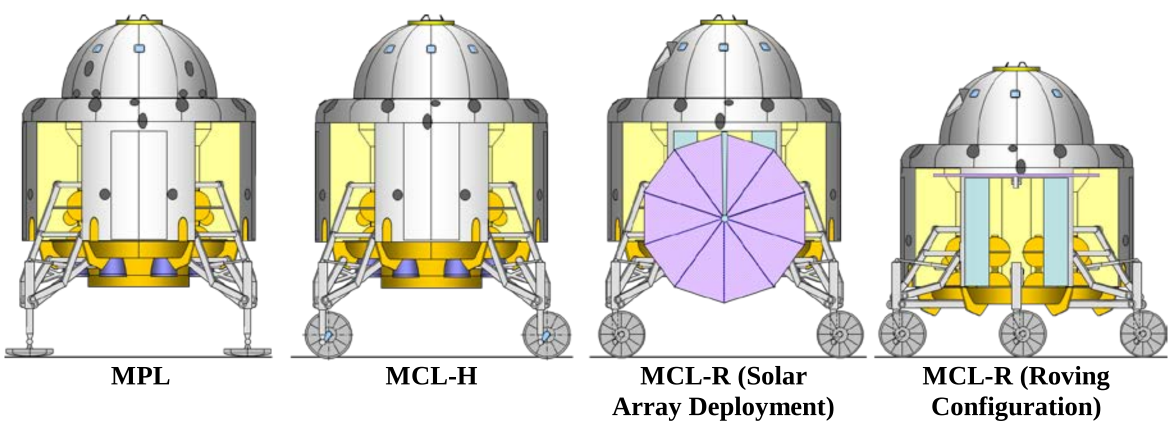


Figure 10. Landed Configurations of Mars Personnel and Cargo Landers.

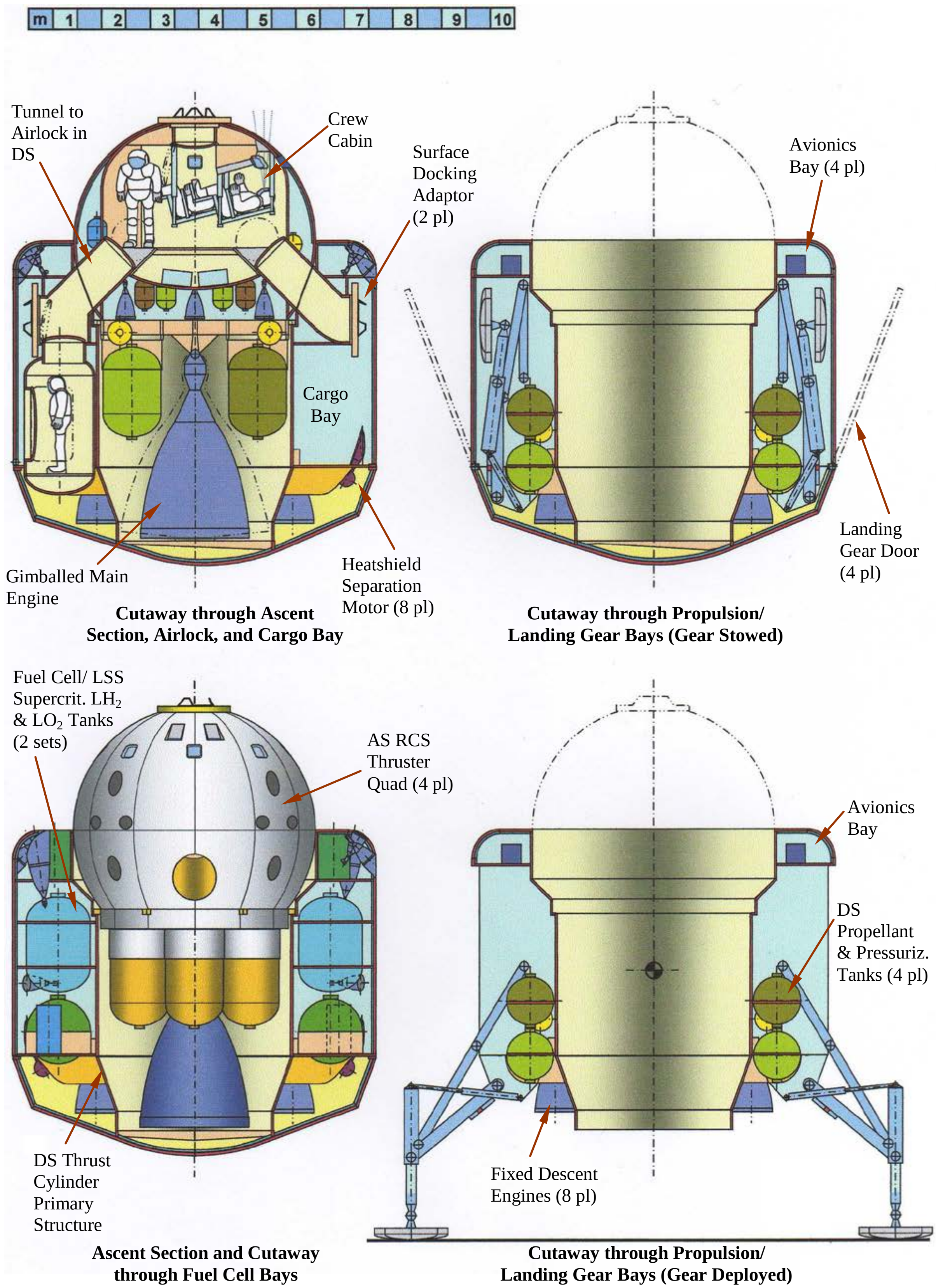
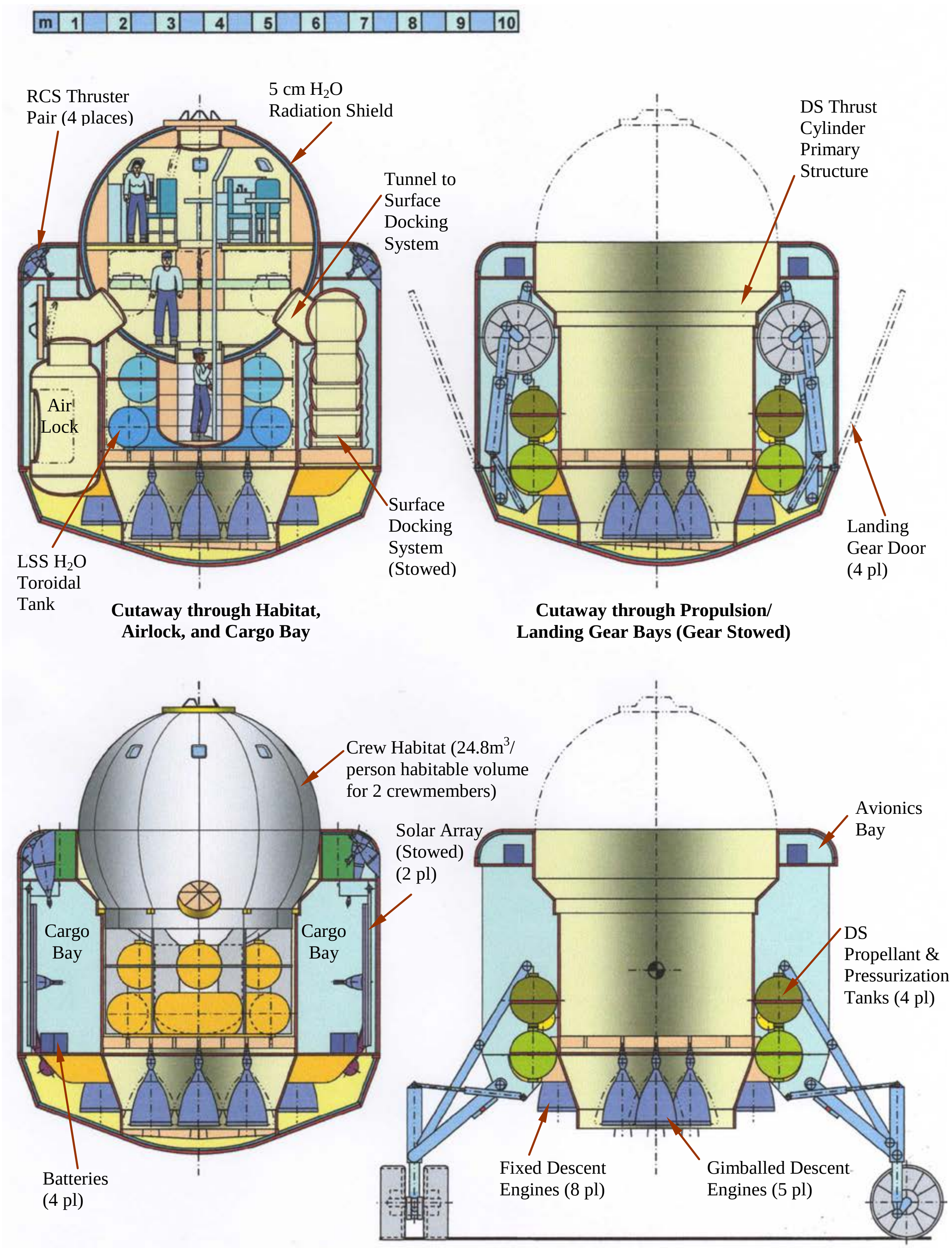


Figure 11. Mars Personnel Lander (MPL) Configuration Drawings – Elevation Views.



Cutaway through Habitat, Airlock, and Cargo Bay

Cutaway through Propulsion/ Landing Gear Bays (Gear Stowed)

Crew Habitat and Cutaway through Side Cargo Bays

Cutaway through Propulsion/ Landing Gear Bays (Gear Deployed)

Figure 12. Mars Cargo Lander, Habitat Variant (MCL-H) Configuration Drawings – Elevation Views.

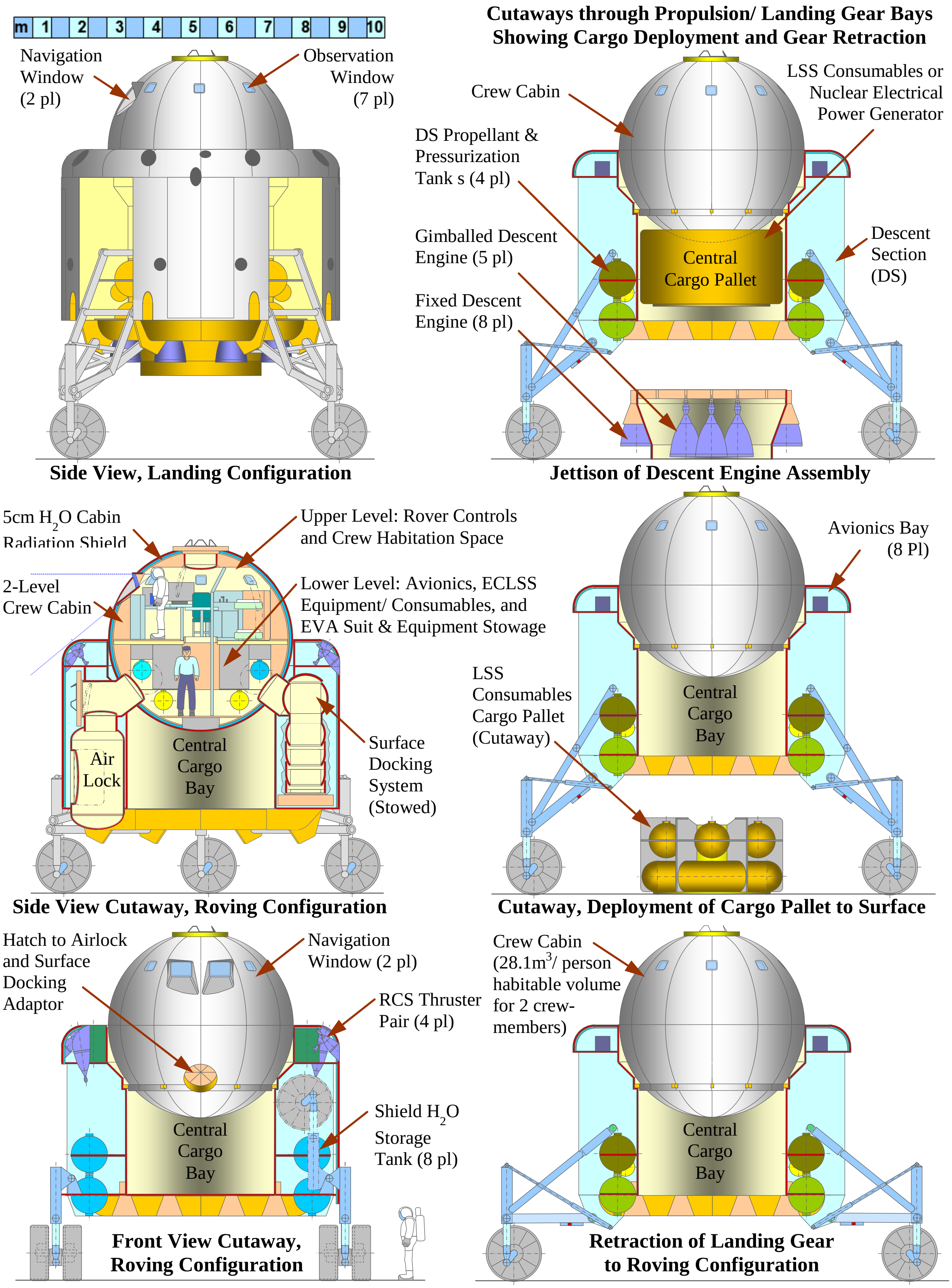


Figure 13. Mars Cargo Lander, Rover Variant (MCL-R) Configuration Drawings – Elevation Views.

Table 3. Initial Mass Breakdown for Mars Landers.

Mars Lander Mass (kg)	MCL-H	MCL-R1	MCL-R2	MPL		
Habitat or Ascent Section (HS or AS)	Habitat Section	Habitat Section	Habitat Section	Ascent Section (AS)		
				Orbiter	Booster	Total
Internal Payload (Including Crew) [1]	170	170	170	500	0	500
Pallet Nuclear Generator Payload (MCL-R2) [2]	0	0	5,000	0	0	0
Pallet Structure/Insulation/Shielding (MCL-R) [2]	0	404	789	0	0	0
Structure, Tanks, Insulation	1,817	1,536	1,536	560	652	1,212
ECLSS and Avionics	234	234	234	307	56	363
Main Propulsion System	330	330	330	37	335	372
Reaction Control System	0	0	0	80	0	80
Dry Mass Margin (15%)	357	315	315	148	157	304
Internal LSS Consumables [3]	6,674	539	539	56	0	56
Pallet LSS Consumables (MCL-R1) [2]	0	5,385	0	0	0	0
RCS Propellant (Usable)	0	0	0	132	0	132
Main Propellant (Usable)	0	0	0	231	9,950	10,181
HS or AS Total Mass, EDL or Ascent	9,581	8,912	8,912	2,050	11,150	13,200
Descent Section (DS)						
Internal Payload [4]	4,000	500	500			500
Crew Cabin Shielding H_2O (Payload) [3]	0	3,619	3,619			0
Structure, Tanks, Insulation	2,077	2,056	2,056			1,727
ECLSS and Avionics	584	1,084	1,084			208
DGB Parachute System	342	342	342			342
Main Propulsion System	487	487	487			487
Reaction Control System	199	199	199			199
Dry Mass Margin (15%)	553	625	625			444
Internal LSS Consumables	0	0	0			717
RCS Propellant (Usable)	215	215	215			215
Main Propellant (Usable)	3,463	3,463	3,463			3,463
DS Total Mass, EDL or Ascent	11,918	12,588	12,588			8,300
Solar Arrays (Jettisoned before EDL)	32	32	32			32
A/B Propellant (Consumed before EDL)	941	941	941			941
DS Total Mass, MOI	12,891	13,561	13,561			9,273
Overall Vehicle						
Lander Total Mass, Start of EDL	21,500	21,500	21,500			21,500
Lander Total Mass, MOI	22,473	22,473	22,473			22,473

[1] MPL AS: 500 kg payload = 4 crew in space suits w/ ELSS plus 20kg of equipment/samples for descent/ascent.
[2] Deployable Pallet Payload: LSS Consumables Package on MCL-R1, and Nuclear Electric Generator on MCL-R2.
[3] Crew cabin shield water is part of internal LSS consumables for MCL-H, but is carried separately for MCL-R.
[4] MCL DS: includes 500 kg for Surface Docking System. MPL DS: includes 4x PLSS Backpacks.

C. Design of Deep Space Vehicles (DSV) and Interface with MPCV

1. DSV Design Overview (DSVs 1, 2, and 3) and Interface with MPCV (DSV3)

The DSV design is derived from the LM3-HAB (MCL-H) design of Ref. 9 and also shares common features with the LM2 (MPL) crew lander of Reference 10. Three DSVs (DSV1, 2, and 3) are included in the MCTV, with power provided by solar arrays on the AGM. The DSV Propulsion Stage (PS) is an annular configuration that surrounds the lower part of the Habitat Stage (HS). It utilizes the MPL/MCL central thrust cylinder structure to efficiently carry loads, and is divided into eight bays by shear panels. The DSV HS provides a three-level habitat for the crew, with $67.9m^3$ of pressurized volume (habitable volume of $48.5m^3$). This provides $24.3m^3$ per person for a four-person crew living in two DSVs. DSV1 and DSV2 share the same HS design, and incorporate variations in the designs of their respective PS. The DSV1 PS primary function is propulsion, while the DSV2 PS primary function is LSS consumables storage for LMO operations. DSV3 is comprised of a PS and a LIDS docking structure (LDS), with an aft-mounted passive LIDS, enabling vehicles with active LIDS to dock there (MPL, MPCV, or DSV). The MPCV is attached to the forward end of the PS by the MPCV-DSV3 Adaptor (MDA). DSV and MPCV configuration drawings are shown in Figs. 14-16. DSV and MPCV design data are shown in Tables 4 and 5.

2. Propulsion Section (PS) (DSVs 1, 2, and 3)

The DSV PS is a modified MPL/MCL Descent Section (DS). Four sets of MPL/MCL landing gear are removed. On DSV1 and DSV3, these are replaced with a set of three main propulsion system (MPS) fuel, oxidizer, and pressurant tanks in each of the four landing gear bays. Two more MPS tank sets are located in the bays used for cargo on MCL, for a total of 12 main propellant tanks and six pressurant tanks. The DSV2 PS instead houses six sets of LSS consumables supercritical LO_2 tanks and water tanks for the LMO phase as shown in Table 11, and smaller reaction control system (RCS) propellant tanks. The MCL surface docking system (SDS) is removed, and the SDS bay becomes the DSV cargo bay. The MPL/MCL DS aft heatshield and four landing gear doors are replaced by aft-facing plume shields and side-facing thermal blankets on the DSVs. The DSV1/DSV3 PS retains the eight 13.6 kN (3,042 lbf) MPL/MCL descent engines (throttleable between 38%-100%) as its main engines. Thrust vector control is implemented by differentially throttling the main engines. DSV2 has no main engines. The DSV1/DSV2/DSV3 PS retains the 6-axis RCS of the MPL/MCL DS, which utilizes 16x 745 N (167 lbf) thrusters for attitude control and translation. DSV main engines and RCS thrusters utilize storable, hypergolic monomethyl hydrazine (MMH) and nitrogen tetroxide (N_2O_4) propellants for reliable operation after years of storage. The DSV1/DSV2 PS houses a personnel airlock and docking hatch in the airlock bay, and an additional docking hatch in the cargo bay opposite the airlock bay. The airlock and docking ports permit MPL/MCL landers to dock with DSV1/DSV2, and are accessible by tunnel from the HS. The DSV3 has no side docking ports and no airlock. Each DSV docking hatch is equipped with an active LIDS. For the MSE mission described in this paper, two MCL-H and two MCL-R (each equipped with a passive LIDS) dock at the four side docking ports available on DSV1 and DSV2. Future work will examine a two-piece DSV2 PS which would permit jettisoning the PS without having to undock DSV1 in LMO. This option would reduce design commonality but improve reliability. It would enable the DSV2 PS to split into two segments that would be jettisoned sideways. Currently, the PS must be jettisoned in the aft axial direction which necessitates undocking DSV1 from DSV2 to provide clearance. Redocking DSV1 is a critical event for mission success.

3. Habitat Section (HS) (DSVs 1 and 2)

The DSV HS is a modified MCL-H habitat section. It has a spherical forward section, the main crew cabin (upper and middle levels of the three-level pressurized crew cabin), and a cylindrical aft section, a Consumables & Equipment Bay (CEB) which houses life support consumables for OTO (DSV2) and ITO (DSV1), along with life support system (LSS) equipment, Li-ion batteries, and thermal control equipment. The spherical main crew cabin provides the crew with 10gm/cm^2 of omnidirectional, passive hydrogenous radiation shielding against galactic and solar cosmic rays. A cumulative 900 day mission dose of 90 centiSievert (cSv), is estimated (worst-case, no landing, crew in DSV1, 2).[14,15] This is the lifetime dose limit for 45 year old females, and below the lifetime limit for 45 year old males. The crew cabin carbon composite outer structural shell supports an inner shielding layer of hydrogenated nanofiber materials (3.36t per DSV). This layer forms the inner wall of a 5cm thick water jacket which provides an additional 5gm/cm^2 (3.59t per DSV). After TMI, water is pumped from a toroidal water storage tank in the aft CEB into the crew cabin water jacket shield tank. The crew then transfers from the MPCV to DSV1/DSV2. The cabin wall shield tank is subdivided into many individual cells. The HS LSS is modeled after the MPCV system, using a partially closed-loop air revitalization system utilizing CO_2 amine scrubbers, and an onboard waste water recovery system to convert gray water and urine into purified water for drinking, washing, and equipment cooling. Waste water recovery of 85% is required to keep the crew cabin water jacket continuously filled. A backup scenario if the waste water recovery system fails will be to sequentially drain fresh water from cabin wall shield tank cells and refill them with gray water. The upper level has the DSV forward docking hatch, with active LIDS, a kitchen/food preparation area, dining area with table and chairs, study desk with computer workstation, and lounge area with a couch and entertainment center. The middle level has crew berthing, with three bunks that can be folded up to open up an exercise area. It also has lockers for clothing, medical equipment, and sanitation supplies. It has separate stalls for a shower and toilet. The lower level is a cylindrical extension of the main cabin located inside the aft CEB, and is the primary food storage location. An aft docking hatch with passive LIDS enables another vehicle with active LIDS (MPL, MPCV, or DSV) to dock there. For the MSE mission described in this paper, one MPL will dock at the DSV1 aft docking hatch. A ladder runs from the aft docking hatch, through all levels, to the forward docking hatch.

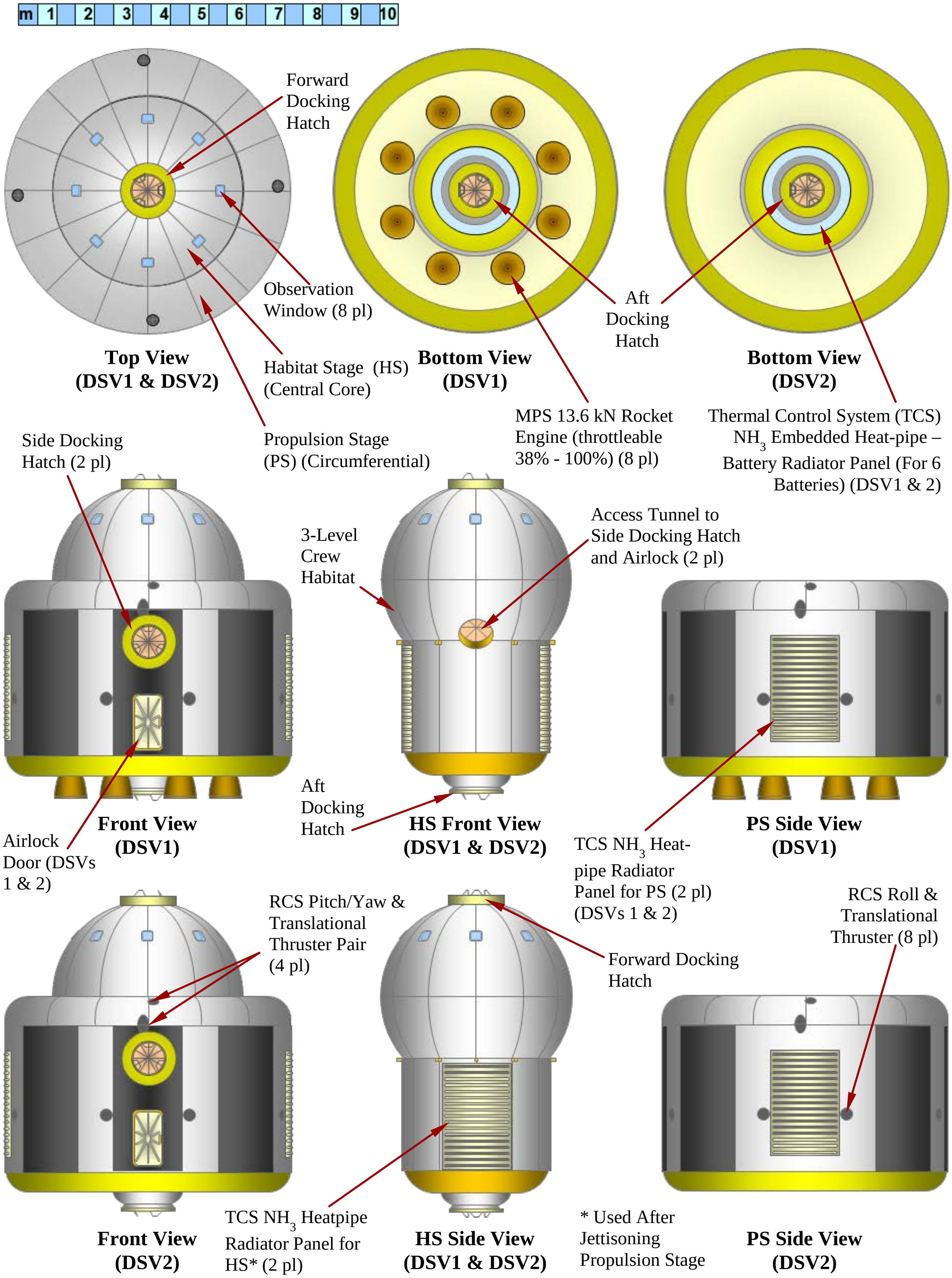


Figure 14. Deep Space Vehicles 1 and 2 (DSV1 & DSV2) – Configuration Four-View.

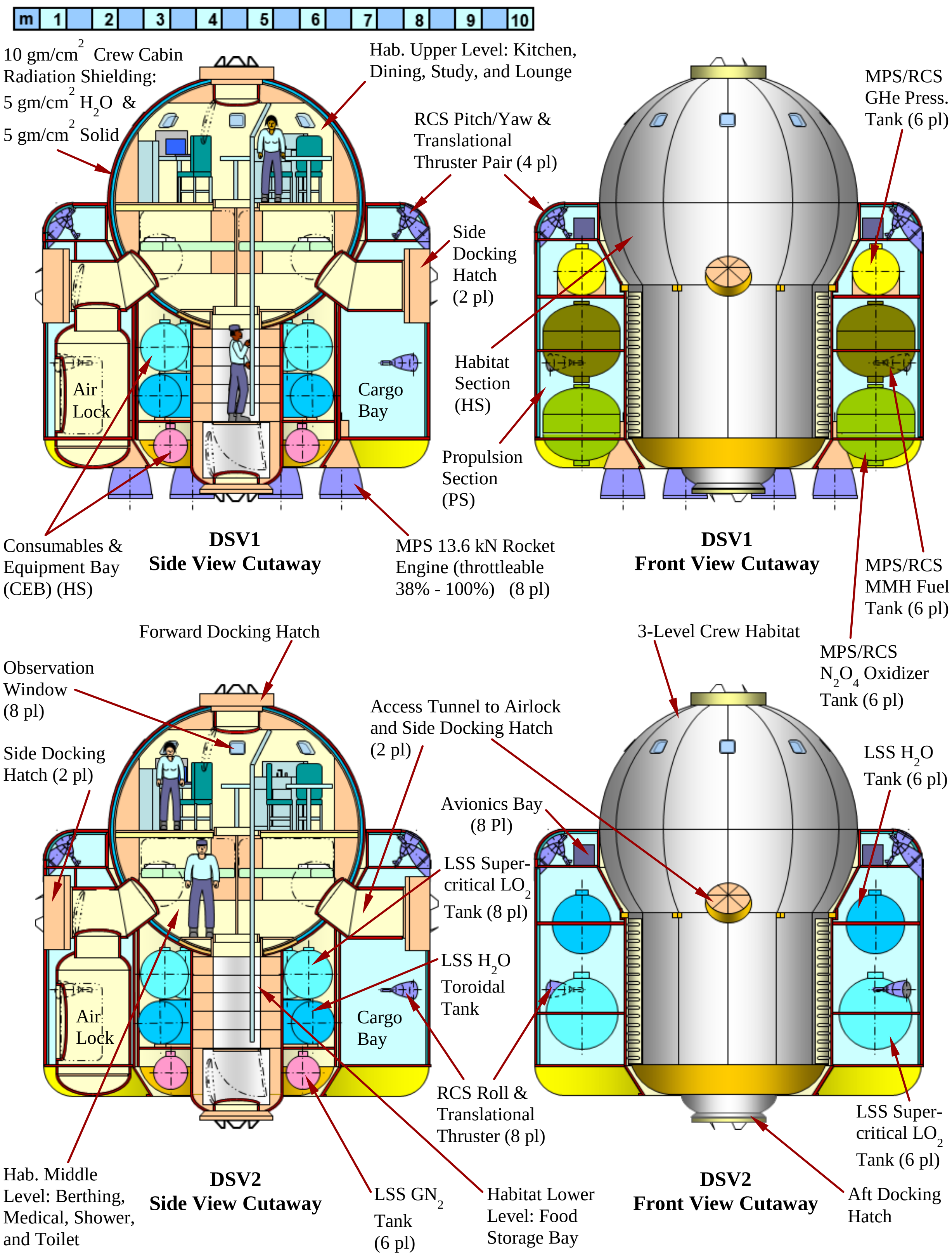


Figure 15. Deep Space Vehicles 1 and 2 (DSV1 and DSV2) – Configuration Front and Side Cutaway Views.

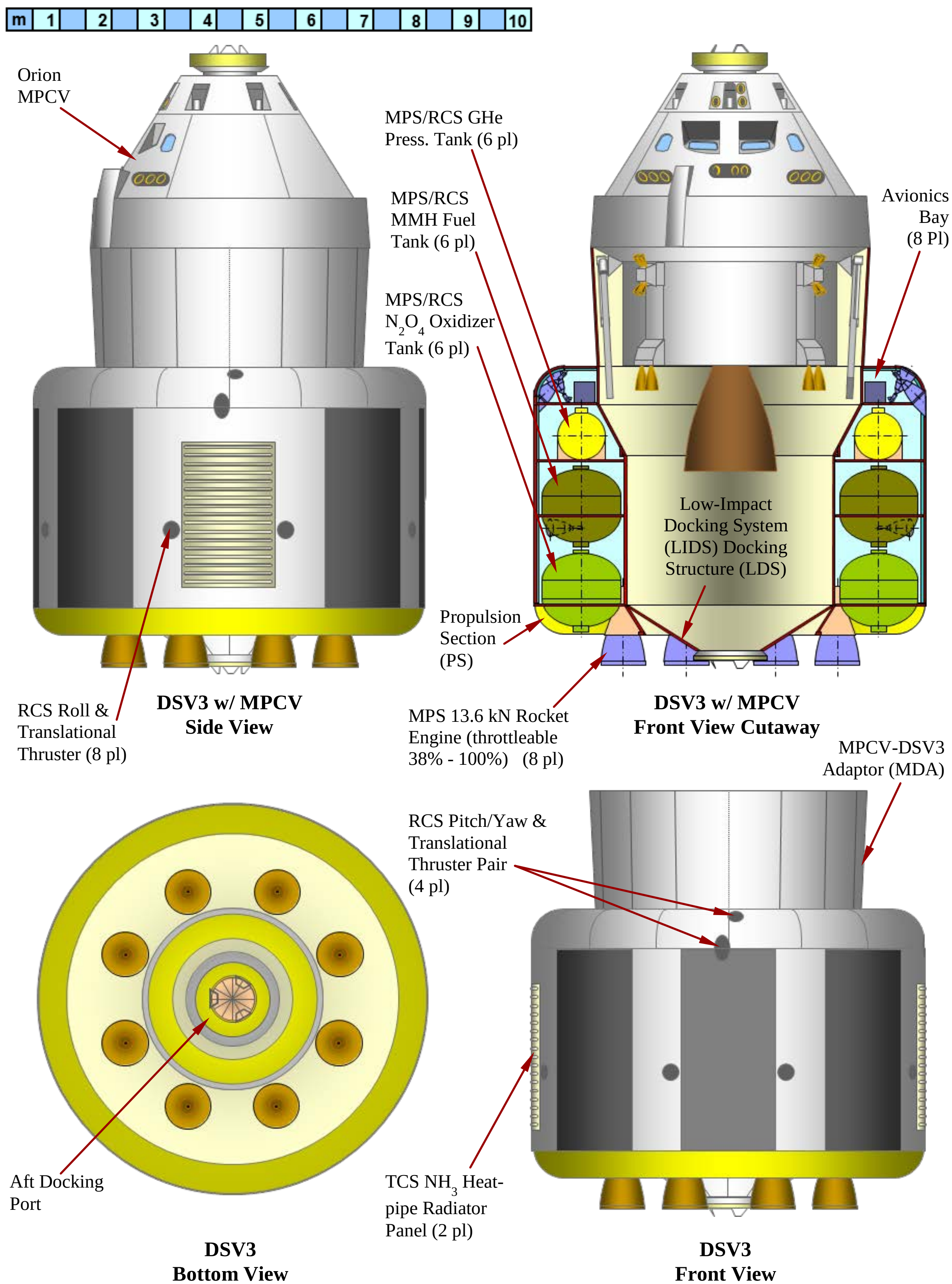


Figure 16. Deep Space Vehicle 3 (DSV3) – Configuration Three-View and Front Cutaway View.

Table 4. DSV1, DSV2, & DSV3 Initial Mass Breakdowns.

Deep Space Vehicle Mass (kg)	DSV1	DSV2	DSV3
Habitat Stage (HS)			(N/A)
Subtotal, Outbound Payload [1]	3,358	3,358	
Structure, Insulation, TCS	1,807	1,807	
Subsystems	384	384	
Dry Mass Margin (15%)	329	329	
Subtotal, HS Inert Mass	2,520	2,520	
Subtotal, HS LSS Consumables [2]	6,830	6,830	
Subtotal, HS RCS Propellant	0	0	
Total Mass, Habitat Stage	12,708	12,708	0
Propulsion Stage (PS)			
Subtotal, Outbound Payload [3]	900	1,300	0
Structure, Insulation, and TCS	520	520	520
Propellant Tanks	992	59	727
Subsystems	184	184	184
(8) Main Engines & Installation	487	0	487
RCS System Dry Mass	99	99	99
Dry Mass Margin (15%)	342	129	303
Subtotal, PS Inert Mass	2,624	992	2,320
Subtotal, RCS Propellant Mass	2,989	1,453	1,616
Subtotal, PS LSS Consumables [2]	0	6,908	0
Subtotal, PS Main Propellant	21,800	0	16,564
Total Mass, Propulsion Stage	28,313	10,652	20,500
Total Mass, DSV	41,021	23,360	20,500

[1] Solid Shielding Mass Shown as Payload; Note, (4) Crewmembers with space suits, ELSS, and PLSS launch in MPCV and transfer to DSV1/DSV2 after TMI burns.

[2] See Section VI.6, Table 14, below, for Masses of DSV1 and DSV2 Life Support Consumables.

[3] DSV1: Airlock; DSV2: Airlock, (2) MMUs & Propellant; DSV1 & DSV2: (2) Active LIDS Docking Adaptor (LDA1).

Table 5. MPCV Initial Mass Breakdown.

Multi-Purpose Crew Vehicle (MPCV)	Mass (kg)
Initial Payload: (4) Crewmembers & Equip.	
(1) Crew Member	80
(1) Spacesuit	35
(1) [1] ELSS Unit	5
(1) [2] EVA PLSS Backpack	45
(1) Crew Member and Equipment	165
Subtotal, Initial P/L: (4) Crew & Equip.	660
Subtotal Non-Propellant Mass	13,475
Subtotal Propellant Mass	7,907
Total Mass	22,042

[1] Emergency Life Support System.

[2] Extra Vehicular Activity, Portable Life Support Sys.

D. Design of Artificial Gravity Module (AGM) and MCTV AG Operations

A key feature of the MCTV is its capability to produce artificial gravity (AG) to prevent deterioration of human tissues that would be caused by prolonged exposure to zero-g. The AGM enables AG operations with four primary functions: (1) it structurally ties the DSV1/DSV2 and MPCV/DSV3 sides of the vehicle together and carries loads between the vehicles during burns and AG operations; (2) it permits crew transfer between the DSV2 and MPCV at the start and end of the mission, and at intermittent times if necessary, via a pressurized tunnel when the DSV2 and MPCV are docked to the AGM. The AGM tunnel has sufficient clearance to permit transit of crewmembers in space suits, if necessary; (3) for AG rotation, the AGM compensates for changing component vehicle masses throughout the mission by extending or retracting AG rails to keep the MCTV center of mass/rotation at the AGM de-spun platform (DSP) center of rotation. The AGM must maintain sufficient stiffness in bending and torsion when AGM rails are fully extended; (4) it provides electrical power and communications during all flight phases. The DSPs permit solar arrays to track the sun and the high gain Communication Transponder Assemblies (CTAs) to track Earth during AG rotation. AGM configuration is shown in Fig. 17. The AGM mass breakdown is shown in Table 6.

The AGM structure consists of three major parts: (1) the AGM structural tunnel, a 2m diameter carbon composite thrust cylinder/pressure vessel with elliptical end domes. It has a docking hatch with passive LIDS at either end. The DSV2 and MPCV, each with active LIDS docking hatches, dock with the AGM tunnel when AG rails are fully retracted; (2) extendable/retractable AG rails, with two sets of four each on the MPCV and DSV2 sides. AG rails extend and retract to control the position of the MCTV center of mass (CM)/rotation, with sufficient (15%) segment overlap at full extension for stability; (3) AG rail-to-vehicle interfaces (RVIs). The MPCV-RVI is a six-legged space frame spanning between the AG rails and the six MPCV launch abort system (LAS) hardpoints. Retractable latches secure the MPCV-RVI to the MPCV LAS attach fittings. The DSV-RVI is an eight-legged space frame/ring frame assembly spanning between AG rails and DSV2 HS cabin and DS thrust cylinder. "Floating" bolts join the ring frame to the HS, to prevent large compressive AGM loads from being reacted by the HS crew cabin during SLS launch. Pyrotechnic bolts join the ring frame to the DSV1 DS, so that the DS can be staged with the HS restrained to the AGM. For the MCTV design presented in this paper, a DSV-RVI was added between DSV2 and DSV1 to react AG tension loads across the docking hatch. Seven major load cases were analyzed. Four compressive

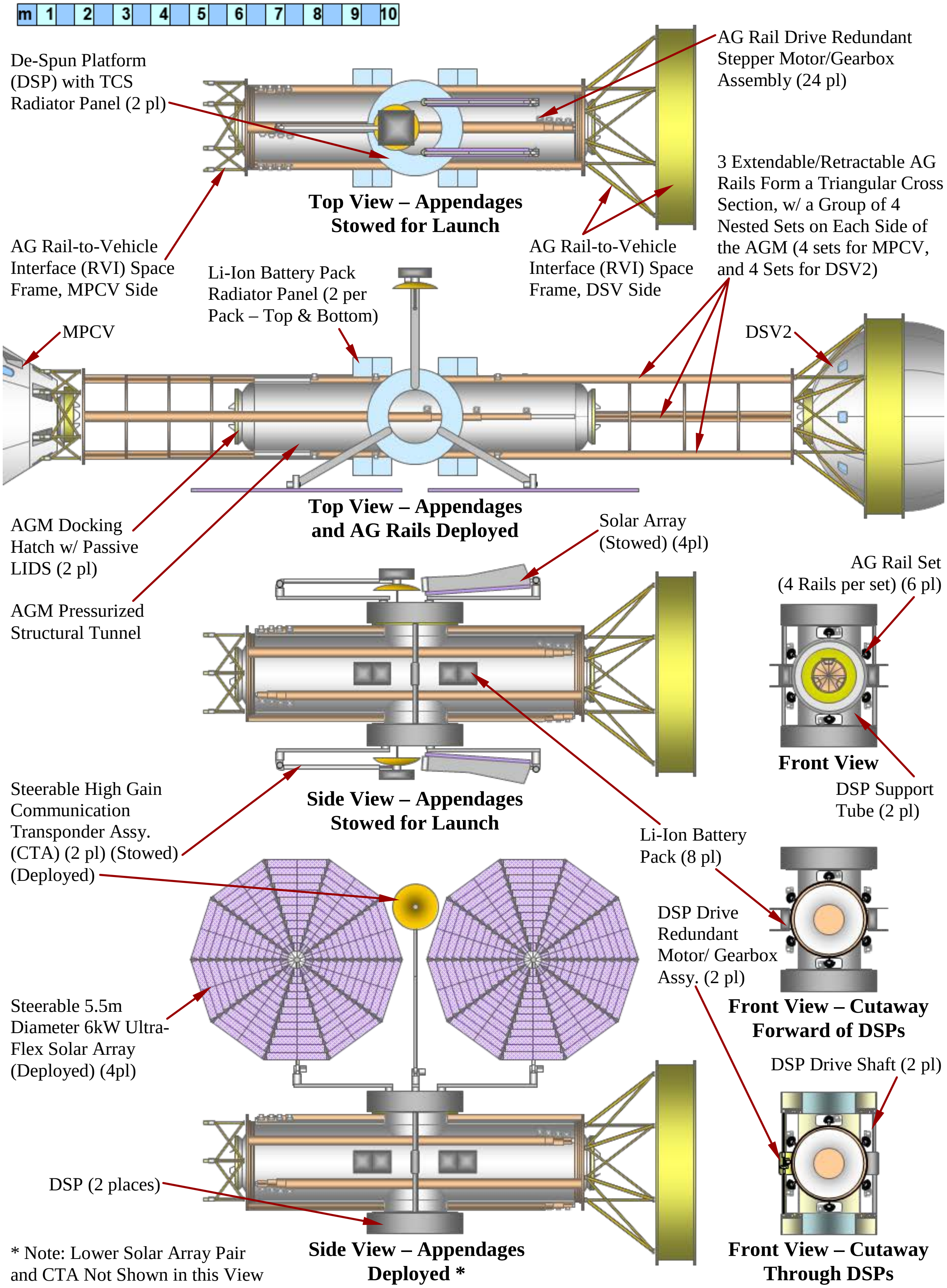


Figure 17. Artificial Gravity Module (AGM) – Configuration Three-View and Cutaway.

cases were: launch, and TMI, MOI, and TEI burns. During these four cases, compressive loads are reacted by the AGM tunnel, DSV-RVI, and DSV2 PS thrust cylinder. Three tensile cases were: hoop and longitudinal stress from the one atmosphere of pressure in AGM tunnel, and MCTV AG rotation at maximum mass.

During AG operations, the MCTV rotates around its center of mass to induce an outward inertial acceleration or AG ($\alpha = r\,\omega^2$, where α is acceleration, r is the radius to the center of rotation, and ω is the angular velocity) as shown in Fig. 18. The literature suggests a minimum of 0.2 g_{0E} to provide a minimum level of traction for the crew to perform useful tasks, and maximum rotation rate of 4 RPM to prevent undesirable side effects caused by Coriolis forces. The MCTV provides 0.379 g_{0E} (Mars surface gravity) at the DSV1 middle level and a minimum of 0.233 g_{0E} at the DSV2 upper level during major coast phases using the following rotation rates: 2.730 RPM (OTO), 3.548 RPM (LMO), and 3.525 RPM (ITO) as shown in Fig. 18. A concern was implementing solar array sun tracking and antenna Earth tracking on a rotating vehicle. Mounting the solar arrays and communication transponder assemblies on the DSPs greatly simplifies this problem and eliminates the need for solar array and antenna tracking at approximately 3 RPM. Continuous rotation is not desirable for mechanism longevity, and precise tracking on a rotating gimbal joint would be problematic to implement. MCTV attitude is controlled in order to maintain DSP rotational axis alignment normal to the ecliptic plane to facilitate solar array sun tracking and communication antenna earth tracking.

Table 6. AGM Initial Mass Breakdown.

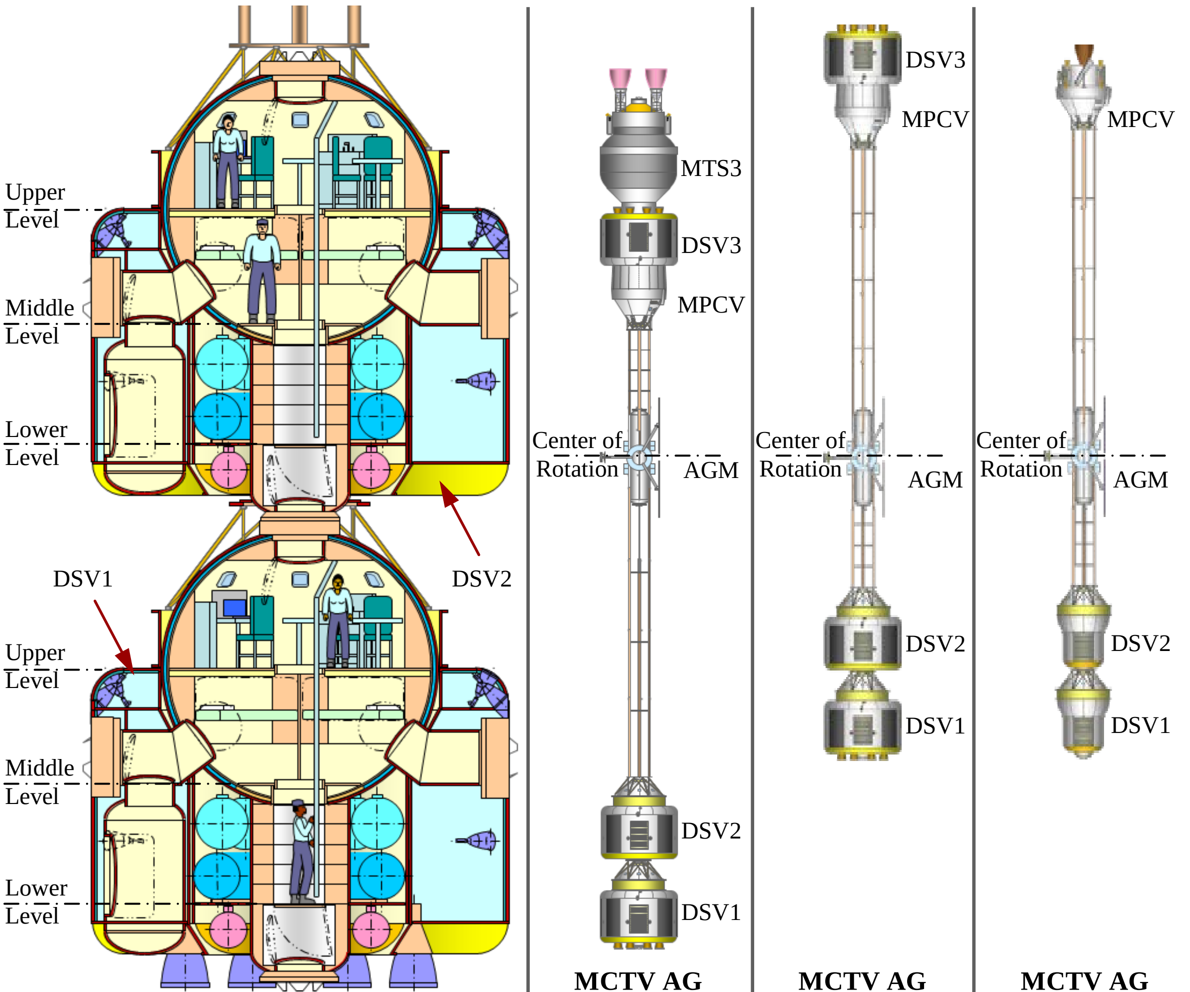
Artificial Gravity Module (AGM)	Mass (kg)
Pressurized Structural Tube (PST)	650
Space Frame Attach Structures (2)	240
(2) Despun Platforms	120
(2) Passive LIDS	100
AG Extension Rails (8 sets of 3)	640
DC Power Electronics	73
(4) Solar Arrays	128
(2) Antennas & Comm Equipment	40
Dry Mass Margin (15%)	299
Total Mass, AGM	2,289

The DSPs are driven by redundant motor/gearbox assemblies and counter-rotate to null AG rotation, providing a stable platform for precise pointing. Accelerometers determine the exact center of rotation to fine tune the CM with extension or retraction adjustments of the AG rails. The AG rails are extended and retracted by redundant stepper motor/gearbox assemblies. Each DSP mounts a pair of 5.5m diameter 6kW Ultra-Flex solar arrays. DC power electronics are contained within each DSP, as well as slip rings to conduct power and ground across rotating joints. The sliding AG rails conduct DC power and ground between the AGM and DSV2/MPCV using slip joints. Each DSP mounts a high gain CTA on an extendable mast. The CTA consists of a radio frequency (RF) electronics compartment, antenna feed and reflector, and two-axis gimbal mount. DSV2 and MPCV communicate with the CTAs wirelessly to eliminate the need for rotating RF joints or extendable waveguides or cables.

E. Design of Cryogenic Propulsion Stages (CPS)

1. Design Overview

The Cryogenic Propulsion Stages for the MEV Architecture were designed by B. Kutter (References 1, 2, and 3). High performance cryogenic LH_2/LO_2 propellants are used to satisfy the high mission δV requirements for TMI and MOI: Earth Departure Stages (EDS) are used only for TMI. Mars Transfer Stages (MTS) are used for TMI, MOI and midcourse burns. The RL10-C-2 engine was selected over the J-2X based its significantly higher vacuum ISP (465.5s vs. 448s). Efforts to simplify the MEV architecture resulted in eliminating the mechanically complex side-mounted MTS designs based on the Centaur booster shown in earlier MEV designs, and using the same basic EDS design for the MTS on both MLTV and MCTV.[4] EDS sizing for MCTV permitted using the same EDS for MLTV, with good thrust/weight for all burns when the number of EDS engines was varied. Thrust/weight requirements dictated 6 engines for MLTV EDS (EDS-L) and 4 engines for MCTV EDS (EDS-C) and MTS for both MLTV and MCTV (MTS-L and MTS-C, respectively). Based on TMI burn mass ratio requirements and SLS launch constraints, the MCTV utilizes an initial burn from a cluster of three equally-sized EDS-C followed by a short MTS-C burn for TMI. The MLTV utilizes an initial burn from one EDS-L followed by a long MTS-L burn for TMI. The bulk of MTS-L propellant (74%) is used for TMI and the bulk of MTS-C propellant is used for MOI (only 26% for TMI). Because of this and the fact that the MLTV EDS/MTS had slightly excess performance, optimizing MTS mixture ratio to accommodate LH_2 boil-off during OTO resulted in MTS-L propellant tanks that are identical to those of the EDS, with a 3.5t LO_2 offload for a proper MOI oxidizer-to-fuel (O:F) mixture ratio. MTS-C needed a 0.6m longer LH_2 tank barrel section and a 0.08m shorter LO_2 tank barrel section to achieve a proper O:F mixture ratio for MOI.



Side View Cutaway – DSV1 and DSV2

MCTV AG Configuration at Start of OTO

MCTV AG Configuration at Start of LMO

MCTV AG Configuration at Start of ITO

Mission Phase	OTO-I[1]	OTO-F[2]	LMO-I[3]	LMO-F[4]	ITO-I[5]	ITO-F[6]
MCTV Rotation Rate (RPM)	2.730	2.730	3.548	3.548	3.525	3.525
Radius Arm to MPCV Cabin Seats (m)	14.65	12.79	30.90	28.38	35.61	31.55
AG Acceleration (m/sec^2)	1.20	1.04	4.26	3.92	4.85	4.30
(Earth g's)	0.122	0.106	0.434	0.399	0.494	0.438
Radius Arm to DSV2 Upper Level (m)	35.13	35.13	16.55	16.55	16.91	16.91
AG Acceleration (m/sec^2)	2.87	2.87	2.28	2.28	2.30	2.30
(Earth g's)	0.292	0.292	0.233	0.233	0.235	0.235
Radius Arm to DSV1 Middle Level (m)	45.53	45.53	26.95	26.95	27.31	27.31
AG Acceleration (m/sec^2)	3.72	3.72	3.72	3.72	3.72	3.72
(Earth g's)	0.379	0.379	0.379	0.379	0.379	0.379

[1] Start of Outbound Transfer Orbit
[2] End of Outbound Transfer Orbit
[3] Start of Low Mars Orbit Operations
[4] End of Low Mars Orbit Operations
[5] Start of Inbound Transfer Orbit
[6] End of Inbound Transfer Orbit

Figure 18. MCTV Artificial Gravity (AG) Configurations during OTO, LMO, and ITO, with Cutaway of DSV1 & 2.

Further study of MCTV TMI requirements resulted in eliminating the two-stage EDS design shown in earlier MEV design iterations that required an intermediate escape orbit with three passes through the Van Allen radiation belts instead of the single pass needed for subsequent designs.[1,2,3] Reference 4 substituted a TMI Booster Assembly (TBA) using three EDS docked together: Two EDS had six engines each. The center (or core) EDS had no engines, and cross-fed its propellants to the other two EDS. This design solution provided good thrust/weight and a reasonable burn time, but was mechanically complicated and less reliable because of the need to mate multiple quick-connect fluid fittings between the three EDS for propellant cross-feed. The TBA presented in this paper utilizes three identical EDS with no propellant cross-feed required. It is discussed in Section II.E.3, below.

2. Design of Earth Departure Stage (EDS-L & EDS-C) and Mars Transfer Stages (MTS-L & MTS-C)

The driving requirements for EDS/MTS are: light weight, with a propellant mass fraction greater than 0.90; high ISP of 465s; thermally efficient, with a propellant mass loss due to boil-off in LEO less than 0.05% per day; and a compact design to fit in the SLS shroud. To satisfy requirements the EDS will be a 7.5m dia., monocoque, common bulkhead design with 77.4t of usable propellant. Use of the BRV to top off LH_2 prior to departure enables the EDS to have a relatively high O:F mass ratio of 5.8:1 (66.0t of LO_2 and 11.4t of LH_2) that minimizes overall stage size. The common bulkhead further reduces the stage height and minimizes parasitic structural mass and heating. The EDS will consist of two 7.5m dia. LH_2 tank end domes and three 5m dia. domes for the LO_2 tank aft bulkhead and the structural and floating common bulkheads. The EDS domes utilize the same bulkhead geometry as Centaur to minimize dome-sidewall transition structure mass, including the LH_2 aft bulkhead transition dome from 5m dia. to 7.5m dia., thanks to lessons learned manufacturing the Titan/Centaur conic transition bulkhead. The domes will be manufactured by butt welding gore sections, equivalent to Centaur. The short 1.12m LH_2 tank and 0.80m LO_2 tank barrels will consist of thin sheet steel, lap welded to the domes. The common bulkhead design will be a larger diameter equivalent to the Centaur-based MTS enhanced common bulkhead design of References 1, 2, and 3. The EDS and MTS will incorporate an advanced thermal protection system and sub-cooled LH_2 in order to minimize propellant boil-off during launch, LEO assembly, and TMI operations. Due to loading the EDS with sub-cooled LH_2, the EDS will achieve a very low boil-off rate during the 1- to 10-month LEO loiter, with less than 16 kg/day of hydrogen boiloff. To satisfy thrust/weight requirements, the EDS-L utilizes six RL10-C-2 engines, and the EDS-C, MTS-L, and MTS-C utilize four RL10-C-2 engines, both mounted in a circular arrangement. Engines are mounted via a thermal standoff to the LO_2 tank sidewall which functions as a thrust barrel to evenly distribute loads to the LO_2 tank. The SLS adapter structure will interface with the EDS at the 7.5m diameter LH_2 tank aft skirt. The LO_2 tank will be suspended inside the inter-stage, similar to the current Delta Cryogenic Second Stage. The EDS separation plane will be derived from the existing Centaur frangible joint, leaving a very short, light weight skirt. EDS, MTS-L, and MTS-C mass breakdowns and usable propellant mass fractions are shown in Table 7. Configurations are shown in Figs. 19-21, and Additional EDS and MTS design details are described in Reference 1.

Table 7. CPS Initial Mass Breakdown.

Mass (kg)	EDS-L	EDS-C	MTS-L	MTS-C
Structure & Propellant System	3,200	3,200	3,200	3,520
Avionics and Power	350	350	422	350
Thermal/MMOD* Protection	700	700	700	700
Propulsion	1,800	1,200	1,200	1,200
Dry Mass Margin (15%)	908	818	828	866
Total Dry Mass	6,958	6,268	6,350	6,636
Residual Propellant (1%)	786	786	786	786
Operating Empty (Burnout)	7,743	7,053	7,136	7,422
Useable Propellant Mass **	77,443	77,443	73,941	77,443
Total Wet Mass	85,186	84,496	81,077	84,865
Usable Propellant Mass Fract.	0.909	0.917	0.912	0.913

* Micro-Meteoroid and Orbital Debris.
** Note: MTS-L has 3,503 kg of LO_2 offloaded for MOI burn mixture ratio control. Actual propellant capacity is the same as that of the EDS.

3. Design of MCTV TMI Booster Assembly (TBA)

Figure 22 describes the configuration, and Section VI.A below, describes the assembly sequence in LEO for the TBA. It is composed of three identical EDS-C (EDS3, 4, and 5) and the CA-C1 adaptor with its three included rotating docking mechanisms. Utilizing two-step EDS positioning during assembly, where each EDS first docks and then rotates into position, enables EDS3, 4, and 5 to sequentially dock to CA-C1 without interfering with each other. Simultaneously rotating all three EDS is designed to minimize changes to vehicle overall angular momentum. Lateral supports and attach fittings enable the three EDS to lock into place and function as a single booster for TMI.

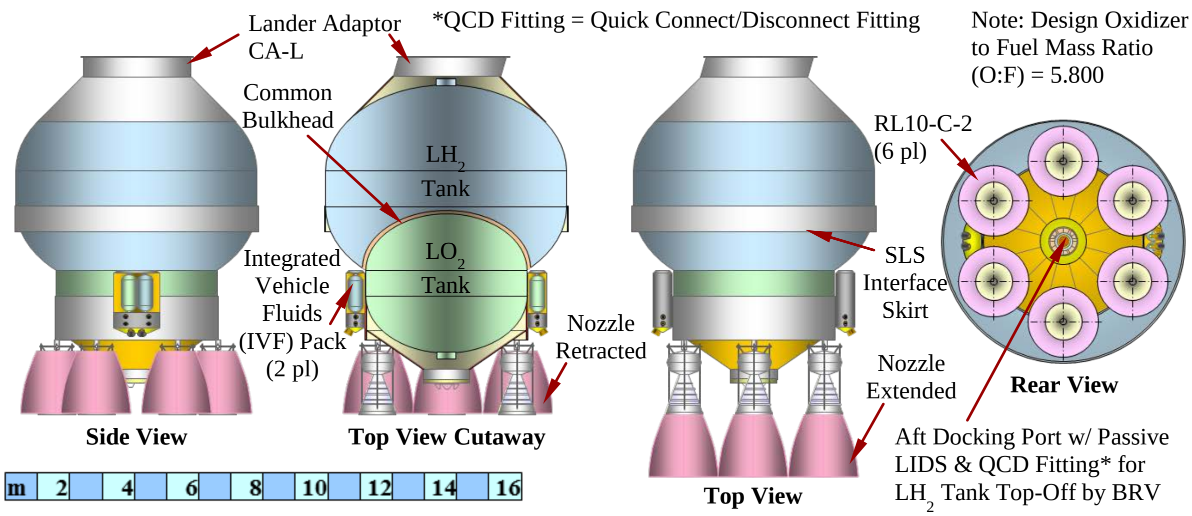


Figure 19. 6-Engine CPS for MLTV: Earth Departure Stage (EDS-L) – Configuration 3-View and Cutaway.

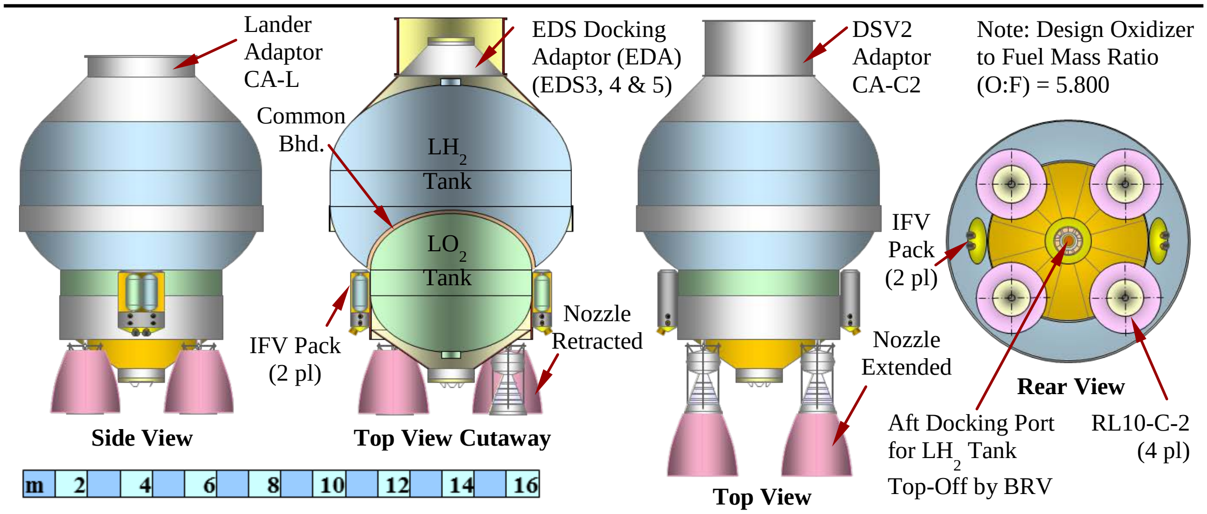


Figure 20. 4-Engine CPS for MLTV: Mars Transfer Stage (MTS-L) & MCTV: (EDS-C) – Config. 3-View/Cutaway.

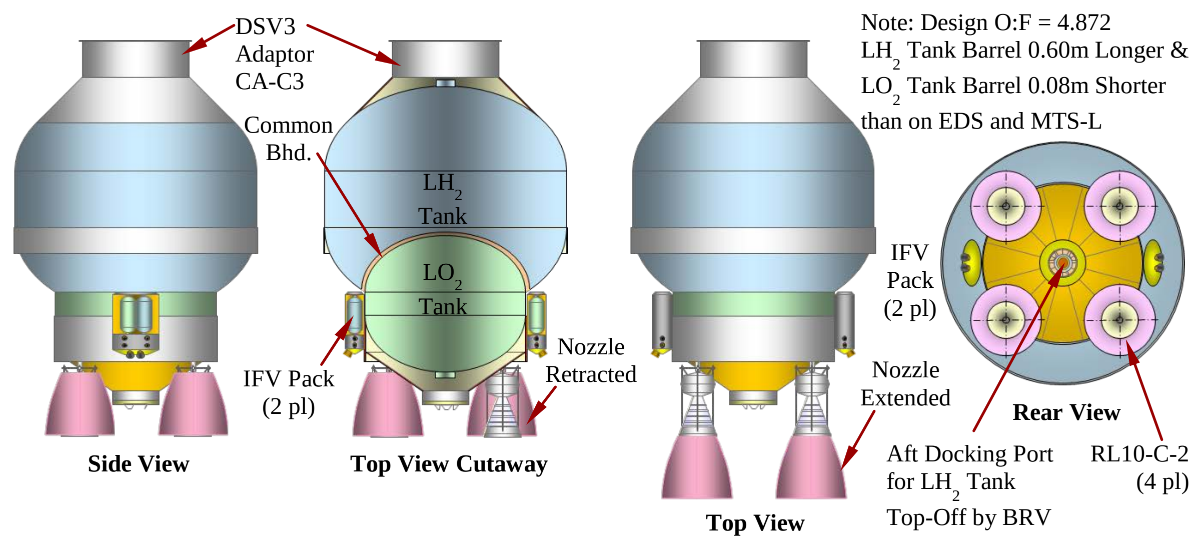


Figure 21. 4-Engine CPS for MCTV: Mars Transfer Stage (MTS-C) – Configuration 3-View and Cutaway.

CA-C1 has two major structural elements: a central thrust cylinder to react DSV1 inertial loads into EDS4 during launch, and a 45-degree annular thrust cone to react thrust loads from the three EDS into the MCTV during TMI.

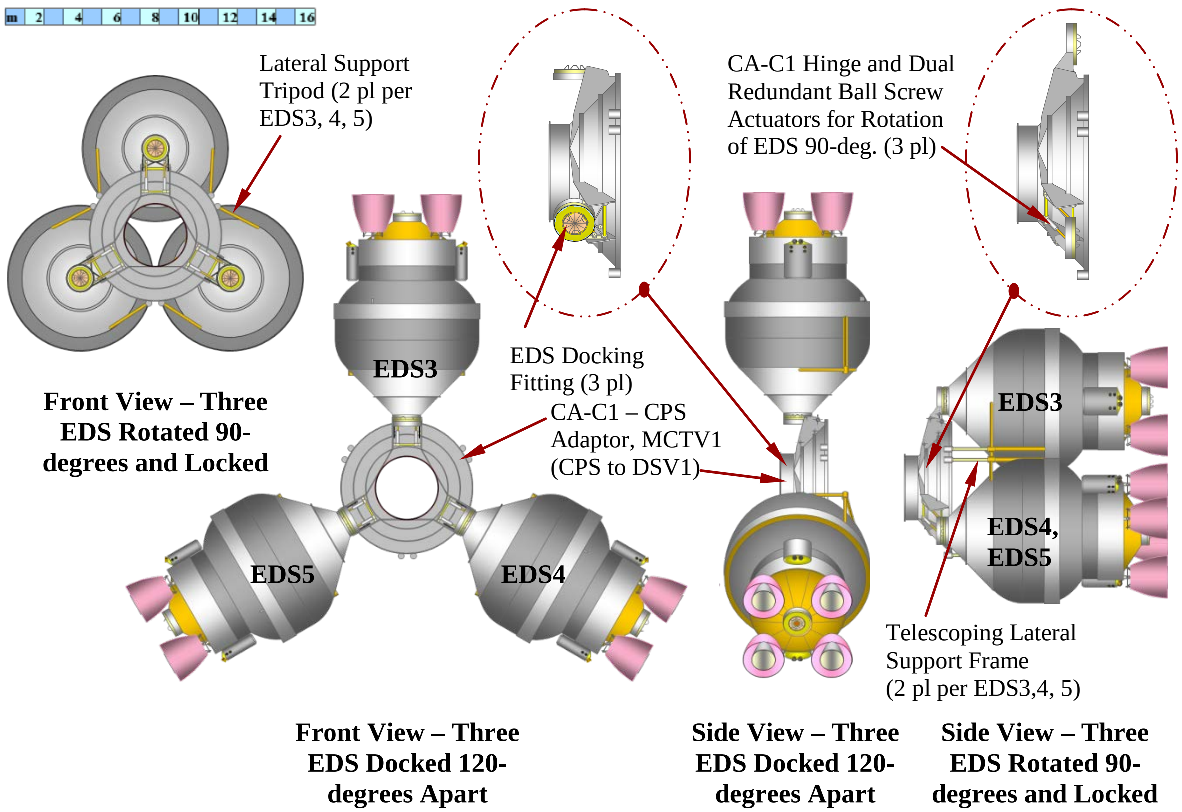


Figure 22. TMI Booster Assembly: EDS3, 4, and 5 Docked to CA-C1 Adaptor – Configuration 2-Views.

F. Design of Booster Refueling Vehicle (BRV)

The concept for refueling the MEV Architecture CPS prior to TMI was designed by B. Kutter (References 1, 2, and 3). The BRV, shown in Figure 23, is designed to top-off MLTV and MCTV booster LH_2 tanks immediately before their respective TMIs to compensate for on-orbit LH_2 boil-off, eliminating the need to have unrealistically short SLS launch intervals. The BRV design must efficiently store LH_2 for months and thus has requirements similar to the EDS. The BRV was designed jointly. It consists of an LH_2 Refueling System (LRS), designed by B. Kutter, which utilizes a large LH_2 storage tank derived from the EDS, and an MEV Service Module (MSM) designed by the author.[1,2,3] The MSM provides propulsion, power, communications, and GN&C for the BRV. It utilizes storable MMH and N_2O_4 propellants for its RCS. The RCS utilizes four 557 N (125 lbf) main axial thrusters and 32x 111 N (25 lbf) 6-axis RCS thrusters of the same type used on the MPCV SM. The MSM mounts a pair of 2.75m diameter 1.5kW Ultra-Flex solar` arrays, 50% scaled from those used on the MCTV AGM and MPCV SM, and a pair of Communications Transponder Assemblies (CTAs) on extendable masts, consisting of a radio frequency electronics compartment, antenna feed, high gain antenna reflector, of the same type used on the MCTV AGM. Solar arrays and CTAs are mounted on two-axis gimbal mounts attached to a de-spun platform which can be used if the BRV-booster assembly is spun for thermal control. The LRS consists of the following: (1) a 7.5m diameter LH_2 tank constructed of two EDS LH_2 tank forward end domes and barrel section that can hold 13.84t of LH_2. The LH_2 tank also protects the overall vehicle from head-on micrometeoroid damage; (2) a thermal protection system and use of sub-cooled LH_2 will be equivalent to the EDS/MTS designs; (3) a LH_2-only version of the EDS/MTS IVF system to provide autogenous pressurization for pressure-fed LH_2 transfer for refueling; and (4), a docking interface with active LIDS and quick-connect/disconnect (QCD) LH_2 cryogenic fluid couplings to allow transfer of LH_2 from BRV to boosters. The BRV will top-off MLTV/MCTV CPS LH_2 tanks using settled propellant transfer. BRV main axial thrusters will be fired to achieve accelerations between 7.12×10^{-4} and 1.03×10^{-3} g's, depending on vehicle configuration, to settle liquid propellants aft. Low-level acceleration has been used on all past cryogenic upper stages to separate liquid and gas, allowing reliable pressure control through venting as well as efficient propellant acquisition.[16]

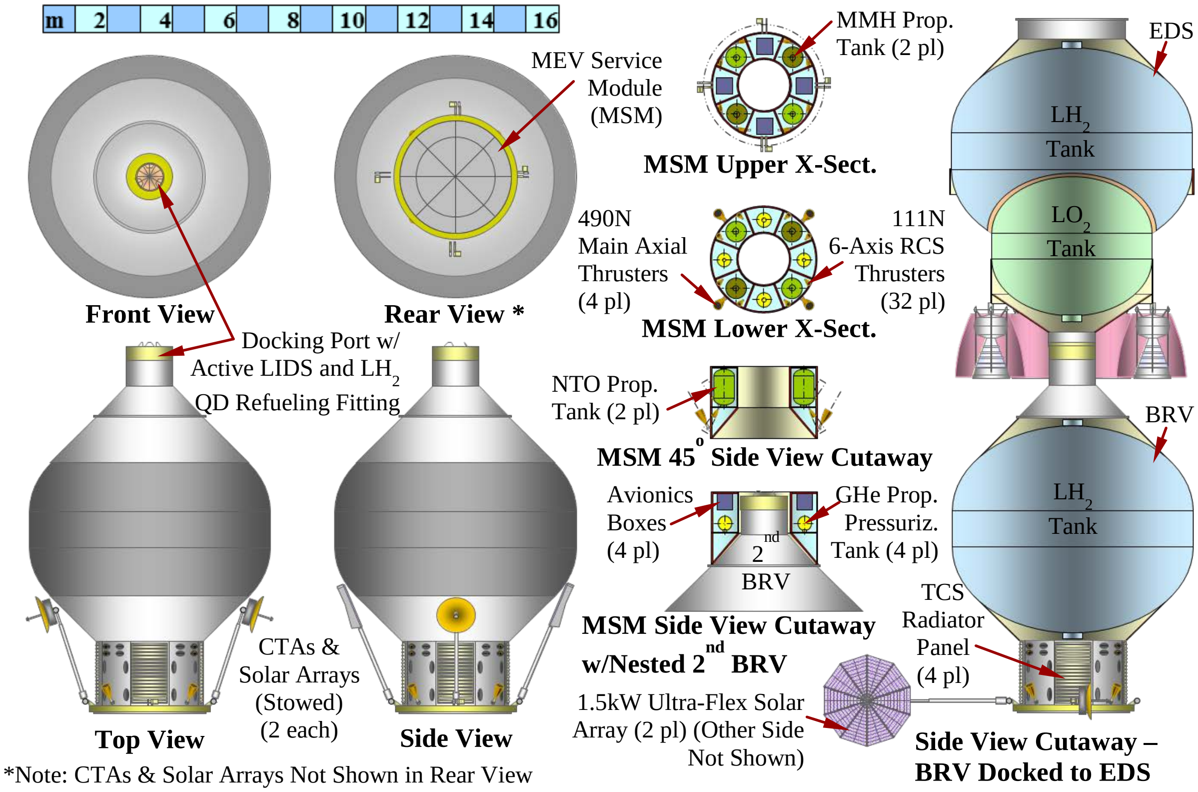


Figure 23. Booster Refueling Vehicle (BRV) – Configuration Four-View, Cutaway, and Cross-Sectional Views.

While Centaur typically uses 10^{-3} g's to 10^{-4} g's, Centaur has demonstrated adequate propellant control with accelerations as low as 10^{-5} g's.[17] With settled propellant transfer, expulsion efficiencies in excess of 99.5% of liquids are typical. The LH_2 transfer process is pressure fed. LH_2 will enter the LH_2 tanks sub-cooled, quenching the GH_2 vapor and sucking in additional LH_2. This "zero-vent fill" transfer process is indifferent to the inevitable liquid splashing and sloshing in the receiving tank. This zero-vent fill process has been demonstrated to be very effective, attaining nearly 100% fill.[18] Replenishment ("top-off") of the EDS and MTS LH_2 tanks prior to MLTV and MCTV TMI burns will be accomplished by the BRV maneuvering behind the EDS/MTS and docking at the refueling port located in the center of the 4 or 6 RL10-C-2 engine cluster. The BRV mass breakdown is shown in Table 8.

Table 8. BRV Initial Mass Breakdown.

Mass (kg)	MSM	LRS
EDS/MTS Docking System		500
Structure & Propellant System	647	1,038
De-Spun Platform	60	
Avionics and Power	72	
Thermal/MMOD* Protection	129	208
Propulsion	50	
Dry Mass Margin (15%)	144	262
Subtotal Dry Mass	1,102	2,008
Usable Propellant	1,219	13,845
Residual Propellant (1%)	12	140
Subtotal Wet Mass	2,333	15,993
Usable Propellant Mass Fraction	0.523	0.866
Total Vehicle		
Initial Launch Mass	18,326	

IV. MEV Mission Analysis

A. Launch of Mission Elements

The MLTVs and MCTV are assembled in LEO from subassemblies launched by eight SLS rockets, shown in Fig. 24 and Table 9. The Vehicle Assembly Point (VAP) is the rendezvous location for the launch subassemblies in the 407 km (220 nmi.) altitude, eastbound, 28.5 degree inclined, circular assembly/parking orbit: subassemblies rendezvous with each other at the VAP and station-keep approximately 500m apart. Table 10 provides launch timelines, propellant boil-off, and refueled propellant masses for refueling MEV mission boosters prior to TMI. Table 11 provides the estimated and assumed masses used for MLTV and MCTV flight performance analyses.

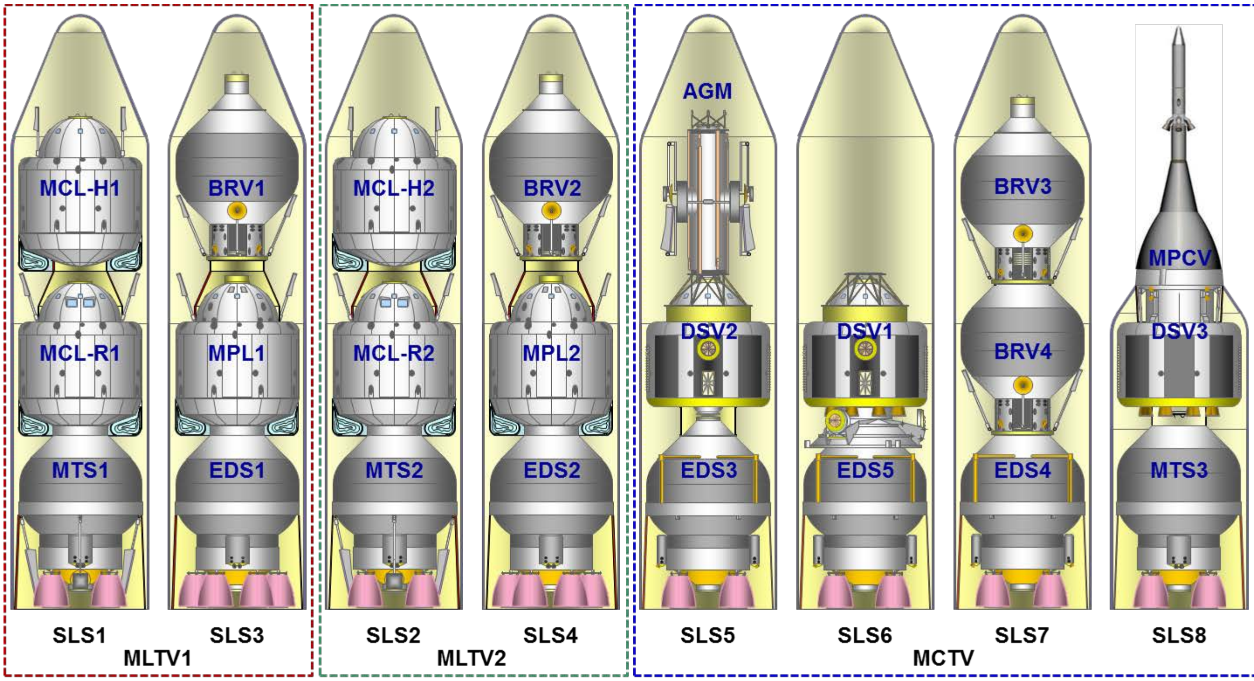


Figure 24. Mars Exploration Vehicle Architecture (MEV) Launch Configurations.

Table 9. Mars Exploration Vehicle Architecture (MEV) Launch Masses.

Mass (t)	Launch Vehicle	SLS1	SLS3	SLS2	SLS4	SLS5	SLS6	SLS7	SLS8
MPCV Launch Abort System (LAS)									7.06
Booster Refueling Vehicles (BRV)			18.83		18.83			36.69	
Mission Payload Elements		45.43	22.47	45.43	22.47	25.65	41.02		43.23
Booster Elements	MTS	81.41		81.41					85.43
	EDS		85.52		85.52	85.82	87.57	85.00	
Injected Mass to LEO (IMLEO)*	Totals per Launch	126.84	126.82	126.84	126.82	111.47	128.59	121.69	128.67
	Totals per Vehicle	MLTV1 =	253.66	MLTV2 =	253.66		MCTV =	490.42	
	Totals per Mission	Refueling Mission =		74.36		Exploration Mission =		997.74	
	Total Architecture				All MEV Elements =		1072.10		
	Color Key =	MLTV1	MLTV2	MCTV	LAS	BRV	SLS8 Pyld. Incl. LAS* =		135.73

* MPCV Launch Abort System (LAS) jettisoned during SLS ascent and not included in IMLEO calculations.

Table 10. Refueling of MEV Mission Booster Elements prior to Trans-Mars Injection (TMI).

Launch Information			Name of Cryo. Prop. Stage	Prop. Boiloff Rate (% / day)	Propellant Mass (kg) *											
Firing Order	Time (days) Before TMI-1	Time (days) Before TMI-2			Initial Prop. Mass	LH2 Boiloff per day	LH2 Loss < TMI-1	Prop. Mass at TMI-1	Prop. Req'd. at TMI-1	LH2 Ref. Mass at TMI-1	Prop. Mass > TMI-1	LH2 Loss TMI-1 to	Prop. Mass at TMI-2	Prop. Req'd at TMI-2	LH2 Ref. Mass at TMI-2	Prop. Mass > TMI-2
SLS1	300	330	MTS-L1	0.02%	73,941	14.79	4,436	69,505	73,941	4,436	(in OTO)					
SLS2	255	285	MTS-L2	0.02%	73,941	14.79	3,771	70,170	73,941	3,771	(in OTO)					
SLS3	210	240	BRV1	0.11%	13,845	15.23	3,198	10,647	N/A	10,647	2,958	457	2,501	N/A	2,501	2,501
			EDS1	0.02%	77,443	15.49	3,253	74,190	77,443	3,253	(Spent)					
SLS4	165	195	BRV2	0.11%	13,845	15.23	2,513	11,332	N/A	11,332	5,006	457	4,549	N/A	4,549	4,549
			EDS2	0.02%	77,443	15.49	2,556	74,887	77,443	2,556	(Spent)					
SLS5	120	150	EDS3	0.02%	77,443	15.49	1,859	75,584	N/A	N/A	75,584	465	75,120	77,443	2,323	(Spent)
SLS6	75	105	EDS4	0.02%	77,443	15.49	1,162	76,281	N/A	N/A	76,281	465	75,817	77,443	1,626	(Spent)
SLS7	30	60	BRV3	0.11%	13,845	15.23	457	13,388	N/A	13,388	13,388	457	12,931	N/A	12,931	9,679
			BRV4	0.11%	13,845	15.23	457	13,388	N/A	13,388	13,388	457	12,931	N/A	12,931	10,840
			EDS5	0.02%	77,443	15.49	465	76,978	N/A	N/A	76,978	465	76,514	77,443	929	(Spent)
SLS8	-15	15	MTS-C	0.02%	77,443	15.49	(Not Yet Launched)		N/A	N/A	77,443	465	76,978	77,443	465	(in OTO)

* Propellant masses include LH_2 and LO_2 unless specified as LH_2 only. Zero boil-off assumed for LO_2.

Table 11. Estimated and Assumed Masses used for MLTV and MCTV Flight Performance Analyses.

Vehicle Component	Acronym	Details	(kg)
Artificial Gravity Module	AGM	AGM Estimated Mass	2,290
CPS Structural Adaptors			
CPS Adaptor, MLTV (MTS & EDS to Landers)	CA-L	CA-L Estimated Mass	330
CPS Adap., MCTV 1 (EDS4 to DSV1 & 3xEDS)	CA-C1	CA-C1 Estimated Mass	2,578
CPS Adaptor, MCTV 2 (EDS3 to DSV2)	CA-C2	CA-C2 Estimated Mass	820
CPS Adaptor, MCTV 3 (MTS3 to DSV3)	CA-C3	CA-C3 Estimated Mass	570
Booster Refueling Vehicle	BRV	BRV Initial Mass	18,346
Four Crew Members			
Crew for Earth Launch and OTO	CM1	Four Crew w/ Space Suits/ PLSS[1]/ ELSS[2]	660
Crew for Mars Ascent and ITO	CM2	Four Crew w/ Suits/ ELSS (no PLSS)	480
Deep Space Vehicles	DSV		
Deep Space Vehicle 1	DSV1	DSV1 Initial, without 4 Crew/ Suits/ ELSS	41,021
Deep Space Vehicle 2	DSV3	DSV2 Initial Mass	23,360
Deep Space Vehicle 3	DSV3	DSV3 Initial Mass	20,500
Earth Departure Stage for MLTVs	EDS-L		
(EDS1, EDS2)		EDS1, EDS2 Initial Mass	85,186
(6 Main Engines)		EDS1, EDS2 Usable Propellant Mass	77,443
		EDS1, EDS2 Burnout Mass	7,743
Earth Departure Stage for MCTV	EDS-C		
(EDS3, EDS4, and EDS5)		EDS3, EDS4, EDS5 Initial Mass	84,496
(4 Main Engines)		EDS3, 4, 5 Usable Propellant Mass	77,443
		EDS3 - EDS5 Burnout Mass	7,053
Miscellaneous Structural Adaptors			
EDS Docking Assembly (EDS3,4, 5-Fwd)	EDA	EDA Estimated Mass	500
Inter-Lander Adaptor	ILA	ILA Estimated Mass	485
Lander-BRV Adaptor	LBA	LBA Estimated Mass	485
LIDS Docking Adaptor-Single (DSV)	LDA1	LDA1 Mass	250
LIDS Docking Adaptor-Dual (MPL)	LDA2	LDA2 Mass	500
LIDS Docking Structure (DSV3)	LDS	LDS Mass	250
Mars Landers			
Mars Cargo Lander - Habitat Variant	MCL-H	MCL-H Initial Mass	22,473
Mars Cargo Lander - Rover Variant	MCL-R	MCL-R Initial Mass	22,473
Mars Personnel Lander	MPL	MPL Initial Mass (Includes LDA2)	22,473
Orion MPCV Components			
Launch Abort System (for MPCV)	LAS	LAS Mass	7,063
MPCV-DSV3 Adaptor	MDA	MDA Estimated Mass	441
Orion Multi-Purpose Crew Vehicle	MPCV	MPCV Initial Mass	21,382
	MPCV	MPCV Initial, plus 4 Crew/ Suits/ PL[3]/ ELSS	22,042
Mars Sample Return Payload	MSRP	MSRP Assumed Mass	20
Mars Transfer Stage for MCTV	MTS-C		
(MTS3)		MTS3 Initial Mass	84,865
(4 Main Engines)		MTS3 Usable Propellant Mass	77,443
		MTS3 Burnout Mass	7,422
Mars Transfer Stage for MLTVs	MTS-L		
(MTS1, MTS2)		MTS1, MTS2 Initial Mass	81,077
(4 Main Engines)		MTS1, MTS2 Usable Propellant Mass	73,941
		MTS1, MTS2 Burnout Mass	7,136
Space Launch System	SLS	Assumed Maximum SLS Payload to VAP	130,000

[1] Portable Life Support System backpack. [2] Emergency Life Support System backpack. [3] Payload.

B. Mass Estimation, Sizing, and Flight Performance Analyses

Masses for MEV components were scaled using data for existing spaceflight hardware where possible, such as the RL10-C-2 engine, MPCV Orion Main Engine (OME), and hardware flown on Space Shuttle or Apollo/Saturn. Test data from developmental hardware such as the MPCV Ultra-Flex solar arrays and Service Module thrusters provided additional anchors. Also included was commercial off-the-shelf space hardware, such as satellite apogee motors, Li-ion batteries, and thrusters, and mass data from pertinent space vehicle studies such as the Altair lunar lander from the Constellation project. Structural analyses were performed for major MEV components, for various important load cases, to validate conceptual design mass scaling laws that were input to the MEV mathematical models. A mathematical model was used to size the MLTV and estimate its flight performance: (1) the EDS-L and (2) MTS-L had variable inert and propellant masses; and (3) the landers were treated as fixed payloads. A second mathematical model was used to size the MCTV and estimate its flight performance: (1) EDS-C and (2) MTS-C had variable inert and propellant masses, and were iterated with the MLTV to derive common designs for the EDS and MTS; (3) the MPCV had fixed inert and variable propellant masses, with fixed initial and final payload masses. Its mass of consumables was held fixed as a mission reserve; (4) AGM mass was fixed throughout the mission; (5) DSV1, DSV2, and DSV3 inert, propellant, consumables, and payload masses varied throughout the mission; and (6) as DSV propellant mass was increased to achieve δV targets, propellant and pressurant tank sizes and masses, and backup structure mass were increased using scaling laws. MLTV/ MCTV math model inputs are shown in Table 11.

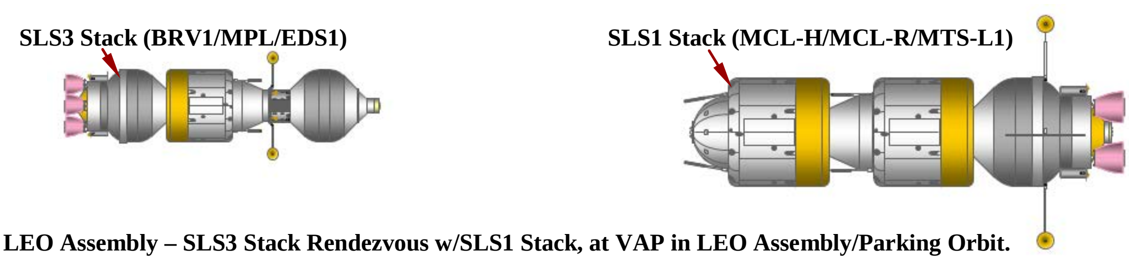
V. MLTV Mission Profile

A. Assembly and Refueling in LEO

MLTV1 assembly and refueling starts 300 days before TMI-1 (Figs. 25a-g): Assembly and refueling of MLTV2 is identical to MLTV1. For MLTV1, the SLS3 stack (BRV1/MPL/EDS1) rendezvous with the SLS1 stack (MCL-H/MCL-R/MTS-L1) at the VAP. BRV1 separates from the SLS3 stack, removing the LBA for disposal (Fig. 25a-b). The SLS3 stack docks with the SLS1 stack to complete MLTV1assembly (Fig. 25c). BRV1 docks at the EDS1 aft refueling port and is parked there until 2 days before TMI-1, when refueling commences: BRV1 fires thrusters to settle propellants and top-off EDS1 LH_2. BRV1 then undocks and re-docks to the MTS-L1 aft refueling port. It fires thrusters to settle propellants and top-off MTS-L1 LH_2. BRV1 then undocks and moves approximately 500m away (Fig. 25d-f). Main engine nozzle extensions deploy on EDS1/MTS-L1 (Fig. 25g). MLTV1 is now refueled and waits for the TMI-1 launch window to open. The MLTV BRVs (1, 2) could provide backup for the MCTV BRVs (3, 4).

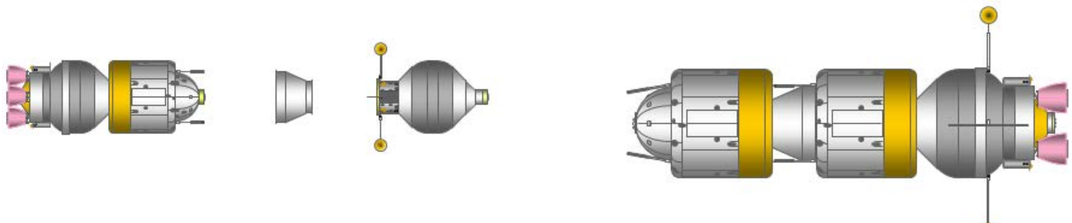
B. Mission Description and Flight Performance, TMI through Lander Rendezvous with MCTV in LMO

Figures 25h-r outline the MLTV mission from TMI burns through lander rendezvous with the MCTV in the LMO parking orbit. TMI is a two-stage burn which uses all of the propellants in the EDS and approximately 74% of the MTS-L propellants (Figs. 25h-j). Note that the MLTV has 144 m/s margin for TMI, which will enable an expanded launch window. During the 210 day outbound transit, the MPL/MCL landers will be kept in a hibernation mode to conserve power. The MLTV lander base is covered in reflective foil and insulation, and is kept pointed at the sun during OTO to shadow the MTS-L cryogenic propellant tanks (Fig. 25k). The MOI burn, shown in Fig. 25l-m, provides approximately 1,000 m/s less dV than needed for insertion into a circular orbit. The landers aerobrake to circularize the orbit as shown in Figs. 25n-q, 26, and 27. References 19-22 provide details of aerobraking utilized by recent unmanned scientific spacecraft to attain circular orbit around Mars with δV deficits comparable to the MLTV. After completion of aerobraking, the landers enter into the 500 km circular parking orbit and rendezvous and subsequently dock to MCTV (Fig. 25r). Figure 26 shows a representative capture orbit. The high hypersonic drag coefficient of the Mars landers enable them to rapidly aerobrake into parking orbit as shown in Fig. 27 MLTV flight performance data for TMI Burns A and B, the MOI Burn, and Aerobraking Burns is summarized in Table 12.

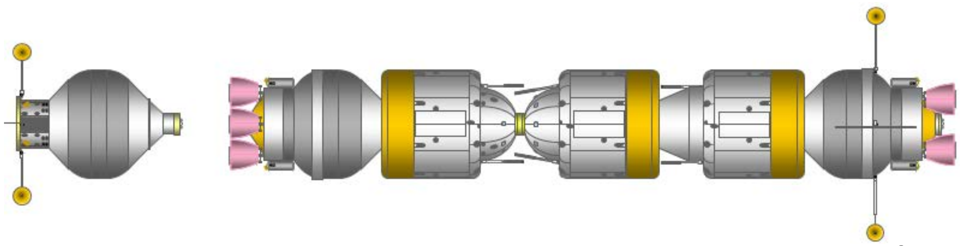


a. LEO Assembly – SLS3 Stack Rendezvous w/SLS1 Stack, at VAP in LEO Assembly/Parking Orbit.

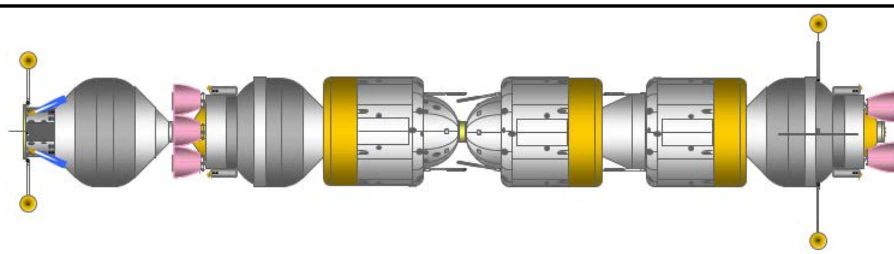
Figure 25. Mission Description – MLTV Assembly through Lander Delivery to MCTV in LMO.



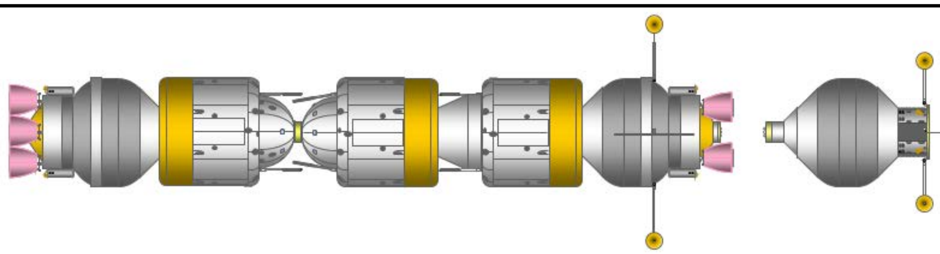
b. LEO Assembly – BRV1 Separates from SLS3 Stack, Removing LBA for Jettison.



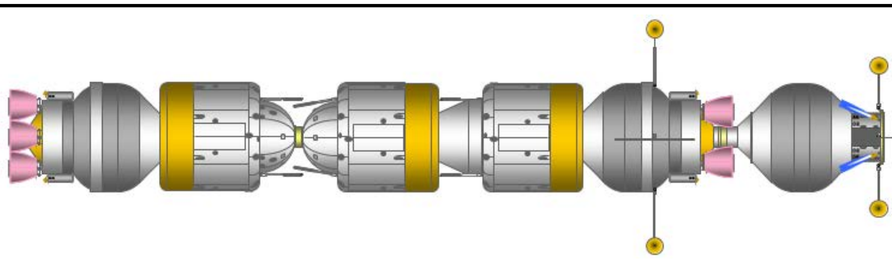
c. LEO Assembly – MPL1/EDS1 (SLS3) Docks w/SLS1 Stack. Assembly Complete. BRV1 aligns for Docking.



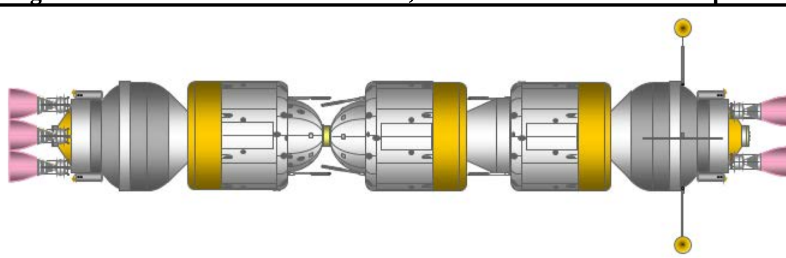
d. LEO Refueling – BRV1 Docks at EDS1 Aft Port, Fires Thrusters to Settle Prop. & Top-Off EDS1 LH_2.



e. LEO Refueling – BRV1 Undocks from EDS1 and Maneuvers to Dock at MTS-L1 Aft Port.

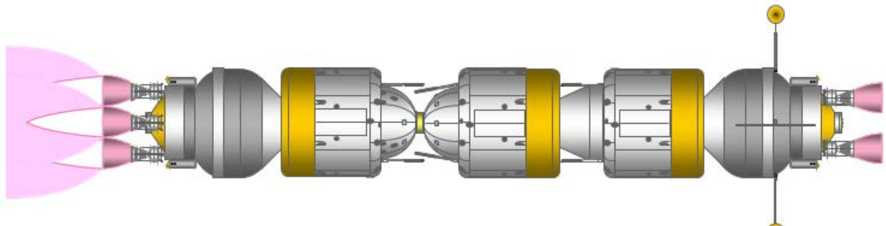


f. LEO Refueling – BRV1 Docks at MTS-L1 Aft Port, Fires Thrusters to Settle Prop. & Top-Off MTS-L1 LH_2.

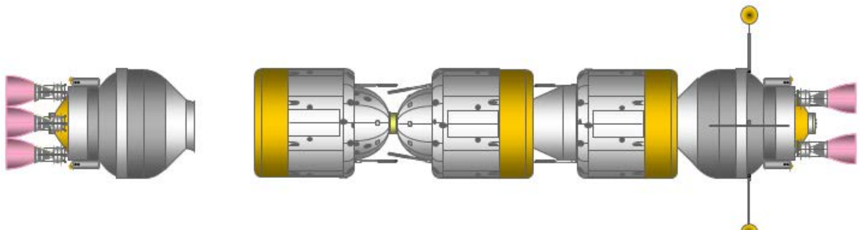


g. Earth Departure – Main Engine Nozzles Extensions Deploy on EDS1 and MTS-L1.

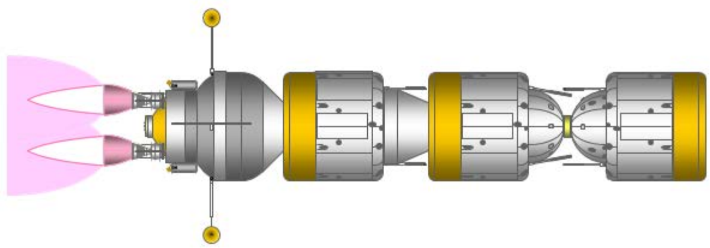
Figure 25. Mission Description – MLTV Assembly through Lander Delivery to MCTV in LMO.



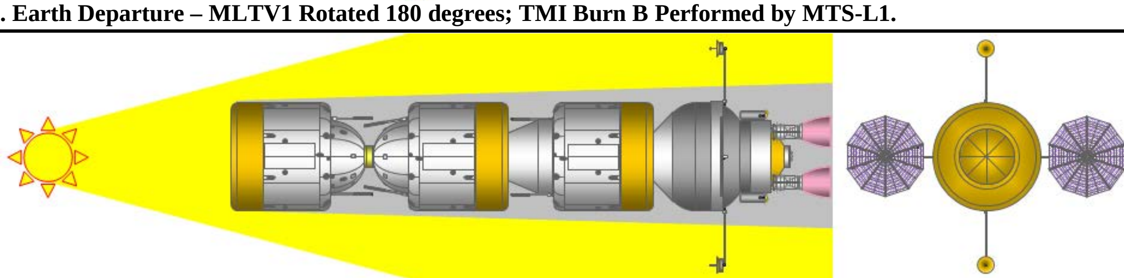
h. Earth Departure – Trans-Mars Injection (TMI) Burn A Performed by EDS1.



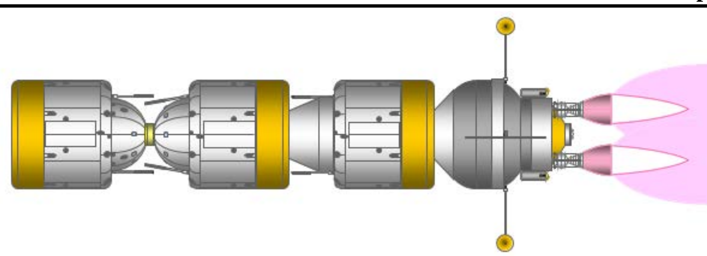
i. Earth Departure –Spent EDS1 Jettisoned after TMI Burn A.



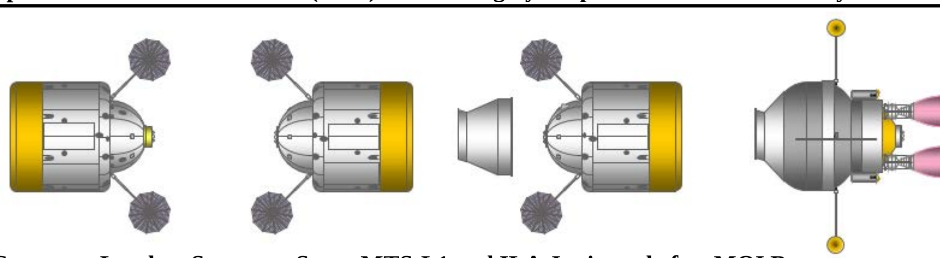
j. Earth Departure – MLTV1 Rotated 180 degrees; TMI Burn B Performed by MTS-L1.



k. Outbound Transit – MLTV1 Points Lander Base Towards Sun to Shadow MTS-L1 Propellant Tanks.

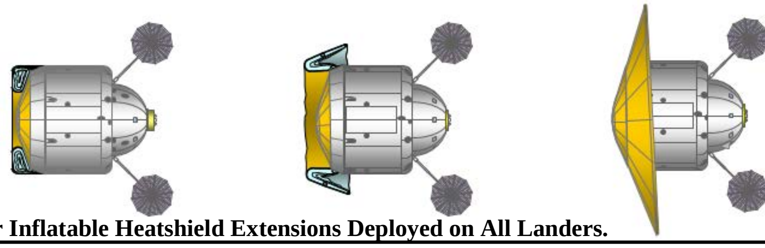


l. Mars Capture – Mars Orbit Insertion (MOI) Burn to Highly Elliptical Orbit Performed by MTS-L1.

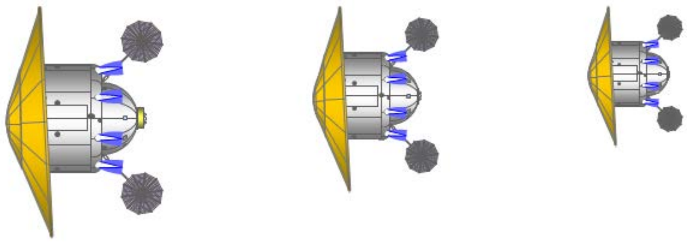


m. Mars Capture – Landers Separate; Spent MTS-L1 and ILA Jettisoned after MOI Burn.

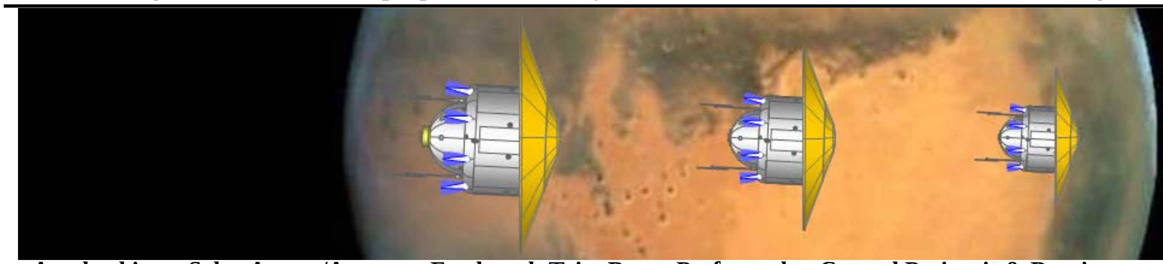
Figure 25. Mission Description – MLTV Assembly through Lander Delivery to MCTV in LMO, Continued.



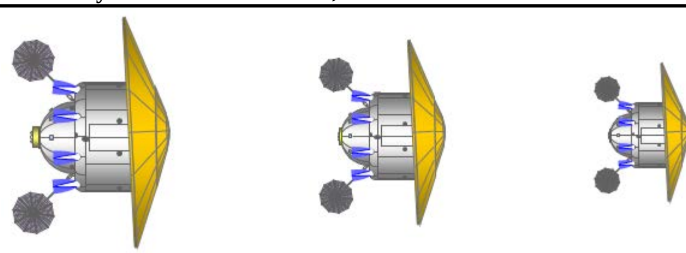
n. Aerobraking – Lander Inflatable Heatshield Extensions Deployed on All Landers.



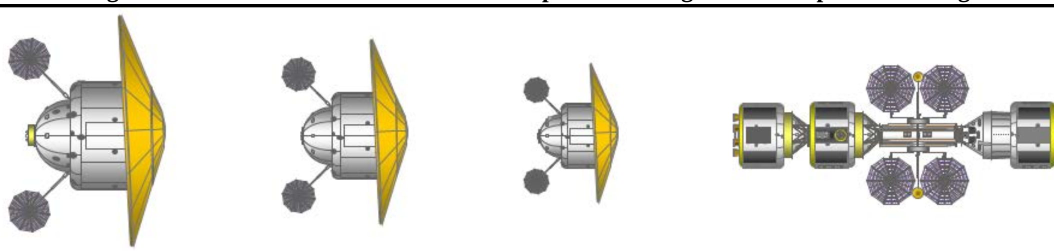
o. Aerobraking – Walk-In Burn at Apoapsis Performed by Lander Retro-Thrusters to Initiate Aerobraking.



p. Aerobraking – Solar Arrays/Antennas Feathered; Trim Burns Performed to Control Periapsis & Density.



q. Aerobraking – Circularization Burn Performed to Stop Aerobraking/Raise Periapsis to Parking Orbit Altitude.



r. Mars Parking Orbit – Landers Maneuver in Parking Orbit to Rendezvous with MCTV.

Figure 25. Mission Description – MLTV Assembly through Lander Delivery to MCTV in LMO, Continued.

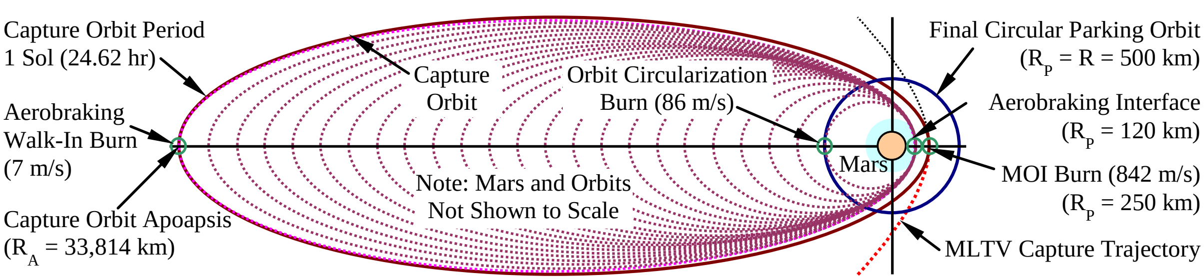


Figure 26. MLTV Propulsive Capture and Lander Aerobraking into Final Parking Orbit.

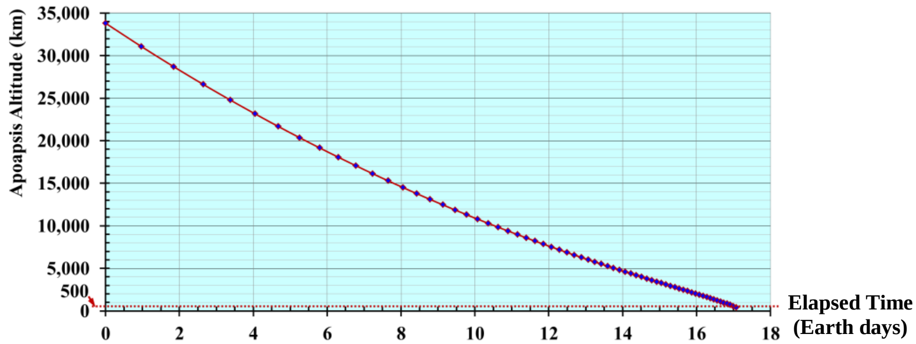


Figure 27. Mars Lander Aerobraking: Apoapsis Altitude vs Time.

Table 12. MLTV Performance for TMI, MOI, and Aerobraking (A/B) Burns.

MLTV Mass (kg)	TMI Burn A	TMI Burn B	MOI Burn	A/B Burns	Final
Items Launched by SLS1[1]					
MCL-H1 LMO Rendezvous Mass	21,532	21,532	21,532	21,532	21,532
MCL-H1 Usable Propellant for A/B [2]	941	941	941	941	0
MCL-H1 Total Mass	22,473	22,473	22,473	22,473	21,532
Inter-Lander Adaptor (ILA)	485	485	485	Jettisoned	Jettisoned
MCL-R1 LMO Rendezvous Mass	21,532	21,532	21,532	21,532	21,532
MCL-R1 Usable Propellant for A/B [2]	941	941	941	941	0
MCL-R1 Total Mass	22,473	22,473	22,473	22,473	21,532
MTS1 Non-Propellant and CA-L	7,466	7,466	7,466		
MTS1 Usable Propellant [2, 3, 4]	73,941	73,941	18,347		
MTS1 and CA-L Total Mass	81,407	81,407	25,813	Jettisoned	Jettisoned
Total Mass	126,840	126,840	71,245	44,947	43,064
Items Launched by SLS3[1]					
MPL1 LMO Rendezvous Mass	21,032	21,032	21,032	21,032	21,032
LIDS Docking Adaptor-Dual (LDA2)	500	500	500	500	500
MPL1 Usable Propellant for A/B [2]	941	941	941	941	0
MPL1 and LDA2 Total Mass	22,473	22,473	22,473	22,473	21,532
EDS1 Non-Propellant and CA-L	8,073				
EDS1 Usable Propellant [2, 3]	77,443				
EDS1 and CA-L Total Mass	85,516	Jettisoned			
Total Mass	107,990	22,473	22,473	22,473	21,532
Total Vehicle					
MLTV1 Stack Initial Mass	234,829	149,313	93,719	67,420	
Propellant Mass Consumed	77,443	54,790	18,347	2,824	
MLTV1 Stack Final Mass	157,386	94,523	75,372	64,596	64,596
Burn Parameters					
Burn Time (min.)	8.92	9.47	3.17	1.60	
Burn Net δV (m/s)	1,829	2,089			
Total δV TMI [5] (m/s)		3,918			
Total δV MOI [5, 6] (m/s)			850		
Total δV Aerobraking Phase [5] (m/s)				129	
Initial Acceleration (m/s^2)	2.816	2.952	4.704	0.939	
Initial Acceleration (T/W) (g_{0Earth})	0.287	0.301	0.479	0.096	
Final Acceleration (m/s^2)	4.202	4.664	5.849	0.980	
Final Acceleration (T/W) (g_{0Earth})	0.428	0.475	0.596	0.100	

[1] MLTV1 launched by SLS1 and SLS3, and MLTV2 launched by SLS2 and SLS4, respectively. [2] Usable propellant masses exclude residuals. [3] MTS-L1 and EDS1 topped off by BRV prior to TMI. [4] 804 kg of propellant boiloff prior to MOI by MTS-L. [5] Includes 2% Flight Performance Reserve (FPR). [6] Includes 25 m/s for OTO course correction burns.

VI. MCTV Mission Profile

A. LEO Assembly and Refueling

MCTV assembly and refueling starts 150 days before TMI-2 and is described in Figs. 28a-q: The SLS5 stack (AGM/DSV2/EDS3) is injected to the VAP and awaits arrival of the SLS6 stack (DSV1/CA-C1/EDS4). The SLS6 stack rendezvous with the SLS5 stack. EDS3 separates from the SLS5 stack. The SLS6 stack docks at the DSV2 aft docking port, and EDS3 temporarily docks at the EDS4 aft port for storage until arrival of the SLS7 stack. SLS7 stack components separate into BRV3, BRV4, and EDS5, and EDS3 undocks from EDS4 (Figs. 28a-f). BRV3, EDS3, and EDS5 sequentially dock together to form the EDS Refueling Subassembly, and BRV4 docks to the aft refueling port on EDS4 on the MCTV subassembly. EDS refueling occurs just before arrival of the crew in the SLS8 stack: BRV3 and BRV4 fire thrusters and perform settled propellant transfer to top-off LH_2 tanks on EDS 3 and EDS4 (and EDS5 using EDS3 internal LH_2 propellant transfer lines) (Figs. 28g-i). BRV3 and BRV4 then undock from EDS3 and EDS4 and station-keep. The SLS8 stack (MPCV/DSV3/MTS3) rendezvous and station-keeps. EDS3, 4, and 5 separate and sequentially dock to three radial CA-C1docking ports spaced 120-deg. apart. The three EDS are then rotated 90 deg. simultaneously, to minimize angular momentum changes, to become parallel with the MCTV. Structural attach fittings and support struts between EDS3, 4, and 5 and CA-C1 are engaged to form the TMI Booster Assembly (TBA). The SLS8 stack then docks with the AGM. This completes MCTV assembly (Figs. 28j-n). BRV4 docks to MTS3 and tops off its LH_2 tank, with BRV3 held in reserve (Figs. 28o-p). BRV4 than undocks and the two BRVs move away and station-keep approximately 500m away from the MCTV. Main engine nozzles extensions deploy on EDS3, 4, and 5 and on MTS3. The two BRVs utilized to top off the MLTVs, BRV1 and BRV2, have sufficient remaining LH_2 onboard, and could function as backups to BRV3 and BRV4. The MCTV is now refueled and ready, and waits for the TMI launch window to open (Fig. 28q).

B. Mission Description and Flight Performance, TMI through Lander Rendezvous in LMO

Figures 29a-k describe the MCTV mission description from TMI through rendezvous with the landers in LMO. TMI utilizes two sequential burns to provide sufficient δV. TMI burn A uses the TBA comprised of EDS3, 4, and 5 and CA-C1. The TBA is jettisoned after completion of TMI Burn A. The MCTV rotates 180 degrees and TMI Burn B is performed by MTS3. Approximately 26% of MTS3 propellants are consumed by TMI Burn B (Figs. 29a-c and Columns 2 and 3 of Table 13). At this point the MCTV is in the outbound transit: The DSV1 and DSV2 crew cabin shield tanks will be filled with water to increase crew passive radiation shielding to 10 gm/cm^2 (Section III.C, above). The crew then transfers from the MPCV through the pressurized AGM tunnel to DSV2/DSV1. This will provide the four-person crew with $24.3m^3$ of habitable volume per person, using the combined habitation volume of DSV1 and DSV2. The AGM tunnel is then depressurized, and MPCV and DSV2 undock from the AGM, and the Artificial Gravity (AG) rails extend for AG rotation. The MCTV is spun-up using DSV1 thrusters to a nominal 2.730 RPM to provide 0.379 g's of AG (Mars surface equivalent) at the DSV2 mid-level crew living quarters. The sequence of events to spin-down the vehicle is the opposite of spin-up. A total of four spin-up/spin-down cycles have been allocated for outbound transit, including three outbound course corrections (OCC), and sufficient mass (2,989kg) of storable RCS propellants in DSV1 has been allocated for this purpose (Fig. 29d). MCTV AG rotation is stopped prior to MOI. AG rails are fully retracted, and the MPCV and DSV2 dock to the AGM. MOI utilizes two sequential burns to provide sufficient δV. Burn A, performed by MTS3, provides the bulk of the MOI δV. The spent MTS3 is then jettisoned. MOI Burn B, performed by DSV3, is used to circularize the 500 km parking orbit (Figs. 29e-g and Columns 4 and 5 of Table 13). The MPCV and DSV2 undock from the AGM for AG operations in LMO until lander arrival (Fig. 29h). On lander arrival, AG operations are stopped and MPCV and DSV2 re-dock to the AGM. DSV1 is then rotated 90-deg. axially with respect to DSV2 to provide clearance for four landers to dock at the DSV1 and 2 side docking ports (Fig. 29i). Six landers rendezvous and dock with the MCTV in preparation for the start of the MSE phase (Figs. 29j-k). Reference 23 was used to generate estimates for Life Support System (LSS) consumables shown in Table 14, which accounts for metabolic usage, cabin leakage, extra-vehicular activity (EVA), and airlock cycling. 45 days margin is provided to the nominal 905 day round-trip MEV mission duration.

C. Mission Abort Options During and Post-TMI

There are multiple TMI and OTO abort scenarios and configurations considering the high energy contained in the MTS-C, DSV1, DSV3, and MPCV propellants. Figure 30 and Table 15 show the design and performance of a TMI abort scenario that uses the SLS8 stack (MPCV/DSV3/MTS-C) for TMI abort. There is a significant amount of excess performance that could be used to expand the window to return to Earth that will be explored in future work.

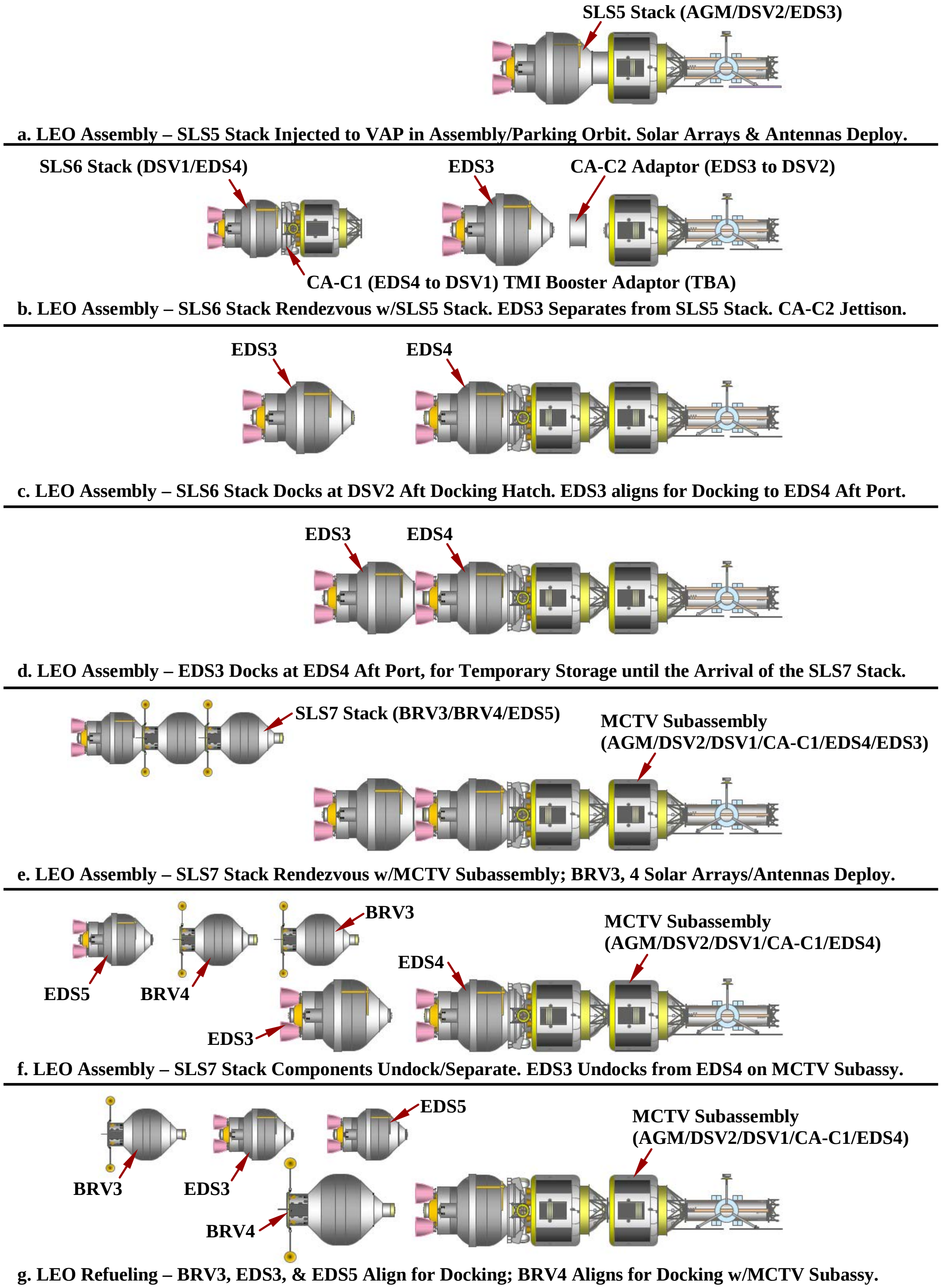
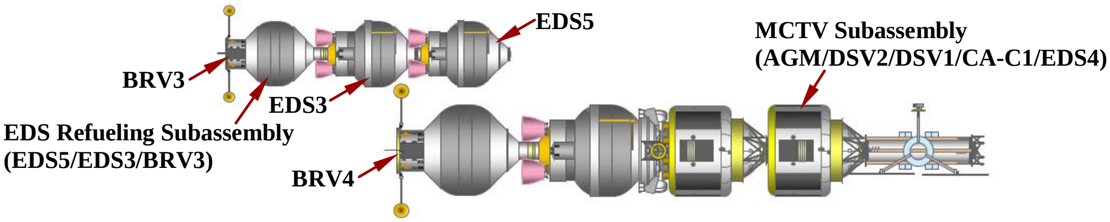
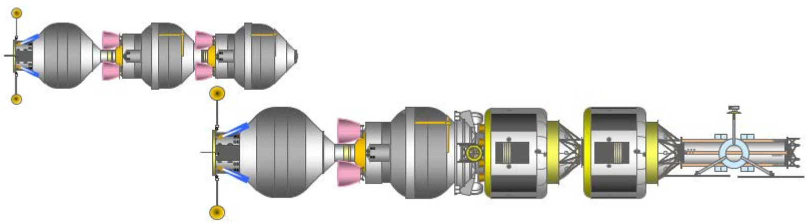


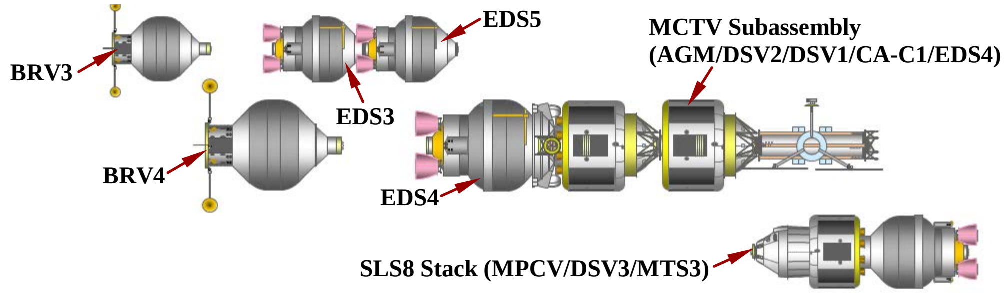
Figure 28. Mission Description – MCTV Assembly and Refueling in LEO.



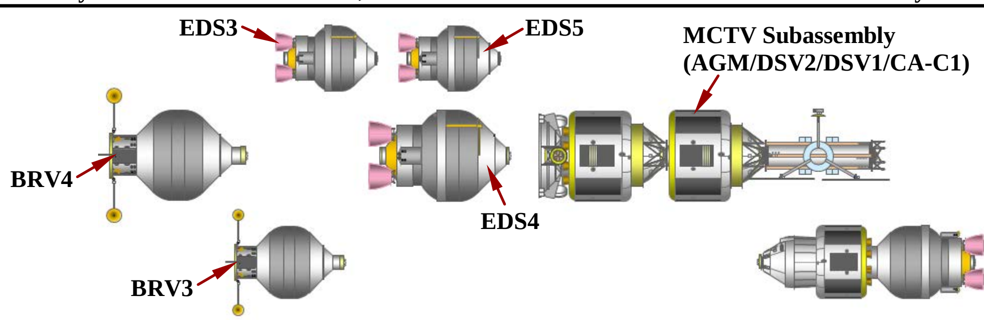
h. LEO Refueling – EDS3, BRV3, and EDS5 Sequentially Dock Together; BRV4 Docks w/MCTV Subassembly.



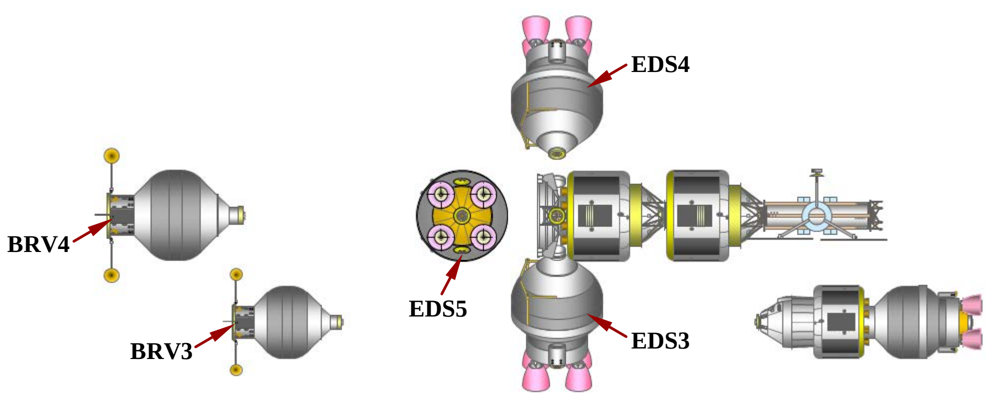
i. LEO Refueling – Axial Thrusters on BRV3 and BRV4 Fire; LH_2 tanks topped off on EDS3, 4, and 5.



j. LEO Assembly – BRV3 & BRV4 Undock; SLS8 Stack Rendezvous with the MCTV Subassembly.

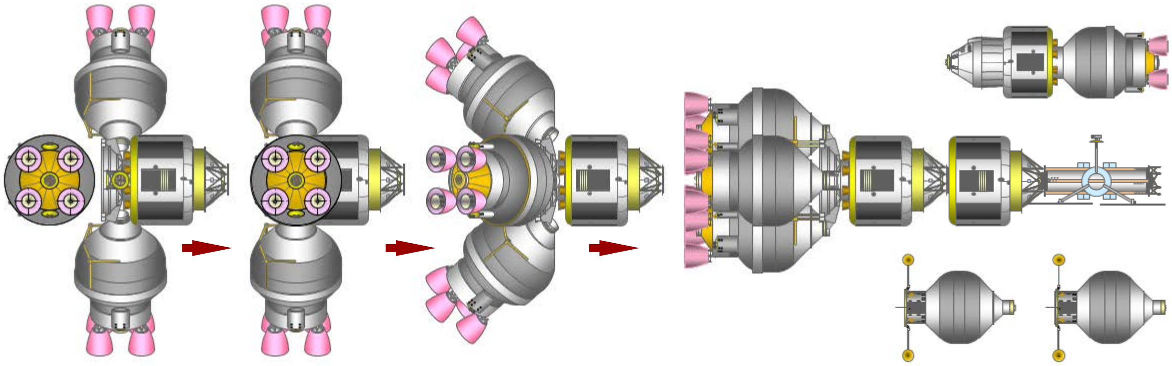


k. LEO Assembly – EDS3 and EDS5 Undock from Each Other. EDS4 Undocks from MCTV Subassembly.

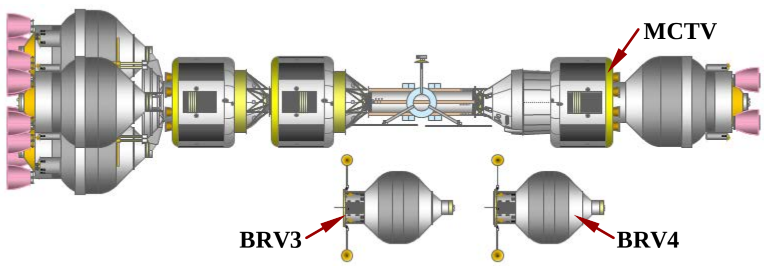


l. LEO Assembly – EDS3, 4, & 5 Align/Sequentially Dock to Three Radial CA-C1 Ports Spaced 120-deg. Apart.

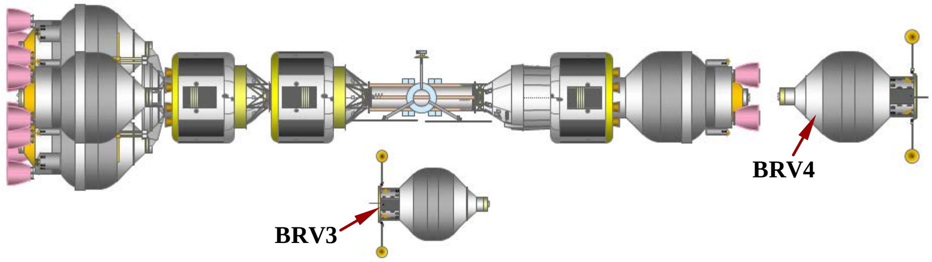
Figure 28. Mission Description – MCTV Assembly and Refueling in LEO, Continued.



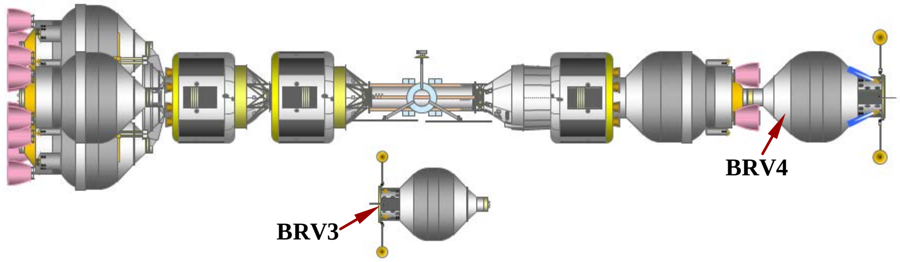
m. LEO Assembly – EDS3, 4, & 5 Sequentially Dock at CA-C1 Radial Docking Ports Spaced 120-deg. Apart; EDS3, 4, & 5 Rotate 90-deg.; Lateral Struts Extend and Lock; TMI Booster Assembly (TBA) Complete.



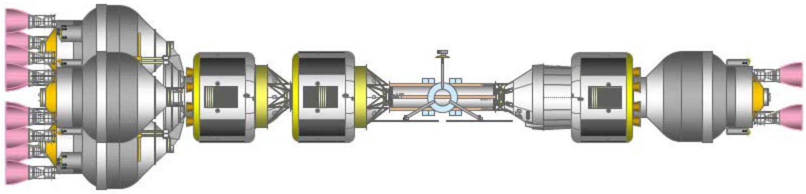
n. LEO Assembly – SLS Stack 8 Docks to MCTV Subassembly. MCTV Assembly Complete.



o. LEO Refueling – BRV4 Aligns for Docking at MTS3 Aft Docking Port.

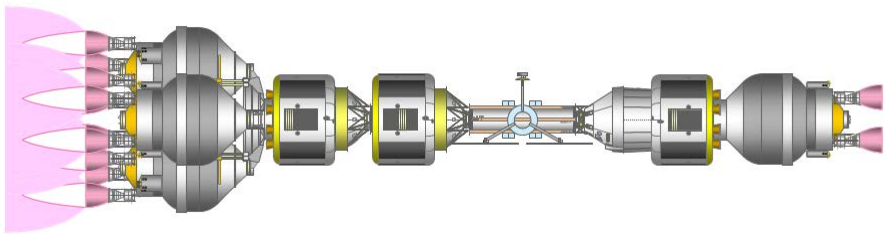


p. LEO Refueling – BRV4 Docks at MTS3 Aft Port. BRV4 Thrusters Fire to Settle MTS3 Prop. & Top-Off LH_2.

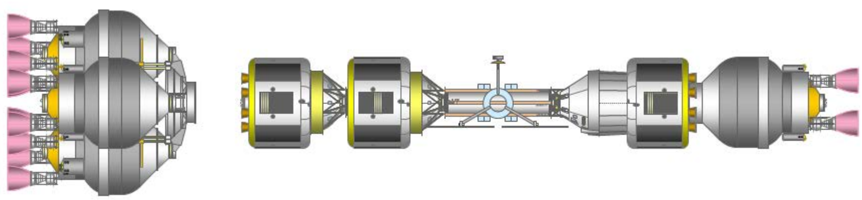


q. TMI Preparations – BRV4 Undocks; BRV3 and 4 Maneuver Away from MCTV for Later Deorbit; Main Engine Nozzle Extensions Deploy on EDS3, 4, 5, & MTS3; MCTV is Ready and Awaits TMI Launch Window.

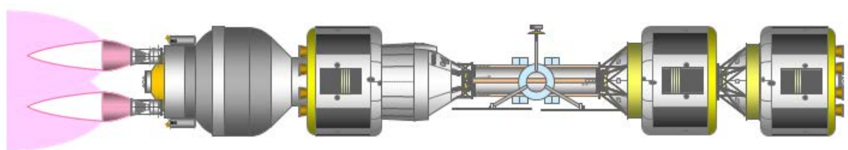
Figure 28. Mission Description – MCTV Assembly and Refueling in LEO, Continued.



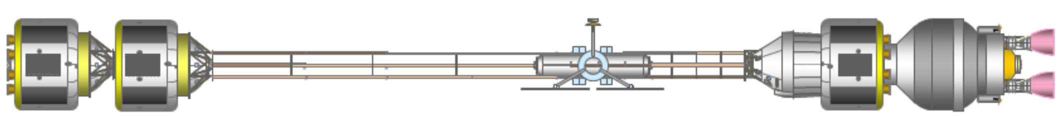
a. Earth Departure – Trans-Mars Injection (TMI) Burn A Performed by EDS3, 4, 5 TMI Booster Assembly.



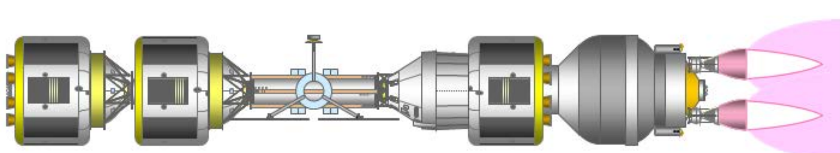
b. Earth Departure – TMI Booster Assembly, with Spent EDS3, 4, and 5, & CA-C1 Jettisoned.



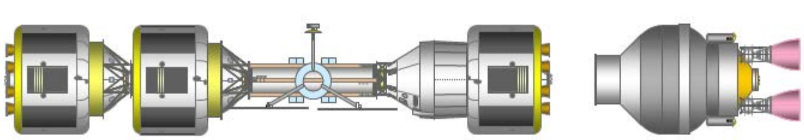
c. Earth Departure – MCTV Rotated 180 Degrees; TMI Burn B Performed by MTS3.



d. Outbound Transit – Crew Transfers from MCTV to DSV1, 2 through Pressurized AGM Tunnel. AGM Depressurized. MPCV & DSV2 Undock from AGM; Artificial Gravity (AG) Rails Extend for AG Rotation.

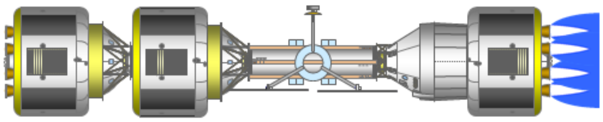


e. Mars Capture – MCTV AG Rotation Stopped and AG Rails Fully Retracted. MPCV and DSV2 Re-dock to the AGM; Mars Orbit Insertion (MOI) Burn A is Performed by MTS3.

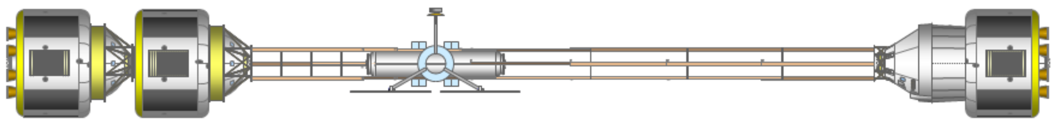


f. Mars Capture – Spent MTS3 Jettisoned.

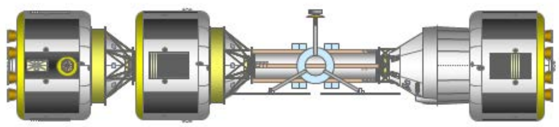
Figure 29. Mission Description – MCTV TMI through MLTV Lander Delivery in LMO.



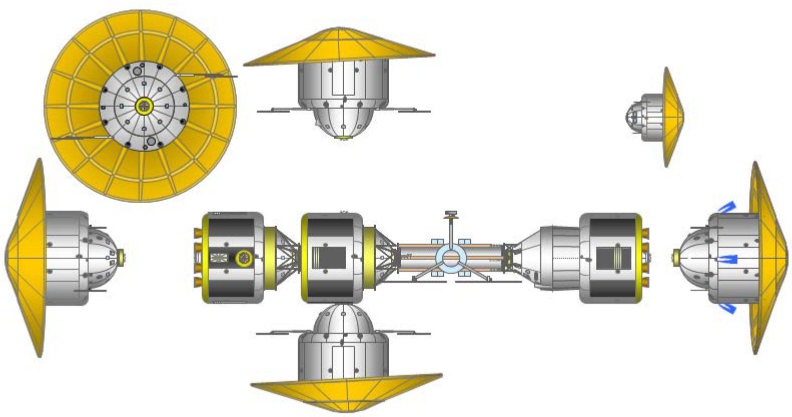
g. Mars Capture – TMI Burn B Performed by DSV3 to a 500 km Altitude Circular Parking Orbit.



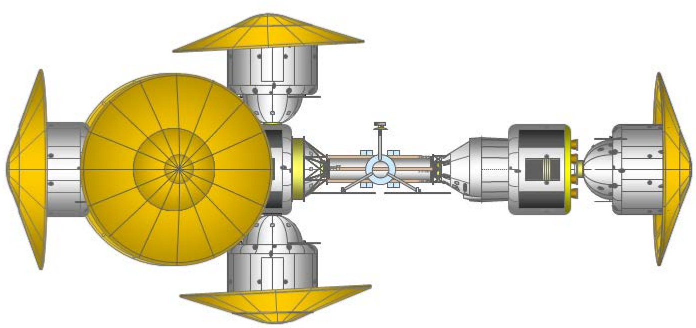
h. LMO Operations – MPCV & DSV2 Undock from AGM and AG Rails Extend for AG Rotation. The Crew in MCTV Await the Arrival of the Landers in order to Initiate the Mars Surface Exploration (MSE) Phase.



i. LMO Operations – AG Rotation Stopped and AG Rails Fully Retracted. DSV1 Rotated Axially 90-Deg. w/ Respect to DSV2 Aft Docking Port to Provide Clearance for Four Landers to Dock at DSV1 & 2 Radial Ports.



j. LMO Operations – Six Mars Landers Rendezvous and Dock to the MCTV in the Parking Orbit.



k. LMO Operations – Six Landers Docked to MCTV in Preparation for the Start of the MSE Phase.

Figure 29. Mission Description – MCTV TMI through MLTV Lander Delivery in LMO, Continued.

Table 13. MCTV Performance for TMI and MOI Burns.

MCTV Mass (kg)	TMI Burn A	TMI Burn B	MOI Burn A	MOI Burn B	Final
Items Launched by SLS5					
AGM	2,290	2,290	2,290	2,290	2,290
DSV2 Inert and Payload	8,169	8,169	8,169	8,169	8,169
DSV2 LSS Cons. & Usable RCS Prop.[1]	15,191	15,191	12,072	12,072	12,072
DSV2 Total Mass	23,360	23,360	20,241	20,241	20,241
EDS3 Non-Propellant and EDA	7,553				
EDS3 Usable Propellant [1, 2]	77,443				
EDS3 Total Mass	84,996	Jettisoned			
Total Mass	110,646	25,650	22,531	22,531	22,531
Items Launched by SLS6					
(4) Crew w/ Suits, ELSS, & PLSS	0	0	660	660	660
DSV1 Inert, Payload, & Propellant	34,191	34,191	31,202	31,202	31,202
DSV1 LSS Consumables	6,830	6,830	6,830	6,830	6,830
DSV1 Total Mass	41,021	41,021	38,692	38,692	38,692
EDS4 Non-Prop., CA-C1, and EDA	10,131				
EDS4 Usable Propellant [1, 2]	77,443				
EDS4 Total Mass	87,574	Jettisoned			
Total Mass	128,595	41,021	38,692	38,692	38,692
Items Launched by SLS7					
EDS5 Non-Propellant and EDA	7,553				
EDS5 Usable Propellant [1, 2]	77,443				
EDS5 Total Mass	84,996	Jettisoned			
Total Mass	84,996	0	0	0	0
Items Launched by SLS8					
(4) Crew w/ Suits, ELSS, & PLSS	660	660	0	0	0
MPCV Inert and Propellant	21,382	21,382	21,382	21,382	21,382
MPCV Total Mass	22,042	22,042	21,382	21,382	21,382
DSV3 Inert, MDA, and LDS	3,011	3,011	3,011	3,011	3,011
DSV3 Usable Main/RCS Propellant [1]	18,180	18,180	18,180	18,180	17,322
DSV3 Total Mass	21,191	21,191	21,191	21,191	20,333
MTS3 Non-Propellant and CA-C3	7,992	7,992	7,992		
MTS3 Usable Propellant [1, 2, 3]	77,443	77,443	55,273		
MTS3 Total Mass	85,435	85,435	63,265	Jettisoned	
Total Mass	128,668	128,668	105,837	42,573	41,715
Total Vehicle					
MCTV Stack Initial Mass	452,904	195,339	167,061	103,796	
Propellant Mass Consumed	232,329	19,747	55,273	858	
MCTV Stack Final Mass	220,575	175,592	111,788	102,938	102,938
Burn Parameters					
Burn Time (min.)	13.38	3.41	9.55	0.42	
Burn Net δV (m/s)	3,288	487	1,836	27	
Total δV TMI [4] or MOI [4, 5] (m/s)		3,775		1,863	
Initial Acceleration (m/s^2)	2.920	2.257	2.639	1.045	
Initial Acceleration (T/W) (g_{0Earth})	0.297	0.230	0.269	0.106	
Final Acceleration (m/s^2)	5.996	2.511	3.944	1.054	
Final Acceleration (T/W) (g_{0Earth})	0.611	0.256	0.402	0.107	

[1] Usable propellant masses exclude residuals. [2] MTS-C and EDS topped off by BRV prior to TMI. [3] 2,423 kg of propellant boiloff prior to MOI by MTS-C. [4] Includes 2% FPR. [5] Incl. 25 m/s for OTO course correction burns.

Table 14. LSS Consumables Endurance for MCTV with 4 Person Crew.

Mission Phase	OTO [1]	LMO [2]	ITO [3]	Assy./Entry [4]	Total
Consumables Location	**DSV2-HS**	**DSV2-PS**	**DSV1-HS**	**MPCV**	**All**
Mission Duration (days)	210	480	210	5	905
Number of Crewmembers	4	4	4	4	4
Mission Endurance (man-days)	840	1,920	840	20	3,620
Design Duration (days)	217	495	217	21	950
Design Endurance (man-day)	868	1,980	868	84	3,800
Margin (days)	7	15	7	16	45
Margin (man-day)	28	60	28	64	180
Crew Cabin Usage					
Non-EVA Man-Days	864.5	1972.0	864.5		
O_2 Consump. Rate (kg/m-day)	0.850	0.850	0.850		
H_2O Cons. Rate before Rec. (kg/m-day) [5]	5.000	5.000	5.000		
H_2O Cons. Rate after Rec. (kg/m-day) [5]	0.750	0.750	0.750		
Food Consump. Rate (kg/m-day)	1.825	1.825	1.825		
Oxygen (kg, Non-EVA m-days)	735	1,676	735		
Water (kg, Non-EVA man-days) [6]	4,323	1,479	4,323		
Food (kg, Total man-days)	1,584	3,599	1,584		
EVA and Airlock Usage [7, 8, 9, 10]					
EVA Man-Days (2 crew per EVA)	3.5	8.0	3.5		
No. of EVAs per Mission Phase	7	16	7		
EVA O_2 Usage (kg)	8.82	20.16	8.82		
EVA H_2O Usage (no recovery) (kg)	44.80	102.40	44.80		
EVA N_2 Usage (kg)	1.63	3.73	1.63		
No. of Airlock Depress./Repress. Cycles	21	48	21		
Airlock O_2 Losses (kg)	2.60	5.94	2.60		
Airlock N_2 Losses (kg)	9.10	20.79	9.10		
Cabin Leakage Losses (kg) [11, 12]					
Cabin Leakage O_2 Losses (kg)	27.2		27.2		
Cabin Leakage N_2 Losses (kg)	95.3		95.3		
LSS Consumable Masses (kg)					
Breathing Oxygen	773	1,702	773		
Water	4,367	1,581	4,367		
Food	1,584	3,599	1,584		
Nitrogen	106	25	106		
Subtotal Consumables Masses	6,830	6,908	6,830		
Total Consumables Mass			20,568		

[1] Outbound Transfer Orbit. [2] Low Mars Orbit (contingency LSS consumables). [3] Inbound Transfer Orbit.

[4] 5d = 2d for launch, injection, and LEO rendezvous, docking, & assembly, and 3 days for end of ITO Earth entry.

[5] Fraction of wastewater recovered = 0.850. [6] Includes additional H_2O to fill DSV1/DSV2 crew cabin shield tanks.

[7] All EVAs performed by pair of crewmembers for safety; 6 hr (0.25 m-day)/EVA x 2 persons = 0.5 man-days/EVA.

[8] EVAs: per 210-day OTO for DSV2; per 480-day LMO for DSV2 (contingency ops.); per 210-day ITO for DSV1.

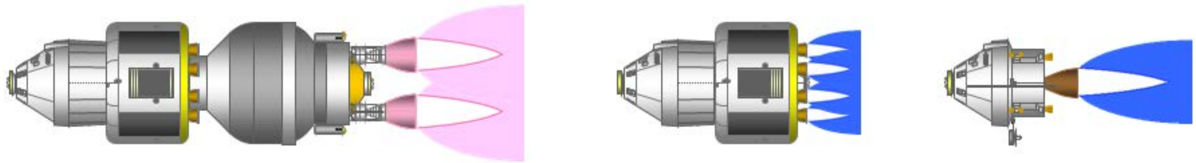
[9] EVA consumption rates (no recovery) (kg/person/6-hr EVA): O_2 = 0.630 kg, H_20 = 3.200, and N_2 = 0.117.

[10] Three airlock depress.-repress. cycles per 2-person EVA; 10% gas (1.76 m3) lost on airlock cycling, based on ISS.

[11] Pressurized vol. (DSV1 = DSV2 = 62.8m^3) includes cabin/tunnels/airlock:; Losses based on 900d mission duration.

[12] Crew cabin air = 80% N_2, 20% O_2 by volume; ρ = 1.198 kg/m3. Crew cabin leak rate = 0.18%/ day, based on ISS.

.



a. TMI Abort Burn A utilizing MTS-C Propulsion System. **b. TMI Abort Burn B utilizing DSV3 Propulsion System.** **c. TMI Abort Burn C utilizing MPCV Propulsion Sys. (OME).**

Figure 30. Trans-Mars Injection Abort Utilizing MPCV/DSV3/MTS-C stack.

Table 15. TMI Abort Performance for MPCV/DSV3/MTS-C stack.

Mass (kg)	Abort Burn A - MTS-C[1]	Abort Burn A - MTS-C[2]	Abort Burn B - DSV3	Abort Burn C - MPCV	Required δV	Excess δV
MPCV, MDA, DSV3, LDS	43,233	43,233	43,233	22,042		
MTS3 and CA-C3	85,435	65,688	0	0		
Stack Initial Mass	**128,668**	**108,921**	**43,233**	**22,042**		
Available Propellant Mass[3]	77,443	57,696	16,564	7,907		
Consumed Propellant Mass[4]	75,181	55,033	16,564	7,559		
Remaining Propellant Mass	2,262	2,663	0	349		
Stack Final Mass	**53,487**	**53,888**	**26,669**	**14,484**		
Velocity Change (m/s)						
δv_{ABORT}	**4,011**	**3,216**	**1,546**	**1,344**		
Total δv_{ABORT}[1]				**6,902**	**3,288**	**3,614**
Total δv_{ABORT}[2]				**6,106**	**3,774**	**2,332**

[1] Abort initiated after TMI Burn A & before TMI Burn B (MTS-C full propellant load).
[2] Abort initiated after TMI Burn B (MTS-C partial propellant load).
[3] At tank O:F mixture ratio = 4.88 [4] At engine O:F mixture ratio = 5.88

D. Mars Orbit Operations and Mars Surface Exploration (MSE) Mission

1. MCTV Operations in Mars Orbit

The TEI launch window opens 480 days (16 mo.) after MOI. MLTVs arrive at Mars 30 days before the MCTV (24d + 6d margin) and execute MOI into a highly elliptical capture orbit. The six landers are released and aerobrake for approximately 17 days before entering the 500 km circular parking orbit. 7 days have been allocated for lander orbit phasing, rendezvous, and docking with the MCTV. Maximum duration for the Mars Surface Exploration mission is 450 days (15 mo.) if no margin is consumed during MCTV aerobraking, phasing, rendezvous, and docking. The last 6 days of the 480 stay time at Mars have been allocated to crew preparations in orbit for TEI. In the event of loss of the landers, the MCTV has sufficient LSS consumables to support the crew in orbit for the full 480 day Mars stay time. In the event of a casualty to the MCTV, the landers could provide LSS consumables to support the crew in orbit for the full 480 day Mars stay time. The landers also provide a significant amount of contingency δV for TEI. This will be explored in future work. Before lander arrival, and after return of the crew, the MCTV will be rotated for AG operations using the same procedure described in section IV.C, above, for the outbound transit, at a nominal 3.548 RPM to provide 0.379 Earth g's (Mars surface equivalent) at the DSV1 mid-level crew quarters. A total of two spin-up/spin-down cycles have been allocated for the LMO phase, and sufficient DSV3 RCS propellant mass (1,614 kg) has been allocated for this purpose.

2. Mars Entry, Descent, and Landing

The Mars Entry, Descent, and Landing (EDL) sequence for the Mars Personnel Lander (MPL) and Mars Cargo Landers (MCLs) is described in detail in Ref. 10. Figures 31a-b and 32a-i show the EDL sequence of events. The MPL/MCL landers are designed to land from an orbit inclined up to 12.5 degrees from the equator, at a MOLA altitude of zero or less, making ~50% of this 25 degree band accessible for exploration (Fig. 32a). Five landers, two MCL habitat variants (MCL-H), two MCL rover variants (MCL-R), and one MPL, are sequentially sent to the surface. The four unmanned cargo landers are first prepared for flight operations and undock from the MCTV and proceed to the surface as shown in Fig 32b. MPL1, with the 4-person crew onboard, undocks from the MCTV as shown in Fig. 32c after confirmation of successful landing of the unmanned cargo landers. MPL2 remains docked to the MCTV in reserve for crew rescue on the surface or in orbit as shown in Fig. 32d. The following description of the EDL sequence of events is the same for each lander, but is shown for MPL1 in Fig. 32e-i. Figure 32e describes the exoatmospheric sequence of events starting from 500 km parking orbit: (1) each lander fires onboard thrusters to fine tune orbital parameters, aligning deorbit burn position to achieve the necessary entry corridor to reach the pre-selected landing zone. (2) The deorbit burn is accomplished using eight deorbit thrusters, and inserts the lander into an elliptical transfer orbit that dips into Mars' atmosphere at its periapsis of 125 km. (3) The lander is reoriented with its heatshield facing forward and (4) solar arrays are jettisoned. (5) Aerodynamic deceleration using the ablative heat shield begins at an entry interface altitude of 150 km, just before periapsis.

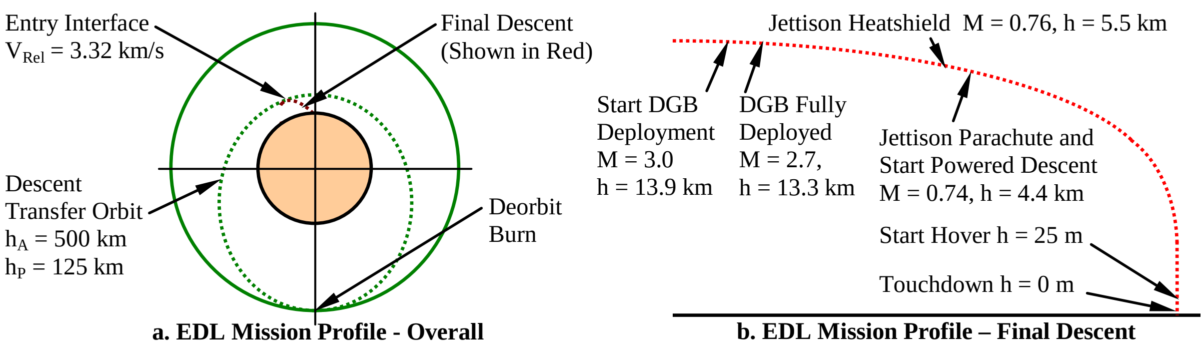
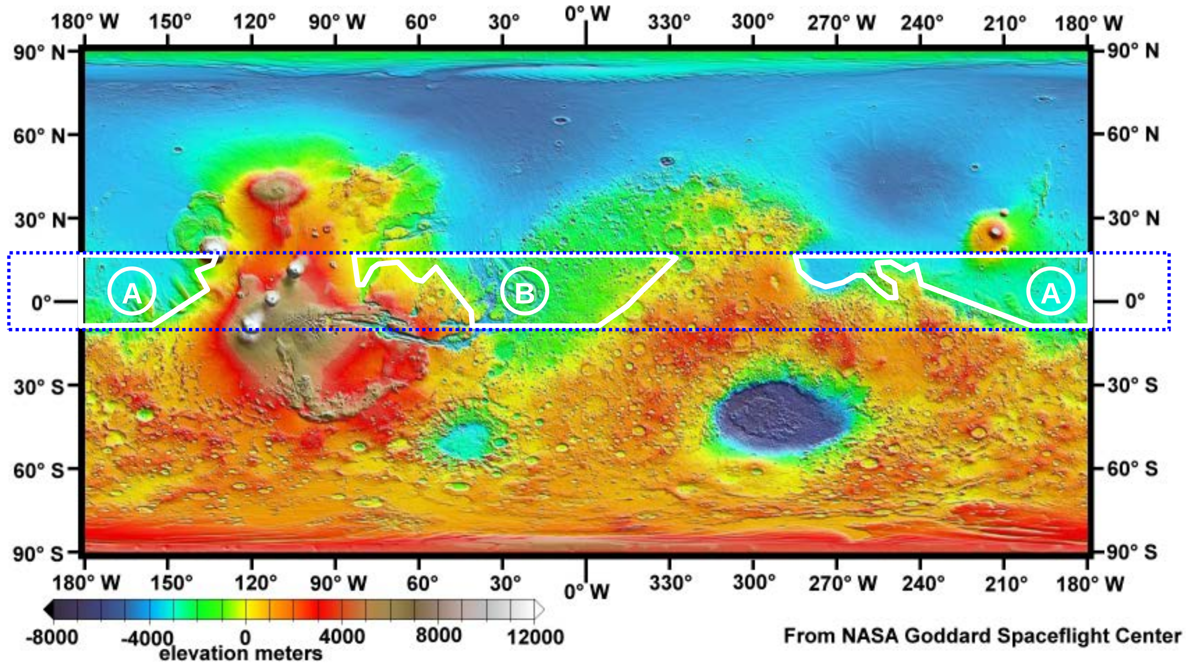


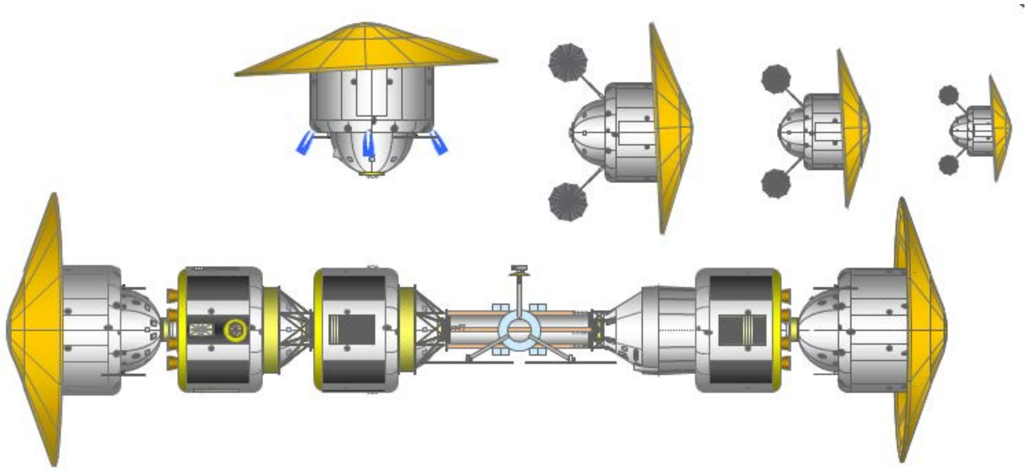
Figure 31. MPL/MCL EDL Mission Profile from the 500 km Altitude Parking Orbit to the Surface.

During the EDL phase, each successive lander will track homing beacons from landers already on the surface to steer their trajectory to a landing near the rendezvous point. Lander surface rendezvous is discussed in Sect. VI.D.3, below. Aerodynamic deceleration using the ablative heat shield continues until the lander has been slowed to Mach (M) = 3.0 at an altitude of 13.9 km. At this point the 27 m diameter DGB parachute is deployed by mortar as shown in Fig. 32f. It is fully inflated at M = 2.7 at an altitude of 13.3 km. It slows the lander to a subsonic speed of Mach = 0.76 at 5.5 km altitude. The rigid heat shield, inflatable HSE, and four landing leg doors are then jettisoned and driven away from the lander by eight solid rocket separation motors as shown in Fig. 32g. The landing legs extend and lock for touchdown after the landing leg doors are jettisoned. The DGB parachute is jettisoned at M = 0.74 at 4.4 km altitude and the powered descent (PD) begins. The MPL utilizes a descent section (DS) that common with the MCL, and has a two-stage ascent section (AS), with booster and orbiter stages. The AS booster has a single, fixed thrust, gimballed 98.2 kN thrust main engine that is used for both descent and ascent to save engine mass and facilitate aborts during PD. During descent it is cross-fed with propellants from the descent stage. The MCL utilizes five, fixed thrust, gimballed descent engines in place of the single MPL main engine. PD features a powered gravity turn phase and a vertical descent phase, both at a constant thrust/weight (T/W) of 2.0, as shown in Fig. 32h. EDL simulations showed that vehicle T/W needed to be at least 1.95 to sufficiently decelerate the vehicle. PD continues with a timed hover phase at T/W = 1.0 at approximately 25m above the surface, and a soft landing phase (Fig. 32i). There is sufficient propellant carried to hover for a maximum of 10s to locate and avoid obstacles.

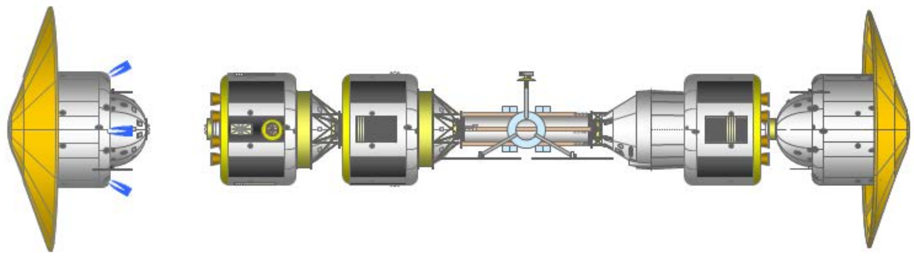
The MPL is capable of abort- to-orbit (ATO) throughout the PD phase, after it decelerates below Mach = 0.74 and the heatshield and parachute have been jettisoned. For ATO, explosive bolts will fire and the descent section will be jettisoned. The ascent booster engine, utilizing quick disconnects, will shift to ascent booster propellants and continue to burn, placing the MPL Ascent Section on an ascent trajectory. Five ATO scenarios were simulated, with initiating altitudes of 4.4 km, 3.0 km, 2.0 km, 1.0 km, and the 25 meter hover point. It was determined that the AS T/W had to be at least 2.0 to prevent the vehicle from impacting the surface after separation from the DS. The ATO requirement therefore sized the MPL main engine. All ATO scenarios examined achieved the 250 km intermediate orbit but had some deficit for orbit raising to the parking orbit. The shortfall was made up by staging the booster and firing the orbiter engines for some period of time. This deficit could be covered in some cases if the orbiter's 178 m/s allocation for plane changes is not needed. In the worst of cases, the crew may not be able to attain the parking orbit altitude using the remaining orbiter propellants. In this case the crew could remotely pilot the MPL2 lander, which was kept docked to the MCTV for crew rescue, to rendezvous with the MPL1 ascent orbiter in the 250 km orbit and transport the crew back to the MCTV in the parking orbit. EDL flight performance data are summarized in Columns 2, 3, and 4 of Table 16. Detailed EDL data and trajectory simulation results are shown in Reference 10.



a. Mars EDL – MPL/MCL Landing Zones: Zones "A" and "B" at or Below MOLA=0, ± 12.5-deg. from Equator.

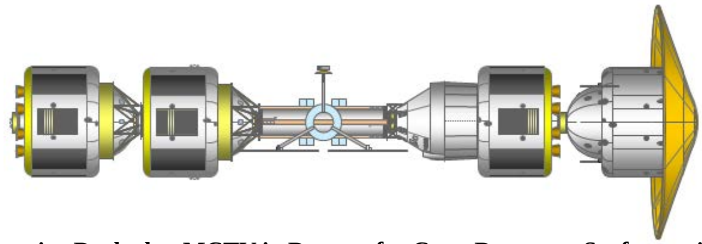


b. Mars EDL – Landers Undock from MCTV; Unmanned Cargo Landers Land before Crew Lands in MPL.

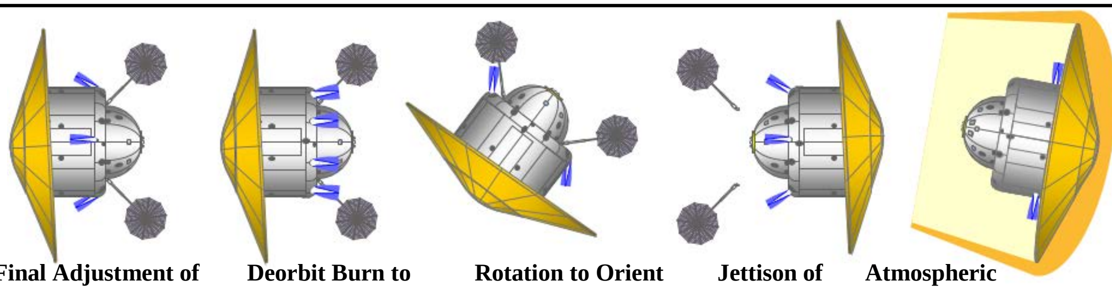


c. Mars EDL – After Unmanned Cargo Landers Land, MPL1 with 4-Person Crew Undocks from MCTV.

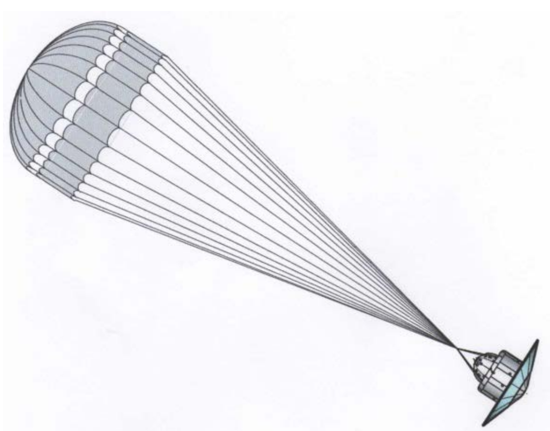
Figure 32. Mission Description – Mars Lander Entry, Descent, and Landing (EDL).



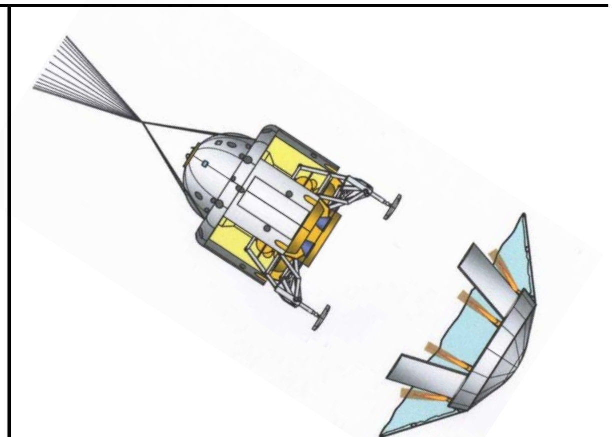
d. Mars EDL – MPL2 Remains Docked to MCTV in Reserve for Crew Rescue on Surface or in Orbit.



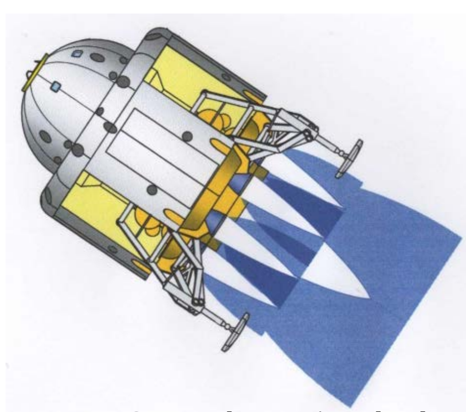
e. Mars EDL – Exoatmospheric Sequence of Events Starting from 500 km Parking Orbit.



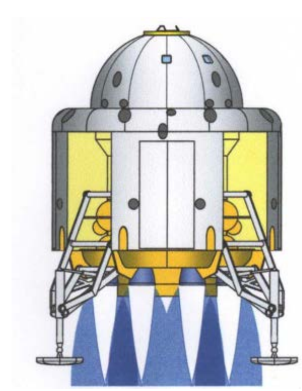
f. Mars EDL – Supersonic Disc-Gap-Band (DGB) Parachute Opens at M = 3.0 (Fully Open at M = 2.7).



g. Mars EDL – Heatshield and Landing Gear Doors Jettisoned at M = 0.76; Landing Legs Deployed.



h. Mars EDL – DGB Parachute Jettisoned and Engines Started for Powered Descent at M = 0.74.



i. Mars EDL – Central Engine Shutdown and Hover (up to 10 s) at h = 25 m; Soft Landing Performed.

Figure 32. Mission Description – Mars Lander Entry, Descent, and Landing, Continued.

Table 16. Lander Performance for Descent and Ascent.

Major Propulsive Burns	EDL - All Landers			Ascent - MPL		
	Deorbit Burn	Unpowered Descent	Powered Descent	Booster Ascent	250 km Orbit	Orbit Raising
Mass (kg)						
Lander Mass in Parking Orbit	21,532					
Solar Arrays Jettisoned	32					
Initial Mass, Start of Descent Transfer	21,500					
Main/RCS Propellant Consumed	867					
Final Mass, End of Descent Transfer	20,633					
Initial Mass, Entry Interface		20,633				
RCS Propellant Consumed		39				
Heatshield & LG Doors Jettisoned		955				
Primary & Redundant DGB Chutes Jettisoned		285				
Final Mass, End of Unpowered Descent		19,354				
Initial Mass, Powered Descent Initiation (PDI)			19,354			
Main Propellant Consumed			2,544			
Final Mass, End of Powered Descent (Landing)			16,810			
Initial Mass, Start of Booster Ascent				13,200		
Ascent Booster Propellant Consumed				9,950		
Final Mass, End of Booster Ascent				3,250		
Initial Mass, Start of Orbit Coast					3,250	
Spent Ascent Booster Jettisoned					1,200	
Final Mass, End of Orbit Coast					2,050	
Initial Mass, Start of Orbit Raising						2,050
Ascent Orbiter Propellant Consumed						231
Final Mass, End of Orbit Raising						1,819
Burn Parameters						
Burn Time (min.)	2.124	N/A	1.144	5.235	N/A	1.043
Total δV for Deorbit Burn [1] (m/s)	128					
Total δV for Unpowered Entry (m/s)		3,141				
Total δV for Powered Descent Burns [2] (m/s)			446			
Total δV for Booster Ascent Burns [3] (m/s)				4,340		
Total δV for Orbit Coast Phase (m/s)					0	
Total δV for Orbit Raising Burns [4] (m/s)						371
Initial Decel/Acceleration or T/W [5] ($g_{0\ Earth}$)	0.100	4.700	0.756	0.758	0.000	0.379
Final Decel/Acceleration or T/W [6] ($g_{0\ Earth}$)	0.104	3.300	0.539	3.078	0.000	0.427
Initial Decel/Acceleration or T/W [5] ($g_{0\ Mars}$)	0.264	12.403	2.000	2.000	0.000	1.000
Final Decel/Acceleration or T/W [6] ($g_{0\ Mars}$)	0.275	8.709	1.420	8.122	0.000	1.127

[1] Includes 29 m/s for maneuvers (orbit corrections) and losses and 2% Flight Performance Reserve (FPR).
[2] Includes 256 m/s for maneuvers (up to a 10 second hover) and losses and 2% FPR.
[3] Includes 826 m/s for maneuvers (up to 5.65 deg. plane change from max. $\pm$12.5-deg. incl.) and losses and 2% FPR.
[4] Includes 232 m/s for maneuvers (up to 3.1 deg. plane change; 50 m/s rendezvous & docking) and losses and 2% FPR.
[5] Peak ballistic deceleration in unpowered descent; [6] Peak parachute deceleration in unpowered descent.

3. Mars Surface Operations

Figure 33 shows a top view of the Mars base camp. Fig. 34 provides details of how the MCLs mate with each other and with the MPL on the surface. Table 17 provides a breakdown of consumables for the MSE mission, and includes allocations for cabin leakage, EVAs, and cycling of airlocks.[23] The MPL carries 80 man-days of onboard LSS consumables, enough for a 20-day contingency mission if a rendezvous with the MCLs is not possible. The two MCL-Hs each provide 560 man-days of LSS consumables, and the two MCL-Rs each provide 60 man-days for a 30-

day roving sortie for a two-person crew. MCL-R1 carries a deployable, 600 man-day consumables payload pallet designed to recharge each MCL-R for five additional 30-day sorties, for a total of 12 30-day roving sorties. MCL-R2 carries a deployable, compact nuclear fission-powered electric generator payload pallet. The total LSS consumables provide up to 16 months surface endurance for the four crew members. Four MCLs land first and traverse individually to a rendezvous point, awaiting arrival of the crew in the MPL. Ideally the MPL should land as close as possible to the MCL rendezvous point to minimize the distance the MPLs must traverse, but not close enough to

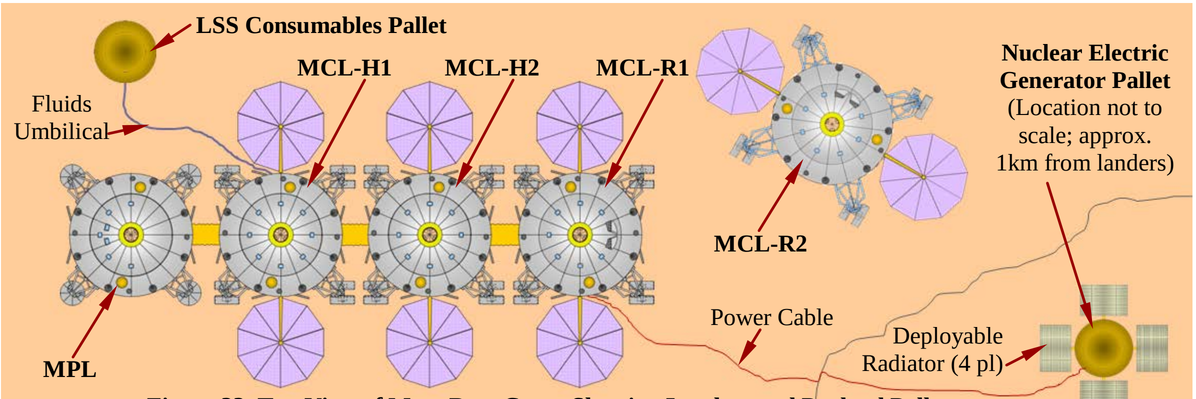


Figure 33. Top View of Mars Base Camp Showing Landers and Payload Pallets.

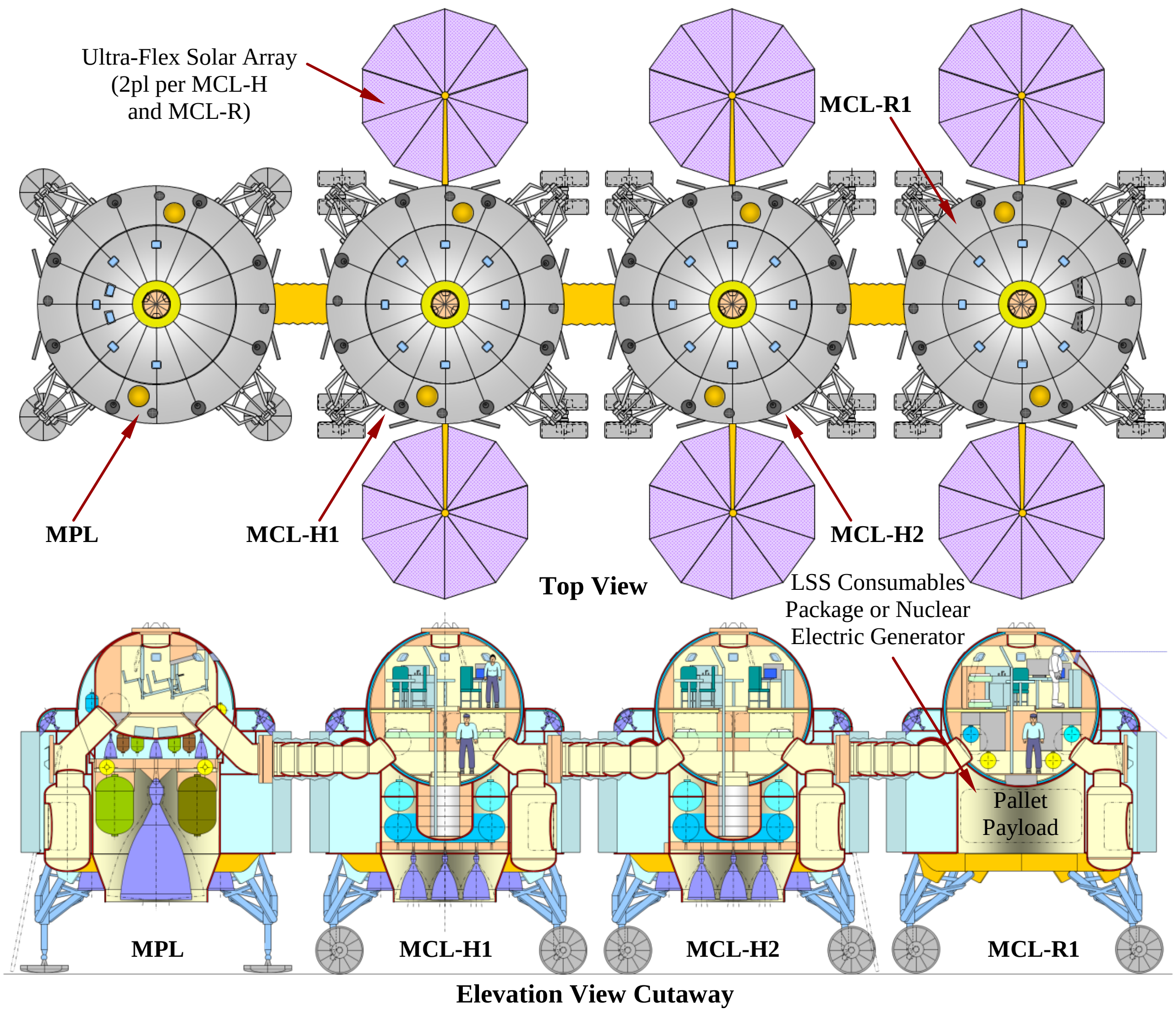


Figure 34. Mission Description, Mars Surface Operations – MPL Docked to (2) MCL-H and MCL-R1.

Table 17. Life Support Consumables Endurance for Mars Landers.

Consumables Location	MCL-H1	MCL-H2	MCL-R1		MCL-R2	MPL1[1]		Total
	Habitat Section	Habitat Section	Payload Pallet	Rover Cabin[2]	Rover Cabin[2]	Descent Section[3]	Ascent Orbiter[4]	on Surface
Duration (days)	280	280	300	30	30	20	2	480
Number of Crew	2	2	2	2	2	4	4	4
Endurance Man-days (m-days)	560	560	600	60	60	80	8	1920
Number of 30-Day Rover Sorties			10	1	1			12
Habitat and Crew Cabin Usage								
Non-EVA Man-Days	515	515	525	52.5	52.5	76	8	
O_2 Consump. Rate (kg/m-day)	0.850	0.850	0.850	0.850	0.850	0.850	0.850	
H_2O Consump. Rate (kg/m-day)[5]	8.325	8.325	4.250	4.250	4.250	5.310	3.500	
Food Consump. Rate (kg/m-day)	1.825	1.825	1.825	1.825	1.825	1.825	1.825	
Oxygen (kg, Non-EVA m-days)	438	438	0	45	45	83	7	
Water (kg, Non-EVA man-days)[6]	4,287	4,287	0	223	223	404	28	
Food (kg, Total man-days)	1,022	1,022	0	110	110	146	15	
EVA and Airlock Usage[7, 8, 9, 10]								
EVA Man-Days (2 crew per EVA)	45	45	75	7.5	7.5	4		
No. of EVAs per Mission or Sortie	90	90		15	15	8		
Number of EVAs per Day	0.20	0.20		0.50	0.50	0.50		
EVA O_2 Usage (kg)	113.4	113.4		18.9	18.9	10.1		
EVA H_2O Usage (no recovery) (kg)	576.0	576.0		96.0	96.0	51.2		
EVA N_2 Usage in EVAs (kg)	21.0	21.0		3.5	3.5	1.9		
Number of Airlock Cycles	270	270		45	45	24		
Airlock O_2 Losses (kg)	33.4	33.4		5.6	5.6	3.0		
Airlock N_2 Losses (kg)	117.0	117.0		19.5	19.5	10.4		
SDS Usage, Cabin Leakage[11, 12, 13]								
SDS O_2 Losses (kg)	1.87	1.87		1.87	1.87			
SDS N_2 Losses (kg)	6.56	6.56		6.56	6.56			
Cabin Leakage O_2 Losses (kg)	12.95	12.95		2.06	2.06	6.22	0.02	
Cabin Leakage N_2 Losses (kg)	45.34	45.34		7.21	7.21	21.79	0.08	
Total LSS Consumables (kg)								
Breathing Oxygen	599	599	730	73	73	83	7	2,157
Water	4,863	4,863	3,190	319	319	455	28	14,009
Food	1,022	1,022	1,095	110	110	146	15	3,505
Nitrogen	190	190	370	37	37	33	6	857
Total LSS Consumables	6,674	6,674	5,385	539	539	717	56	20,528

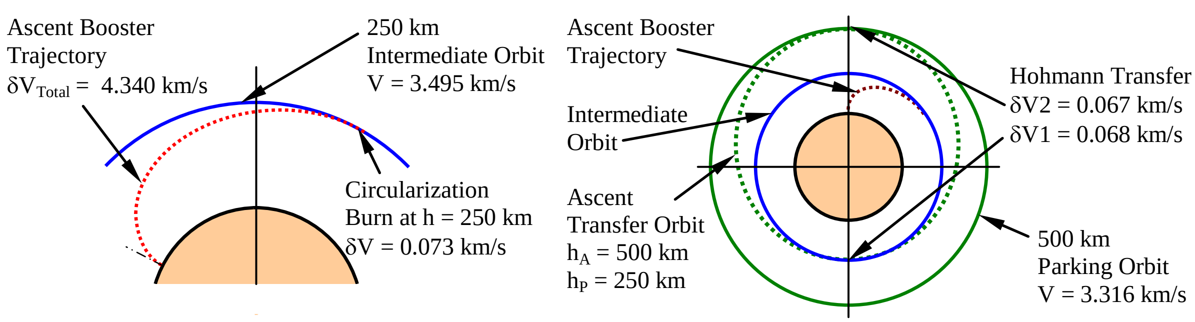
[1] MPL2 held in reserve and not included in surface endurance calculation. MPL2 has same consumables load as MPL1.
[2] Each MCL-R lands w/ initial consumables load of 60 man-days (1 sortie); MCL-R consumables recharged from pallet.
[3] MPL H_2O supplied by effluent of LH_2-LO_2 fuel cells located in Descent Section: 5.31 kg/m-day at max. power output.
[4] Ascent Orbiter consumables reserved for ascent & contingency and are not included in surface endurance calculations.
[5] MCL-H H_2O recovery rate = 0.85; No recovery on MCL-R/ MPL. [6] Incl. additional H_2O to fill MCL-H cabin shield.
[7] All EVAs performed by pair of crewmembers for safety; 6 hr (0.25 man-day)/EVA x 2 persons = 0.5 man-days/EVA.
[8] EVAs: per 450-day mission for MCL-H; per 30-day sortie per MCL-R; per 20-day contingency mission for MPL.
[9] EVA consumption rates (no recovery) (kg/person/6-hr EVA): O_2 = 0.630 kg, H_20 = 3.200, and N_2 = 0.117.
[10] Three airlock depress.-repress. cycles per 2-person EVA; 10% gas (0.465 m^3) lost on airlock cycling, based on ISS.
[11] 8 SDS depress-/repress. cycles w/10% gas loss (0.176 m^3) per cycle, per 450-day mission of MCL-H or MCL-R.
[12] Pressurized vol. (m^3) includes cabin, SDS, & airlock: MCL-H = 60.1, MCL-R = 57.3, MPL = 28.9 (24.2 AS only).
[13] Crew cabin air = 80% N_2, 20% O_2 by volume; ρ = 1.198 kg/m3. Crew cabin leak rate = 0.18%/ day, based on ISS.

Allow MPL descent engine exhausts to damage the MCLs during PD. A minimum separation of 200 meters should be adequate. Although the MCLs are able to traverse up to 1.0 km per day, the MPL must land within 20 km of MCLs to achieve a linkup before its Descent Section consumables run low. Dust storms or bad terrain could limit the distance that MCLs could traverse in 20 days. As a reasonable upper limit, the separation distance should not exceed 10 km. Accurate navigation during descent and landing is therefore required to achieve the full 450 day mission duration. Precision landing systems, including aerodynamic steering, active terrain sensing, and hi-fidelity powered descent steering and guidance systems are currently being developed for future unmanned Mars landers to enable landing accuracy within 10 km of a surface target. Figure 34 shows the MPL docked to two MCL-H and one MCL-R using the MCL surface docking system (SDS) to connect the vehicles. The SDS includes a tunnel with three degrees-of-freedom to compensate for reasonable variations in pitch, yaw, and elevation. Once the MPL is mated to the MCL-Hs, the four-person crew will move into the two MCL-Hs, each having a 5 cm thick shielding water jacket and 48.5m^3 of habitable volume (24.3m^3 of habitable volume per person, the same as the MCTV DSV1/DSV2). The MCL-R rover pressurized cabin also features 5 gm/cm^2 of water shielding to enable the crew to explore large areas of the surface in a pressurized, shielded habitat. Prior to the crew departing the surface in the MPL Ascent Section, the MCLs are undocked and driven a safe distance away from the MPL to prevent engine exhaust from blasting off MCL parts which could strike/damage the MPL. Additional MSE mission operations will be detailed in future work.

4. Crew Return from Surface to Parking Orbit

Figures 35a-b and 36a-g describe the MPL return flight. The MPL ascent trajectory returns the crew from the surface to a 250 km intermediate orbit shown in Fig. 35a, from launch latitudes between 0.0 and $\pm$12.5 degrees. During a nominal ascent (or abort to orbit during powered descent), the MPL ascent section (AS) is launched from the Descent Section (DS). Explosive bolts separate the AS from the DS and the AS rises rapidly at a T/W of 2.0 as shown in Figs. 36a and b. The AS Booster δV of 4340 m/s includes a small 73 m/s burn to circularize the orbit, an allocation of 338 m/s for a 5.65 degree plane change 2% Flight Performance Reserve on δV. The Ascent Booster, with a simple, reliable, single pressure-fed engine, places the MPL ascent section into the low but stable intermediate circular orbit of 250 km altitude, where the crew could be rescued by the rescue MPL in the event of a failure of the Ascent Orbiter propulsion system. The MPL Ascent Booster has sufficient performance for SSTO to the 500 km parking orbit if only small plane changes were required. After achieving orbit, the Ascent Booster is jettisoned as shown in Fig. 36c. Later, the Ascent Booster will reenter due to gradual atmospheric drag and burn up.

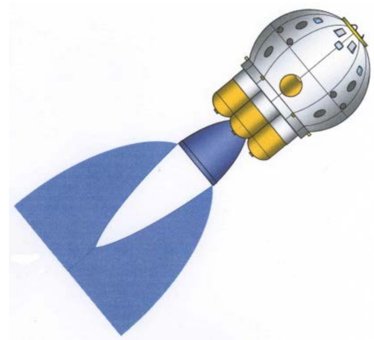
The AS Orbiter will coast in the 250 km orbit to set up proper initial parameters for the orbit raising maneuver to rendezvous with the MCTV in the 500 km parking orbit. The crew uses the Ascent Orbiter's propulsion system to raise its orbit to the 500 km circular parking orbit using a Hohmann transfer as shown in Figs. 35b and 36d. Ascent Orbiter δV includes 135 m/s for the Hohmann Transfer plus allocations of 178 m/s for a 3.1 degree plane change during orbit raising, 50 m/s for rendezvous and docking, and 2% Flight Performance Reserve on δV for a total of 371 m/s. The crew uses the Ascent Orbiter's RCS thrusters to rendezvous and dock with MCTV as shown in Figs. 36e-f. The crew transfers the Mars samples and themselves into the MCTV, and jettisons the Ascent Orbiter and rescue MPL (MPL2), along with the two LDA2s into the parking orbit as shown in Fig. 36g. MPL2 will subsequently dock with the MPL1 Ascent Orbiter and use its RCS thrusters to provide adequate separation from the MCTV. MPL2, with attached MPL1 Ascent Orbiter, will deorbit itself using its deorbit thrusters and be disposed of by burning up during reentry in Mars' atmosphere. MPL ascent flight performance data are summarized in Columns 5, 6, and 7 of Table 16. Detailed MPL ascent data and trajectory simulation results are shown in Reference 10.



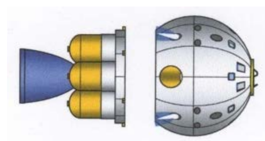
a. Ascent from Surface to Intermediate Orbit **b. Orbit Raising from Intermediate Orbit to Parking Orbit**

Figure 35. MPL Ascent Mission Profile from Mars Surface to the 500 km Parking Orbit.

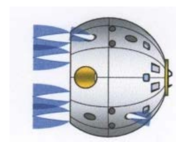
a. Return to Parking Orbit – MPL Two-Stage Ascent Section (AS) Launches from Descent Section.



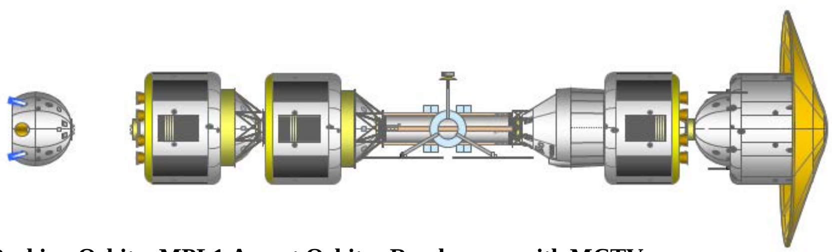
b. Return to Parking Orbit – AS Ascends to 250 km Intermediate Orbit using Ascent Booster Propellant.



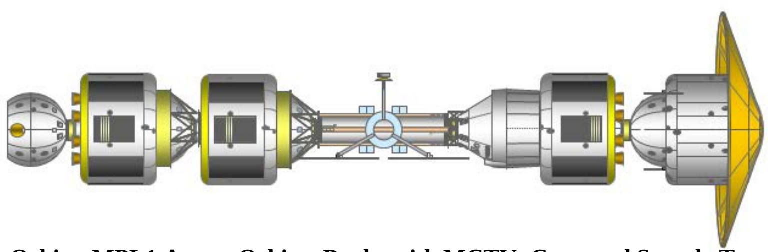
c. Return to Parking Orbit – MPL Spent Ascent Booster Jettisoned in Intermediate Orbit.



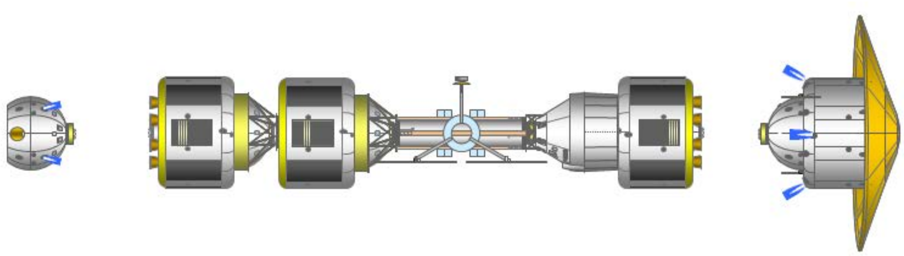
d. Return to Parking Orbit – MPL Ascent Orbiter Ascends to Parking Orbit using Hohmann Transfer.



e. Return to Parking Orbit – MPL1 Ascent Orbiter Rendezvous with MCTV.



f. Return to Parking Orbit – MPL1 Ascent Orbiter Docks with MCTV; Crew and Sample Transfer to MCTV.



g. Return to Parking Orbit – MPL1 Ascent Orbiter and MPL2 Undock and Maneuver into Parking Orbit for Later Deorbit and Disposal with Attached LDAs; Conclusion of Mars Surface Exploration Phase.

Figure 36. Mission Description – Mars Lander Ascent to Orbit and Conclusion of Surface Exploration Phase.

5. The Second, Reserve MPL (MPL2) Provides Options for Abort and Rescue

Providing a second crew lander (MPL2) will enhance mission safety and reliability: it would permit two landing mission attempts, enabling an exploration landing mission to still occur in the event of an ATO during the first crew landing attempt. Having the reserve MPL docked to the MPCV in orbit also enables this lander to be used to rescue the landing party if it became stranded on the surface or in the 250km intermediate orbit due to a casualty to MPL1.

E. Return to Earth from Mars Parking Orbit

Figures 37 and 38a-s describe the return of the MCTV to Earth from the Mars parking orbit. Figures 38a-f show preparations for TEI: LMO AG rotation is terminated, AG rails retract to minimum, and MPCV and DSV2 dock to the AGM. DSV1 undocks from DSV2 and DSV2 Propulsion Section (PS), containing excess consumables and solid waste, is jettisoned. DSV1 then re-docks to the DSV2 Habitat Section (HS). Figures 38g-l show the TEI sequence, which uses three sequential burns to provide sufficient δV. TEI burn A uses the DSV1 PS propulsion system. This burn puts the MCTV in a highly elliptical escape orbit as shown in Figs. 37 and 38g-i. TEI burn B is performed by DSV3, and TEI burn C is performed by the MPCV, both at periapsis of the escape orbit as shown in Figs. 37 and 38j-l. At this point the MCTV is in the ITO. The four-person crew will continue to have 24.3m^3 of habitable volume per person during ITO using the combined habitation volume of DSV1 HS and DSV2 HS. The MCTV will be spun up for AG operations as shown in Fig. 38m, using the same procedure described in Section VI.B, above for OTO, at a nominal 3.525 RPM to provide 0.379 Earth g's (Mars surface equivalent) at the DSV2 mid-level. The MCTV will be spun-down for up to three inbound course correction (ICC) burns and re-spun up after the conclusion of the burns. A total of four spin-up/spin-down cycles have been allocated for ITO. The MPCV will perform all ITO ICC burns. Sufficient RCS propellant mass (789 kg) has been reserved in MPCV SM propellant tanks for this purpose.

Figure 38n shows the MCTV approaching Earth. The vehicle has passed within the 924,133 km radius of the Earth's activity sphere, where the Earth's gravitational influence exceeds that of the Sun. The crew is now less than 48 hours from Earth arrival. The MCTV is spun-down to 0 RPM, AG rails fully retract, and the DSV2 and MPCV dock to the AGM. The crew departs DSV1/DSV2, transferring Mars samples into the MPCV, and prepares for return to Earth in the MPCV. Latches on the MPCV AG rail-to-vehicle interface unlock and disengage from the six MPCV Launch Abort System hardpoints. The MPCV undocks and separates from the AGM/DSV2/DSV1 stack as shown in Fig. 38o. This occurs at a radius of approximately 800,000 km, when the MPCV is approximately 36 hours away from the entry interface point (Earth periapsis altitude of 125 km). The MPCV adjusts its trajectory by performing Entry Corridor Control (ECC) burns with its primary axial thrusters, and main engine if needed, as shown in Fig. 38p. The MPCV Service Module (SM) is jettisoned just before the MPCV reaches the entry interface point as shown in Fig. 38q, and the SM will burn up in the atmosphere. The MPCV performs a hyperbolic direct entry as shown in Fig. 38r, using the Earth's atmosphere to decelerate. The MPCV is recovered using parachutes in an ocean landing as shown in Fig 38s, and the crew and MPCV are recovered by naval assets. The bulk of the AGM/DSV1/DSV2 stack will also burn up in the atmosphere, with its entry targeted at an area of open ocean to avoid debris landing in populated areas. This is the conclusion of the Mars exploration mission, however it is assumed that the crew and Mars samples will be quarantined as was done for the Apollo 11, 12, and 14 Moon landing missions. Table 18 provides a summary of MCTV flight performance data for the TEI and ECC burns.

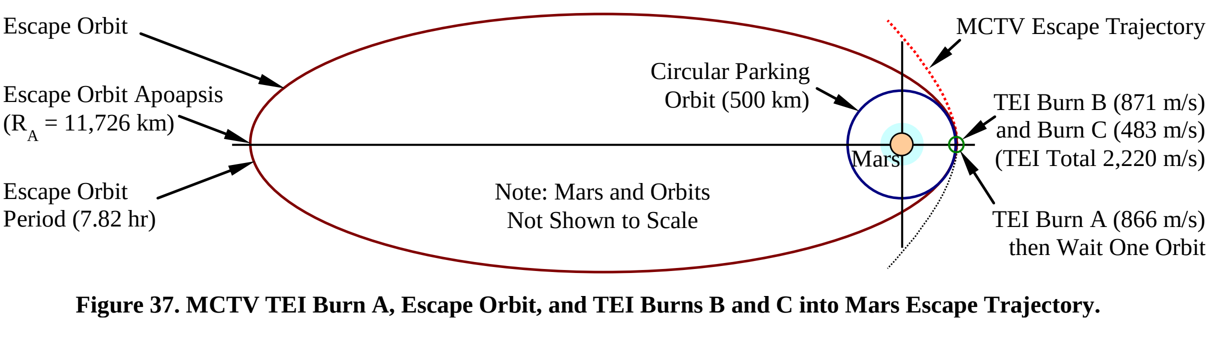
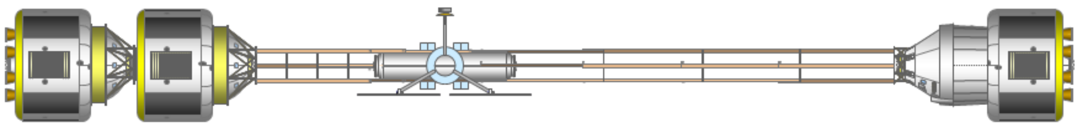


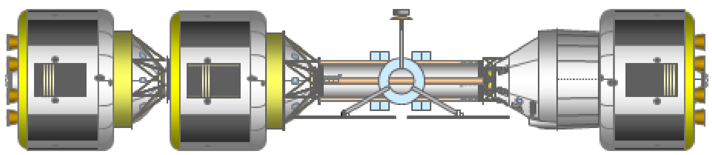
Figure 37. MCTV TEI Burn A, Escape Orbit, and TEI Burns B and C into Mars Escape Trajectory.

F. Return to Earth From Mars Parking Orbit – TEI Abort

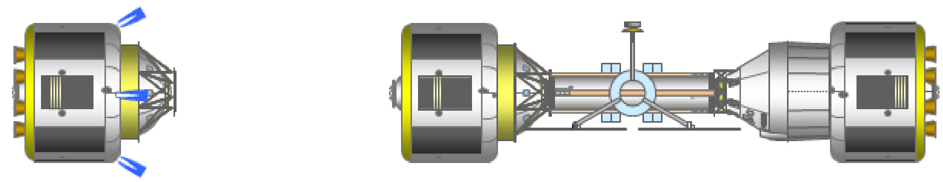
Figure 39 and Table 19 show the design and performance of the ITO Contingency Configuration which consists of the MPCV and DSV1. This configuration would require that the crew spend the entire ITO in zero-g and in half the shielded volume of the nominal DSV1/DSV2 combination, but is viable for a TMI casualty or propulsion deficit.



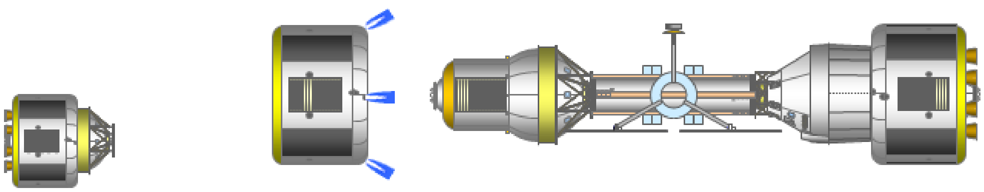
a. Mars Departure – Post Mars Surface Exploration AG Operations; Crew Awaits TEI Launch Window.



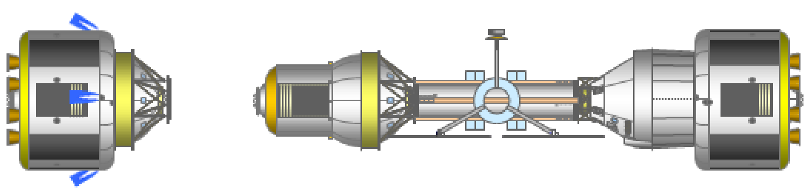
b. Mars Departure – AG Rails Retract to Minimum Position.



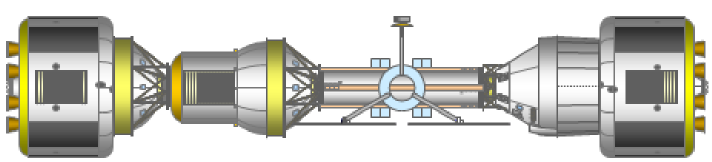
c. Mars Departure – DSV1 Undocks From DSV2 to Allow Jettison of DSV2 Propulsion/Consumables Section.



d. Mars Departure – DSV2 Propulsion/Consumables Section Jettisoned (Includes Excess Food and Waste).

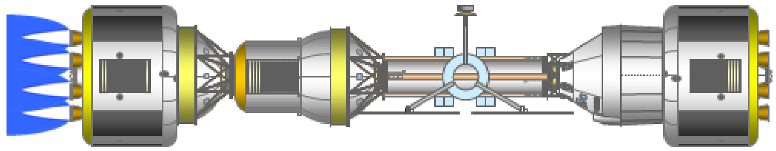


e. Mars Departure – DSV1 Aligns to Re-Dock to DSV2 Aft Port.

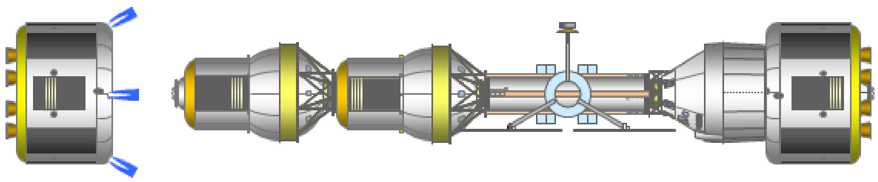


f. Mars Departure – DSV1 Re-Docks to DSV2 Aft Port; Crew Prepares for TEI Burn A.

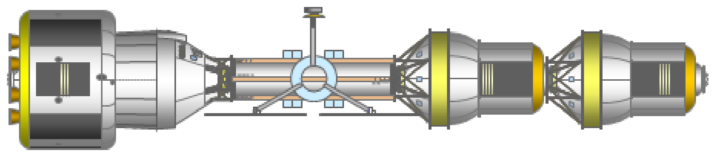
Figure 38. Mission Description – MCTV Return from Mars Parking Orbit to Earth.



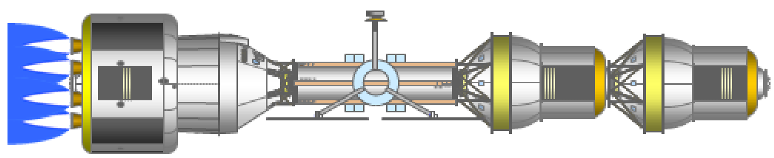
g. Mars Departure – DSV1 Performs Trans-Earth Injection (TEI) Burn A.



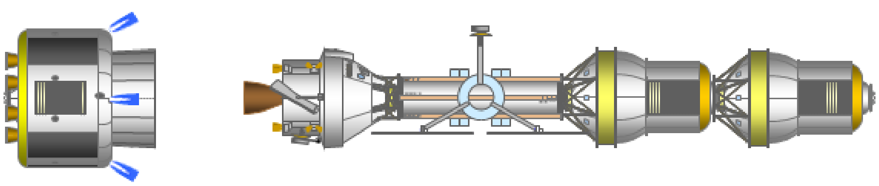
h. Mars Departure – Spent DSV1 Propulsion Section Jettisoned; MCTV now in Elliptical Escape Orbit.



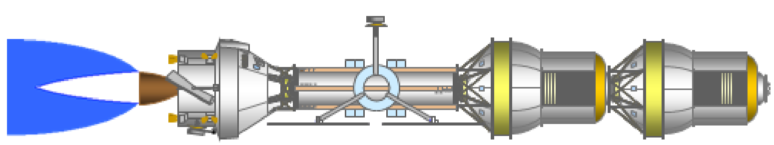
i. Mars Departure – MCTV in Escape Orbit; Vehicle Rotated 180 Degrees; Crew Awaits TEI Burn B.



j. Mars Departure – MCTV in Escape Orbit; DSV3 Performs TEI Burn B.

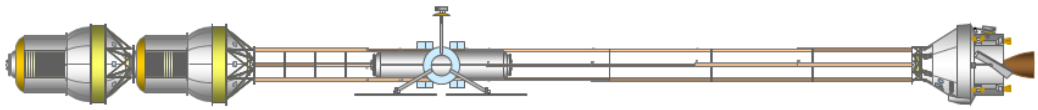


k. Mars Departure – MCTV in Escape Orbit; Spent DSV3 and MPCV-DSV3 Docking Adaptor (MDA) Jettisoned.

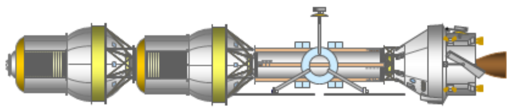


l. Mars Departure – MCTV in Escape Orbit; MPCV Performs TEI Burn C.

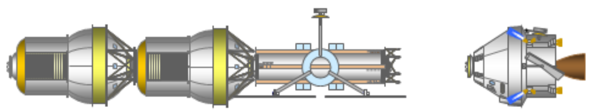
Figure 38. Mission Description – MCTV Return from Mars Parking Orbit to Earth, Continued.



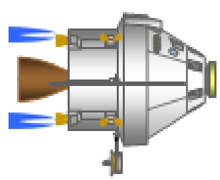
m. Inbound Transit – AG Rails Extend for MCTV AG Operations.



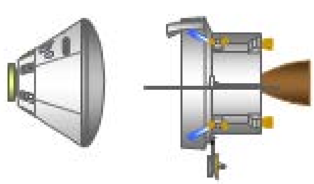
n. Earth Return : Spin-Down to 0 RPM; AG Rails Retract Fully; Crew & Samples Transferred to MPCV.



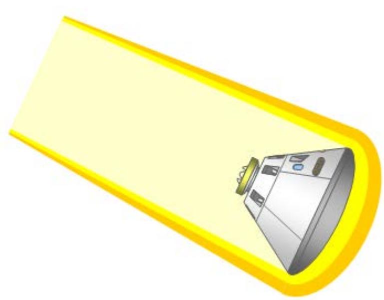
o. Earth Return: Crew Departs in MPCV. MCTV Components DSV1, DSV2, and AGM Jettisoned.



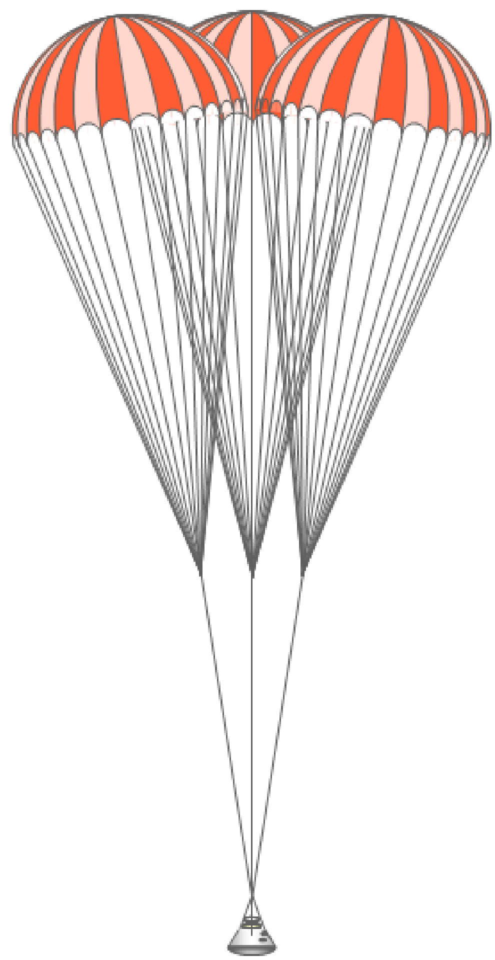
p. Earth Return: MPCV Entry Corridor Control Burn.



q. Earth Return: MPCV Service Module Jettisoned.



r. Earth Return: MPCV Crew Module Direct Entry.



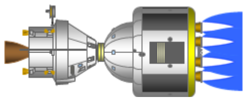
s. Earth Return: Crew Module Parachute Recovery.

Figure 38. Mission Description – MCTV Return from Mars Parking Orbit to Earth, Continued.

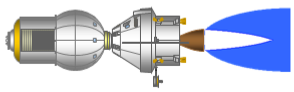
Table 18. MCTV Performance for TEI and Entry Corridor Control (ECC) Burns.

MCTV Mass (kg)	TEI Burn A	TEI Burn B	TEI Burn C	ECC Burn	Final
DSV1					
HS Payload [1, 2]	4038	4038	4038		
HS Inert Mass	2,520	2,520	2,520		
HS LSS Consumables	6,830	6,830	6,830		
Habitat Stage Subtotal	13,388	13,388	13,388		
PS Payload (Airlock, 2x LDA1)	900				
PS Inert Mass	2,624				
Usable RCS Propellant Mass [3]	50				
PS Operating Empty Mass	3,574				
Usable Main Propellant Mass [3]	21,800				
Propulsion Stage Subtotal	25,374	Jettisoned			
DSV1 Total Mass	38,762	13,388	13,388	Jettisoned	
DSV2					
Crew Habitat (HS) Total	9,589	9,589	9,589		
Propulsion Stage (PS) Total	Jettisoned				
DSV2 Total Mass	9,589	9,589	9,589	Jettisoned	
AGM					
AGM Total Mass	2,290	2,290	2,290	Jettisoned	
MPCV					
Payload Mass [2]	0	0	0	680	680
MPCV Inert Mass	13,475	13,475	13,475	13,475	13,475
MPCV Operating Empty Mass	13,475	13,475	13,475	14,155	14,155
MPCV Usable Propellant Mass [3]	7,907	7,907	7,907	349	0
MPCV Total Mass	21,382	21,382	21,382	14,504	14,155
MDA					
MDA Mass	441	441	Jettisoned		
DSV3					
Inert Mass	2,320	2,320			
Usable RCS Propellant Mass [3]	50	0			
Operating Empty Mass	2,370	2,320			
Usable Main Propellant Mass [3]	15,706	15,706			
DSV3 Total Mass	18,076	18,026	Jettisoned		
LDS					
LDS Mass	250	250	Jettisoned		
Total Vehicle					
MCTV Stack Initial Mass	90,790	65,366	46,649	14,504	
Propellant Mass Consumed	21,800	15,706	6,770	349	
MCTV Stack Final Mass	68,990	49,660	39,879	14,155	14,155
Burn Parameters					
Burn Time (min.)	10.74	7.74	10.81	0.56	
Burn Net δV (m/s)	866	871	483		
Total δV TEI [4, 5]			2,220		
Total δV ECC [4, 6]				78	
Initial Acceleration (m/s^2)	1.195	1.660	0.716	2.303	
Initial Acceleration (T/W) (g_{0Earth})	0.122	0.169	0.073	0.235	
Final Acceleration (m/s^2)	1.573	2.185	0.837	2.359	
Final Acceleration (T/W) (g_{0Earth})	0.160	0.223	0.085	0.240	

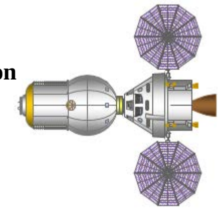
[1] Includes Solid Biological Shielding; [2] (4) Crew w/ Spacesuits & ELSS, and 20 kg of Return Samples; [3] Usable propellant masses exclude residuals. [4] Includes 2% Flight Performance Reserve. [5] Includes 25 m/s for ITO course correction burns. [6] ECC Burn includes 50 m/s for main burn and 25 m/s Mission Reserve, plus 2% FPR = 77 m/s.



a. **TEI Abort Burn A using DSV1 Propulsion System.**



b. TEI Abort Burn B using MPCV Propulsion System



c. ITO Contingency Configuration (Zero-g): DSV1 HS and MPCV.

Figure 39. TEI Abort, ITO Contingency Configuration

Table 19. TEI Abort Performance, MPCV/DSV1 stack.

Mass (kg)	Abort Burn A - DSV1	Abort Burn B - MPCV	Total Abort δV	Req'd δV	Excess δV
MPCV	21,382	21,382			
DSV1	38,762	13,388			
Stack Initial Mass	**60,144**	**34,770**			
Available Propellant	21,800	7,907			
Consumed Propellant	21,800	7,559			
Remaining Propellant	0	349			
Stack Final Mass	**38,344**	**27,211**			
Velocity Change (m/s)					
δv_{ABORT}	**1,441**	**784**	**2,225**	**2,219**	**7**

VII. Key Enabling Technologies

Key enabling technologies needed for human exploration of Mars are shown in Table 20. The 2033 opportunity is less than 18 years away. Development must start very soon to ensure these key technologies are ready in time.

Table 20. Continued Development of Key Advanced Technologies Needed to Enable Human Exploration of Mars.

Transfer Vehicle Assembly	130t lift capable SLS to inject large (130t, 33m L x 7.5m D) payloads into LEO while minimizing no. of launches.
	Autonomous station-keeping, rendezvous, and docking of subassemblies to assemble MLTV and MCTV in LEO.
	Capability to assemble three CPS into a cluster of sufficient mass for MCTV TMI (TMI Booster Assembly).
DSV	Sufficient habitation volume and radiation shielding to support human long-duration (30 mo.) deep space missions.
	Large internal storage capability for OTO, LMO, and ITO LSS consumables and TEI δV propellant.
	Centrifugal artificial gravity to prevent deterioration of human tissues due to prolonged exposure to zero-g.
CPS	Enabling high δVs for TMI and MOI in a compact package, while minimizing overall IMLEO of MLTV/ MCTV.
	Very low LH_2 /zero LO_2 boiloff, enabling Mars missions with reasonable durations for LEO assembly and OTO.
	BRVs for CPS LH_2 top-off to compensate for boiloff, maximize performance, and relax launch intervals.
Landers	Lightweight, inflatable, ablative heatshields to enable heavy landers w/ low ballistic coefficients (e.g. MPL/MCL).
	Large (up to 30m dia.) supersonic DGB parachutes to enable landers in the 21t mass range (e.g. MPL and MCL).
	Precision landing systems to permit landers to land in proximity to/rendezvous with pre-positioned surface assets.
MCTV	Upgrade to heat shield/ TPS for higher heat loads encountered during a direct Earth entry from Mars transfer orbit.
Life Support Systems	Highly reliable, lightweight, and durable regenerative LSS equipment to minimize consumables mass and IMLEO.
	Low-loss cryogenic LSS consumables storage (supercritical LO_2 and LH_2) for long-duration (30 mo.) missions.
	Passive radiation protection, including use of consumables for shielding and “dual-mode” composite structures.
Mars Surface Equipment	Compact, high power nuclear reactor-powered electric generators to provide primary power for human habitation, exploration activities, and collection and processing machinery for in-situ resource utilization (ISRU).
	Robust equipment including space suits, rovers, power systems, communications gear, and scientific equipment.
	ISRU equipment to significantly reduce consumables mass needed to be transported from Earth to Mars.

VIII. Conclusion

The MEV architecture is a conceptual design for landing humans on Mars using chemical propulsion, existing or near-term technology, and common modular elements to minimize development cost and risk. It provides key features needed to keep a four person crew healthy and safe during a 30 month mission: sufficient habitation volume (24.3 m^3/person), artificial gravity (0.379 Earth g’s - Mars surface equivalent) to prevent deterioration of the human body caused by prolonged exposure to zero-g, and sufficient passive biological radiation shielding (10 gm/cm^2) surrounding habitation spaces to shield the crew from cosmic and solar radiation and prevent radiation sickness. The MEV architecture utilizes lander aerobraking at Mars to minimize IMLEO and the number of assembly launches and associated launch costs. Commonality was stressed in the designs of landers, DSVs, and CPS to minimize unique designs, maximize design reuse, and reduce developmental cost and risk. Other common features include standard launch stacking and fairings. The design philosophy and operations concepts stress safety, reliability, and redundancy and feature: simple docking for LEO assembly; redundant engines and subsystems; abort modes during TMI, lander descent/ascent, and TEI; and use of dual crew landers to enhance crew safety and mission redundancy, providing a capability for crew rescue from the surface of Mars or from Mars orbit. With inherent modularity, the MEV architecture could enable an economical “flexible path" approach to retire risk and achieve progressively more ambitious “stepping stone” human solar system exploration missions: starting with flights in Earth and lunar orbit, then missions to NEO asteroids and moons of Mars, and ultimately the Mars surface exploration mission (Fig. 40).

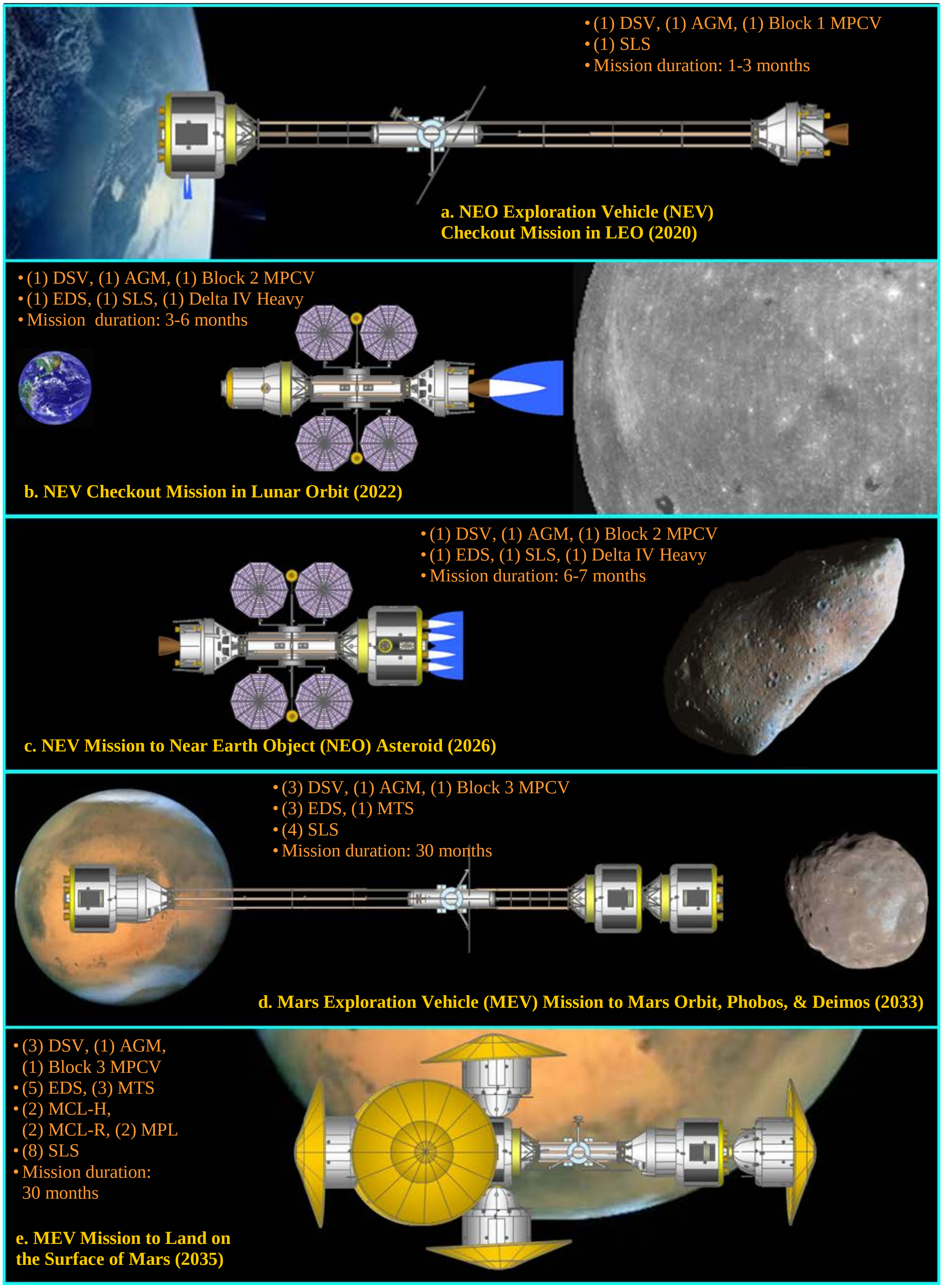


Figure 40. Flexible Path Missions Enabled by the Modular Mars Exploration Vehicle (MEV) Architecture.

References

[1] Benton, Sr., M. G., Kutter, B., Bamford, R.A, Bingham, R., Todd, T., and Stafford-Allen, R., "Modular Space Vehicle Architecture for Human Exploration of Mars using Artificial Gravity and Mini-Magnetosphere Crew Radiation Shield," AIAA-2012-0633, 50th AIAA Aerospace Sciences Meeting and Aerospace Exposition, Nashville, Tennessee (2012).

[2] Benton, Sr., M. G., Kutter, B., Bamford, R.A, Bingham, R., Todd, T., and Stafford-Allen, R., "Mars Exploration Vehicle (MEV) Architecture for Human Exploration of Mars, with Artificial Gravity and Mini-Magnetosphere Crew Radiation Shield," GLEX-2012.08.2.8x12759, IAF/AIAA 2012 Global Space Exploration Conference, Washington, DC (2012).

[3] Benton, Sr., M.G., "Conceptual Space Vehicle Architecture for Human Exploration of Mars, with Artificial Gravity and Mini-Magnetosphere Crew Radiation Shield," AIAA-2012-5114, AIAA SPACE 2012 Conference and Exposition, Pasadena, CA (2012).

[4] Benton, Sr., M. G., "Conceptual Space Vehicle Architecture utilizing Common Modular Elements for Near-Term Human Exploration of Mars," AIAA-2014-4239, AIAA Space 2014 Conference, San Diego, CA (2014).

[5] Benton, Sr., M. G., Bamford, R.A, Bingham, R., Todd, T., Silva, L., and Alves, P., "Concept for Human Exploration of NEO Asteroids using MPCV, Deep Space Vehicle, Artificial Gravity Module, and Mini-Magnetosphere Radiation Shield," AIAA-2011-7138, 44th AIAA SPACE 2011 Conference & Exposition, Long Beach, California (2011).

[6] Bamford, R., et al., "The interaction of a flowing plasma with a dipole magnetic field: measurements and modeling of a diamagnetic cavity relevant to spacecraft protection," Plasma Physics and Controlled Fusion, Vol. 50, 12, 124025, Dec. 2008.

[7] Hopkins, J. B., Pratt, W. D., "Comparison of Deimos and Phobos as Destinations for Human Exploration and Identification of Preferred Landing Sites," AIAA 2011-7140, 44th AIAA SPACE 2011 Conference & Exposition, Long Beach, CA (2011).

[8] Woodcock, Gordon, "Designing an Enduring Mars Campaign," AIAA-2011-7214, 44th AIAA SPACE 2011 Conference & Exposition, Long Beach, California (2011).

[9] Benton, Sr., M. G., "Spaceship Discovery – NTR Vehicle Architecture for Human Exploration of the Solar System," AIAA-2009-5309, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Denver, Colorado (2009).

[10] Benton, Sr., M. G., "Crew and Cargo Landers for Human Exploration of Mars - Vehicle System Design," AIAA-2008-5156, 44th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Hartford, Connecticut (2008).

[11] Benton, Sr., M. G., "Crew Exploration Lander for Ganymede, Callisto, and Earth's Moon - Vehicle System Design," AIAA-2009-5179, 45th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Denver, Colorado (2009).

[12] Benton, Sr., M. G., "Conceptual Design of Crew Exploration Lander for Asteroid Ceres and Saturn Moons Rhea and Iapetus," AIAA-2010-0795, 48th AIAA Aerospace Sciences Meeting, Orlando, Florida (2010).

[13] Benton, Sr., M. G., "Conceptual Common Modular Design for Crew and Cargo Landers and Deep Space Vehicles for Human Exploration of the Solar System," AIAA-2013-5355, AIAA Space 2013 Conference, San Diego, CA (2013).

[14] De Angelis, G., Clowdsley, M.S., Nealy, J.E., Singleterry, R.C., Tripathy, R.K., Wilson, J.W., "Radiation Shielding Analysis for Deep Space Missions," in proceedings of Space Technology and Applications International Forum (STAIF-2003) CP 0-7354-0114-4, edited by M. El-Genk, American Institute of Physics, New York, pp. 979-980 (2003).

[15] Cucinotta, F.A, Schimmerling, W., Wilson, J.W., Peterson, L.E., Badhwar, G.D., Saganti, P.B., and Dicello, J.F, "Space Radiation Cancer Risk Projections for Exploration Missions: Uncertainty Reduction and Mitigation," NASA Johnson Space Center Report, JSC-29295 (2001).

[16] Kutter, Bernard "Settled Cryogenic Propellant Transfer", AIAA 2006-4436, http://www.ulalaunch.com/site/docs/publications/SettledCryogenicPropellantTransfer.pdf

[17] Kutter, Bernard "Ongoing Launch Vehicle Innovation at United Launch Alliance", IEEE 2010-1020, http://www.ulalaunch.com/site/docs/publications/ULA-Innovation-March-2010.pdf

[18] Taylor, W.J., Chato, D.J.; "Comparing the Results of an Analytical Model of the No-Vent Fill Process with No-Vent Fill Test Results for a 4.96 m3 Tank", AIAA-1992-3078 (1992).

[19] Smith, J. C., and Bell, J. L., "2001 Mars Odyssey Aerobraking," AIAA 2002-4532, AIAA/AAS Astrodynamics Specialist Conference and Exhibit, August 2002, Monterey, California (2002).

[20] Gladden, R. E., "Mars Reconnaissance Orbiter: Aerobraking Sequencing Operations and Lessons Learned," SpaceOps 2008 Conference (Hosted and organized by ESA and EUMETSAT in association with AIAA), AIAA 2008-3353.

[21] Johnston, M. D., Esposito, P. B., Alwar, V., Demcak, S. W., Graat, E. J., and Mase, R. A., "Mars Global Surveyor Aerobraking At Mars," AAS 98-112 (1998).

[22] Mottinger, B., "Aerobraking: Mars Global Surveyor and Further Analysis of Aerobraking Options," ASEN 5050 Space flight Dynamics Course, Fall 2000 (online reference).
URL http://ccar.colorado.edu/asen5050/projects/projects_2000/mottinger/ [cited 8/12/2011].

[23] Jones, H., "Design Rules for Life Support Systems," 33rd International Conference on Environmental Systems (ICES), ICES40, Advanced Life Support and Systems Analysis I, Society of Automotive Engineers, SAE-2003-01-2356 (2003).