PROPULSIVE AND LOGISTICAL FEASIBILTY OF ALTERNATIVE FUTURE HUMAN-ROBOTIC MARS EXPLORATION ARCHITECTURES

by

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B.Sc. Mechanical Engineering Co-operative
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Submitted to the Department of Aeronautics and Astronautics
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ABSTRACT

This thesis extends the work on a shared human and robotic mission to the Martian system presented at the Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) 2010 competition by a team of MIT graduate students. Particular attention is paid to the transportation infrastructure and its ability to support the human and robotic mission from a logistics and supply chain standpoint.

The original human and robotic mission was analyzed along with several variants including the use of Advanced Chemical Propulsion instead of Nuclear Thermal Rockets and the decomposition of the original mission into several that could, in the spirit of the Flexible Path, form the final steps on the way to a human landing on Mars. Comparison of selected figures of merit, such as the mass required in Low-Earth Orbit, number of sites explored, and crew-exploration days, gives mission designers a means to begin down-selecting mission concepts at this early phase and focus analysis efforts on the most promising concepts.

In general, compared to NASA's Human Exploration of Mars Design Reference Architecture 5.0, the human and robotic mission concept requires 16% less mass in Low-Earth Orbit, is less complex, and explores six areas as opposed to a single locale. Further, mission variants, including one that hypothesizes a progression of Mars missions on the Flexible Path, are feasible and offer a flexible and modular way of progressively exploring the Martian system with the ultimate goal of landing humans on the surface of Mars.

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A big thank you goes to my friends, those that I made in Edmonton, at MIT, and across the globe, for empathizing, commiserating, celebrating, and lining up at the fire hose with me. A final thank you goes to Jia, Nelson, Dorian, Yves, and Anthony, who never cease to keep me grounded, entertain my whimsy, and make me smile.

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1 Introduction

1.1 *The Ultimate Goal: Humans on the Surface of Mars*

The year in which this thesis has been written, 2011, is of particular, if somewhat dubious, interest to the pioneers of aeronautics and astronautics. It bookends a period of unprecedented growth in humans in aerospace followed by an anticlimactic denouement.

In 1927, eighty-four years prior, Charles Augustus Lindbergh, completed his historic solo non-stop flight across the Atlantic Ocean from New York to Paris. An international hero, his flight inspired a generation of engineers, aviators, and dreamers to push the envelope of aeronautics, carving out a place in the skies for humankind.

Moving ahead to 1969, forty-two years after the flight of the "Spirit of St. Louis," the human race experienced another "giant leap." Neil Armstrong, accompanied by Edwin "Buzz" Aldrin, landed and walked on Earth's largest natural satellite with their crewmate Michael Collins orbiting overhead. In the forty-two years after Lindbergh's flight, humans had come from flying across the Atlantic Ocean from North America to Europe to flying across the cosmic ocean from the Earth to the moon and returning safely.

Now, move ahead another forty-two years to 2011. Soon after Apollo 11, a study chaired by then-vice-president Spiro Agnew was conducted to investigate a human landing on Mars that ultimately lost its momentum (Augustine et al., 2009). A variety of other human Martian exploration proposals have been made in the intervening years (Boston, 1984; Zubrin and Baker, 1992; Zubrin and Wager, 1997; National Aeronautics and Space Administration [NASA], 2004; NASA Mars Architecture Steering Group [NASA], 2009), none of which resulted in much more than paper designs. The painful reality is that, in terms of human space exploration, the forty-two years after Apollo 11 were far less moving than the forty-two years before.

That is not to say that we have experienced an extraterrestrial vacuum since Apollo 11. Achievements of human ingenuity such as the space stations Skylab, Mir, and International Space Station (ISS), the multitude of robotic explorers sent to investigate extraterrestrial surfaces, and the creation of an interstellar ensemble of observers and probes from the Hubble Space Telescope to the Voyager 1 spacecraft attest to the continued advancement of the space science and robotic space exploration efforts.

Notwithstanding recent successes, one cannot help but think that *human* space *exploration* beyond low-Earth orbit (LEO) has stalled. There is little debate that for a human landing within the inner solar system, Mars is the location of most scientific, practical, and colonial interest (Mars Exploration Program Analysis Group [MEPAG], 2008; Augustine et. al., 2009). Yet, it has yet to be explored and it is not entirely obvious how it should be explored.

The goal of this thesis, therefore, is to analyze and compare the feasibility of several proposed human Martian exploration architectures. The missions investigated take on many forms, from standalone sorties that serve as an advanced precursor to a human landing on Mars to an extended Martian exploration campaign.

1.2 Research Motivation

The primary motivation for this project is to expand on the study performed by Cunio et al. (2010a; 2010b). The study focused on comparing a humans-to-surface mission to Mars with one where humans oversee robotic explorers from areostationary orbit (called humans-in-orbit), but never actually land on the surface of Mars. This analysis assumed "isoperformance," that is to say it was assumed that a transportation architecture capable of the launch, trans-Mars and trans-Earth injections, and satisfaction of the crew demands for resources was in place for both mission modes. As such, this thesis attempts to investigate the implications of this assumption in greater detail.

Further, Cunio et al. (2010a) define and analyze a single humans-in-orbit concept of operations. While they discuss the merits of this mission mode compared to humans-to-surface, several variants of this mission concept can be constructed that may provide further advantages depending on the technological, environmental, and political context. These alternate scenarios are investigated in this thesis.

Cunio et al. (2010a) also note that the humans-in-orbit mission mode fits on the Flexible Path, a concept proposed by Augustine et al. (2009) that is reviewed further below. In this thesis, an example extended Mars exploration campaign in the spirit of the Flexible Path is defined and analyzed.

Finally, another motivation for this thesis was to demonstrate extended use of SpaceNet, a space logistics modeling program developed at MIT and described thoroughly in Grogan (2010). Grogan develops and analyzes four case studies to demonstrate the breadth of SpaceNet's modeling capability. This thesis attempts to expand on the case study library, bolstering the range of SpaceNet's applicability.

1.3 Related Literature

This section contains an overview of the literature that appears most frequently throughout the thesis. Because a large fraction of the supporting literature is specific to particular missions proposals, those are reviewed individually in the appropriate chapters.

Cunio et al. (2010a) describes a shared human and robotic mission to Mars. The defining characteristic of this mission is that humans do not descend to the Martian surface. Instead, they remain in orbit and tele-operate robotic hopping explorers on the surface of Mars. Concurrently, humans can explore the Martian moons, Phobos and Deimos, and nominally achieve sample return from the Martian surface and both moons. This mission was demonstrated to be less costly, less risky, more quickly achievable than a humans-to-surface mission, and a viable stepping-stone of the Flexible Path (explained further below).

NASA (2009), better known as the *Human Exploration of Mars Design Reference Architecture 5.0* (henceforth denoted as "DRA 5.0"), is the most recent incarnation, under the Vision for Space Exploration introduced in 2004 (NASA, 2004), of the NASA-proposed mission architecture for a human landing on Mars. It utilizes the elements of the Constellation Program, namely the Ares I and Ares V launch vehicles and the Orion Crew Exploration Vehicle, and presents a mission timeline and a very preliminary design of the surface assets. The nominal architecture features nuclear thermal rockets (NTRs), pre-positioning of surface assets before astronaut arrival, and travel to and from Mars on the conjunction-class mission trajectory.

Augustine et al. (2009), titled *Seeking a Human Spaceflight Program Worthy of a Great Nation* (henceforth denoted as the "Augustine Report"), present an independent review of the American human spaceflight program. In effect, they propose three classes of options: one that closely follows the program of record, one that preserves the moon as the exploration destination, and the "Flexible Path" which aims to opportunistically explore inner solar system bodies. The Flexible Path is structured so that technological advancement and operational experience both lead eventually to a human landing on the Martian surface.

While a large body of literature is focused on potential human missions to the Martian surface and neighborhood, what is missing is a high-level logistics evaluation of a family of missions, such as the one presented in the Augustine Report, along common dimensions. This thesis attempts to fill that gap.

SpaceNet is a free software tool that "models space exploration from a supply chain and logistics architecture perspective" (de Weck et al., 2009). It is culmination of several years of work done at MIT beginning with prototyping in 2005-2006 leading to the release of a public version complete with source code and a development and user community in 2010 (Grogan, 2010). It allows users to perform space mission feasibility studies, from a logistics and supply chain perspective, and visualize results and figures of merit in several useful ways. SpaceNet Version 2.5r2 is the primary version used throughout this analysis.

2 Feasibility Analysis of a Shared Human and Robotic Mars Mission (SHRMM)

2.1 Description of SHRMM

SHRMM is a mission concept designed by a team of MIT graduate students for the Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) 2010 competition. A report detailing the mission has been written (Cunio et al., 2010a) and a brief summary of the mission follows here with additional technical details appearing in Appendix B.

2.1.1 Mission Concept Vision

SHRMM was envisioned to act as a stepping-stone between missions for which we have performed and for which we have gained expertise, such as Earth-orbit missions to the International Space Station (ISS) and lunar surface missions during the Apollo program, and the ultimate human exploration mission goal in the inner solar system, the surface of Mars (Augustine et al., 2009) as shown in Figure 1.

The rationale is to eliminate the requirement for heavy, expensive, and complex systems, such as a Mars surface habitat and Mars ascent vehicle, and also to bypass potentially dangerous maneuvers like Mars entry, descent, and landing with humans aboard heavy payloads. By doing so, the cost, complexity, and risk of the mission is reduced, and experience can be gained in areas such as long-term human spaceflight and tele-robotic operation while value is returned through human-guided exploration and surface sample return. All this leads to a mission that is more readily implementable, though one should recognize the most significant downside of not being able to have "boots on the ground" during our first human mission to Mars.

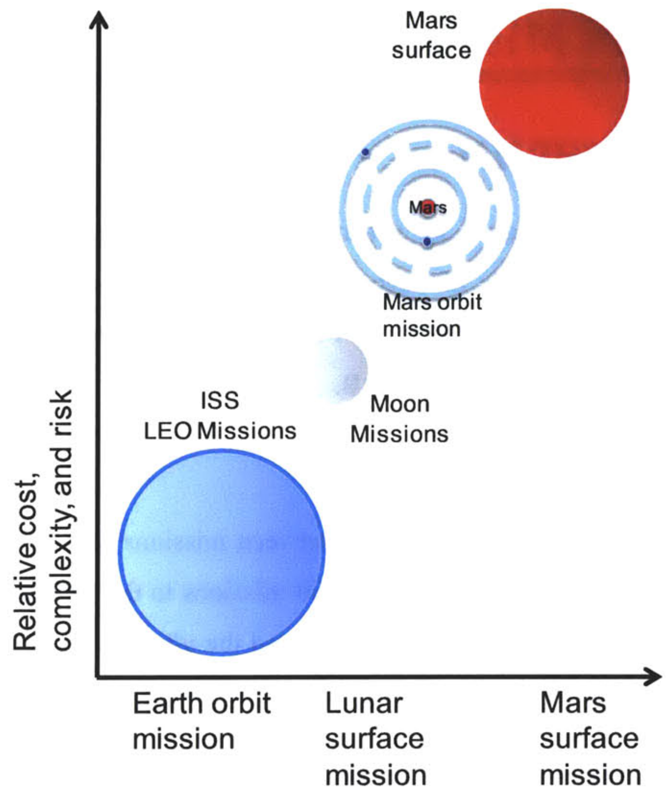

Figure 1: SHRMM Mission Concept (adapted from Cunio et al. (2010a))

2.1.2 Concept of Operations

Figure 2 shows a bat chart of SHRMM in the Martian neighborhood. The stacks, consisting of, among other things, the Mars Transit Vehicle (MTV), hoppers, Mars Ascent Vehicles (MAVs), and the Pirogue excursion vehicle first enter areostationary Mars orbit (ASO). From there, the habitat and MTV remain in orbit around Mars while the hoppers and MAVs descend to the Martian surface. There, the hoppers perform exploration while being supervised remotely by the crew in orbit. The hoppers collect samples, return them to the MAVs, which then ascend and rendezvous with the habitat where they are further analyzed and stowed for the return journey to Earth. ASO (17,032 km altitude and 0° inclination) was chosen specifically to allow the astronauts to have an uninterrupted line of sight to one Martian hemisphere, allowing for continuous communication with the hoppers below.

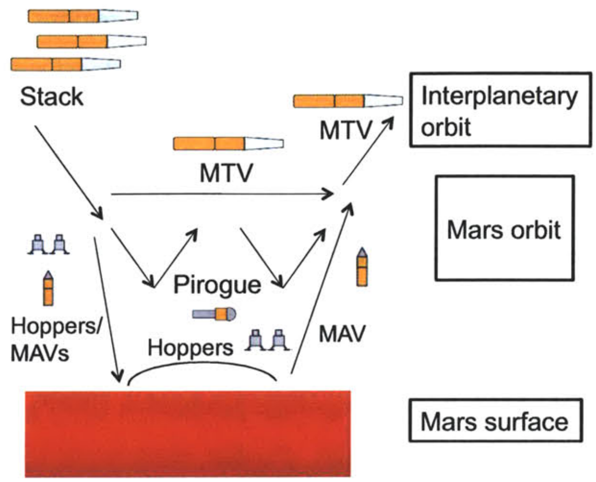

Figure 2: SHRMM Bat Chart (adapted from Cunio et al. (2010a))

Meanwhile, two of the crewmembers utilize the Pirogue vehicle, designed expressly for exploration of the Martian moons, to travel to Phobos and Deimos with a trip back to the MTV between the two. At the Martian moons, the crew performs extravehicular exploration and retrieves samples to return to the MTV.

When the exploration phase is complete, the crewmembers and samples are loaded into the MTV, which then performs the Trans-Earth Injection (TEI) maneuver, returning the crew back to Earth.

The crew nominally consists of six astronauts, four astronauts working in shifts to tele-operate the hoppers on the Martian surface and two astronauts trained to perform the extravehicular explorations using the Pirogue. Four pairs of hoppers, eight in total, are sent to the surface with each pair matched up to a MAV. The rationale for sizing SHRMM, based on considerations of mass, ISS astronaut shift schedules, and human supervisory control, is given in greater detail in Cunio et al. (2010a).

2.1.3 Results and Conclusions

Table 1 shows the results of the SHRMM analysis presented in Cunio et al. (2010a), and their comparison to DRA 5.0 (which is denoted the Humans-to-Surface mission mode in Cunio et al. (2010a) and was taken as the reference human surface mission architecture). The cells shaded in green indicate the better of the two mission modes for a given dimension. SHRMM requires 180.5 metric tons (mT) in Mars orbit while DRA 5.0 requires 355.5 mT, a reduction of nearly 50%. However, in the nominal DRA 5.0, approximately 200 kg of samples are returned from the Martian surface while in SHRMM, approximately only 4 kg of samples are returned. This is balanced by the 150 kg that are expected from the surface of the Martian moons, something that does not occur in DRA 5.0, and is of scientific interest (MEPAG, 2008; Galimov, 2010). Furthermore, potentially four different regions can be accessed on Mars in SHRMM, a boon to scientific variety, while only the immediate outpost surroundings can be accessed in DRA 5.0.

The development and build costs were estimated to be 70% lower in SHRMM compared to DRA 5.0. However absolute cost numbers were not referenced due to uncertainty in their accuracy. Theoretically, three technologies are below Technology Readiness Level (TRL) 6 in SHRMM (Mars ascent, asteroid operations, and zero-boil off cryogenic propellant), while five do not meet this threshold in DRA 5.0 (Mars ascent, heavy Mars EDL, Mars in-situ propellant production (ISPP), Mars surface power, and zero boil-off cryogenic propellant) (Cunio et al., 2010a). Further, rendezvous with the MTV immediately prior to the return journey is mission- and life-critical in DRA 5.0, while only mission-critical in SHRMM.

Finally, while the stay time in the Martian neighborhood is many times higher in DRA 5.0, 500 days compared to 40, SHRMM triples the number of bodies visited allowing for a wider variety of scientific return.

Cunio et al. (2010b) conclude that SHRMM represents a "simpler, safer, lighter" approach to a human mission to Mars. Indeed, given the results presented in Table 1, SHRMM provides a more widespread human presence in the Martian system for less mass and development and build cost, while relinquishing the focus of landing and concentrating exploration on the Martian surface for an extended period of time.

Table 1: Comparison of SHRMM to Humans-to-Surface Mission Mode (adapted from Cunio et al. (2010a))

Comparison Basis	SHRMM	NASA DRA 5.0
Wet mass in Mars orbit	180.5 mT	355.5 mT
Samples mass from Mars	~4 kg	~200 kg
Samples mass from moons	150 kg	None
Regions accessed on Mars	4 (1 per hopper/MAV team)	1 (outpost locale)
Normalized development/build cost	~0.3	1.0
Technologies below TRL 6	3: Mars ascent, asteroid ops, cryogenic zero boil-off	5: Mars ascent, heavy Mars EDL, MARS ISPP, Mars surface power, cryogenic zero boil-off
Stay time at Mars	40 days	500 days
Bodies visited	3	1

2.1.4 Assumptions in SHRMM

The SHRMM study presented in Cunio et al. (2010a) assumes, in regard to the launch vehicle infrastructure and transit phases, "isoperformance" between DRA 5.0, and SHRMM. This was done to facilitate direct comparison of the exploration capabilities between DRA 5.0 and SHRMM while the two missions were in the neighborhood of Mars (Cunio et al., 2010a).

The basic assumptions in the SHRMM analysis were as follows:

1. The launch vehicles presented in DRA 5.0, essentially variations on the Constellation launch vehicle family (NASA, 2009), or very similar launch vehicles would be capable of delivering the required elements for SHRMM.
2. The mission infrastructure would be able to satisfy the demand for crew provisions (e.g., food, water, hygiene items, and waste disposal items) for the duration of the outbound journey, exploration phase, and return journey.

While Cunio et al. (2010a) showed the potential advantages and disadvantages of embarking on a mission like SHRMM, the aforementioned assumptions have not yet been verified and are the focus of the remainder of this chapter.

2.2 Feasibility Analysis

To further develop the Shared Human and Robotic Mars Mission concept, a feasibility study focusing on the propulsive and crew provisions supply network was performed. The analysis was done using the space exploration logistics software SpaceNet Version 2.5r2 (http://spacenet.mit.edu/). The objective of the feasibility study is to assess the ability of the elements proposed in DRA 5.0 to satisfy the propulsive and crew provision demands of SHRMM.

2.2.1 Feasibility Analysis Assumptions

The following assumptions were made in the feasibility analysis:

1. All elements in the supporting infrastructure were modeled as specified in DRA 5.0. Where conflicting information was found, an educated guess was made as to which value was carried through the feasibility analysis as well as consultation with Grogan (2010). A summary of the elements modeled is shown in Table 2 (NASA, 2009), including the three MTV stacks that will be defined and discussed further below.

2. A notable absence from the above list is the Ares I crew launch vehicle. Because crew launch to Low Earth Orbit (LEO) is a single launch isolated logistically from the rest of the mission infrastructure, it was not necessary to model the Ares I in detail and instead it was assumed that a capable crew launch vehicle would be available to deliver the crew to LEO.
3. Demand for crew provisions are assumed to be a constant 7.5 kg per crewmember daily, with an approximate breakdown being 2 kg for food, 3.5 kg for water, 1 kg for gases, 0.5 kg for hygiene items, and 0.5 kg for waste disposal items (Grogan, 2010). The demand rate is assumed independent of the mission phase (i.e., transit, tele-operations, or extravehicular exploration).
4. Only mass feasibility is considered. At this current time, the volume and cost of the mission elements both in DRA 5.0 and SHRMM are considered too uncertain to be of meaningful use.
5. DRA 5.0 assumes the use of zero boil-off LH2 cryocoolers (NASA, 2009) to prevent propellant loss during the duration of the outbound transit and exploration phases. The assumption of zero boil-off is thus carried over to this feasibility analysis.
6. DRA 5.0 implicitly makes the assumption of having in-space restart-able engines. Consequently, this feasibility analysis also assumes this technology is available.
7. Additional mass for spares is included in the mass specifications for the elements in DRA 5.0 (NASA, 2009). The ancillary elements relevant to SHRMM, generally associated with exploration and science, are comparatively significantly lighter and operate for a shorter period of time, and it is assumed that their demand for spares is negligible in the context of the demand for crew provisions.

Propulsive feasibility during the exploration phase, the time when the crew is in the Martian vicinity, is not considered. During this time, only the Pirogue vehicle is used for propulsive maneuvers, and this propulsive feasibility was investigated in Cunio et al. (2010a).

Table 2: Summary of DRA 5.0 Elements

Name	Mass (mT)	Max Crew	Max Cargo (mT)	Fuel Mass (mT)	I_{sp} (s)	Description
Ares V SRB	106.5	0	0	685	269	Ares V Solid Rocket Booster (2 per Ares V)
Ares V Core	173.7	0	0	1,587	414	Ares V Core Stage
Ares V Interstage	9.2	0	0	0	-	Ares V Interstage
Ares V EDS	26.4	0	0	253	449	Ares V Earth Departure Stage
Ares V PLF	9.0	0	0	0	-	Ares V Payload Fairing
NTR	33.7	0	0	59.4	950	Nuclear Thermal Rocket
NTR (S)	41.7	0	0	59.7	950	Nuclear Thermal Rocket with Radiation Shield
In-line LH2 Tank	10.8	0	0	34.1	950	Liquid Hydrogen Tank
In-line LH2 Tank (S)	21.5	0	0	69.9	950	Liquid Hydrogen Tank with Radiation Shield
LH2 Drop Tank	14.0	0	0	73.1	950	Liquid Hydrogen Tank (jettisoned in transit)
MTH	27.5	6	5.3	0	-	Mars Transfer Habitat
CEV	6.0	6	0.5	0	-	Orion Crew Exploration Vehicle
CFC	1.9	0	7.94	0	-	Contingency Food Canister
SM	4.0	0	0	0	-	Orion Service Module
LST	8.9	0	0	0	-	Long Saddle Truss
SST	4.7	0	0	0	-	Short Saddle Truss
DM	1.8	0	0	0	-	Docking Module
Cargo MTV #1	*168.0*	*0*	*0*	*93.5*	*950*	*Cargo MTV #1 Stack*
Cargo MTV #2	*192.3*	*0*	*0*	*93.5*	*950*	*Cargo MTV #2 Stack*
Crewed MTV	*351.4*	*6*	*13.74*	*202.7*	*950*	*Crewed MTV Stack*

2.2.2 Trajectory Analysis

Propulsive requirements in ΔV for a conjunction class (i.e., long stay) mission for launch windows between 2031 and 2046 for both an all-propulsive trajectory and a trajectory with the ability to aerobrake during Mars Orbit Insertion (MOI) were calculated. In the analysis, it was assumed that vehicles would leave from a 407-km circular LEO and insert into a 230 km x 33,793 km 1-sol orbit around Mars (NASA, 2009). Also, the results presented are for the conjunction class mission, as this is the nominal design reference mission chosen for its long stay time at Mars and lower ΔV compared to the opposition (i.e., short stay) mission class.

SHRMM is built around the opposition mission class which affords the advantage of reducing the overall human exposure to space radiation. Thus, an astrodynamics analysis is required to determine the ΔV requirements for an opposition class mission for the various maneuvers: TMI, MOI, and TEI. Furthermore, while the lower ΔV requirements associated with conjunction class missions can still be utilized for cargo flights used to pre-position assets in SHRMM, care must be taken to adjust the ΔV requirements to reflect MOI into ASO as opposed to the orbit suggested by DRA 5.0.

Casalino et al. (1998) present complete potential trajectory options between the years 2000 and 2037. Each outbound TMI opportunity is matched with an appropriate return TEI opportunity, and the trajectories are categorized as conjunction and opposition classes, some with outbound and inbound midcourse corrections or Venus flybys.

The analysis performed by Casalino et al. (1998) assumed a TMI maneuver executed from a 500-km LEO and subsequent insertion into a 403-km altitude periapsis 1-sol Martian orbit, hereafter referred to as Reference Mars Orbit (RMO). It was then necessary to extend the analysis of Casalino et al. (1998) account for the additional ΔV required to reach ASO.

Figure 3 shows the burn sequence used to reach ASO and then to hyperbolically escape during TEI, essentially using a planetary flyby approach and a minimum-energy Hohmann Transfer (Larson and Wertz, 1999). To reduce dependence on speculative technology and also for conservatism, an all-propulsive (i.e., non-aerocapture) MOI was assumed. First, during the hyperbolic TMI approach trajectory that has been mid-course corrected to produce a periapsis passage through ASO, the spacecraft performs a retrograde burn to insert into ASO. The spacecraft remains in ASO during the duration of the exploration phase of the mission. After the exploration phase, the spacecraft performs a burn to put itself into an Areostationary Transfer Orbit (ATO) before finally performing the TEI burn at the periapsis putting it on a hyperbolic escape trajectory bound for Earth.

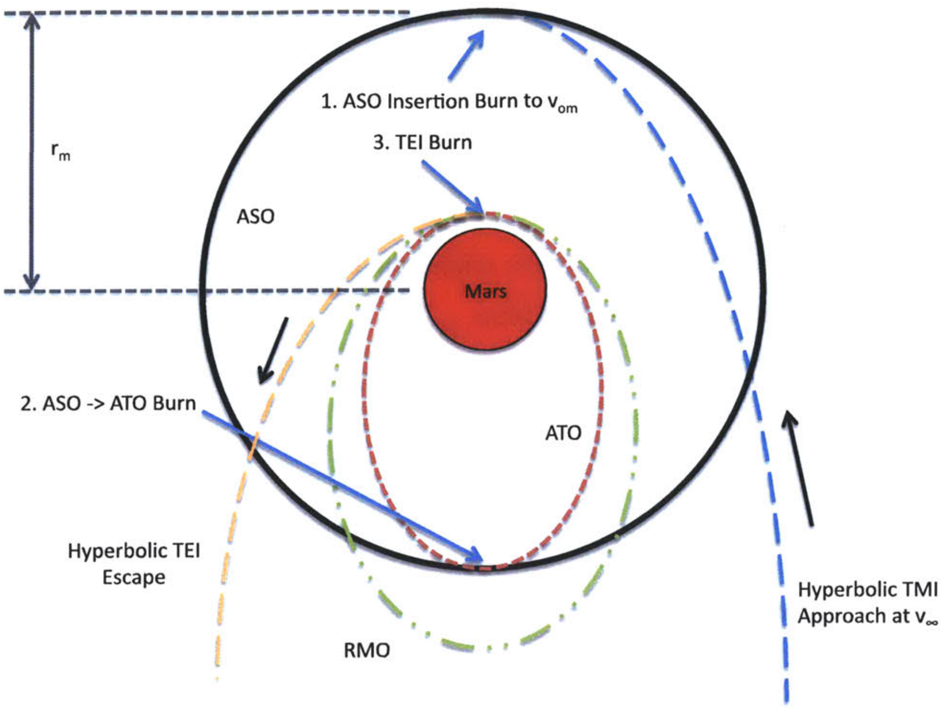

Figure 3: Mars Orbit Insertion and Trans-Earth Injection Burn Sequences (not to scale)

The analysis of the burn sequence follows from Battin (1999). The ΔV required for MOI utilizes a set of three equations describing a close pass of a planet during a flyby, shown in Equation (1) along with their supporting equations shown in Equation (2). In these equations, is half the turn angle, v_{∞} is the incoming speed of the spacecraft relative to the planet, v is the circular speed of the spacecraft at the minimum passing distance r, r is the point of aim, μ is the standard gravitational parameter of Mars (4.28×10^{13} m^3/s^2), and a, is the semimajor axis of the hyperbolic flyby trajectory.

$$\sin v = \frac{1}{1+\frac{v_\infty^2}{v_{om}^2}}$$

$$\tan v = \frac{\mu}{r_a v_\infty^2} \tag{1}$$

$$r_a = r_m\sqrt{1+2\frac{v_{om}^2}{v_\infty^2}}$$

$$v_\infty = \sqrt{-\frac{\mu}{a_h}}$$
$$v_{om} = \sqrt{\frac{\mu}{r_m}} \tag{2}$$

Equation (3), the equation for the Mean Motion, relates the orbital period P and the semimajor axis a through the standard gravitational parameter of Mars u.

$$\frac{2\pi}{P} = \sqrt{\frac{a^3}{u}} \tag{3}$$

The radii of the apoapsis and periapsis of an orbit, r and r_n respectively, can be related through the definition of the semimajor axis as in Equation (4).

$$r_a = 2a - r_n \tag{4}$$

The Vis-viva Integral, shown in Equation (5), relates, at a spacecraft in an orbit with semimajor axis a, its velocity v, and its radius r.

$$v^2 = \mu\left(\frac{2}{r} - \frac{1}{a}\right) \tag{5}$$

The above equations can be used, in conjunction with the characteristics of RMO and results presented in Casalino et al. (1998), to calculate the ΔV requirements for SHRMM near Mars. The results are shown in Table 3 along with a standard assumption of 9.8 km/s for launch into LEO (Larson and Wertz, 1999) and the assumed maneuver dates. As a point of verification, Wade (2008) notes that an opposition class mission would have a total round-trip ΔV requirement of 19.8 km/s compared to the value of 18.5 km/s calculated here.

Table 3: ΔV Requirements for SHRMM

Maneuver	ΔV Requirement (m/s)	Date
Launch from Earth to LEO	9,800	-
Opposition Class TMI	4,244	Jun 12, 2036
Opposition Class MOI	2,067	May 13, 2037
Conjunction Class TMI	3,567	Apr 17, 2033
Conjunction Class MOI	2,067	Nov 3, 2033
TEI from ASO	2,375	Jul 12, 2037
Round-trip Total (opposition class)	*18,486*	-
TMI, MOI, and TEI (opposition class)	*8,686*	-
Outbound Total (conjunction class)	*15,434*	-
TMI and MOI (conjunction class)	*5,634*	-

2.2.3 Initial Results

By performing a rough overall aggregate comparison of the propulsive and crew provision demands to their respective supply capacities, it is readily evident that the infrastructure outlined in DRA 5.0 cannot support SHRMM without some modifications.

The crewed Mars Transfer Vehicle (MTV), responsible for transporting, among other things, the crew to and from the vicinity of Mars, flies the opposition class mission. According to Table 3, this mission mode requires a total ΔV of 8,686 m/s from the MTV. However, analysis of the DRA 5.0 crewed MTV shows it has a total ΔV capability of only 7,838 m/s, representing a shortfall of 848 m/s.

In terms of crew provisions, given that the particular opposition class mission trajectory assumed implies 595 days of crewed flight, the total crew provisions demand at 7.5 kg per day per person amounts to a total mission demand of approximately 26.8 mT. However, from Table 2 it is evident the total crew provision capacity (of the MTH, CFC and CEV) is approximately 13.7 mT representing a 13.1 mT deficit.

Thus, in regards to propulsive and crew provision consideration, DRA 5.0 cannot support SHRMM without some form of modification.

2.2.4 Modifications to the Feasibility Analysis of SHRMM

Firstly, a new element, called the TEI LH2 Drop Tank, was introduced. This tank is structurally identical to the LH2 Drop Tank described in DRA 5.0 but is filled to only 48% capacity and is pre-positioned in ASO with the other cargo on the conjunction class mission trajectory. During the exploration phase, the crewed MTV will attach with the TEI LH2 Drop Tank and use its contents for the TEI maneuver after the exploration phase is over.

Secondly, the crew provisions demand rate was reduced to 3.375 kg per person daily from the original 7.5. This represents an assumption that a 95% water closure rate and increased reusability of hygiene and waste disposal items can be achieved (Grogan, 2010).

With these two modifications, the full-out mission feasibility analysis was performed, and the results are presented in the next section.

2.2.5 Analysis, Results, and Discussion

Mission Overview

Figure 4 shows the SHRMM exploration network. The mission will be modeled from launch at Kennedy Space Center (KSC) to assembly in LEO, transit to ASO, exploration of the Martian surface and Martian moons, and finally the return journey to splashdown in the Pacific Ocean (PAC). Explained further below, red arcs represent edges where ΔV calculations are explicitly performed while yellow arcs represent abstracted flights with no explicit fuel or ΔV requirements (de Weck et al., 2009).

Figure 5 shows a bat chart outlining the location and movement of exploration assets over the course of SHRMM. In the Cargo Pre-positioning phase, four Ares V launches position the assets for construction of two Cargo MTVs which are then sent on a conjunction class trajectory to ASO. Later, when the opposition class launch window opens, four more Ares V launches position the elements required for the construction of the Crewed MTV. The crew is then launched and rendezvous with the crewed MTV which then performs the opposition class TMI maneuver. When the crewed MTV reaches ASO, the exploration phase detailed in Cunio et al. (2010a) is carried out. During the exploration phase, the TEI LH2 Drop Tank is mated with the Crewed MTV. When this is complete, the Crewed MTV performs the TEI maneuver to splashdown in PAC. The timeline of important milestones for SHRMM is shown in Table 4.

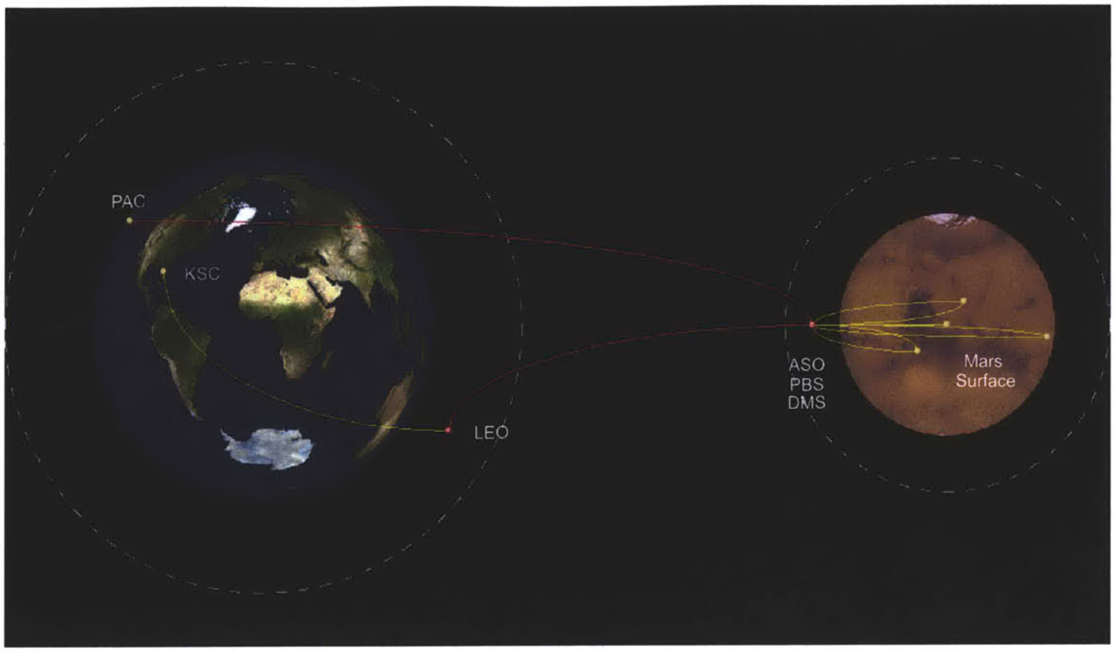

Figure 4: SHRMM Exploration Network

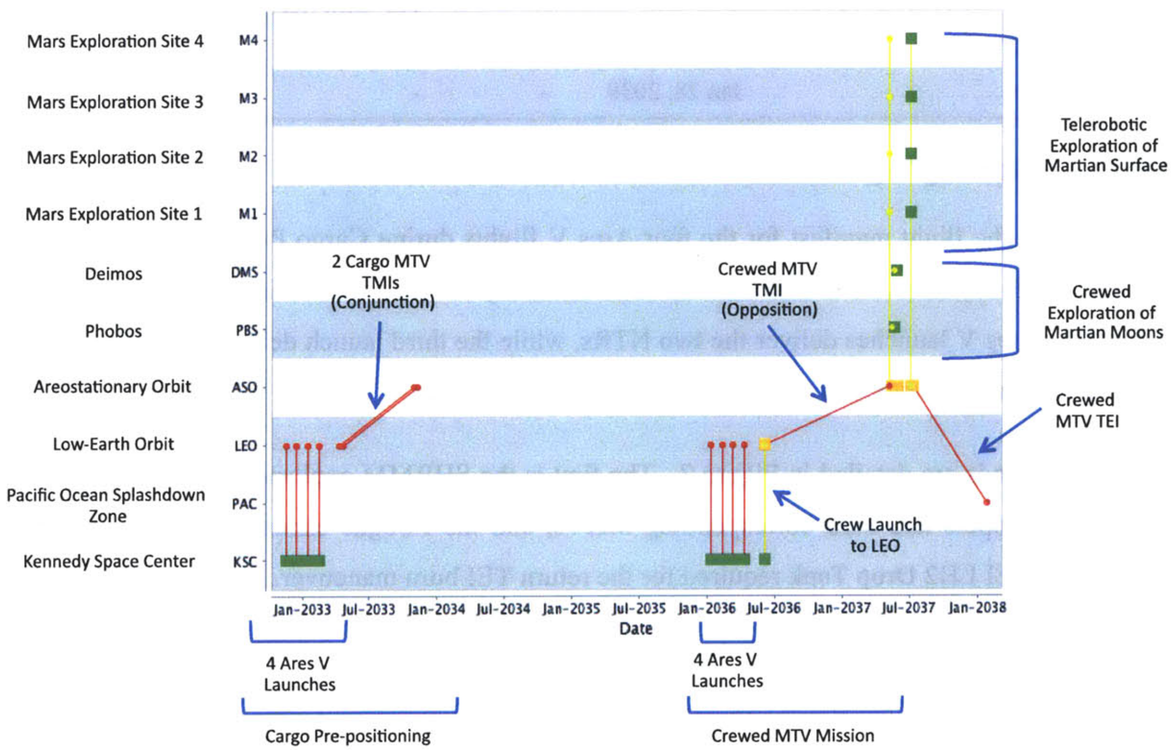

Figure 5: SHRMM Exploration Bat Chart

Table 4: SHRMM Schedule

Event	Date	Origin	Destination	Duration (days)
Cargo Ares V Launch 1	Nov 17, 2032	KSC	LEO	0.1
Cargo Ares V Launch 2	Dec 17, 2032	KSC	LEO	0.1
Cargo Ares V Launch 3	Jan 16, 2033	KSC	LEO	0.1
Cargo Ares V Launch 4	Feb 12, 2033	KSC	LEO	0.1
Cargo MTV #1 TMI	Apr 11, 2033	LEO	ASO	202
Cargo MTV #2 TMI	Apr 21, 2033	LEO	ASO	202
Cargo MTV #1 MOI	Oct 30, 2033	-	-	-
Cargo MTV #2 MOI	Nov 9, 2033	-	-	-
Crewed MTV Ares V Launch 1	Jan 12, 2036	KSC	LEO	0.1
Crewed MTV Ares V Launch 2	Feb 11, 2036	KSC	LEO	0.1
Crewed MTV Ares V Launch 3	Mar 12, 2036	KSC	LEO	0.1
Crewed MTV Ares V Launch 4	Apr 11, 2036	KSC	LEO	0.1
Crew Launch	Jun 5, 2036	KSC	LEO	0.1
Crewed MTV TMI	Jun 5, 2036	LEO	ASO	335
Crewed MTV MOI	May 6, 2037	-	-	-
Exploration Phase	May 7, 2037	ASO	M1, M2, M3, M4, PBS, DMS	60
Crewed MTV TEI	Jul 12, 2037	ASO	PAC	200
Splashdown	Jan 28, 2038	-	-	-

Cargo Pre-positioning Flight Manifest

Figure 6 shows the flight manifest for the four Ares V flights during Cargo Pre-positioning. The flights are spaced at 30-day intervals to allow for on-orbit assembly as was assumed in DRA 5.0 (NASA, 2009). The first two Ares V launches deliver the two NTRs, while the third launch delivers the two In-Line LH2 Tanks and the fourth launch delivers the two Cargo MTV payloads.

These two payloads are detailed in Figure 7. The first is the SHRMM exploration payload, consisting of four pairs of hoppers and their corresponding MAVs, and the Pirogue excursion vehicle. The second payload is the TEI LH2 Drop Tank required for the return TEI burn maneuver.

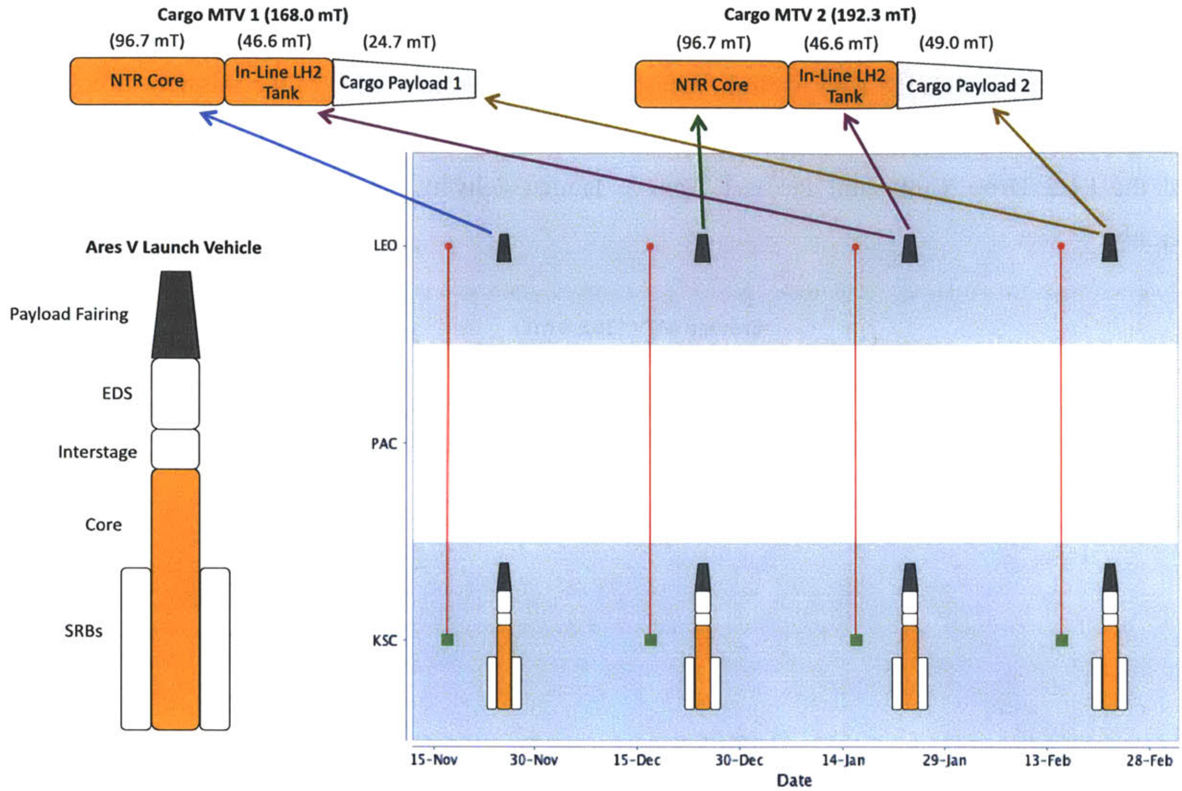

Figure 6: Cargo Pre-positioning Ares V Flight Manifest

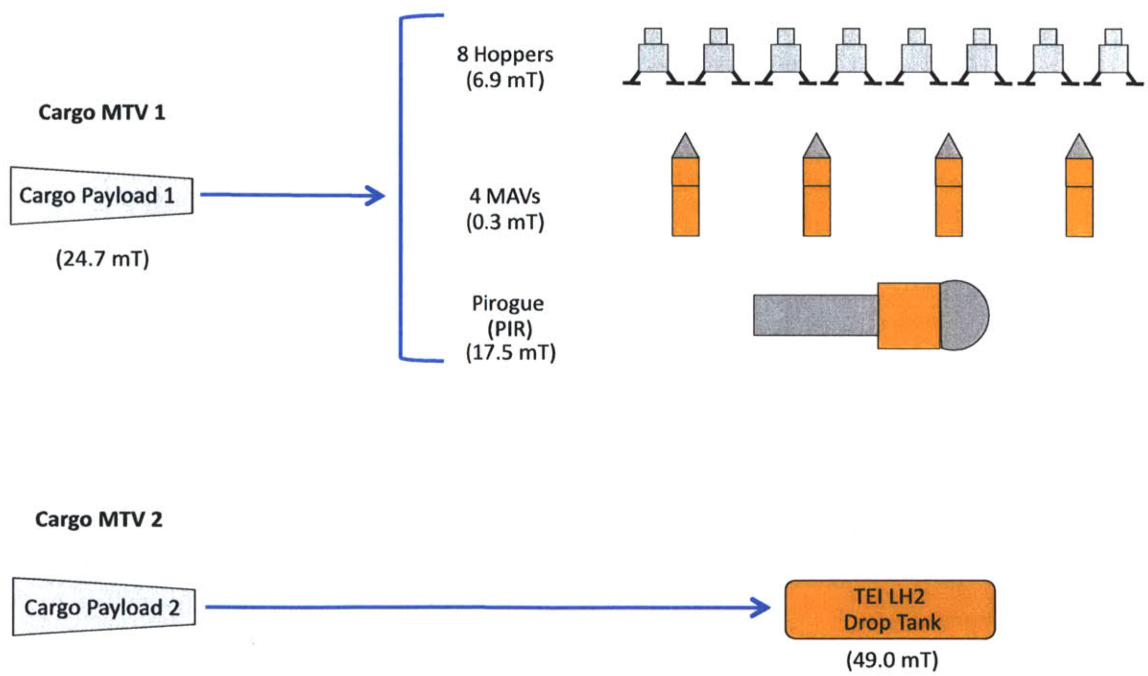

Figure 7: Cargo MTV Payloads

Crewed MTV Mission Flight Manifest

Figure 8 similarly shows the Ares V flight manifest for the Crewed portion of the mission. The first Ares V launch delivers a radiation-shielded NTR, the second the radiation-shielded In-Line LH2 Tank, the third the LH2 Drop Tank, and the last Ares V launch delivers the CFC, MTV, and CEV and SM assembly.

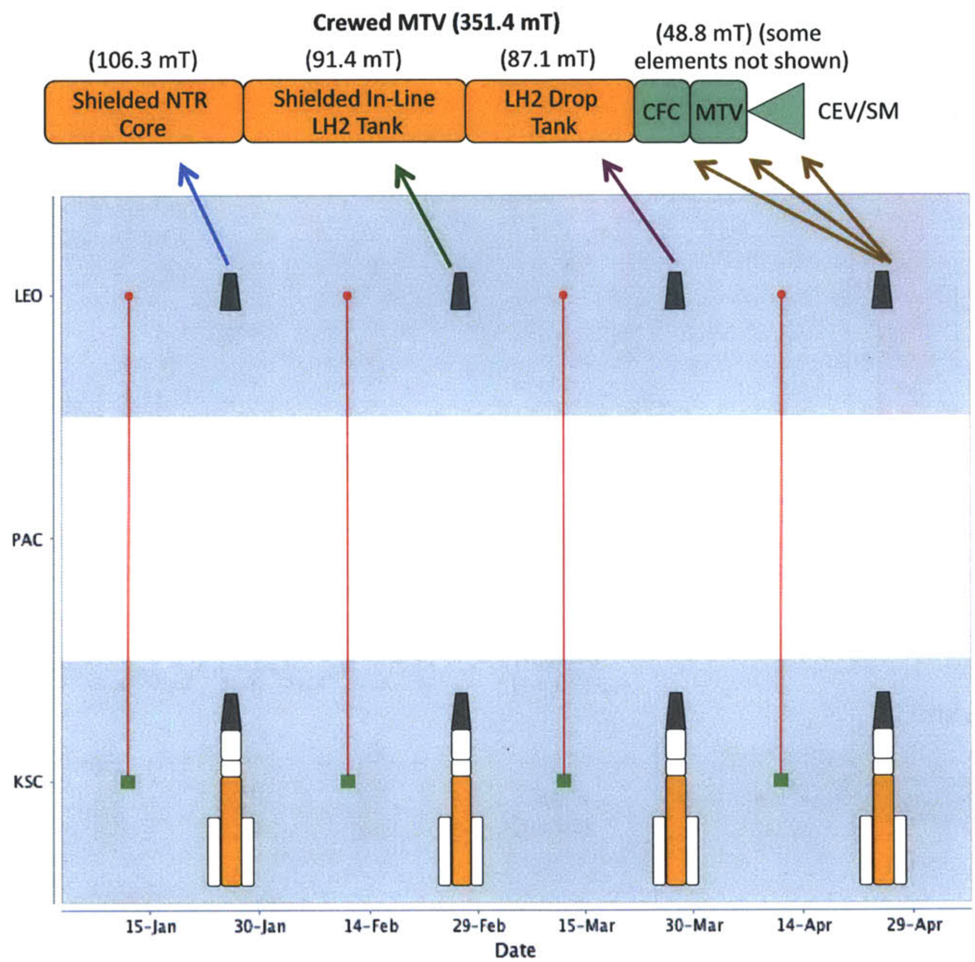

Figure 8: Crewed Mission Ares V Launch Manifest

Results and Discussion

Table 5 shows the profile of propellant usage for the vehicles of interest in SHRMM. Readily, several observations can be made from these results.

1. SHRMM is feasible from a propulsive prospective using the DRA 5.0 infrastructure given the use of the TEI LH2 Drop Tank. While on-orbit refueling is not required, a rendezvous and subsequent attachment of the TEI LH2 Drop Tank to the Crewed MTV must occur in ASO.

2. The Ares V launch vehicles are utilized essentially to full capacity. This is not surprising as the heaviest Ares V payloads in both SHRMM and DRA 5.0 are the common NTR and radiation-shielded NTR.
3. Of the three MTVs, Cargo MTV #1, carrying the SHRMM exploration payload, has the largest propellant margin. This extra capacity can be utilized in several ways. First, the extra capacity can be downsized with consideration given to Cargo MTV #2 which uses an identical design but has a smaller propellant margin. The extra capacity can also be used to pre-position other assets for future exploration missions. Finally, an ASO fuel depot could potentially be used in lieu of the TEI LH2 Drop Tank, possibly rendering Cargo MTV #2 unnecessary.

Table 5: Propellant Usage in SHRMM

	Remaining Propellant (mT)				
Event	**Cargo Ares V Group***	**Cargo MTV #1**	**Cargo MTV #2**	**Crewed Ares V Group***	**Crewed MTV**
Pre-launch	2,957 ■	93.5 ■	93.5 ■	2,957 ■	202.7 ■
Cargo MTV Ares V Launches	20.0 ↓	93.5	93.5	2,957	202.7
Cargo MTVs TMI and MOI	20.0	23.3 ↓	6.3 ↓	2,957	202.7
Crewed MTV Ares V Launches	20.0	23.3	6.3	12.9 ↓	202.7
Crewed MTV TMI and MOI	20.0	23.3	6.3	12.9	40.0 ↓
Attach TEI LH2 Drop Tank	20.0	23.3	6.3	12.9	75.0 ↑
Crewed MTV TEI	20.0	23.3	6.3	12.9	20.9 ↓
Margin (of capacity)	*0.8%*	*24.4%*	*6.7%*	*0.4%*	*8.8%***

* minimum of the group of four Ares V launch vehicles
** capacity taken as original propellant load plus TEI LH2 Drop Tank load
■ maximum capacity
↓ propellant from this vehicle was used
↑ propellant was added to this vehicle

Similarly, Table 6 shows the profile of crew provision usage for SHRMM. Again, several observations can be made from these results.

1. SHRMM is feasible from a crew provision perspective given the assumed demand rate of 3.375 kg per person daily.
2. The CFC, while used in DRA 5.0 to provide contingency provisions in the event of a mission abort, must be used in SHRMM to satisfy crew demands.
3. Pre-positioning of crew provisions is not necessary. All required crew provisions can be transported on the Crewed MTV. Thus, an element serving the function of providing contingency

crew provisions is not necessary in SHRMM since no crew provisions are ever separated from the crew.

Approximately 1,244 kg of crew provisions remain unused at splashdown. This mass can be used to account for packaging mass, as a zero-tare crew provision mass was assumed in this analysis.

Table 6: Crew Provisions Usage in SHRMM

	Remaining Crew Provisions (kg)			
Event	**MTV**	**CFC**	**CEV**	**Pirogue**
Pre-launch	5,300 ■	7,940 ■	50 ■	455 ■
Crewed MTV MOI	5,300	1,494 ↓	50	455
Crewed MTV TEI	5,300	23 ↓	50	361 ↓
Splashdown at PAC	883 ↓	0 ↓	0 ↓	361
Margin (of capacity)	*16.7%*	*0%*	*0%*	*79.3%*

■ maximum capacity
↓ crew provisions from this vehicle were used

Table 7 shows several figures of interest comparing DRA 5.0 to SHRMM. Figures highlighted in green represent the superior figure in a pair wise comparison. Again, several interesting observations can be made.

1. Only eight Ares V launches carrying 706.0 mT to LEO are required in SHRMM as compared to nine for DRA 5.0 carrying 848.7 mT for DRA 5.0. Indeed, SHRMM is a lighter and simpler mission as a large portion of the mass eliminated is in the form of the surface habitat, heavy ascent vehicle, and entry, descent, and landing systems.
2. Although SHRMM is a lighter mission, it requires more propellant from its MTVs because it is on the opposition class trajectory.
3. Six sites from all three major bodies in the Martian system are sampled in SHRMM as opposed to just the area around the surface habitat in DRA 5.0.
4. DRA 5.0 allows for more concentrated exploration, providing 3,000 crew-days on Mars while SHRMM allows for disseminated exploration of the Martian system for a total of 360 crew-days.

Table 7: SHRMM Figures of Interest

Figure of Interest	DRA 5.0 (NTR, I_{sp} 950 s)	SHRMM (NTR, I_{sp} 950 s)
Ares V launches	9	8
Crew launches	1	1
Total mass in LEO (mT)	848.7	706.0
Number of sites sampled	1 (habitat locale)	6 (4 sites on Mars, Phobos, Deimos)
MTV propellant usage (mT)	356.8	374.2
Crew consumables demand (mT)	15.3	12.5
Crew consumables remaining (mT)	14.4	1.2
Crew-days of exploration (crew-days)	3,000	360

2.3 Conclusions

Given the modifications discussed, including an additional TEI LH2 Drop Tank and assuming a certain level of performance from water closure and crew provision reusability, SHRMM is feasible using the DRA 5.0 vehicle architecture.

SHRMM, being lighter, requiring fewer complex systems, and avoiding the need for heavy entry, descent, and landing on Mars, is a viable stepping stone toward utilizing the nominal DRA 5.0 architecture for a human surface mission to Mars. The primary trade is between the shorter explorations of multiple sites in SHRMM for the longer exploration of a single site in DRA 5.0. SHRMM represents a partial buildup and validation of the required systems, spreading out the cost of development and construction while returning scientific and inspirational value.

3 Variations on SHRMM

Three variations on SHRMM are analyzed in this chapter, and a further four spinoff missions, making up a potential Martian exploration campaign, are defined in Chapter 4. To aid the reader in following these variations, a mission "family tree" is shown in Figure 9.

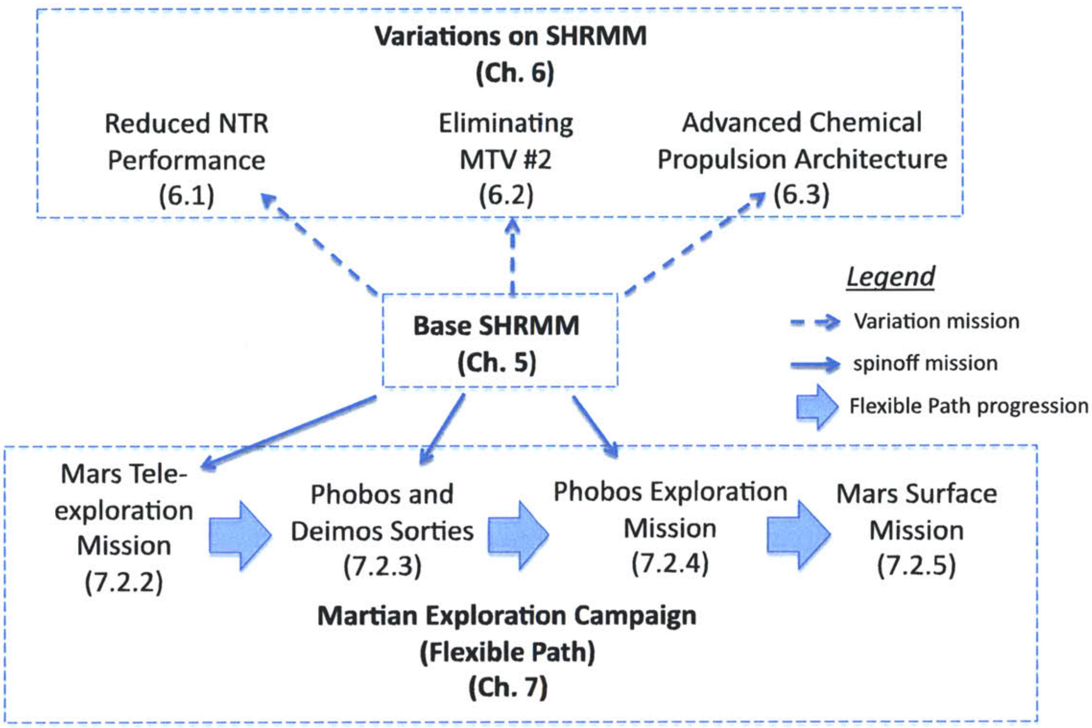

Figure 9: Future Human Mars Exploration Mission Family Tree

3.1 Reduced NTR Performance

In the feasibility analysis presented in Chapter 2, a specific impulse of 950 s was assumed representing the most optimistic performance of the NTR predicted by DRA 5.0. To investigate the robustness of this assumption, the feasibility analysis was repeated for the most pessimistic NTR specific impulse prediction, 875 s. Table 8 shows the propellant usage profile and demonstrates that even with the lowest predicted NTR performance, the concept of operations introduced in Chapter 2 remains feasible from a propulsive standpoint with a propellant margin of 1.1% on Cargo MTV #2.

Table 8: Propellant Usage in SHRMM (875 s NTR Specific Impulse)

	Remaining Propellant (mT)				
Event	**Cargo Ares V Group***	**Cargo MTV #1**	**Cargo MTV #2**	**Crewed Ares V Group***	**Crewed MTV**
Pre-launch	2,957 ■	93.5 ■	93.5 ■	2,957 ■	202.7 ■
Cargo MTV Ares V Launches	20.0 ↓	93.5	93.5	2,957	202.7
Cargo MTVs TMI and MOI	20.0	19.0 ↓	1.0 ↓	2,957	202.7
Crewed MTV Ares V Launches	20.0	19.0	1.0	12.9 ↓	202.7
Crewed MTV TMI and MOI	20.0	19.0	1.0	12.9	23.1 ↓
Attach TEI LH2 Drop Tank	20.0	19.0	1.0	12.9	58.1 ↑
Crewed MTV TEI	20.0	19.0	1.0	12.9	15.2 ↓
Margin (of capacity)	*0.8%*	*20.3%*	*1.1%*	*0.4%*	*6.4%***

* minimum of the group of four Ares V launch vehicles

** capacity taken as original propellant load plus TEI LH2 Drop Tank load

■ maximum capacity

↓ propellant from this vehicle was used

↑ propellant was added to this vehicle

Table 9 shows Table 7, the SHRMM figures of interest, appended with the figures of interest from the 875 s NTR specific impulse analysis. Figures highlighted in green represent superiority when compared to DRA 5.0. Essentially, as expected, the lower specific impulse mission requires more propellant, and has a lower overall propellant margin when compared to DRA 5.0. Notwithstanding the reduced NTR performance, DRA 5.0 still requires less propellant than SHRMM while SHRMM has a larger propellant margin.

Table 9: SHRMM Figures of Interest (with 875 s NTR Specific Impulse)

Figure of Interest	**DRA 5.0 (NTR, I_{sp} 950 s)**	**SHRMM (NTR, I_{sp} 950 s)**	**SHRMM (NTR, I_{sp} 875 s)**
Ares V launches	9	8	8
Crew launches	1	1	1
Total mass in LEO (mT)	848.7	706.0	706.0
Number of sites sampled	1	6	6
MTV propellant usage (mT)	356.8	374.2	389.5
Crew consumables demand (mT)	15.3	12.5	12.5
Crew consumables remaining (mT)	14.4	1.2	1.2
Crew-days of exploration (crew-days)	3,000	360	360

Further analysis shows that the minimum NTR specific impulse for which this concept of operations is feasible is 863 s, the specific impulse at which Cargo MTV#2 requires its entire propellant load to complete its flight. At 863 s, 8.2 mT of propellant remain in the Crewed MTV after the Crewed MTV

TEI maneuver. If the amount of propellant in the TEI LH2 Drop Tank is optimized to simultaneously minimize the propellant margin in Cargo MTV #2 and the Crewed MTV, this concept of operations is feasible at a minimum specific impulse of 835 s.

3.2 Eliminating Cargo MTV #2

Although the use of a dual Cargo MTV architecture provides robustness from a propellant feasibility standpoint, significant savings can be realized if Cargo MTV #2 is eliminated. Essentially, if the TEI LH2 Drop Tank can be positioned in ASO using Cargo MTV #1, there would be no need to launch a second Cargo MTV.

Figure 10 shows the SHRMM bat chart without Cargo MTV #2. The mission progression is essentially the same as the original plan presented in Chapter 2 with three modifications. First, as was the objective, Cargo MTV #2 has been eliminated. Second, only three Ares V launches are required during the Cargo Pre-positioning mission phase as the Ares V launch dedicated to positioning the NTR Core stage for Cargo MTV #2 is no longer required. Third, because one fewer Ares V launch is required, the start date of the Cargo Pre-positioning phase was moved back thirty days to December 17, 2032.

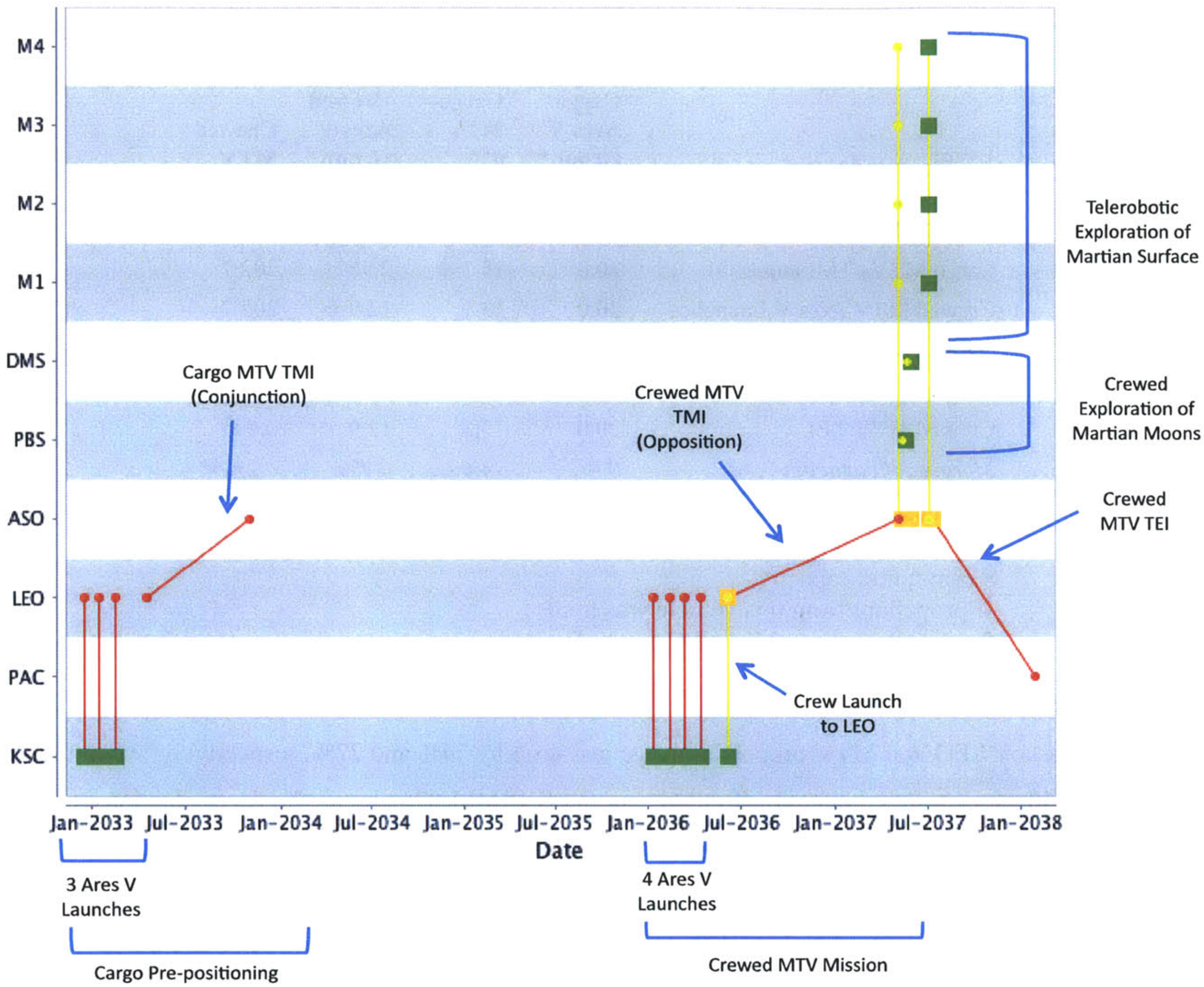

Figure 10: SHRMM Exploration Bat Chart (without Cargo MTV #2)

Table 10 shows the propellant usage profile for SHRMM after Cargo MTV #2 has been eliminated assuming a specific impulse of 950 s. The TEI LH2 Drop Tank, loaded with 8.5 mT of propellant as opposed to 35 mT as in the original feasibility analysis which allows the TEI LH2 Drop Tank to be positioned by Cargo MTV #1. After the Crewed MTV TEI maneuver, 0.4 mT of propellant remains in the Crewed MTV.

Table 11 shows the figures of interest of the SHRMM with no Cargo MTV #2, for both a 950 s and 875 s specific impulse, against DRA 5.0 and the original SHRMM mission mode. Again, figures highlighted in green are superior to DRA 5.0. In the 875 s case, 23 mT of propellant are loaded onto the TEI LH2 Drop Tank.

Table 10: Propellant Usage in SHRMM (without Cargo MTV #2, 950 s NTR Specific Impulse)

	Remaining Propellant (mT)			
Event	**Cargo Ares V Group***	**Cargo MTV #1**	**Crewed Ares V Group***	**Crewed MTV**
Pre-launch	2,957 ■	93.5 ■	2,957 ■	202.7 ■
Cargo MTV Ares V Launches	20.0 ↓	93.5	2,957	202.7
Cargo MTVs TMI and MOI	20.0	13.1 ↓	2,957	202.7
Crewed MTV Ares V Launches	20.0	13.1	12.9 ↓	202.7
Crewed MTV TMI and MOI	20.0	13.1	12.9	33.0 ↓
Attach TEI LH2 Drop Tank	20.0	13.1	12.9	41.5 ↑
Crewed MTV TEI	20.0	13.1	12.9	0.4 ↓
Margin (of capacity)	*0.8%*	*14.0%*	*0.4%*	*0.2%***

* minimum of the group of four Ares V launch vehicles
** capacity taken as original propellant load plus TEI LH2 Drop Tank load
■ maximum capacity
↓ propellant from this vehicle was used
↑ propellant was added to this vehicle

Immediately, one notices that in the case of no Cargo MTV #2, one fewer Ares V launch is required, and the total mass in LEO and MTV propellant usage and drop by 24% and 22%, respectively, when the two SHRMM 950 s cases are compared. Similarly, in the SHRMM 875 s case, the two reductions are 22% and 18%, respectively. This represents a significant savings in launch mass, complexity, and overall cost.

Removing Cargo MTV #2 from the mission concept is not without technological risk. For the single Cargo MTV mission, again by simultaneously minimizing the remaining propellant in the Cargo and Crewed MTV, the mission can be completed with a minimum specific impulse of 865 s. Compare this to 835 s, which is the minimum specific impulse for which the two-Cargo MTV SHRMM will be feasible. This highlights that the ability to significantly reduce mission cost by using a single Cargo MTV is contingent on a minimum NTR performance requirement. If the capability of the NTR is uncertain, the dual Cargo MTV SHRMM mode will provide more robustness guarding against the downside risk of loss of mission.

Table 11: SHRMM Figures of Interest (without Cargo MTV #2)

Figure of Interest	DRA 5.0 (NTR, I_{sp} 950 s)	SHRMM (NTR, I_{sp} 950 s)	SHRMM (NTR, I_{sp} 875 s)	SHRMM (no Cargo MTV #2; NTR, I_{sp} 950 s)	SHRMM (no Cargo MTV #2; NTR, I_{sp} 875 s)
Ares V launches	9	8	8	7	7
Crew launches	1	1	1	1	1
Total mass in LEO (mT)	848.7	706.0	706.0	536.2	550.7
Number of sites sampled	1	6	6	6	6
MTV propellant usage (mT)	356.8	374.2	389.5	291.2	321.1
Crew consumables demand (mT)	15.3	12.5	12.5	12.5	12.5
Crew consumables remaining (mT)	14.4	1.2	1.2	1.2	1.2
Crew-days of exploration (crew-days)	3,000	360	360	360	360

3.3 Advanced Chemical Propulsion In-space Transportation Architecture

DRA 5.0 presents an alternate in-space transportation architecture for a human mission to Mars, the so-called Advanced Chemical Propulsion (ACP) architecture. The concept involves using multiple-stage vehicles made up of separate propulsive elements for the major mission maneuvers, namely TMI, MOI, and TEI (NASA, 2009). The propulsive elements are designed to emphasize commonality and a certain level of modularity allowing adjustment of the vehicle propulsive output depending on the mission trajectory. An analysis was performed to assess the feasibility of using ACP to support SHRMM.

DRA 5.0 does not report the predicted specific impulse of ACP so instead it was calculated from the NTR specifications by assuming equivalent performance of the Cargo MTVs in both the NTR and ACP architectures since the implication is that both architectures can be used to support the DRA 5.0 reference mission. Table 12 shows the ACP specific impulses that correspond to the upper and lower bounds of the predicted NTR specific impulse.

Table 12: Corresponding NTR and ACP Specific Impulse

NTR Specific Impulse (s)	ACP Specific Impulse (s)
875	482
950	523

The analysis proceeded in the same manner as in Chapter 2, allowing for in-space restart-able engines, implicitly assumed in DRA 5.0, and assuming a constant crew demand of 3.375 kg per person daily for crew provisions.

Figure 11 shows the bat chart for the ACP incarnation of SHRMM. Three Ares V launches are required in the Cargo Pre-positioning phase, carrying the hoppers, MAVs, Pirogue, and Cargo MTV propulsive stages. In the Crewed MTV Mission phase, five Ares V launches are used to construct the Crewed MTV. The crew launch then follows shortly afterward and the mission progresses as before.

When a specific impulse of 523 s is assumed, corresponding to the upper bound NTR specific impulse of 950 s, ACP suffers from the same challenge as NTR: the TEI maneuver for the return journey not feasible from a propulsion perspective. Under these assumptions, an additional ΔV of 608 m/s is required at TEI. Fortunately, ACP can deliver enough crew provisions to satisfy demands.

A second TEI stage, exactly the same as the TEI stage already propelling to the Crewed MTV, was used to provide the extra ΔV as a solution analogous to including the TEI LH2 Drop Tank in the NTR architecture. The second TEI stage is pre-positioned in ASO with the Cargo MTV and is docked to the Crewed MTV before the now two-stage TEI maneuver. With this modification, SHRMM supported by the ACP in-space transportation architecture is feasible from both a propulsive and crew provisions standpoint.

Using a similar methodology, the ACP specific impulse was reduced to determine the minimum propulsive performance required to support SHRMM. This value was found to be 516 s, representing a fairly small margin of underperformance for which SHRMM can be supported by ACP. The limiting maneuver in this case is the MOI stage for the Crewed MTV.

Table 13 shows that compared to the NTR in-space propulsion architecture (Table 11), ACP requires a considerable increase in LEO mass (753.0 mT compared to 706.0 or 550.7 mT) and also uses significantly more propellant (approximately 520 mT compared to at most 389.5 mT), a direct result of the lower efficiency of the ACP architecture propulsion stages. Furthermore, ACP is not as robust as NTR, being able to tolerate only a 1.3% decrease in specific impulse before the concept of operations requires a substantial redesign. This underscores the decision NASA made, selecting NTR as its design reference in-space transportation architecture, essentially shifting risk from mission operations to technology development.

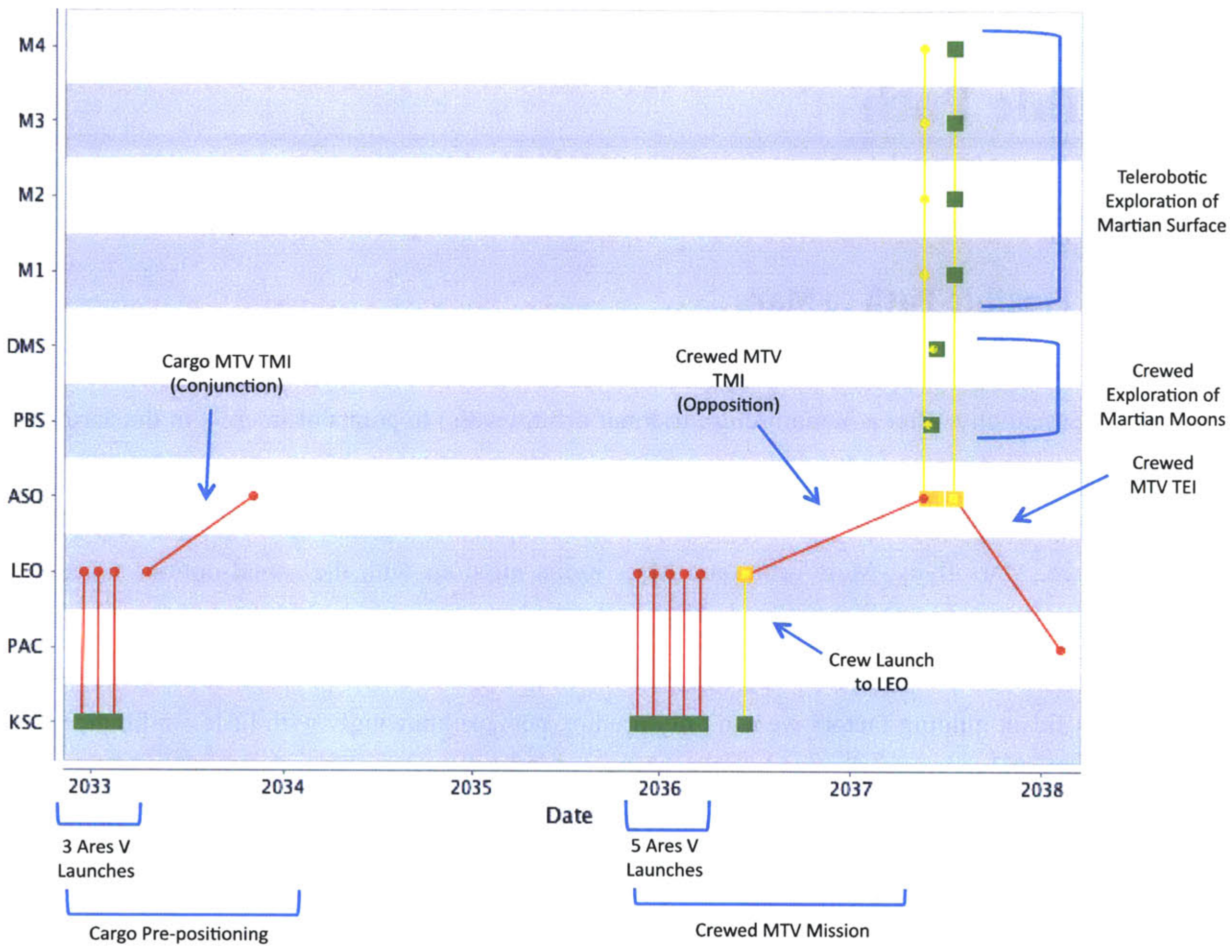

Figure 11: ACP SHRMM Bat Chart

Table 13: Advanced Chemical Propulsion Architecture Figures of Interest

Figure of Interest	SHRMM (ACP, I_{sp} 523 s)	SHRMM (ACP, I_{sp} 516 s)
Ares V launches	8	8
Crew launches	1	1
Total mass in LEO (mT)	753.0	753.0
Number of sites sampled	6	6
MTV propellant usage (mT)	518.4	522.6
Crew consumables demand (mT)	12.5	12.5
Crew consumables remaining (mT)	1.2	1.2
Crew-days of exploration (crew-days)	360	360

4 A Martian Exploration Campaign Along the Flexible Path

4.1 Background

4.1.1 The Flexible Path to Mars

In Augustine et al. (2009), the notion of the Flexible Path to Mars is elucidated. Figure 12 illustrates its philosophy. Essentially, after a human return to lunar orbit, visit(s) to points of interest in the earth-moon and earth-sun systems (e.g., earth-sun Lagrange point L1), and mission(s) to NEOs, several options then lead to the ultimate goal of landing humans on the surface of Mars. These options include a combination of lunar surface, Mars flyby, Mars orbit, and Mars moon missions with the actual options taken being directed by technological advancements, scientific discoveries, political direction, and budgetary constraints. One theme common to these four forces is they are all important and uncertain; they represent significant guiding factors we can only predict, perhaps knowingly with little confidence, in the present. The Flexible Path is thus responsive to the resolution of future uncertainties, deferring programmatic decisions until more information is available, and advances progress toward a human Mars surface mission.

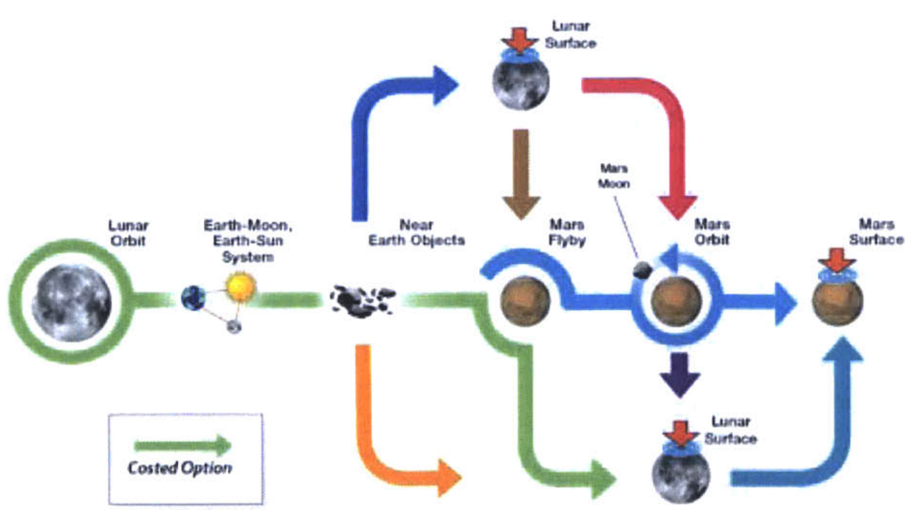

Figure 12: The Flexible Path to Mars (reproduced from Augustine et al. (2009))

4.1.2 Propellant Depots

The use of propellant depots as a method of enabling high-energy space missions has been considered for at least forty-five years (Morgan, 1965). A variety of depot architectures, with the aim of enabling or reducing the cost of lunar or Martian exploration, has been suggested. For example, Keaton (1985) investigates a depot in a halo orbit at Sun-Earth L4 and Zegler and Kutter (2010) consider a depot in Earth-Moon L2.

Regardless of the location, one general argument for use of a propellant depot put forth by Zegler and Kutter (2010) is the reduction of overall long-term exploration costs by utilizing existing, reliable, and (relatively) inexpensive launch vehicles to ferry propellant, a low-value commodity, to LEO. They argue that moving propellant to LEO, representing approximately 70% of mass launched to orbit, should be a "go-do" task that "can take place without significant development or risk." Further, they argue that instead of bolstering launch vehicles with extra stages to enhance propulsive capabilities, forcing each individual mission to supply and carry all of its required energy, a propellant depot in LEO can provide an "energy savings account" so that launch vehicles can concentrate on moving high-value payloads to orbit while the depot provides the required propellant for interplanetary injection.

In his report, Griffin (2005) addresses the economic and risk-reduction advantages of not only employing propellant depots, but also privatizing their operation. Essentially, the risk of operating the depot reliably and efficiently is transferred to industry, which through profit motive and competition aims to lower the cost of operation and achieve consistent performance. NASA exploration missions can then take advantage of these services when required, but also bypass them if they are too uncertain an option leaving private companies to bear the brunt of the economic fallout. As before, newly developed launch vehicles focus on moving payloads and other mission-specific elements while positioning propellant in orbit is done by industry using simpler and less costly launch systems.

Tanner et al. (2006) describe an interesting potential application of propellant depots in the context of the human exploration of Mars. After the launch of a payload (such as a Mars surface habitat or interplanetary transit habitat) aboard an Ares V rocket, instead of jettisoning the EDS used to boost the payload into LEO, it is refueled by a propellant depot and used to inject the payload into a Mars-bound trajectory, precluding the requirement of either the NTR- or ACP-defined in-space transportation stages. As seen in the above analyses, launching and then requiring Earth-orbit rendezvous of payloads and in-space transportation stages results in added complexity in the form of LEO construction and would also demand the development and build costs of a clean-sheet design. Instead, if those stages were replaced by the utilization of a refueled EDS, the aforementioned benefits of a propellant depot could be gained along with relaxing the requirement for advanced chemical propulsion stages and, perhaps more significantly, sidestepping the environmental and policy labyrinth of justifying the use of nuclear propulsion in space. Tanner et al. (2006) conclude that using the EDS in conjunction with a propellant depot stationed in LEO is more cost-effective than employing NTRs, though it should be noted that this study was based on an earlier version of DRA 5.0.

As the chapter progresses, it will be evident that a propellant depot in Mars orbit is also required. This notion has been suggested in literature, such as in O'Leary (1992), where use of a Space Shuttle External Fuel Tank as a propellant storage device in Mars orbit is investigated. In this analysis, less emphasis will be placed on the design and possible use of legacy components for the propellant depot, and instead more focus will be put on its requirements from a logistical perspective.

4.1.3 Mission Opportunity

Given the potential benefits of establishing a propellant depot in LEO and its ability to support a human surface exploration mission to Mars, there is a possibility that this architecture could also support SHRMM and other Flexible Path missions. More importantly, the propellant depot could be a link between SHRMM and a human mission to the surface of Mars, first enabling SHRMM to provide initial scientific value and exposure to operating in deep space and Mars orbit, and then transitioning to a human surface mission. In this way, SHRMM acts as a stepping-stone along the Flexible Path leading eventually to "boots on the ground" of Mars as it was originally envisioned (Cunio et al., 2010a).

Thus, the remainder of this chapter focuses on the analysis of an exploration campaign to Mars, beginning with SHRMM and culminating in a human landing on the surface of Mars, enabled by the use of propellant depots.

4.1.4 A Note on Boil-off

In regard to the technical issue of boil-off, Zegler and Kutter note that while "existing, demonstrated technologies can effectively achieve zero boil-off for oxygen, it is far more difficult to accomplish this for hydrogen" (Zegler and Kutter, 2010). In the analysis that follows, as throughout the rest of this thesis, for model simplicity it is assumed that zero boil-off can be achieved for both oxygen and hydrogen, although it is noted as a significant technical barrier to the emplacement of propellant depots.

4.2 Concept of Operations

Four missions were defined and analyzed for propulsive and crew provision logistics feasibility in SpaceNet. These missions, detailed further in the sections that follow, are:

- Mars Tele-exploration Mission (MTM)
- Phobos and Deimos Sorties (PDS)
- Phobos Exploration Mission (PEM)
- Mars Surface Mission (MSM)

The missions are designed to be modular, self-sufficient, and form a progression toward landing humans on the surface of Mars. The point of continuity between the missions is the propellant depot, allowing variable injection of energy into the mission according to propulsive requirements. In line with the Flexible Path, some or all of the missions leading up to MSM can be modified, delayed, or cancelled depending on the prevailing situation. Because of their independence, except possibly through requirements in the propellant depot if a reusable depot is employed, none of the missions explicitly require the completion of any other mission, though the more missions performed, the farther humans advance along the space exploration learning curve.

In the following analysis, it is assumed that opposition and conjunction class trajectories, along with their propulsive requirements, repeat every 26 months. While it is not precisely true that the propulsive requirements remain the same for each launch window (due to slight variations in orbital characteristics, see Ishimatsu (2008)), the differences are considered negligible at this level of analysis.

Before the commencement of these missions, propellant depots must be designed, built, and positioned for refueling support. The next section overviews the depot infrastructure design.

4.2.1 Propellant Depot Infrastructure

Two types of propellant depots are required to enable this set of missions: one stationed in LEO and one in Mars orbit. The LEO propellant depot (LPD) is constructed, before the commencement of any of the four missions, over the course of three Ares V launches, having a total dry mass of 52.2 mT and a propellant capacity of 255 mT yielding a propellant mass fraction of 0.83. Similarly, the Mars Orbit propellant depot (MPD) has a dry mass of 11.1 mT and a propellant load of 54.3 mT for a propellant mass fraction of 0.83. These mass fractions agree well with literature as shown in Table 14.

In addition, a propellant refueling module (PRM) was modeled as the method of storing propellant bound for the LPD. Its design was based on analysis by Tanner et al. (2006): a dry mass of 38.2 mT and a propellant load of 85 mT and sized to be launched on an Ares V. An alternative PRM design, to be used with the Delta IV Heavy, is also presented in Tanner et al. (2006). Using the Delta IV Heavy instead of the Ares V would be aligned with the goal of using less costly launch vehicles with flight experience, and the choice of using the Ares V as the primary refueling vehicle was made to simplify the modeling since it has already been assumed that the Ares V has been designed and built.

The MPD is not refueled after use; new MPDs are transported as necessary to provide refueling capabilities in Mars orbit.

Table 14: Propellant Mass Fraction for LOX/LH2 Propellant Depots

Useable Propellant (mT)*	Propellant Mass Fraction	Reference
100	0.848	(Street, 2006)
50	0.860	(Street, 2006)
50	0.840	(Flaherty et al., 2007)
76.5	0.814	(Tanner et al., 2006)
221	0.832	(Tanner et al., 2006)

*This figure takes into account expected boil-off.

4.2.2 Mars Tele-exploration Mission (MTM)

The first of the four missions, MTM, shown in Figure 13, is a derivative of SHRMM. Two spacecraft are sent to ASO. First, the cargo payload consisting of three robotic exploration teams (each involving two hoppers and one MAV) and an MPD is launched to LEO using an Ares V rocket. The EDS is then refueled before it is put on a conjunction class trans-Mars trajectory where it then inserts into ASO and loiters there waiting for the crew. During the next available launch window, a crewed payload consisting of a CEV, MTH, and six crewmembers are launched on an opposition class trans-Mars trajectory after also being refueled in LEO. After a propulsive MOI into ASO, the crew rendezvous with the cargo payload, send the three hopper/MAV teams to the surface and perform robotic exploration as outlined in SHRMM, and also refuel the EDS in preparation for TEI. Samples are launched to the MTH which subsequently returns to earth after spending approximately sixty days in ASO.

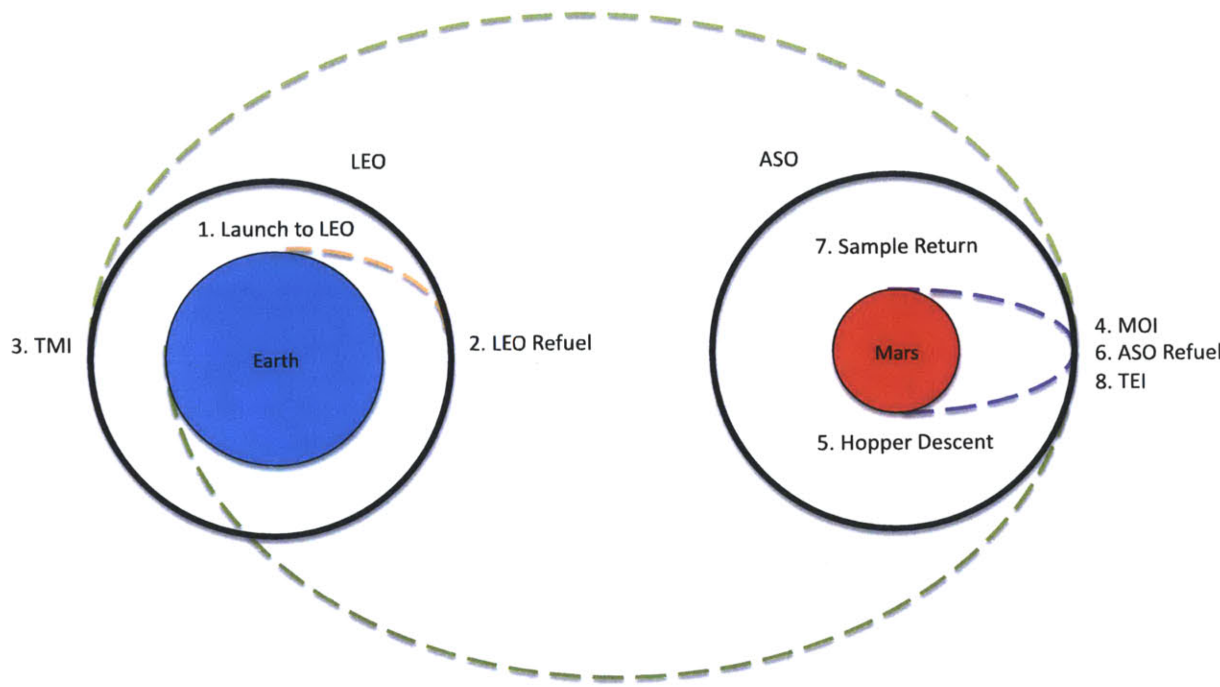

Figure 13: Mars Tele-exploration Mission

In the context of the Flexible Path, this mission represents the first human stay in Martian orbit. From a scientific standpoint, this also represents the first return of Martian samples, especially samples that can be analyzed by humans before their return to earth. The crew would have the opportunity to demonstrate and practice joint human and robotic exploration, Mars orbit rendezvous, and gather more information on the health effects (i.e., radiation, microgravity, and psychology) of extended deep space travel and exploration.

The primary reason SHRMM was separated into two separate missions is to satisfy propulsion requirements. A fully fueled EDS is not capable of performing the all-propulsive TMI and MOI maneuvers, necessitating the division of SHRMM into two smaller missions. However, there is a resulting benefit in the form of reduced individual mission complexity, in effect lengthening the Flexible Path and allowing the acquisition of more operational experience in smaller portions.

4.2.3 Phobos and Deimos Sorties (PDS)

Figure 14 overviews PDS which represents the complement of MTM; that is, the combination of MTM and PDS is SHRMM. Again, in total, two spacecraft are sent to ASO and again, they both consist of a LEO-refueled EDS and a payload. The first is a cargo payload consisting of the Pirogue excursion vehicle, a 1-mT science package, and an MPD. This payload is pre-positioned in ASO on a conjunction class trajectory and awaits the arrival of the crewed payload consisting of a CEV, MTH, and six crewmembers which arrive on the next available opposition class launch window. After successful rendezvous with the cargo payload in ASO, two crewmembers embark on a seven-day sortie to Phobos, explore and gather samples, and then return to ASO. Then, two other crewmembers (or the same pair) repeat the exercise for Deimos. Finally, after the EDS has been refueled, the crew embark on the return journey after spending approximately sixty days in the Martian neighborhood.

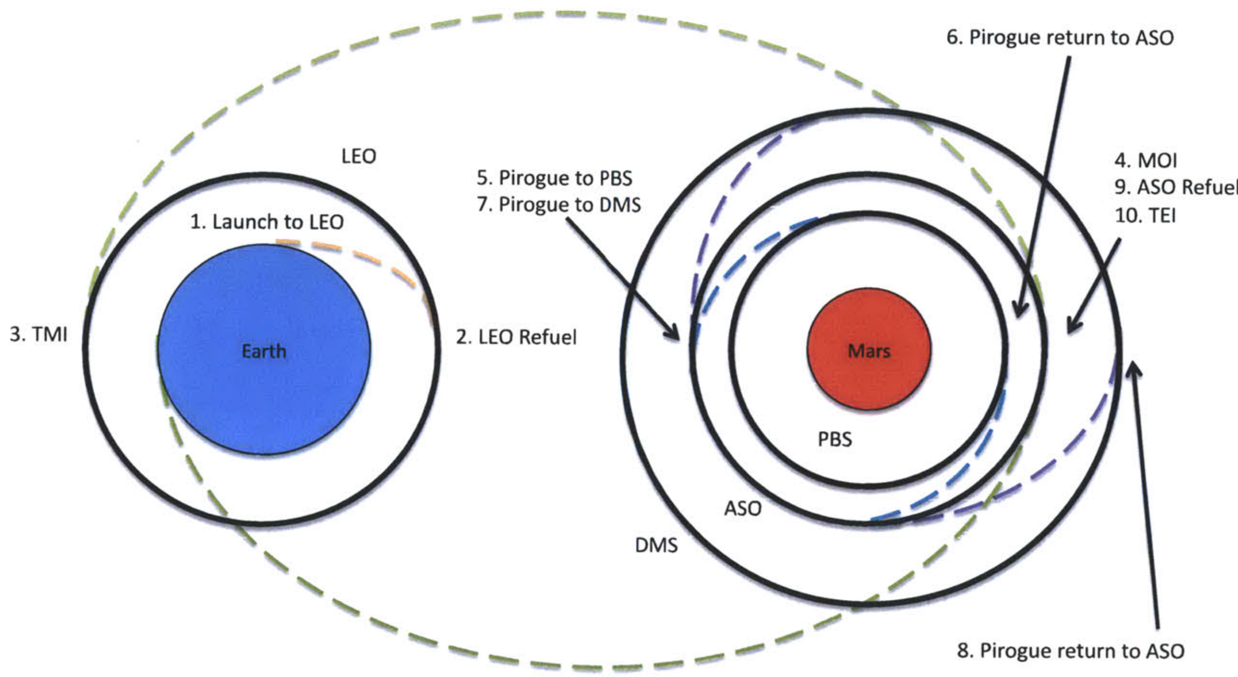

Figure 14: Phobos and Deimos Sorties

For the Flexible Path, this mission represents the first direct human contact with a body in the Martian system. Large samples (on the order of hundreds of kilograms) can be gathered from both Martian moons, analyzed in orbit, and returned to earth for detailed investigation. Further experience is gained in Mars orbit rendezvous, long-term human space travel, and "landing" on what is essentially an asteroid, while from an inspirational standpoint this mission represents the first human landing on another moon in the solar system.

4.2.4 Phobos Exploration Mission (PEM)

Discoveries from previous missions would direct the goals of future missions. For example, the confirmation of water on Phobos may channel efforts into a dedicated Phobos exploration mission. Without such information at this time, given the premise of the Flexible Path's philosophy one can only speculate on Phobos' scientific value.

O'Leary (1987) compares the advantages and disadvantages of a Phobos exploration mission compared to a Deimos mission from operational, energetic, and scientific standpoints. The basic conclusion is that at, at a high level, there are advantages to going to either Phobos or Deimos first, and the differences between the two are not very large.

MEPAG (2008) notes that the Martian moons are of scientific importance primarily because their origins are not understood and further exploration is warranted. Galimov (2010) further highlights that Phobos is potentially a unique object for studying the mechanism of planet formation as it is believed to be an asteroid captured in Mars orbit and largely unchanged by secondary processes, possibly relict material of the solar system.

As such, a dedicated Phobos exploration mission is included to demonstrate how the propellant depot architecture can support these scientific and exploration goals.

Figure 15 shows a high-level representation of PEM. The primary difference between PEM and both MTM and PDS is that the vehicles for PEM are stationed in PBS as opposed to ASO and all mission assets remain in Phobos orbit instead of being spread over different locations in the Martian system. From a modeling perspective, the consequent change in propulsion requirements was determined to be 5.6 km/s for a conjunction class TMI and all-propulsive MOI while a round-trip opposition class trip would require 8.8 km/s. These figures were calculated using the methodology presented in Section 2.2.2. O'Leary (1988) calculates that for non-aerobraking missions, a Phobos rendezvous would require 5.4 km/s and a round-trip mission to Phobos requires 7.3 km/s. Though it is not explicitly stated, these figures seem to represent a conjunction class mission opportunity, supported by the good agreement between the cargo mission ΔV values. Regardless, these figures suggest the propulsion requirements used in this analysis are conservative.

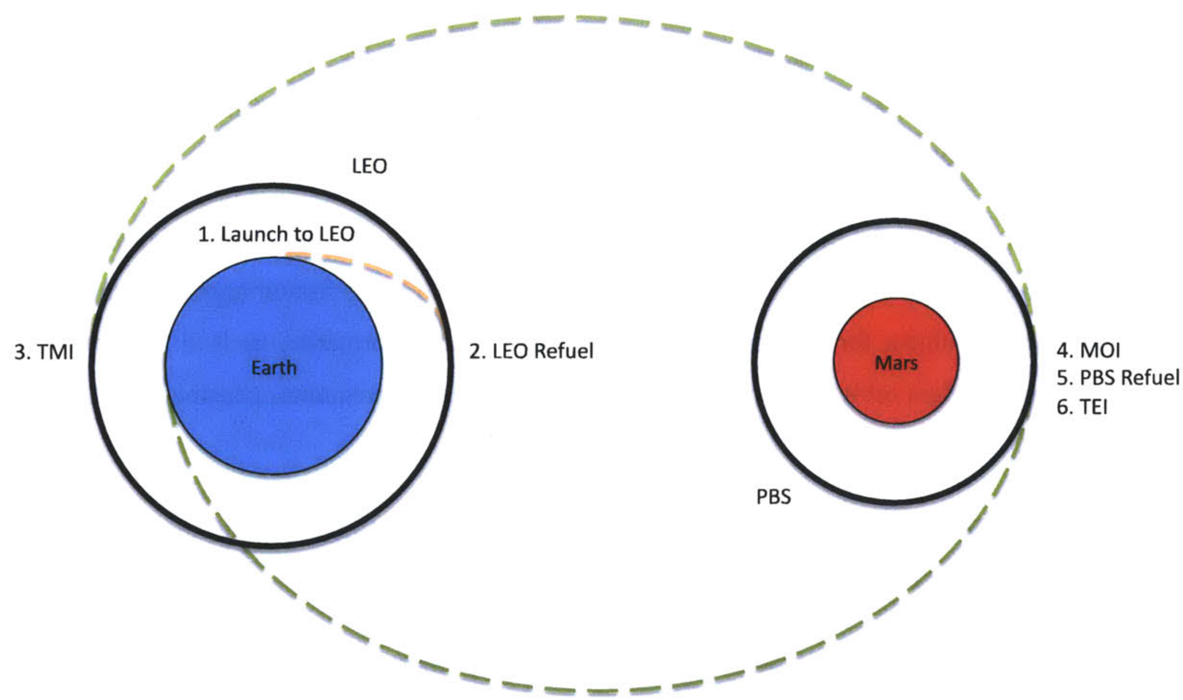

Figure 15: Phobos Exploration Mission

The mission begins as in MTM and PDS with a cargo payload launched on a conjunction class trajectory after being refueled in LEO. It inserts into Phobos orbit and loiters there while the crewed payload is launched, refueled, and performs the TMI maneuver on the next opposition class opportunity. The crew then spends approximately sixty days in Phobos vicinity, gathering samples and performing science, after which it refuels the EDS and performs the TEI maneuver. One detail to note is that the propellant depot, for the Phobos Exploration Mission, is left in Phobos orbit which would limit its reusability for future missions based in ASO.

This mission, hopefully leveraging on experience gained during previous NEO missions, allows for an extended and concentrated study of Mars' closest companion and the harvesting of large quantities of surface samples. Scientifically, this has been postulated as valuable, though only the passage of time and the resolution of future uncertainties can validate this hypothesis. From Phobos, close observations can also be made of the Martian surface, scouting a potential base location for the eventual human Mars surface mission.

All three Mars orbit missions also provide experience in valuable semi-autonomous crew operations. Because of the communications delay, crews will be required to function at some level without Earth-based support. Testing crew capability in missions with comparatively less danger to crew safety (ones with reduced extra-vehicular activity and no EDL) allow experience to be gained while not concurrently assuming maximum risk.

4.2.5 Mars Surface Mission (MSM)

MSM (shown in Figure 16) is the end goal of the Flexible Path. It involves sending four spacecraft to Mars. The first carries an MPD and the CFC, a contingency to sustain the astronauts in the event that they must abort Mars EDL, thereby being cut off from the crew provisions pre-positioned on the surface. The second and third spacecraft carry the Surface Habitat (SHAB) and Mars Descent Ascent Vehicle (MDAV) as suggested by DRA 5.0. The fourth and final spacecraft carries the six crewmembers in the MTH along with the CEV for Earth re-entry. The three cargo payloads are launched during one conjunction class launch window while the crewed spacecraft follows approximately twenty-six months later. All spacecraft travel on the conjunction class trajectory and are parked in a Reference Mars Orbit (RMO), specified as a 250 x 33,793 km 1-sol orbit by DRA 5.0. Shortly after reaching RMO, the SHAB descends to the Martian surface and begins preparations for the arrival of the crew.

When the crewed spacecraft reaches RMO, it first rendezvous with the MPD and CFC and refuels the EDS to prepare for mission abort should it be necessary. After being checked-out, the crew descends to the Martian surface in the MDAV and nominally spends the next 530 days exploring the local area. At the end of their surface stay, the crewmembers, along with 250 kg of surface samples, ascend to RMO, rendezvous with the MTH and CEV, and perform the inbound TEI maneuver.

This mission is the capstone of the Flexible Path exploration strategy. It leverages experience from gained from previous missions (in, for example, long-term space travel, crew autonomy, and Mars orbit rendezvous) while introducing new elements like crewed EDL, in-situ resource utilization, surface exploration after extended microgravity exposure, and crewed ascent from the Martian surface. An unprecedented volume of samples will be returned to earth for examination, as well as inspiration for the current and future generation of astronauts, scientists, and engineers.

In terms of modeling, the ΔV requirements were taken directly from DRA 5.0, as were the designs of the SHAB and MDAV surface assets. As with the previous three missions, the mission propulsive requirements dictated that an MPD be positioned in RMO to provide propellant for TEI.

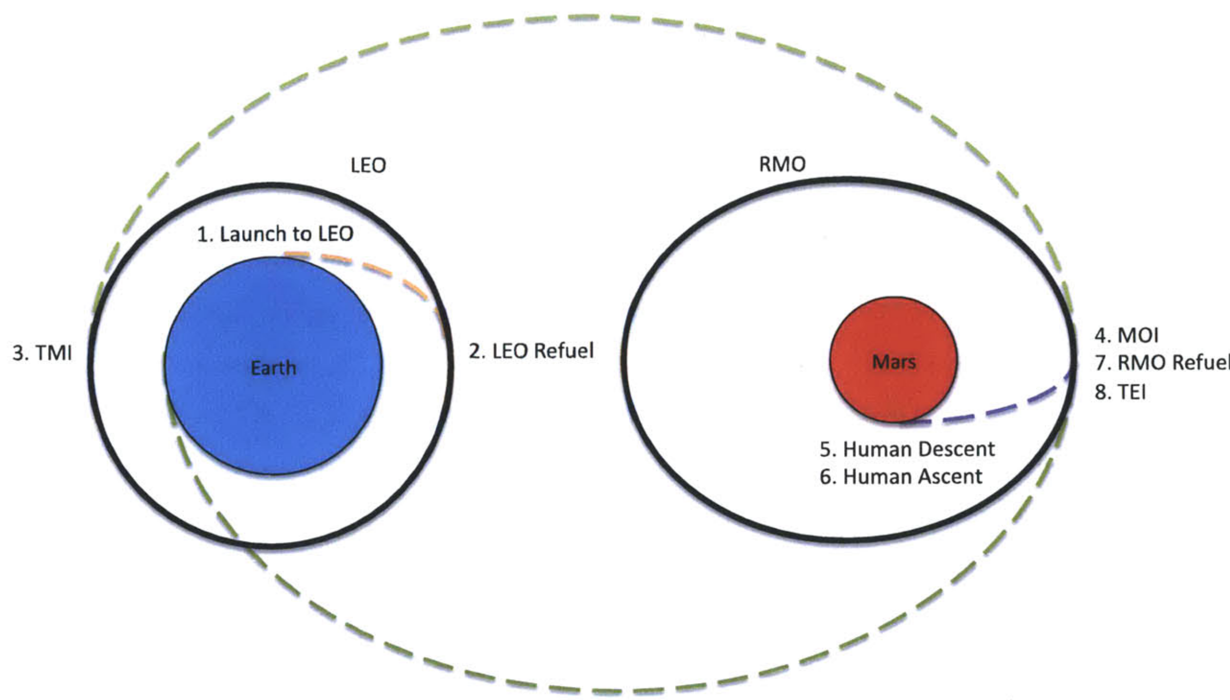

Figure 16: Mars Surface Mission

Further, Grogan (2010) highlights the inadequacy of the logistics infrastructure specified in DRA 5.0 in two respects. First, the crewmembers are forced to utilize the CFC not as contingency supplies but necessary supplies to bring them to mission completion. Grogan's solution was to manifest an additional CFC to serve as contingency supplies which is the solution adopted here. Second, the crew provisions demand while on the Martian surface was assumed to be reduced to 2.375 kg per person daily from the 3.375 kg per person daily during in-space travel as suggested by Grogan (2010). Even at this rate of consumption, the Martian surface assets do not have enough capacity to support the 530-day exploration phase. To solve this problem, the crew provisions capacity for both the SHAB and MDAV were both increased by 1 mT. As noted by Grogan (2010), because of the tight propellant margins for the SHAB and MDAV, this additional capacity may have to come at the expense of science equipment and/or other exploration assets.

4.3 Analysis, Results, and Discussion

The analysis of the exploration campaign was performed using SpaceNet Version 2.5r2. The missions were modeled under the same assumptions used in the feasibility analysis of SHRMM, listed in Section 2.2.1, along with the modifications to the MSM described above in Section 4.2.5. This includes the assumption that human EDL to and ascent from the Mars surface are feasible maneuvers when the elements in DRA 5.0 are utilized.

For the Martian exploration campaign, Figure 17 and Table 15 show the exploration network and location designations, accordingly. Compared to the single mission defined in SHRMM, this campaign does not necessarily contain many more locations visited, but instead the revisiting of locations for longer periods of time and by different assets (i.e., robotic explorers versus human explorers).

Figure 17: Mars Exploration Campaign Network

Table 15: Mars Exploration Campaign Locations

Body	Location	Description
Earth	KSC	Kennedy Space Center
Earth	LEO	Low Earth Orbit
Earth	PAC	Pacific Ocean Splashdown Zone
Mars	ASO	Areostationary Orbit
Mars	PBS	Phobos Orbit
Mars	DMS	Deimos Orbit
Mars	RMO	Reference Mars Orbit
Mars	MV	Mawrth Vallis
Mars	GC	Gale Crater
Mars	HC	Holden Crater Fan

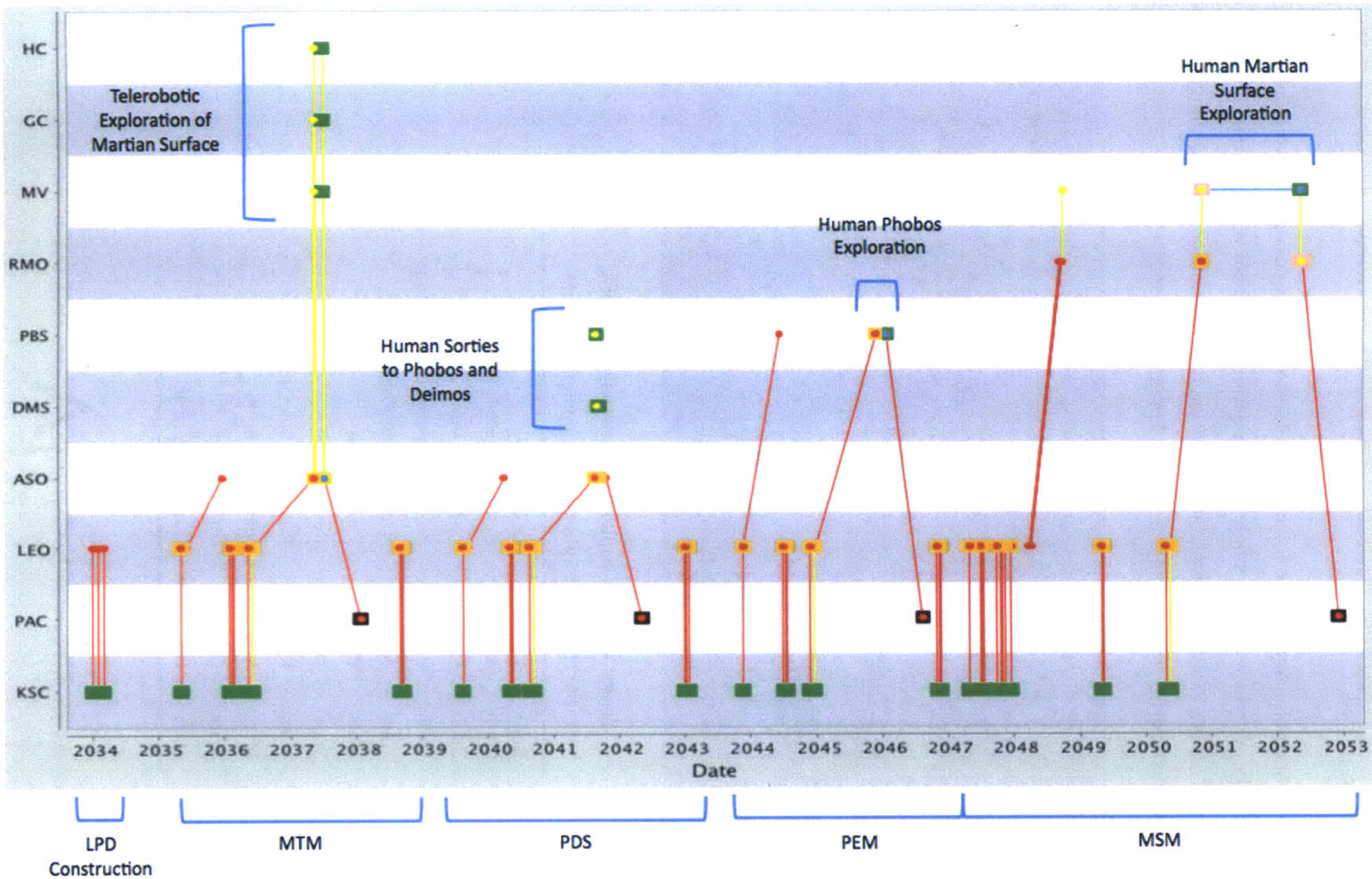

Figure 18: Mars Exploration Campaign Bat Chart

Figure 18 shows the complete bat chart for the Mars exploration campaign assuming a nominal progression with each mission executed once (though there can be value in repeating missions with identical or similar objectives). It shows the five broad phases of the mission: the construction of the LPD and the four exploration missions that follow. It highlights the use of the propellant depot, as most of the missions are refueling flights from KSC to LEO compared to the relatively few flights that are bound for the Martian system.

Further, the bat chart highlights the range of exploration sites visited over the course of the campaign, using both robotic and human explorers, and the notion of revisiting sites to build on previous knowledge, experience, and infrastructure.

The timeline used in this analysis is somewhat arbitrary. It is not necessarily required that the mission timeline be adhered to given the periodic nature of the TMI windows. It may be attractive to lengthen the mission timeline in certain phases, especially in ones where refueling missions are concentrated, to allow for mission delays and launch failures. There is a trade, however, as the propellant depot will degrade in operability and may have to be replaced before the end of the campaign as a 10-year service life has been assumed previously in literature (Street, 2006) and the campaign presented in Figure 18 suggests a 20-year timeline. While explicit replacement of the LPD was not modeled, its similarity to the PRM justifies the assumption that should an LPD be rendered inoperable, the next PRM launches can be replaced with LPD launches, and a new LPD can be constructed without loss of continuity.

Table 16 shows the figures of interest for the Martian Exploration Campaign. Several observations can be made from these results:

1. All four missions are feasible from a propulsive and crew provisions logistics standpoint.
2. Although all four missions are feasible, they have tight propellant margins. The remaining propellant in the EDS, as a percentage of the propellant used, ranges from 0.9-4.6%. Down-scoping scientific payloads or use of propellant-saving technologies, such as aerocapture, may be necessary to mitigate risk of loss of mission and crew.
3. A clear buildup of human exploration and mission complexity is demonstrated. The first three missions involve a gradually increasing number of human-days spent interacting with Martian bodies. Concurrently, MSM constitutes somewhat of a "double mission" requiring twice as many Ares V launches and approximately twice as much total mass in LEO. At the same time, however, the scientific return in robot- and human-days of exploration increases nearly tenfold while the mass of returned samples gradually increases.

Several more Ares V launches, when compared to the original DRA 5.0, are required. This stems from the lower specific impulse attributed to the EDS (449 s) as opposed to the higher NTR and ACP specific impulses (from Table 12: 875-950 s and 482-523 s, respectively). The trade here is between Ares V launches and reduced design and build costs along with the associated complexity involved with the specialized NTR and ACP in-space transportation stages. As mentioned before, the Ares V refueling launches could be replaced by Delta IV Heavy launches to further reduce reliance on launch vehicles that currently exist only in paper form.

Table 16: Martian Exploration Campaign Figures of Interest

Figure of Interest	MTM	PDS	PEM	MSM	*Campaign Totals*
Ares V launches (mission payloads)	2	2	2	4	*10*
Ares V launches (PRM payload)*	6	6	6	11	*29*
Crew launches	1	1	1	1	*4*
Total mass in LEO** (mT)	681.7	681.7	681.3	1,448.7	*3,493.4*
Number of sites sampled	3	2	1	1	*5*
Returned sample mass (kg)	3	150	150	250	*553*
EDS propellant usage (mT)	510.9	510.9	511.9	1,019.1	*2,552.8*
EDS propellant remaining (mT)	4.7	4.7	4.8	47.3	*61.5*
Crew consumables demand (mT)	12.5	12.5	12.5	15.3	*52.8*
Crew consumables remaining (mT)	1.2	1.2	1.2	12.3	*15.9*
Robotic-days of exploration (robot-days)	360	0	0	1,060	*1,420*
Human-days of exploration (human-days)	0	28	360	2,120	*3,568*

*Includes launches required construct LPD
**Includes mass of stack immediately before TMI

4.4 Conclusions

From a propulsive and crew provisions logistics perspective, this exploration campaign is feasible and is aligned with the overarching philosophy of the Flexible Path as outlined in The Augustine Report. The missions presented represent a gradual ramp up in human exploration of Martian-system bodies culminating in a human landing on Mars. At the onset, during MTM, no human exploration occurs beyond the confines of the MTH. As the missions progress, humans spend longer and longer periods of time directly interacting and exploring Martian-system bodies while drawing on a pool of continually increasing operational experience.

Further, this set of missions does not have to be strictly adhered to. Their modular nature, enabled by the use of propellant depots and in-space refueling, allowing for the addition, modification, delay, and cancellation of any number of missions, precludes the burden of a critical path of tasks that must be performed en route to a Mars landing, which is especially important in the context of evolving budgetary constraints. For example, Phobos could be used as a base of tele-operations, as suggested by the Augustine Report, effectively combining MTM and PEM into a single exploration effort.

Additionally, common elements (e.g., LPD and EDS) are used to provide the in-space transportation capabilities for all missions, allowing for repetitive use and thereby building flight experience and bulwarking technical confidence. Lunar and Lagrange point missions could also be conducted using the EDS and propellant depot architecture, allowing the amortization of the design, development, and testing costs of the LPD and EDS to be amortized over a prolonged campaign. As a result, the use of specialized in-space propulsion stages (e.g., NTR, shielded NTR, and ACP TEI and TMI stages) serving only one mission is not required. Reiterating, the propellant depot serves as an "energy savings account" (Zegler and Kutter, 2010) that can provide a correctly metered amount of propellant for the mission at hand.

While consideration of issues such as inability to achieve zero boil-off, reduced component reliability, and desire for increased levels of risk mitigation may result in smaller exploration payloads and down-scoped mission objectives than what is presented in this potential campaign, the overall campaign architecture is the focus of this analysis. However, certain technologies, like aerocapture, that could significantly reduce the overall propulsive requirements, were not taken advantage of because of their uncertain technological readiness. Their use would bolster the margins in all missions discussed above.

No attempt was made to quantify the cost of the campaign. Because of the breadth of new systems required and uncertainty in technological advancement and evolution of exploration directorates, it was seen as being too imprecise to be of useful interpretation.

5 Technology Investment and Real Options

5.1 Introduction

The campaign described in Chapter 4 represents a possible gradual evolution of human exploration of the red planet rather than an "all-at-once" approach. Though it commences with missions specifically designed, among other considerations, with reduced dependence on enabling technologies, some thought should be given to what corresponding technological evolution is required to support such a campaign.

Specifically, technological innovation will be required in the areas of space radiation protection during long-duration spaceflight, strategies to mitigate and recover from microgravity environments, and rendezvous with small bodies like Phobos and Deimos, just to name a few. Some capabilities, such as long-duration medical treatment, support multiple missions while other capabilities, such as in-situ resource production, may only serve the humans-to-surface mission mode. In an ideal situation, NASA would have all the resources necessary to obtain all required capabilities for all projected missions. However, in a budget-constrained environment, a methodology is required to optimally determine investment technology portfolios and their sequencing.

This challenge extends further than the Mars campaign suggested in this thesis. A general theme of the Flexible Path is the potential exploration of a number of locations in the inner solar system, from NEOs to Lagrange points to the lunar surface. To achieve this, an even more diverse technology portfolio is required implying an increased number of possible portfolio development sequences, and an even greater need to systematically and effectively select and phase investment options.

As with many large, long, and capital-intensive projects, technology development in the realm of human space exploration is fraught with uncertainty. Some of these uncertainties include probability of successful development, probability of successful infusion, cost, and budgetary uncertainty (Elfes et al., 2006). Their presence further complicates the already complex problem of determining an optimal technology investment portfolio in a scientific, non-market based context. There already exists a body of literature concerning this problem, a brief summary of which follows below.

5.2 *Literature Review*

5.2.1 The Black-Scholes Equation

A real options approach to technology investment selection employing the use of the Black-Scholes Equation is proposed by Shishko and Ebbeler (1999) and Shishko et al. (2004). They develop a computation procedure to quantify the option value of a given technology, allowing for a comparison against the development cost to quantifiably justify investment in the technology. It essentially likens investment in a technology to the purchase of an option. The investment enables but does not necessitate the exercise of a "real" option to produce new products with potentially high returns, analogous to exercising a financial option at a favorable time in the future.

A case study applying this framework to ultra-lightweight propellant tanks (UPT) is presented. The shadow price for investment into UPT is calculated based on the (launch) cost savings that would be achieved if the new UPT technology were available. The case study demonstrates that, under the assumptions made on flight rate, spacecraft characteristics, development costs, and discount rate, the UPT option value is high enough to warrant development investment.

5.2.2 The START Methodology

The START methodology is a method of systematically and transparently phasing technology investment portfolios under budget constraints. It has been developed at the NASA Jet Propulsion Laboratory over approximately ten years and is the subject of a number of publications (Smith et al., 2003a; Smith et al., 2003b; Weisbin et al., 2004; Derleth et al., 2005; Weisbin et al., 2005; Elfes at el., 2006; Lincoln et al., 2006; Weisbin et al., 2006; and Adumitroaie, 2010).

START, though continually evolving, essentially solicits expert estimates on a plethora of subjects such as required technological advances to enable future missions, mission preferences, probability of successful development, probability of successful infusion, capability-enhanced probability of mission success, development costs, time required for technological maturation, and simplified utility curves. The technologies are then non-dimensionally scored and conditioned on probability of successful development, and compared to the estimated development cost to yield a benefit-cost ratio. An optimization is then performed to determine the investment portfolio that maximizes total benefits under a specified budget constraint. The results are visualized as a temporally sequenced optimal profile, enabled missions for various budget levels, and the depiction of the "competition border," the frontier that divides funded technologies and deferred ones. Post-processing of the results include sensitivity and robustness analyses to check how the results vary when the inputs are perturbed. Several case studies have been performed and documented to illustrate the implementation of the START methodology (Weisbin et al., 2004; Derleth et al., 2005; and Lincoln et al., 2006).

5.2.3 Research Opportunity

START is a useful methodology. It is a quantifiable, traceable, and adaptable way of collecting, organizing, and processing information in support of determining optimal technology investment portfolios. Because of its acceptance and continued development at NASA, gauged proximally by the number of papers that continue to be generated on the subject, it will ground the discussion throughout the rest of this chapter.

START's capabilities continue to evolve. One key capability is its capacity for handling uncertainty. The methodology itself cannot inherently generate estimates on uncertain parameters, leaving that to expert opinion, but it can and does incorporate uncertainty (such as uncertainty in development costs) into its analysis allowing for explicit consideration of a very real phenomenon. However, other uncertainties may warrant inclusion into the START framework as well.

In the wake of recent events, the cancellation of the Constellation Program, the uncertainty in mission targets (NEOs, the moon, or Mars), and in the spirit of the Flexible Path, one uncertainty that should be taken into account is the mission target. Does the optimal technology portfolio support the current mission and other missions if goals change in the future?

One method of mitigating this type of uncertainty is flexibility (de Neufville and Scholtes, 2011). Flexibility reconfigures a system, in this case a technology portfolio, in order to maximize auspicious outcomes and minimize unfavorable ones after observing the occurrence of triggering events. In its current form, the START methodology does not explicitly address flexibility in the technology investment portfolio, especially in the face of overarching uncertain mission goals.

Because of time constraints, incorporating flexibility considerations into the START methodology and performing a case study on human Mars mission technologies was not feasible. However, a discussion of how flexibility could be modeled follows, in addition to the hopefully achievable types of insights on the flexibility of the portfolio.

5.3 Proposed Flexibility Analysis Methodology

With the START methodology having already been developed to its current state, flexibility analysis can be easily implemented. The required steps are outlined below.

5.3.1 Predict Future Mission Goals

Currently, mission preferences are defined as single point estimates, essentially given weights to denote their relative importance (Lincoln et al., 2006). In order to perform a flexibility analysis, the evolution of these preferences over time needs to be modeled. Essentially, the mission preferences must be treated as uncertain parameters.

For example, one could assume that every four years, there is a possibility that an incoming president introduces a new exploration policy, altering the mission preferences in the process. Concurrently, upcoming robotic missions such as the Mars Science Laboratory, ExoMars, and robotic lunar missions could influence the probability that NASA will be directed toward a different mission goal as scientific discoveries are made. Finally, impetus from international entities such as cooperative partnerships or mutual competition may spur changes in NASA's human exploration targets.

The author recognizes this is a particularly difficult task. This type of uncertainty emerges from many factors, factors like political context, technological evolution and revolution, unprecedented scientific discovery and public interest, that are in and of themselves difficult to model.

5.3.2 Implementation of Temporal Simulation with Decision Rules

Temporal simulation with decision rules has been used in previous work (Lin, 2008). Essentially, this entails defining a discrete time step, for example one year, and performing a random number draw to simulate whether or not mission preferences change as dictated by the model devised in Section 5.3.1. Because of the stochastic nature of the uncertainty model, sometimes a change will occur and sometimes it will not.

At this point a decision will have to be made. If the mission preferences do not change, the original optimal investment portfolio (found at the beginning of the evaluation period as per the current START procedure) will still be optimal, indicating that no restructuring of the portfolio is necessary. However, if mission preferences do change, an optimization can be performed to determine a new optimal investment portfolio.

Figure 19 shows a time-expanded decision network (TDN) for a hypothetical technology portfolio. Before the commencement of the technology development period, all three technologies, R, Y, and G, are not in development. At the initial portfolio optimization, technologies R and Y are selected for development. Some time later, a chance event causes a change in mission preferences, and a subsequent re-optimization of the technology portfolio takes place. In this example, technology Y is dropped in favor of technology G. As time continues, in this example, no further mission preference altering events occur, and technologies R and G end up being developed with technology Y on the shelf, an unexpected outcome considering the initial portfolio optimization results.

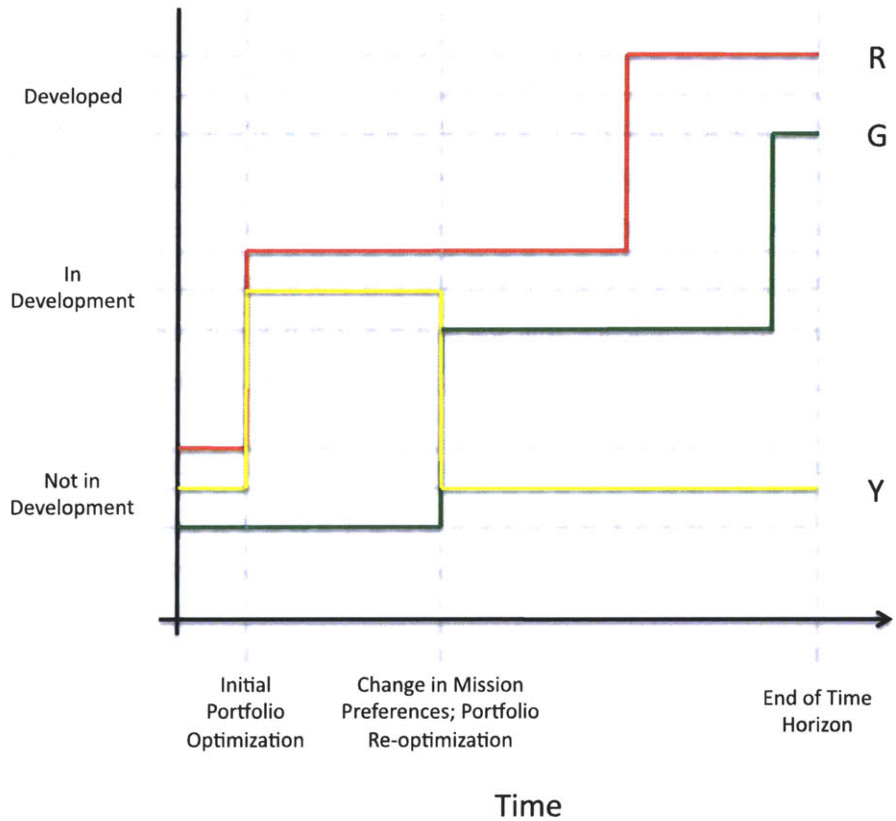

Figure 19: Time-Expanded Decision Network for Technology Selection

There should be some switching costs associated with abandoning some technologies and taking on the development of others. A decision would have to be made with each new optimal investment portfolio: will the increase in utility afforded by adopting the new portfolio be worth the reconfiguration costs? Thresholds would be set for each of these parameters to automate the decision-making process.

During the temporal simulation, at each time step a check is made for changed mission preferences and a consequent re-optimization of the investment portfolio, and a check against the decision rule to determine whether or not the new portfolio is accepted. At the end of a specified time horizon, metrics can be calculated to determine the value of flexibility, such as:

- total switching costs incurred,
- number of missions enabled,

- whether or not the target mission was enabled, and
- increase in utility during the development timeframe.

Using a Monte Carlo simulation framework, this simulation can be repeated many times, each time using a randomly generated instance of mission preference uncertainty, and aggregate statistical measures can be calculated for the simulation metrics, giving an overall picture of the performance of the portfolio optimization strategy under uncertainty.

5.3.3 Extension to General Uncertainties

Mission preferences are not the only uncertain parameters in this technology selection problem. Use of temporal simulation can also enhance the modeling of other uncertainties that vary in time. For example, it is not guaranteed that funded technologies will in fact be successful as there is a certain degree of technological uncertainty. If a technology's development looks less promising in the future, flexibility can be introduced that reduces investment in that particular technology and provides funding for other, more promising technologies. In a sense, this type of analysis hopes to simulate the passage of time which brings about the resolution of future uncertainties, and most importantly, the reaction of technology portfolio managers to those resolved uncertainties.

5.4 Alternative Analysis Method

The above methodology requires a large amount of data collection. Not only is the information required for the START analysis necessarily required, but also estimates on future mission goals which are uncertain and not easily predicted. In particular, because of time and data constraints, the methodology proposed in Section 5.3 is not implemented in this thesis. Instead, an alternative, simplified methodology is proposed here and applied to human exploration of Mars.

Essentially, this method attempts to prioritize a list of technologies and then investigates the effects of changing mission preferences. There is no consideration given to more refined factors like cost, probability of acceptance, probability of success, etc., found in the START analysis, and as such, is a drastic simplification of the realities of technological investment and development. However, its advantage is that it requires minimal amounts of data, and looks to highlight some trends in technological investment when the future mission goals are uncertain.

This methodology is illustrated below through application to the human Mars exploration campaign developed in Chapter 4.

5.5 Application to Human Mars Exploration

The NASA Human Exploration Framework Team (HEFT) recently released a summary on a possible human space exploration framework (NASA, 2011). Contained within was a mapping of technology applicability to destination overview for 59 technologies, ranging from cryogenic boil-off to dust mitigation, and 10 destinations ranging from LEO to the Martian surface. The map denotes the applicability of each technology to each destination, rating as "not applicable," "may be required," "probably required," and "required technology." In this analysis, those categorizations are given the numerical values of 0, 1, 2, and 3, respectively. This mapping for three selected missions (MTM, PDS, and MSM as defined in Chapter 4) is shown in Table 17.

Table 17: Technology to Destination Mapping (adapted from NASA (2011))

#	Description	MTM	PDS	MSM
1	LO2/LH2 reduced boil-off flight demo	3	3	3
2	LO2/LH2 reduced boil-off & other CPS tech development	3	3	3
3	LO2/LH2 zero boil-off tech development	2	2	2
4	in-space cryo prop transfer	0	0	0
5	energy storage	3	3	3
6	electrolysis for life support (part of energy storage)	3	3	3
7	fire prevention, detection & suppression (for 8 psi)	3	3	3
8	environmental monitoring and control	3	3	3
9	high-reliability life support systems	3	3	3
10	closed-loop high reliability life support systems	2	2	2
11	proximity communications	2	3	3
12	in-space timing and navigation for autonomy	3	3	3
13	high data rate forward link (ground & flight)	3	3	3
14	hybrid RF/optical terminal (communications)	3	3	3
15	behavioral health	3	3	3
16	optimized exercise countermeasures hardware	3	3	3
17	human factors and habitability	3	3	3
18	long duration medical	3	3	3
19	biomedical countermeasures	3	3	3
20	space radiation protection – GCR	3	3	3
21	space radiation protection – SPE	3	3	3
22	space radiation shielding – GCR & SPE	3	3	3
23	vehicle systems management	3	3	3
24	crew autonomy	3	3	3
25	mission control autonomy	3	3	3
26	common avionics	3	3	3

27	advanced software development/tools	3	3	3
28	thermal management (e.g., fusible heat sinks)	3	3	3
29	mechanisms for long duration, deep space missions	3	3	3
30	lightweight structures and materials (HLLV)	3	3	3
31	lightweight structures and materials (in-space elements)	3	3	3
32	robots working side-by-side with suited crew	2	3	3
33	tele-robotic control of robotic systems with time delay	2	3	3
34	surface mobility	0	0	3
35	suitport	0	3	2
36	deep space suit (block 1)	1	3	0
37	surface space suit (block 2)	0	0	3
38	NEA surface ops (related to EVA)	0	3	0
39	environment mitigation (e.g., dust)	0	2	3
40	autonomously deployable very large solar arrays	3	3	3
41	SEP demo	3	3	3
42	solar electric propulsion (SEP) stage	3	3	3
43	fission power for nuclear electric propulsion (NEP)	1	1	1
44	nuclear thermal propulsion (NTP) engine	1	1	1
45	fission power for surface missions	0	0	3
46	inflatable habitat flight demo (flight demo launch)	2	2	2
47	inflatable habitat tech development (including demo)	2	2	2
48	in-situ resource utilization (ISRU)	0	0	3
49	TPS – low speed (<11.5 km/s; avocat)	3	3	3
50	thermal protection systems (TPS) – high speed	2	2	2
51	NEA auto rendezvous, prox ops, and terrain relative nav	0	3	3
52	precision landing	0	0	3
53	entry, descent, and landing (EDL)	3	2	3
54	supportability and logistics	1	1	2
55	LOX/methane RCS	0	0	2
56	LOX/methane propulsion stage – pressure fed	0	0	2
57	LOX/methane propulsion stage – pump fed	0	0	2
58	in-space chemical (non-toxic reaction control system)	0	1	0
59	HLLV oxygen-rich staged combustion engine	1	1	1

Legend
0 – Not applicable
1 – May be required
2 – Probably required
3 – Required technology

While it is not clear how HEFT generated this mapping or whether or not is considered comprehensive, it is used in an attempt to apply the alternative analysis method described in Section 5.4. Note that TRL is not explicitly taken into account, and could implicitly manifest itself in the cost of developing a given technology.

In sequencing these technologies for portfolio investment, consideration should be given to their costs of development, times for development, and other factors as considered in the START analysis. Another consideration should be the flexibility of the portfolio that is defined, in particular the reduction of switches necessary to transition from one optimized portfolio under a certain set of uncertain assumptions to one found in the future for different goals.

5.5.1 Possible Campaign Paths

For the purposes of this case study, three possible campaign paths were defined using the missions indicated in the columns of Table 17.

The nominal campaign path has humans progressing sequentially from MTM to PDS, and finally to MSM. In terms of complexity and mission risk, this represents more or less a natural mission progression. This path is called the Base Case.

The second campaign path postulates that a scientific discovery during MTM instigates a delay in PDS, and instead focus is put immediately on MSM. This path is called Scientific Discovery.

The third and final campaign path postulates that before MTM is even launched, political direction necessitates that MSM is directly pursued. This mission path would forego MTM and concentrate on PDS after MSM. This path is called Political Direction.

5.5.2 Alternative Flexibility Analysis

The enabling technologies are sequenced for each of the three defined mission. A mission-enabling mindset is used, such that technologies are ranked based on their ability to contribute to the envisioned campaign first by the most imminent mission, next by the second-most imminent, and third by the third-most imminent. While this was the method chosen for this case study, one more akin to what is used in the START methodology, the so-called "democratic" method that seeks to optimize overall portfolio utility (Derleth et al., 2005), could be employed instead.

For organizational reasons, the technologies in Table 17 were grouped and color-coded as "blocks" with identical relevance for the three mission types, and these technology "blocks" are shown in the first column (labeled Color Legend) of Figure 20. The numbers in Figure 20 correspond to the technology identification numbers in Table 17. These blocks were then sequenced adhering to the method described above for each of the three possible campaign progressions, with the result shown in the three other columns of Figure 20 (labeled Base Case, Scientific Discovery, and Political Direction).

The three result columns in Figure 20 are read from the top to the bottom. Technology "blocks" appearing at the top of the list have higher priority, that is, they should be developed first, over "blocks" lower down. The colored boxes overlaid on top with the white text shows the technology development that is required for a given mission (MTM, PDS, or MSM). For example, the final technology "block" that must be developed to enable MTM in the Base Case consists of technologies 43, 44, and 59. Afterwards, five other technologies must be developed for PDS, and finally two "blocks" consisting of eight technologies must be further developed for MSM.

Several conclusions can be drawn from Figure 20:

1. There is a large degree of commonality between the required technologies. After the initial mission is enabled (MTM or MSM), a relatively few number of additional technologies are required to enable subsequent missions.
2. Because of the commonality involved, the degree of flexibility, the ability to switch between one path to another, is higher than if many technologies useful for only one mission existed.
3. Targeting MTM first enables a mission with fewer required technologies than MSM.
4. After MTM is complete, a decision can then be made to either continuing pursuing the Base Case scenario or switch to the Scientific Discovery path. There does not seem to be a high switching cost in this scenario.
5. Development of MSM first, along the Political Direction path, delays the enabling of any of the three missions.

These conclusions represent potential assertions that can be made with this type of analysis. Again, the goal is to attempt to introduce considerations for flexibility into the technology portfolio selection analysis in order to recognize uncertainties in mission direction.

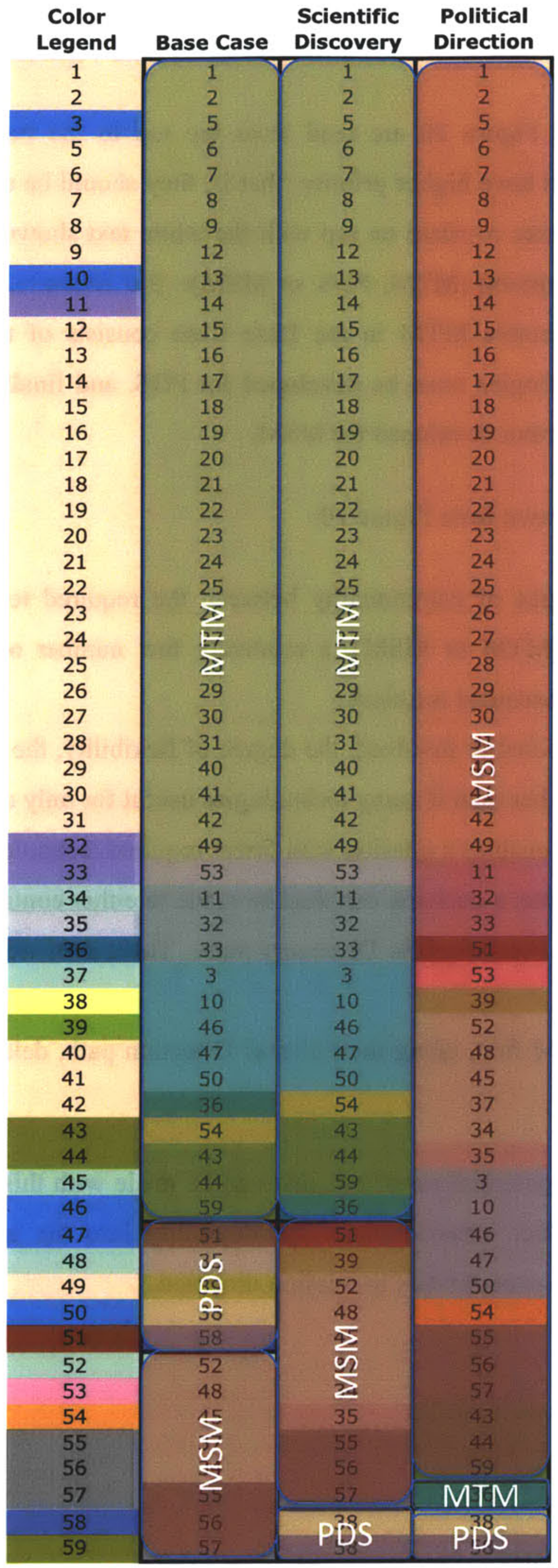

Figure 20: Flexibility Analysis of Enabling Technologies for Human Mars Exploration

5.6 Conclusions and Future Work

This chapter attempted to lay the framework for inclusion of flexibility analysis into the technology portfolio investment optimization problem. Two different methods were suggested: introducing flexibility with Monte Carlo simulation and decision rules into the START method and performing a simplified technology ranking to observe possible trends. Neither method has been developed to a great degree, that being left for future work. In particular, it would be especially interesting to apply the START methodology to the human Mars exploration campaign developed in this thesis and then incorporate uncertainty as described in this chapter.

6 Conclusions and Future Work

In this thesis, an attempt was made to better assess the feasibility of a human mission to Mars, particularly the shared human and robotic mission (humans-in-orbit) presented by Cunio et al. (2010a; 2010b) and related variants. A summary of the results is presented here, along with some concluding remarks and areas for future work.

With assumptions on crew provisions demand rate and the inclusion of an additional propellant tank, the shared human and robotic mission presented by Cunio et al. (2010a; 2010b) offers a viable alternative to the traditional humans-to-surface mission architecture. It involves less overall mass, a subset of the required technologies, and allows for sampling of multiple sites when compared to a surface-landing mission.

Variants on the humans-to-orbit mission were made to investigate the robustness of the mission to changes in the transportation infrastructure. For example, the humans-in-orbit mission can be conducted with a minimum NTR specific impulse of 835 s, while Grogan (2010) found that for 875 s, the humans-to-surface mission outlined by DRA 5.0 is infeasible. If the NTR specific impulse is 865 s or higher, only one cargo MTV is required to support the mission, leading to a mass savings of 22-24% in LEO. Finally, an investigation of the Advanced Chemical Propulsion transportation architecture showed that the humans-to-orbit mission is feasible only for the most optimistic predictions of the advanced chemical specific impulses.

Four missions were defined giving an example of how the Flexible Path could develop to completion: a tele-robotic mission from areostationary orbit, a Phobos and Deimos sortie mission, a dedicated Phobos exploration mission, and a Mars surface mission. In this sequence, humans progress from remaining in the MTH to interacting directly with Martian-system bodies for longer and longer periods of time. Common elements, use of propellant depots, and modular missions allow for flexibility in both individual mission objectives and overall campaign direction.

One conclusion of this thesis is that several mission architectures can viably, from a logistics perspective, take humans to Mars. Although no attempt is made to choose which is better from a scientific value point of view, the mass estimates presented are a useful first-order screening criterion to grade relative mission complexity and costs. In that vein, none of the missions appear infeasible, and all offer novel opportunities from both scientific and operational perspectives. Table 18 shows the figures of interest for all mission architectures studied in this thesis.

Table 18: Summary Figures of Interest

Figure of Interest	DRA 5.0	SHRMM						Mars Exploration Campaign			
	NTR	NTR		NTR (no Cargo MTV #2)		ACP					
	950 s	950 s	875 s	950 s	875 s	523 s	516 s	MTM	PDS	PEM	MSM
Ares V launches	9	8	8	7	7	8	8	8	8	8	15
Total mass in LEO (mT)	848.7	706.0	706.0	536.2	550.7	753.0	753.0	681.7	681.7	681.3	1,448.7
Number of sites sampled	16	6	6	6	6	6	6	3	2	1	1
Returned sample mass (kg)	4	4	4	4	4	4	4	3	150	150	250
Robotic-days of exploration (robot-days)	1,060	332	332	332	332	332	332	360	0	0	1,060
Human-days of exploration (human-days)	1,940	28	28	28	28	28	0	0	28	360	2,120

Compared to DRA 5.0, this thesis attempts to take a different approach to reference mission definition. Instead of specifying a single mission, a family of possible missions, all attempting to utilize a common transportation infrastructure, gradually build operational experience, and offer varied scientific returns is explored. The goal is to avoid an Apollo-like phenomenon, where a grand ambition is sought with no logical, incremental follow-on to foment further exploration. In this thesis, one large goal is replaced with several smaller ones, and as the pursuit of those seems to be feasible, the hope is that they will one day be realized.

Whether or not that will actually happen is unknown, though in the author's opinion much more study will be done before any meaningful actions are taken. As such, there are many areas that can be investigated further in the future. For example, all analyses performed in this thesis were on the basis of mass feasibility. Volume feasibility is the next logical step, ensuring that the elements will fit inside the launch vehicles and other defined infrastructure elements. Further, more detailed design of those elements would aid greatly, lending much more credibility to the analysis results.

Though several mission variants were considered here, this is by no means a comprehensive list. For example, a one-way mission, covered recently by Schulze-Makuch and Davies (2010), is an interesting alternative to a return mission. A logistical analysis was done on such a mission, but because it is not as related to the other missions in this thesis, it is presented in Appendix A. Further, Mars missions, especially a one-way mission, lead to the question of eventual colonization of Mars. While this is reality that is far off into the future, it is by no means too early to begin thinking about the eventual permanent casting off from terrestrial shores, across the cosmic ocean, to not only *the* New World, but perhaps *a* New World.

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Appendix A Feasibility Analysis of a One-way Mission to Mars

A.1 Background

A number of proposals have been made for a one-way mission to Mars. Schulze-Makuch and Davies (2010) cite that doing so would cut costs several fold, possibly as much as by 80% as there is no need to send the fuel and supplies necessary for the return journey, and there is no need to rehabilitate astronauts after long-term exposure to the reduced gravity environments of the Martian surface and free space.

Furthermore, Schulze-Makuch and Davies (2010) note that a one-way mission would not be a suicide mission. In fact, certain risks, such as powered flight through the Martian atmosphere and radiation exposure during interplanetary travel are effectively halved. It is expected that the crew, postulated to be two males and two females, would be re-supplied periodically for some length of time (from decades to possibly centuries) while slowly but increasingly becoming more self-sufficient. The ultimate hope is that over several decades more colonists would be sent until the Martian population expands to 150, the hypothesized critical mass for the colony to begin reproducing and sustaining a long-term settlement.

Other proposals are less ambitious. McLane III (2006) asserts that a human can be placed on Mars using current technology if ascent from the Martian surface is not necessary. The proposal is for a single astronaut to go to Mars, thereby reducing the long mission lead times (for conception, design, and fabrication of necessary exploration elements) and reducing the possibility of funding cuts and subsequent program postponement or cancellation.

A word should be given to the ethics of a one-way Mars mission. The majority of arguments against a one-way mission, especially a mission with a single astronaut, center around the abandonment or sacrifice of human lives to a hostile and alien environment. In response, Schulze-Makuch and Davies (2010) cite that for the first explorers of the New World such as Columbus, there was no guarantee of survival and even less commitment from the Old World in terms of resupply and support. Contrast this with one-way missions to Mars featuring constant communication with Earth and a dedicated population with the intent and means to monitor and sustain the human pioneers.

A.2 Analysis Setup and Assumptions

A logistics feasibility analysis was done to verify some of the claimed merits of a one-way mission as opposed to a conventional return mission, such as MSM at the end of the campaign discussed in Chapter 4.

To minimize crew demands, a mission concept of operations similar to the "lone wolf" scenario presented by McLane III (2006) is assumed. A single astronaut is sent to the surface of Mars and is assumed to live out the rest of his or her life there, a time postulated to be approximately twenty years (Schulze-Makuch and Davies, 2010).

During that time, McLane III (2011) estimates a required resupply of 10,000 lb per year (equivalent to 12.4 kg per day) of food, water, oxygen, and so on from Earth to sustain the astronaut. Since this estimate is of significant importance, an independent calculation of the logistical requirements was made below.

Further, it was assumed that the EDS and propellant depot in-space transportation infrastructure was used (see Chapter 4) so a more meaningful comparison can be made to a more conventional return human mission. A Mars Resource Canister (MRC) was designed based on a scaled-down version of the DRA 5.0 CFC and MDAV descent stage, with the capacity to deliver 10 mT of supplies to the Martian surface.

A.2.1 Calculation of Resupply Requirements

Table 19 summarizes the breakdown of the resupply requirements required for a one-way mission to the Mars surface. There are two major elements to resupply, namely crew provisions and equipment spares.

Table 19: One-Way Mars Mission Crew Demands

Demand	Resupply Rate (kg/person/day)
Crew Provisions	2.375
Equipment Spares	9.9
Surface Habitat	*5.5*
Power Generation System	*2.0*
Surface Rover	*2.4*
In-situ Resource Utilization System	*0.3*
Communication System	*~0*
Total	***12.575***

In the case of crew provisions, the same 2.375 kg per person per day assumption used in all previous analysis (see Chapter 4) was applied, essentially assuming nearly complete closure in the water cycle and reusability of hygiene and waste disposal items. Also, it assumes in-situ oxygen production.

Equipment sparing mass was calculated as 10% of the element mass per year of operation (Grogan, 2010). The surface habitat, power generation system, surface rover and in-situ resource utilization system were taken from NASA DRA 5.0, while the mass of the necessary communications system was assumed to be negligible based on estimates made by Yue et al. (2010). For element masses taken from NASA DRA 5.0, it is assumed that resupply is not required for the first 17 months of operation (essentially the length of surface time for a conjunction-class human surface mission) because this sparing mass has already been included in the estimates provided (Grogan, 2010).

Implicitly, it is assumed here that the surface assets can be used indefinitely for the entire mission (i.e., twenty years) without the need for complete replacement. While this is likely unrealistic, it is difficult to judge the operational life of the surface elements because of the relatively uncharacterized Martian environment and the little (i.e., zero) operational data for the surface elements which only exist as paper designs.

The total required resupply rate is 12.575 kg per day, which is within 2% of the estimate given by McLane III (2011). Thus, in the analysis that follows, it is assumed that the required resupply rate is 10,000 lb per year, or 12.4 kg per day.

A.3 Analysis Results and Discussion

A.3.1 Concept of Operations

Figure 21 shows the bat chart for the one-way mission to Mars. There are, essentially, two phases. The first phase is concerned with moving all appropriate assets to the right place. The LEO Propellant Depot is first constructed. Shortly afterward, the Martian surface infrastructure, namely the equipment listed in Table 19 (denoted the SHAB payload) and an MRC, are put on conjunction-class trajectories via two separate Ares V launches and EDSs after they are refueled in LEO. The MRC descends to the surface while the SHAB payload loiters in RMO.

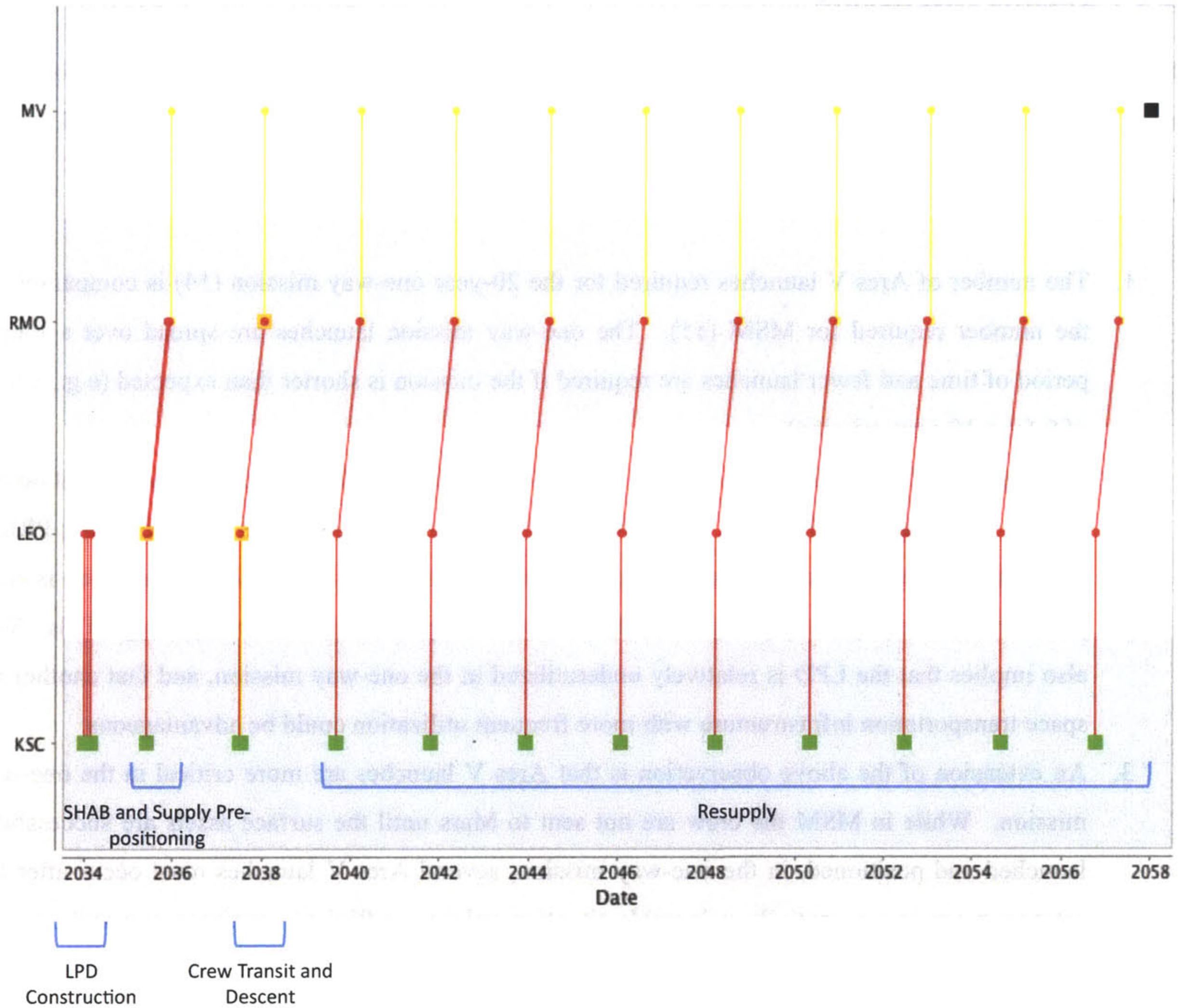

Figure 21: One-Way Mars Mission Bat Chart

On the next conjunction-class launch opportunity, a single astronaut is launched and journeys to Mars using the MTH defined in DRA 5.0. Nominally, the MTH inserts into RMO on January 15, 2038. The astronaut then rendezvous with the SHAB payload and uses it to descend to the surface of Mars, hopefully near the pre-positioned MRC.

The astronaut then begins surface operations while being resupplied every 26 months (i.e., every time the conjunction-class trajectory window becomes available) with a single MRC, the equivalent of providing 10,172 lb of resupply per year. This continues until the astronaut can no longer function, assumed to be 20 years after arrival.

A.3.2 Results Discussion

Table 20 shows the figures of merit for a one-way mission to Mars that lasts 20 years and also one that lasts for 10 years, and compares it to the Mars Surface Mission (MSM) introduced in Section 4.2.5.

Several observations can be made from the figures of interest:

1. The number of Ares V launches required for the 20-year one-way mission (14) is comparable to the number required for MSM (15). The one-way mission launches are spread over a longer period of time and fewer launches are required if the mission is shorter than expected (e.g., a total of 9 for a 10-year mission).
2. The majority of the Ares V launches for the one-way mission is for resupply, launches that do not require refueling from the LPD, while the majority of the MSM launches carry refueling PRMs. From this, it can be concluded that the majority of mass required for the one-way mission is crew provisions and equipment spares while that for MSM is propellant for the departing EDSs. This also implies that the LPD is relatively underutilized in the one-way mission, and that another in-space transportation infrastructure with more frequent utilization could be advantageous.
3. An extension of the above observation is that Ares V launches are more critical in the one-way mission. While in MSM the crew are not sent to Mars until the surface assets are successfully launched and positioned, in the one-way mission, several Ares V launches must occur after the astronauts are in a potentially vulnerable situation unless a sufficient contingency margin can be accumulated on the Martian surface.
4. The total required mass in LEO is lower for the one-way mission, even for one that could last 20 years. In fact, only a 33% increase in mass is required to double the mission duration from 10 years to 20 years, highlighting the initial mass investment required to enable the mission.
5. The one-way mission does not currently have the capacity to return samples, but a sample return element could be included as part of the concept of operations.
6. Because there is only one astronaut in the one-way mission, accumulating an equivalent number of human-days of exploration takes considerably more time. Thus, the one way mission, effectively lasting 14 times as long as MSM, only increases the human-days of exploration by 2.3 times.

Table 20: One-way Mars Mission Figures of Interest

Figure of Interest	MSM	One-way (10 years)	One-way (20 years)
Ares V launches (mission payloads)	4	1	1
Ares V launches (PRM payload)*	11	3	3
Ares V launches (MRC payload)	-	5	10
Crew launches	1	1	1
Total mass in LEO** (mT)	1,448.7	826.5	1,102.5
Number of sites sampled	1	1	1
Returned sample mass (kg)	250	0	0
Robotic-days of exploration (robot-days)	1,060	0	0
Human-days of exploration (human-days)	2,120	3,650	7,300

*Includes launches required to construct LPD
**Includes mass of stack immediately before TMI

One aspect of the one-way mission that is not highlighted in Table 20 is the extendibility of this analysis to larger crew sizes, the effect of which being potentially beneficial (e.g., possibly the prevalence of crew depression would be decreased and provisions could be made for reproduction and child-rearing, but at the same time, intra-crew conflicts could arise). As Table 19 shows, only approximately 19% of the resupply demand is for crew provisions, the complement being sparing for the surface elements. As such, to employ financial terminology, the variable cost of increasing the crew size is small in comparison to the fixed operating cost of fielding the mission, especially since the surface elements were sized in DRA 5.0 for a crew of six. Some thought should be given to the effect on the launch vehicle size and resupply capacity, but a one-way mission with multiple crewmembers could be a more attractive and yet still viable option.

Overall, the one-way mission represents an alternative human mission to Mars. It features several advantages, requiring less propellant and will most likely be cheaper as it is lighter overall and does not require significant technological advancement to become feasible.

On the other hand, it also has its disadvantages. There is no plan for human return, introducing ethical and policy debates, and also negating the possibility of studying the physiological effects of long-term space flight (although it affords the somewhat sadistic possibility of investigating the psychological effects of long-term space exile). Further, launch criticality becomes an issue as each launch has more of a direct impact on astronaut survival given the infrequency of viable launch windows. Along the same thread, high surface asset reliability (i.e., for the SHAB, ISRU plant, etc.) is crucial to mission success.

Appendix B Details on the Shared Human and Robotic Mission (SHRMM)

This appendix gives more details on SHRMM, going deeper into various aspects of the mission definition. Further detail can be found in Cunio et al. (2010a).

B.1 Architectural Comparison

Table 21 shows an architectural comparison between SHRMM and DRA 5.0. Cunio et al. (2010a) assumed "isoperformance" of the two missions during the transit and return phases of the mission, with divergence between the two occurring in the vicinity of Mars. Table 21 readily shows the diffuse nature of SHRMM, exploring and sampling from three bodies compared to the concentrated nature of DRA 5.0.

Table 21: SHRMM and DRA 5.0 Mission Architectures Comparison (adapted from Cunio et al. (2010a))

Mission Phase	SHRMM	NASA DRA 5.0
Launch	Same	
Transit	Same: about 180 days	
Stay time	About 40 days	About 500 days
Mars Arrival	Dock/Orbit/Deploy	Land
Mars Operations	Tele-operate/Moon EVA	Surface exploration
Science	Samples from 3 bodies	Samples from Mars
Exploration	Hoppers/Pirogue/EVA	Pressurized/Unpressurized rovers/EVA
Ascent from Mars	One hopper with samples	Large MAV with crew
MTV Rendezvous	Mission-critical, not life-critical	Mission-critical and life-critical
Return Transit	Same	
Reentry	Same	

Figure 22 compares the bat charts of the two mission architectures, focusing on the differences in asset location over the course of the two missions. Again, one recognizes the disperse nature of SHRMM, deploying assets to more locations of interest in the Martian neighborhood compared to DRA 5.0.

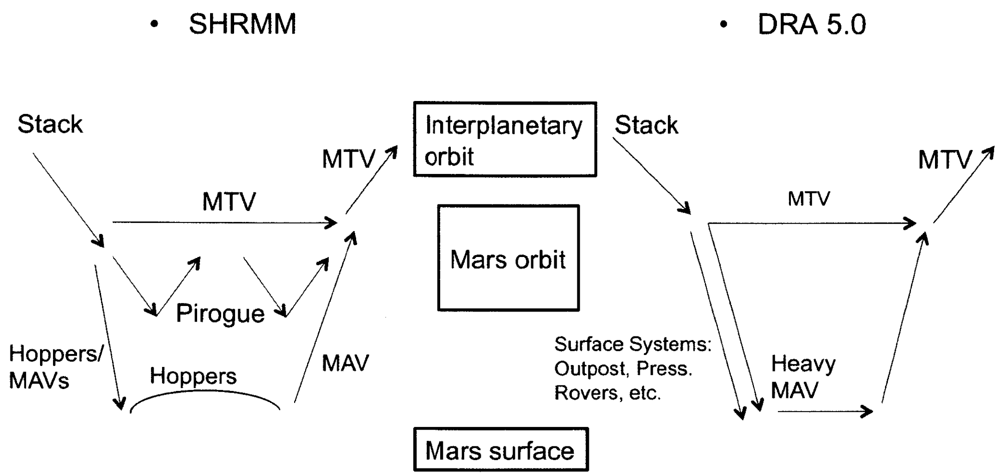

Figure 22: SHRMM and DRA 5.0 Bat Chart Comparison (adapted from Cunio et al. (2010b))

B.2 SHRMM Vehicle Properties

Three vehicles were designed to a conceptual level to evaluate the feasibility of SHRMM: the planetary hopper, its associated Mars Ascent Vehicle (MAV), and the Pirogue excursion vehicle. Details of each of the vehicles are given below with, again, more detail appearing in Cunio et al. (2010a).

B.2.1 Planetary Hopper Design

The hopper design was performed based on the model described in Yue et al. (2010). It was assumed that each hopper would be self-sufficient, insomuch as it would harbor its own solar array, lithium-ion batteries, communications system, chemical rocket engine, and scientific payload. The engine was designed to allow for ten total hops each with a horizontal distance of 500 m.

Each hopper payload enters the Martian atmosphere and lands using a 70° aeroshell which is jettisoned at Mach 1.7 so parachutes can be deployed. The chemical rocket engine slows the hopper to a speed of 3.3 m/s before touchdown. This descent trajectory and the associated subsystems were specified using historical considerations from American robotic landings on Mars since Viking 1 and 2. With the mass of the aeroshell, each hopper weighs 857 kg.

B.2.2 Mars Ascent Vehicle

The purpose of the MAV is to return a 1-kg Martian soil sample to ASO for rendezvous with the MTV. A two-stage ascent architecture, the first stage employing solid rocket boosters and the second stage using hydrazine bi-propellant, was used to achieve the 6.0 km/s required to reach ASO.

The MAV mass breakdown is shown in Table 22, which indicates that the total MAV mass is 336.1 kg. It was decided to reduce overall mission mass by dedicating two hoppers to a single MAV.

Table 22: Mars Ascent Vehicle Mass Breakdown (adapted from Cunio et al. (2010a))

Vehicle Stage	Mass (kg)
Sample Canister	4.1
MAV Second Stage	118.4
MAV First Stage	213.6
Total	**336.1**

B.2.3 Pirogue Excursion Vehicle

The Pirogue, a conceptual drawing of which is shown in Figure 23, is designed to allow two astronauts to rendezvous with both Martian moons with an intervening return to the MTV in ASO. Calculation of the ΔV requirements for the Phobos and Deimos excursions were performed using skewed-axis velocity analysis and the Battin-Vaughan Algorithm (Battin, 1999).

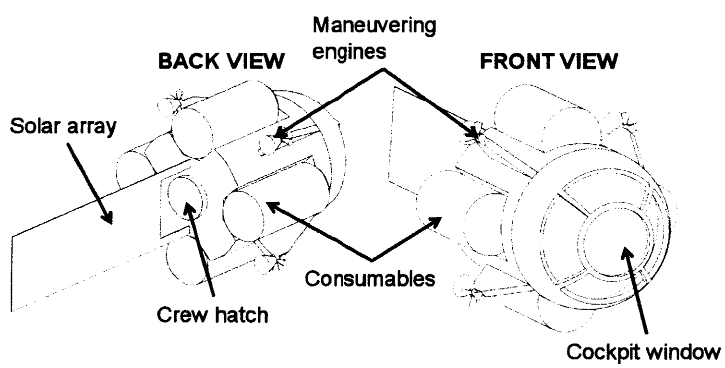

Figure 23: Pirogue Excursion Vehicle (adapted from Cunio et al. (2010a))

As the sphere of influence for both moons exist within each moon's radius, it was assumed that a trailing or leading orbit at close distance could be maintained with minimal station-keeping requirements. A 40-day timeframe was defined as the allowable window in which both sorties take place, and each sortie was allowed to last between 2 and 7 days. Using these constraints, a genetic algorithm was used to calculate the optimal ΔV requirements.

Figure 24 shows the result of the optimization as a plot of stay time at the Mars moons versus the required round trip ΔV. It shows that there is a multitude of feasible missions that can be flown to Phobos and Deimos for approximately 2.4 and 0.6 km/s, respectively. For the purposes of sizing the Pirogue, a growth margin of 30% was applied to these estimates to account for simplifying assumptions and other unknown complications.

Because of the microgravity environment on both planets, the Pirogue does not land on either moon in the conventional sense. Instead, the Pirogue approaches the target moon and matches orbits at a distance of a few dozen meters. The astronauts can then exit the Pirogue using suitlocks and appropriate extravehicular suits, and utilize inertial tether lines and cold-gas propelled backpacks to traverse to, around, and back from the target moon. Further information on mission operations near an asteroid, a reasonable analogue to the Martian moons, can be found in Massachusetts Institute of Technology 16.89 Graduate Design Class (2010).

The Pirogue design, as indicated in the mass breakdown in Table 23, carries scientific equipment and allocates space for samples from the moons, providing for an opportunity for in-situ science and sample return. Fully fueled, the Pirogue weighs in at approximately 17,500 kg.

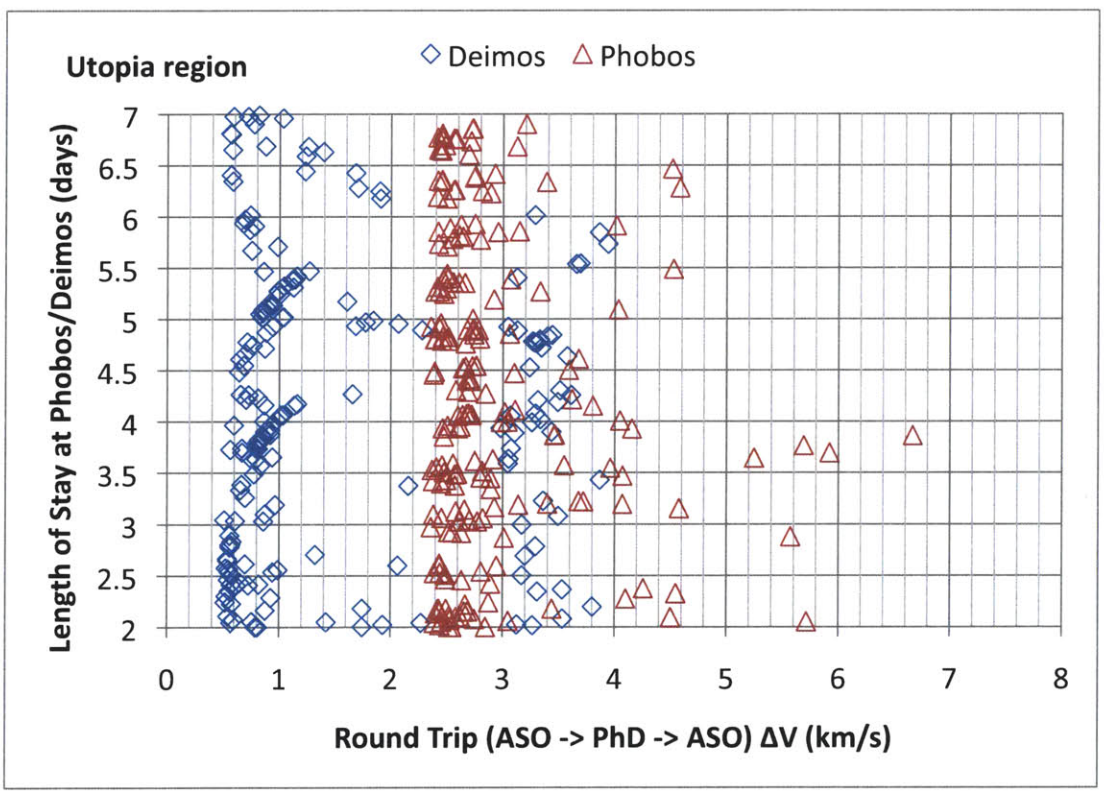

Figure 24: ΔV Requirements for Phobos and Deimos (PhD) Sorties

Table 23: Pirogue Excursion Vehicle Mass Breakdown (adapted from Cunio et al. (2010a))

Pirogue Excursion Vehicle Subsystem	Mass (kg)
Structure	1,445
Life support	455
Comm., sensors, and computation	105
Power	275
Mission	875
Propulsion	10,333
Growth Margin	*30%*
Total in Mars Orbit	**17,469**

Appendix C Reflections on SpaceNet Version 2.5r2

The majority of the analyses presented in this thesis were performed in SpaceNet Version 2.5r2. At this time, SpaceNet is an open source program under continual revision with the goal being its widespread use in logistical planning in long-term space campaigns. As such, in order to aid in further development, an account of the author's impressions of SpaceNet Version 2.5r2 follows below.

First, much appreciation is offered to Paul T. Grogan, the Lead Developer of SpaceNet Version 2.5r2. Without his tireless support and advice, some aspects of this thesis would not have been possible, or would have been frustratingly tedious.

This leads into the first point: while SpaceNet Version 2.5r2 is simple to use and is applicable to many mission types and scenarios, there are some concepts that cannot be modeled in the current release of SpaceNet. A prime example is on-orbit refueling, which was modeled in SpaceNet only after Mr. Grogan provided a patch enabling this capability. Without such contact with the Lead Developer or his willingness to further SpaceNet's capabilities, or the willingness to dive into SpaceNet's source code, modeling the use of fuel depots would have been extremely difficult.

Another piece of advice given to the author by Mr. Grogan was to save scenario files as little as possible. At times, saving a scenario through the graphical user interface (GUI) would result in scenario files that were not complete. These files would be essentially unusable, as they were missing scenario information and would not open again in the GUI. Remedying this issue would save much irritation on the part of the modeler.

Further, Mr. Grogan also suggested increasing the amount of RAM SpaceNet accesses by executing it through the command line prompt. This capability, previously unknown to the author, helped greatly during the modeling of large scenarios with many events, which is otherwise impossibly sluggish.

That being said, notwithstanding the aforementioned potential improvements, SpaceNet is an intuitive program providing users the ability to quickly model, analyze, and visualize space mission campaigns. The actual analysis engine in SpaceNet could be replicated from scratch using a number of platforms, but SpaceNet uniquely and usefully offers advantages over self-made models.

First, SpaceNet enforces a standard definition of model elements, giving the modeler a checklist of items that need to be tracked down for proper element definition giving structure and efficiency to the data-gathering process. Along the vein of standardization, SpaceNet also facilitates sharing and discussion of model files in a common environment, removing traditional barriers such as idiosyncrasies in model definition, disparities in modeler competence, and incompatibilities in programming platforms.

SpaceNet also offers built-in feasibility checks which, while conceptually simple, are tedious to program in models built from scratch. This allows the modeler to focus on defining the campaign itself, leaving the more or less automatable task of checking feasibility to SpaceNet.

Finally, SpaceNet offers a number of visualization options such as bat charts, demand curves, and animations that summarize the premise and key metrics of a campaign and that can be created with minimal effort on the part of the modeler. These graphics would require a substantial amount of time to generate manually, again allowing the modeler to focus more on logistics and less on image processing.

Overall, SpaceNet was instrumental in the writing of this thesis. It is already extremely valuable in its current state and, with further enhancement, should become a mainstay of space logistics analysis both at NASA and with the greater public community.