

Trades Between Opposition and Conjunction Class Trajectories for Early Human Missions to Mars

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Candidate human missions to Mars, including NASA's Design Reference Architecture 5.0, have focused on conjunction-class missions with long crewed durations and minimum energy trajectories to reduce total propellant requirements and total launch mass. However, in order to progressively reduce risk and gain experience in interplanetary mission operations, it may be desirable that initial human missions to Mars, whether to the surface or to Mars orbit, have shorter total crewed durations and minimal stay times at the destination. Opposition-class missions require larger total energy requirements relative to conjunction-class missions but offer the potential for much shorter mission durations, potentially reducing risk and overall systems performance requirements. This paper will present a detailed comparison of conjunction-class and opposition-class human missions to Mars vicinity with a focus on how such missions could be integrated into the initial phases of a Mars exploration campaign.

The paper will present the results of a trade study that integrates trajectory/propellant analysis, element design, logistics and sparing analysis, and risk assessment to produce a comprehensive comparison of opposition and conjunction exploration mission constructs. Included in the trade study is an assessment of the risk to the crew and the trade offs between the mission duration and element, logistics, and spares mass.

The analysis of the mission trade space was conducted using four simulation and analysis tools developed by NASA. Trajectory analyses for Mars destination missions were conducted using VISITOR (Versatile Impulsive Interplanetary Trajectory OptimizeR), an in-house tool developed by NASA Langley Research Center. Architecture elements were evaluated using EXploration Architecture Model for IN-space and Earth-to-orbit (EXAMINE), a parametric modeling tool that generates exploration architectures through an integrated systems model. Logistics analysis was conducted using NASA's Human Exploration Logistics Model (HELM), and sparing allocation predictions were generated via the Exploration Maintainability Analysis Tool (EMAT), which is a probabilistic simulation engine that evaluates trades in spacecraft reliability and sparing requirements based on spacecraft system maintainability and reparability.

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Nomenclature & Acronyms

<i>AU</i>	=	Astronomical Unit
<i>CPS</i>	=	Cryogenic Propulsion Stage
ΔV	=	Delta-Velocity
<i>DSH</i>	=	Deep Space Habitat
<i>DSV</i>	=	Deep Space Vehicle
<i>ECLSS</i>	=	Environmental Control and Life Support System
<i>EVA</i>	=	Extra-Vehicular Activity
<i>EMAT</i>	=	Exploration and Maintainability Analysis Tool
<i>EXAMINE</i>	=	EXploration Architecture Model for IN-space and Earth-to-orbit
<i>HELM</i>	=	Human Exploration Logistics Model
<i>HEO</i>	=	High Earth Orbit
<i>ISS</i>	=	International Space Station
<i>IMLEO</i>	=	Initial Mass in Low Earth Orbit
<i>ISP</i>	=	Specific Impulse
<i>LDEO</i>	=	Lunar Distance Earth Orbit
<i>MOI</i>	=	Mars Orbital Insertion
<i>MPCV</i>	=	Multi-Purpose Crew Vehicle
<i>RCS</i>	=	Reaction Control System
<i>SEP</i>	=	Solar Electric Propulsion
<i>SLS</i>	=	Space Launch System
<i>TEI</i>	=	Trans-Earth Injection
<i>TMI</i>	=	Trans-Mars Injection
<i>VISITOR</i>	=	Versatile ImpulSive Interplanetary Trajectory OptimizeR

I. Introduction

A critical trade in the analysis of crewed deep space missions involves the investigation of the trajectories used for transit to Mars vicinity. There are two basic classes of trajectories that can be utilized for high-thrust, human exploration missions to Mars: conjunction-class and opposition-class. Conjunction-class missions are characterized by minimal total energy requirements and extended mission durations. Opposition-class missions include high delta-velocity (ΔV) maneuvers that result in lower total crewed mission durations^[1]. While both classes have been investigated as part of initial trade studies, conjunction-class missions have generally been the focus of most detailed Mars mission studies. The propellant penalties associated with increases in ΔV have deterred space architects from considering the advantages that short duration, opposition architectures may offer for early, crewed exploration missions.

NASA's Design Reference Architecture 5.0^[2] (DRA 5.0) and Addendums 1^[3] and 2^[4] included an initial, high-level analysis characterizing the impacts of trajectory on mission architectures and payloads. However, the sensitivity of propellant load to trajectory led to the conclusion that opposition-class missions would be difficult to execute with current propulsion technologies.

Deeper analysis may reveal that the actual propellant payloads for opposition-class missions, while almost certainly greater, could be reasonably close to propellant requirements for conjunction-class missions. Total ΔV is not a direct indicator of propellant requirements or required launch mass. The split in ΔV between maneuvers is a critical factor, as the total propelled mass can vary greatly for each of the burns that make up the mission. A significant fraction of the total ΔV for opposition-class missions can occur on the Earth return burn, where the total propelled mass is much lower. In addition, the total payload mass of the habitat, logistics, spares, and crew can be much smaller for an opposition-class mission, due to the shortened mission duration. Conjunction opportunities also allow for "fast-transit" solutions, in which ΔV is increased during both phases of transit to reduce inbound and outbound transit durations to around 120 days, however total mission durations remain greater than 850 days. Such trajectory cases were not investigated in this study.

Because of the shorter mission duration, opposition-class concepts could play a critical role in the development of an integrated campaign for human exploration of Mars vicinity. Risk for initial human Mars missions will be very high, as the durations that humans spend in space will be stretched far beyond what has presently been accomplished. Progressive increases in mission duration and required element capabilities would allow NASA to gain experience in deep space missions and to buy-down risk over time. While crewed missions to Mars will ultimately include long-stay mission architectures, opposition trajectories should be considered as a viable first step in maturing exploration capabilities.

II. Considering Opposition

Utilizing current and conceptual near-term propulsion technologies, human exploration missions to Mars vicinity will involve the use of either conjunction or opposition class trajectories. A round-trip mission to Mars is a double rendezvous problem, where trajectory solutions must be found for both the outbound leg from Earth to Mars and the return leg from Mars to Earth. Conjunction-class trajectories, often referred to as "long stay" missions, benefit from the planetary alignment of Earth and Mars for both the departure and return legs of the mission, minimizing total ΔV requirements. This results in short transit durations and long durations in Mars space, on the order of 400-600 days. Total mission durations for conjunction-class missions are typically on the order of 1000 days. A representative conjunction-class trajectory is shown in Figure 1.

"Short stay" opposition-class trajectories benefit from planetary alignment for only one leg of the mission. Typically, an opposition mission will utilize an optimized trajectory, similar to that for a conjunction mission, for the outbound leg but will then use a higher-energy trajectory for the return leg. These missions result in longer total transit times but significantly shorter durations in Mars vicinity, typically less than 90 days. The net result is that opposition-class missions can have significantly shorter total crewed durations away from Earth. However, the total duration is variable and directly linked to the ΔV expended on the return leg. Specific opposition-class trajectories may or may not include Venus fly-bys on either the outbound or inbound legs of the mission. A representative opposition-class trajectory is shown in Figure 2.

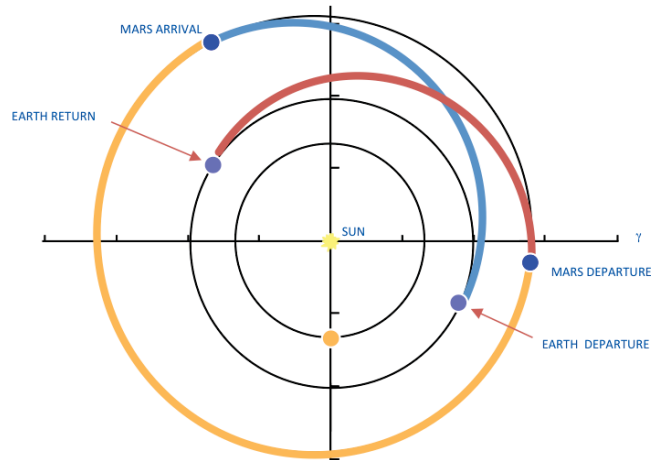


Figure 1. Representative Conjunction Trajectory Concept [5]

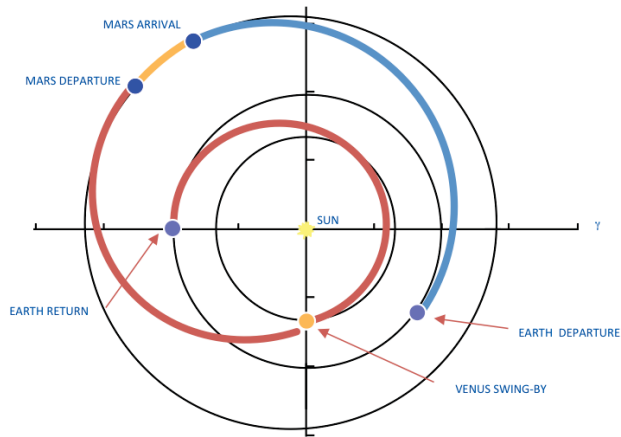


Figure 2. Representative Opposition Trajectory Concept [5]

Evaluation of the propulsive requirements for both trajectory concepts yields substantially larger total ΔV requirements for opposition trajectories. These impacts of ΔV on propellant requirements can be demonstrated by the ideal rocket equation, which yields exponential growth in propellant as ΔV increases (Eq. 1). The idealized relationship between propellant mass and ΔV , as defined by the rocket equation, indicates that, given a fixed propelled mass and ISP, a 100% increase in ΔV will result in an almost 400% increase in propellant mass.

$$M_{prop} = M_{empty} * e^{\left(\frac{\Delta V}{I_{sp} * g_0}\right)} - M_{empty}$$

Where:

(1)

M_{prop} = Required Propellant Mass

M_{empty} = Propelled Mass

ΔV = Required Change in Velocity

I_{sp} = Specific Impulse

g_0 = Gravitational Constant

Opposition-class missions are typically eliminated from further consideration based on the results of this idealized analysis. The argument is made that opposition concepts require too great a total propellant load and potentially require an unwieldy number of propulsion stages, launches and rendezvous' to be viable for Mars missions. Combined with the shorter duration at Mars, and therefore a smaller amount of time to explore and to perform science, these options are eliminated.

There are, however, drawbacks to conjunction-class missions, particularly for initial human exploration. Conjunction trajectories involve long total crewed mission durations - on the order of 1000 days - with little ability to vary total mission time. Longer mission durations increase the exposure of the crew to risk and require longer total functional lifetime for spacecraft systems, including propulsion stages. For initial missions to Mars, the durations spent away from Earth will be much larger than has previously been achieved for human missions. This leap in capabilities increases the total mission risk.

The initial characterization of opposition-class missions oversimplifies the relationship between total ΔV and propellant mass. Short stay trajectories are intrinsically non-symmetric with larger ΔV investments required for a single leg of the mission. This does present an added complexity in determining the trajectory, but also provides opportunities to optimize ΔV expenditure across the mission. Optimization of the ΔV splits is achieved by pushing much of the overall propulsive burden to mission phases in which the propelled mass is smallest. This strategy clearly promotes allocating much of the ΔV budget to the return phase of the mission, when trans-Mars Injection (TMI) and Mars Orbital Insertion (MOI) propellant and stages have already been expended and a substantial portion of consumables has been used and discarded.

The initial characterizations of opposition-class missions also typically ignore the reduction in propelled mass that is associated with the much shorter mission durations. If it is assumed that the crewed mission must provide sufficient consumables and habitable/storage volume for the entire mission duration, then the total logistics and volume requirements for conjunction-class missions are much larger than for opposition-class. This assumption would apply for early Mars orbital or short surface stay missions, where the crew would remain in the deep space habitat (DSH) for a large portion of the stay at Mars. Even in cases where the crew is not expected to stay in the DSH, it may be necessary to outfit the habitat for the full duration for contingency purposes.

While required payload and propellant mass are two primary drivers in the comparison between conjunction and opposition class missions, there are other issues that are also important to consider. Most opposition-class missions include a Venus fly-by maneuver and reduced perihelion distance in transit. This maneuver will expose the crew to some additional risk. Another concern when evaluating the feasibility of a progressive exploration campaign is architecture extensibility. Particularly for a campaign that utilizes a combination of opposition and conjunction concepts, it is critical that mission elements remain compatible while enabling capabilities to build-up across mission constructs. Steps were taken within the trade study to ensure multilateral architecture usability. Major concerns with respect to element extensibility include commonality in habitation systems, propulsion stages and liquid rocket engines.

The objective of this study was to conduct a consistent comparative analysis of opposition and conjunction class Mars exploration missions to a level of detail requisite for a fair and credible assessment. Candidate missions were evaluated using common ground rules and assumptions and analyzed using a common set of tools. The study involved detailed assessments of mission trajectories and finely resolved evaluations of payload requirements, including propellant wet mass, propellant inert and dry masses, propulsive system mass, habitation sizing, and logistics and sparing requirements. Figure 3 demonstrates the major contributing factors considered in this study to analyze total payload mass.

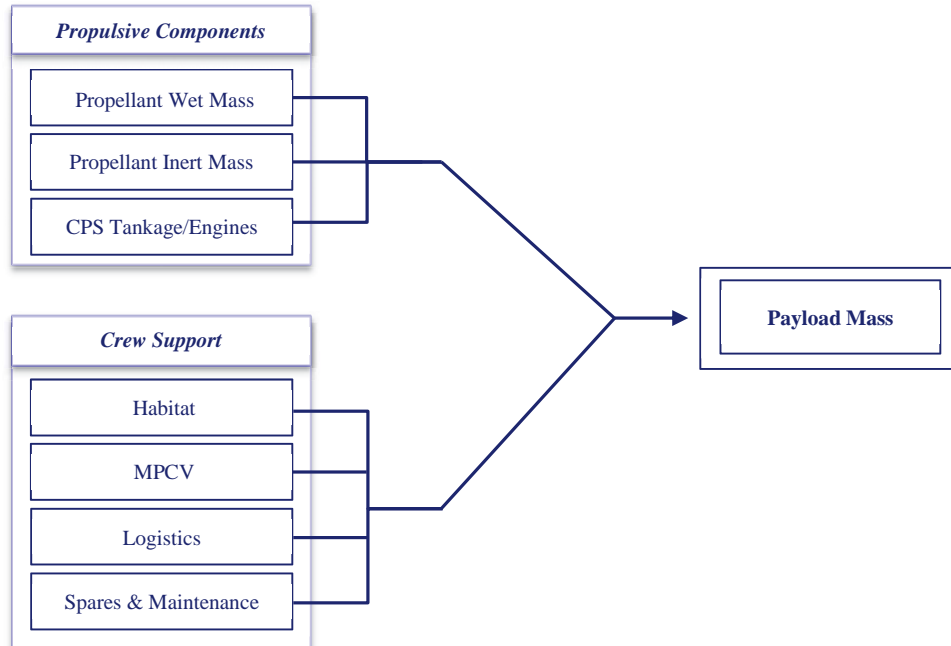


Figure 3: Primary Payload Contributors

Multiple trajectory strategies were evaluated to define optimized burn splits with respect to payload mass over the mission duration. Launch modeling further enhanced mission detail, allowing for summaries of total delivered mass and mapping of the element delivery progression and aggregation strategies. A conservative approach was taken to all performance computations to assure that analysis results accurately reflect attainable exploration mission constructs.

A review of the primary campaign constructs allows for a comprehensive characterization and comparison of exploration concepts. Risk buy-down strategies were examined, and the evolution of necessary capabilities was assessed to develop an overall description of the risks associated with each trajectory class.

III. Mars Exploration Concept Assessment Results

A. Ground Rules and Assumptions

The two cases investigated for this study were a conjunction-class, long-stay, mission and an opposition-class, short-stay mission. To ensure consistent comparative analysis across cases, both trajectory concepts utilized similar spacecraft aggregation strategies, as well as similar transit propulsion architectures. Uncrewed mission elements were delivered via Space Launch System (SLS) Block 2 to high Earth orbit (HEO) where all unmanned stack elements were then aggregated. Modeling of SLS Block 2 performance assumed the inclusion of a new Upper Stage and Advanced Booster to allow for delivery capabilities on the order of 130t to LEO, such that performance capabilities were in-line with those described in the *2014 SLS Program Mission Planner's Guide*^[6] (SLSP MPG). Solar electric propulsion (SEP) was used to transfer the aggregated stack to the crew rendezvous point in lunar distance Earth orbit (LDEO). The crew was directly inserted into LDEO for stack rendezvous using SLS and Multi-Purpose Crew Vehicle (MPCV). Both cases utilized similar chemical propulsion systems, with a liquid Oxygen (LOX) and Methane (CH₄) propellant, to complete the TMI, MOI, and trans-Earth injection (TEI) burns.

Trajectory solutions assumed Earth departure at a 407 by 380,000 kilometer LDEO orbit. Mars propulsive capture was assumed for both cases. The conjunction trajectory entered into an elliptical 1-sol parking orbit, while the opposition trajectory utilized a 250 km x 7,660 km parking orbit to enable an energy efficient tangential departure burn. This allows for descent stage Mars atmospheric entry at or below 4.7 km/s for both cases.

It was assumed that any mission destination elements and cargo are pre-deployed to Mars vicinity and therefore, are not included in this analysis. As a result, variations in destination architectures and entry, descent, landing (EDL) performance were not included in determining mission payload. No transit elements or propulsion stages are pre-positioned at Mars, with the full stack being aggregated prior to the initial Mars transit burns. As such, no in-mission

rendezvous was necessary to enable Earth return. Transit habitats were sized to accommodate a nominal 4 crewmembers for the entire mission duration. It was assumed a MPCV was carried in the stack for the entirety of the mission with direct MPCV Earth re-entry for both cases, with re-entry velocity constrained to 13 km/s to ensure the Venus fly-by did not produce excessive entry speeds at Earth.

The duration in Mars vicinity for opposition class-missions was fixed at 40 days. However, the total mission duration was left as a variable in the trajectory analysis, in order to assess the relationship between total duration and launch requirements. A Venus fly-by maneuver, constrained to a minimum 0.7 AU perihelion distance, was allowed on the opposition trajectory.

All conjunction transit occurred at a perihelion radius outside that of Earth. Both trajectories utilized a low-energy 2033 transit opportunity (2033 is widely considered a “good” opportunity, with minimal energy requirements). All solution strategies involved the application of substantial margins (e.g., 4% ΔV maneuvers) to ensure a conservative result. Where applicable, performance assumptions remained conservative to ensure attainable architecture constructs.

B. Trajectory Assessment

Mission trajectories were developed using an impulsive mission design tool, VISITOR^[7], developed internally by NASA Langley Research Center. Required departure and arrival hyperbolic excess velocity vectors for the outbound and inbound transit legs were defined utilizing the standard Lambert method. Solutions were derived via a grid-refinement technique, in which a coarse grid of departure dates and flight times was refined using a genetic algorithm (GA) heuristic process. A Pattern Search (PS)^[8] algorithm was applied to repeatedly resolve the grid in order to find best solutions. A 4% margin was applied to all ΔV solutions and 5% margin to reaction control system (RCS) maneuvers to ensure enough excess performance to complete transit with minor variations in departure date.

A conjunction-class mission was selected for detailed analysis that had a total duration of 1,005 days, with 558 days in the elliptical 1-sol parking orbit.

An opposition-class trajectory was selected for analysis that included a 40-day stay in Mars orbit and resulted in a total crewed mission duration of 560 days. Opposition-class trajectories with even shorter mission durations were evaluated; however, the 560-day duration represented a “knee” in the curve with ΔV requirements increasing rapidly for shorter mission durations. Figure 4 provides a representative plot of opposition total mission durations versus transit ΔV , with the 560-day stay time being the minimum energy point on the curve.

Long durations in Mars orbit allow for a natural precession of periapsis because the orbiting spacecraft can utilize tangential capture and escape burns without performing additional plane change maneuvers. This phenomenon known as a “free-apotwist” condition^[9], is easily achieved within a conjunction trajectory framework. However, as opposition class missions are constrained to short durations in Mars orbit, the opportunity for natural periapsis precession is greatly restricted. To avoid the additional propulsive penalties associated with a plane change burn maneuver, a free-apotwist solution was derived for the opposition mission case. By entering an elliptical Mars parking orbit of 250 by 7,660 kilometers at a sharp, 88-degree inclination, periapsis was able to sufficiently precess during the 40-day duration at Mars to allow for a single tangential departure burn. As a result, the opposition trajectory avoids an additional plane-change burn maneuver while in Mars orbit. Note that a portion of the increased MOI ΔV necessary to insert into a high-inclination Mars orbit is recovered through decreased landing propulsive requirements. For the opposition case presented in this study, surface-landing ΔV is reduced by 0.4 km/s relative to the conjunction case due to the low Mars orbital apoapsis (7,660 km) of the opposition case.

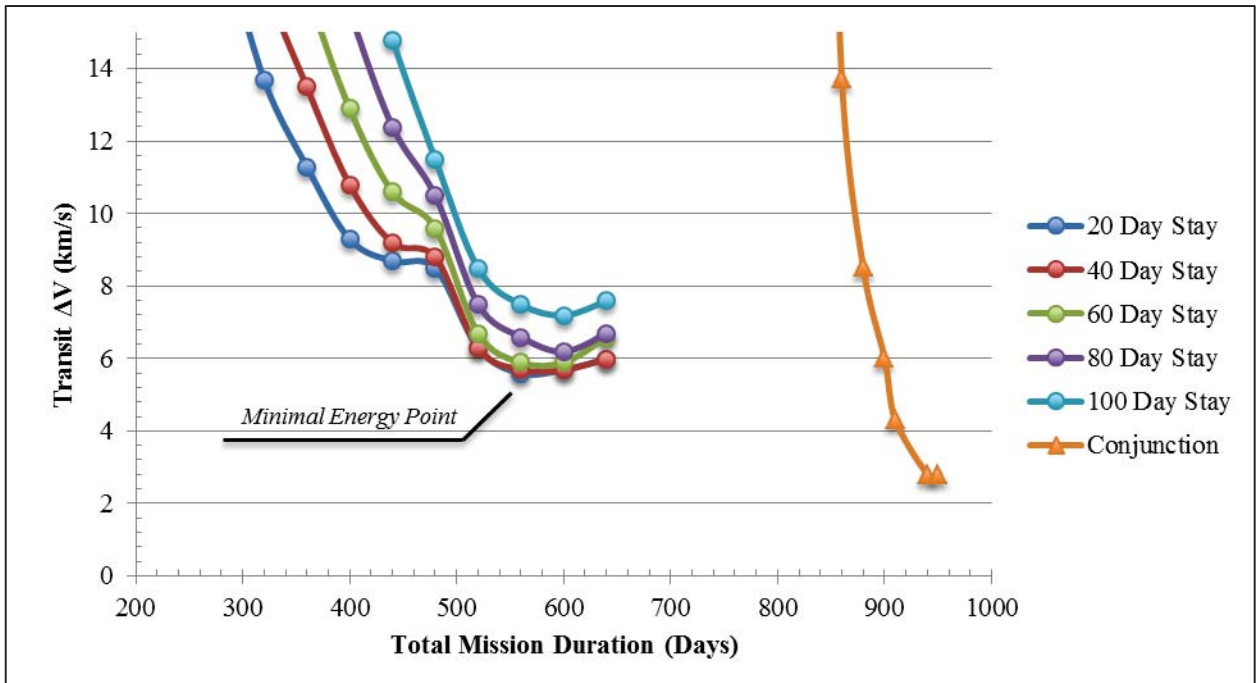


Figure 4: Transit ΔV Variation with Total Opposition Mission Duration

Table 1 provides a summary set of characteristics for each mission option. ΔV requirements for the selected trajectories are provided in Table 2. Note that the “Mission Total” represents only transit and orbital burns for the crew mission. ΔV penalties due to departure declination were not assessed in this study, although they are expected to be small and of the same magnitude for both trajectory cases. Requirements for pre-deploy of destination systems and any maneuvers out of the Mars destination orbit for exploration at the destination are not included. In addition, requirements for launch and positioning of stack elements in LDEO are not included in this table, since those would be the same for either mission approach.

Table 1. Summary of Results

	Mission Duration (Days)	Duration in Mars Orbit (Days)	Total ΔV (km/s)	SEP Aggregation Point	Mars Parking Orbit
Conjunction	1005	558	2.81	407 km x 380,000 km	1-Sol Elliptical
Opposition	560	40	5.69	407 km x 380,000 km	250 km x 7,660 km

Table 2. Selected Trajectory Analysis Results

Case	Mission Total		Trans-Mars Injection		Mars Orbital Insertion	Trans-Earth Injection	
	ΔV (km/s)	Time (days)	ΔV (km/s)	Time (days)	ΔV (km/s)	ΔV (km/s)	Time (days)
Conjunction	2.81	1005	0.50	198	1.25	1.06	197
Opposition	5.69	560	0.61	177	1.75	3.33	342
Difference	+103%	-445	+23%	-21	+28%	+215%	+145

The significance of the trade between mission duration and the individual ΔV requirements for each maneuver is immediately apparent when comparing the results for the two trajectory cases. A total increase of 103% in total ΔV results in a 445-day (44%) decrease in total mission time. Using the split optimization strategy described above, a

15%-85% transit ΔV budget allocation was assigned to the TMI and TEI stages respectively. As a result, the return phase of the opposition trajectory is the major differentiator between the total mission ΔV requirements. However, it is this ΔV increase that allows for the substantial reduction in total mission duration relative to the conjunction case.

C. Payload Assessment

To provide a detailed characterization of the element loading for opposition and conjunction mission concepts, logistics, spares, and volumetric needs were analyzed for each mission to determine crew requirements, manifested mass, and total habitat volume requirements. These factors have a large influence on the total habitation element loaded mass, and thus are drivers in total propelled mass.

A consumables analysis was conducted using the Human Exploration Logistics Model (HELM), a parametric modeling tool developed by NASA to support human exploration habitat architecture studies. HELM integrates consumables consumption rates; mission duration; extra-vehicle activity (EVA) frequency and duration; crew size; and environmental control and life support system (ECLSS) reclamation efficiencies and usage rates to model expected consumables requirements for exploration missions. Using historical values derived from International Space Station (ISS) heritage data, scaling factors and ECLSS operational efficiencies were adjusted to model expected consumption rates for a future DSH ^[10]. The direct scaling of most consumables products produces an overall linear relationship between mission duration and logistics requirements.

Determination of the sparing requirements for habitation systems was conducted using the Exploration Maintainability Analysis Tool (EMAT) ^[11]. A comprehensive model of crew critical DSH systems was developed at the component level using a combination of ISS heritage system architectures and expected future system developments, per the input of habitation subject matter experts. All component reliability data –mean time between failures (MTBFs) and K-factors – were derived from historical ISS performance data. The DSH system models used in this study, along with a functional description of EMAT, are described in further detail in the 2013 *Assessment of Maintainability for Future Human Asteroid and Mars Missions*. ^[12] The spares mass results represent the total mass of spare components necessary to achieve satisfactory expectation of habitat functionality over the duration of the missions. As durations increase, the exposure to component failures increases, and as a result, additional spares must be manifested to ensure safe operations. However, the functional relationship remains sub-linear, as additional spare components provide stepped gains in system reliability, rather than smoothly varying increases.

Individual transit habitats were sized to accommodate the mission durations associated with each mission case, including crew habitable volume and storage volume. Habitat architecture, configured as a monolithic cylindrical unit with a single internal shuttle class airlock, was assumed to support 4 crewmembers for the entirety of the mission. MPCV was not leveraged to offset habitable volume. Logistics packaging and storage requirements specific to each mission concept were integrated when developing the habitat volume and structural components. System sizing was conducted using a set of NASA developed parametric habitat system modeling tools. Figure 5 provides a summary of the habitat sizing for each mission case.

Habitat Sizing: 2033 Opposition Class Mission	
Volume Sizing	Vol., m ³
Habitable Volume	78.3
Total Pressurized Volume	161.5
Mass Sizing	Mass, kg.
Structure	3,373
Systems	14,498
Utilization	500
Growth	4,026
Dry Mass Subtotal	17,871
Consumables	8,661
Spares and Maintenance	3,110
ECLSS Consumable Fluids	612
Inert Mass Subtotal	27,144

Habitat Sizing: 2033 Conjunction Class Mission	
Volume Sizing	Vol., m ³
Habitable Volume	78.3
Total Pressurized Volume	204.9
Mass Sizing	Mass, kg.
Structure	3,853
Systems	16,116
Utilization	500
Growth	4,507
Dry Mass Subtotal	19,969
Consumables	15,549
Spares and Maintenance	4,887
ECLSS Consumable Fluids	682
Inert Mass Subtotal	36,200

Figure 5. Habitat and Consumables Sizing

Given the similar sized crew for both mission cases, the major differentiator in payload mass for logistics and spares loading is mission duration. Since both element masses scale directly with mission duration, conjunction

trajectories require significantly larger payloads relative to opposition missions. As a result, the long-stay mission requires a 25% increase in total habitat mass and an increase in total habitat volume of 21% over the shorter duration opposition class mission.

The conjunction class mission requires that 31% of total non-propulsive payload mass be attributed to consumables and spares, while opposition requires only 20%. Consumables and sparing sensitivities to total mission duration have a critical impact on loaded element mass, and provide a key, differentiating factor between the two trajectory cases.

D. Mission Design

Once trajectory and payloads are defined for each mission, integrated mission designs were developed for each of the opposition and conjunction cases. By utilizing the mission-specific ΔV and payload parameters, propulsive and launch requirements were resolved. All propellant mass, engine and tank sizing, and launch loading were conducted within the EXAMINE^[13] tool.

Propulsive requirements are a direct manifest of trajectory ΔV requirements and loaded mass. Using an iterative process within EXAMINE, propellant mass solutions were obtained for each propulsion stage. Determining the propellant wet masses for the opposition case involved imparting total stage sizing constraints to assure launch feasibility; therefore, propellant wet mass per stage was restricted to enable packaging (along with CPS, RCS, inert masses, and margin) on a single SLS Block 2. As a result, the complete MOI burn for the opposition trajectory involves a minor contribution from the TMI stage prior to the TMI jettison and the dedicated MOI stage burn. The propulsive wet mass requirements for each stage are given in Table 3 below.

Table 3. Propellant Wet Mass Requirements

	TMI Stage (tons)	MOI Stage (tons)	TEI Stage (tons)	Total Propellant Mass (tons)
Conjunction	22.8	41.4	22.3	86.5
Opposition	89.4*	88.7	89.8	267.9

* - Includes both TMI and partial MOI burn

Solutions for propulsive requirements must include dry mass components sizing for each stage. Complete stage sizing constitutes determination of the CPS dry, inert, and RCS mass. The CPS used in this study burned cryogenic LOX/CH₄ propellants and utilized a single-stage cryogenic fluid management (CFM) system to achieve zero boil-off (ZBO). CPS mass was parametrically sized using a MSFC developed curve fit. The model assumes a 3 x 30 klb_f engine arrangement with 355 seconds I_{sp}. CPS sizing for each mission stage is displayed in Table 4.

Table 4. CPS Inert Mass Sizing

	TMI Stage (tons)	MOI Stage (tons)	TEI Stage (tons)
Conjunction	9.2	9.5	8.9
Opposition	13.9	14.3	13.1

Given low thrust to initial mass at departure, finite burn gravity losses were computed to assure stage architecture feasibility. The results are provided in Table 5. Since both opposition-class and conjunction-class TMI departures were from LDEO, gravity losses were of minimal impact and well within the 4% propulsive margin added to the impulsive ΔV s.

Table 5. Gravity Loss Assessment Results

	Total Thrust (klb _f)	T/W at TMI Epoch	Gravity Losses (m/s)
Conjunction	90	0.247	< 1.0
Opposition	90	0.116	6.0

The propellant requirements listed above are for the crewed mission departing from LDEO. The total launch requirements for the Mars mission will include propulsive requirements to position all elements in LDEO prior to crew arrival at the stack. There are numerous options for positioning of elements in LDEO. In order to evaluate

launch requirements, this study assumed that all elements, except the MPCV with crew, were delivered to LDEO using SEP. Because the crew is not launched until the stack is assembled, the time constraints on the positioning of elements are not as significant as for the crewed portion of the mission. This makes SEP an efficient option for the positioning of elements. In the assumed concept, elements are launched on SLS Block 2 to HEO, where they are aggregated. A SEP system then propels the uncrewed stack to LDEO. The crew is then launched in an MPCV capsule on an SLS Block 2 and sent directly to LDEO. The MPCV docks with the integrated stack in LDEO and then departs for Mars. Figures 6 and 7 illustrate the entire mission structures for the conjunction-class and opposition-class concepts respectively.

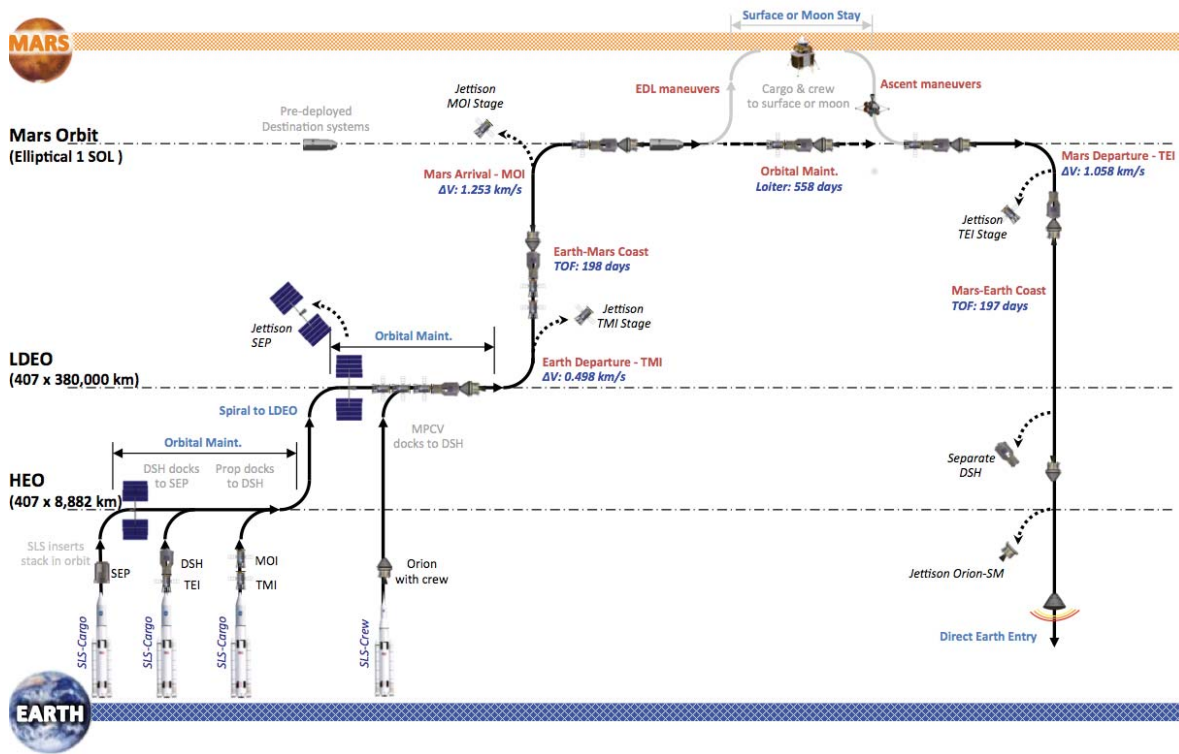


Figure 6. Conjunction Mission Outline

The HEO at which the stack is integrated with the SEP was optimized for each case, balancing SLS launch capacity with propulsive requirements at LDEO in an effort to maximize the utilization of SLS payload capacity. For the conjunction-class mission, the largest payload required was 92.0 t, thus the maximum apogee orbit the SLS Block 2 was able to deliver 92.0 t was a HEO of 407km X 8,882km. For the opposition-class mission, the largest single payload required was 114.5 t. Thus, the same SLS Block 2 was able to deliver the larger 114.5 t payloads to a lower HEO orbit of 407km X 2,100km. It should be noted that a 10% program mission reserve mass was applied to the net SLS payload delivery capability to promote a conservative result.

The results of the launch and aggregation assessment indicated that for both concepts a single SLS Block 2 launch was sufficient to deliver the SEP system, including propellant, required to move the integrated spacecraft stack from HEO to LDEO. With similar SEP power capabilities, the transit time from HEO to LDEO will be longer for the opposition case, due to the lower initial HEO orbit and the larger stack mass.

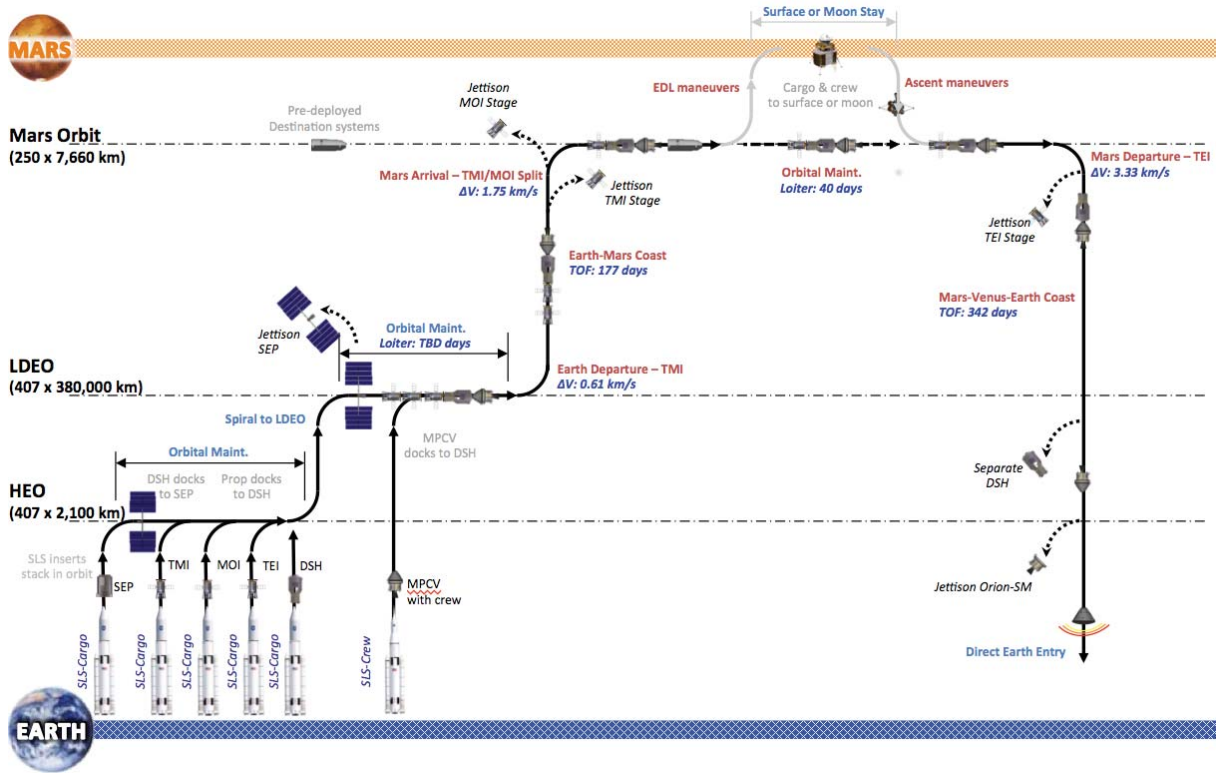


Figure 7. Opposition Mission Outline

Figures 8 and 9 outline the required launches for each case. The conjunction-class mission requires a total of four SLS Block 2 launches: one for the SEP system, two for the Mars spacecraft, and one for the crew in MPCV. The opposition-class mission requires a total of six SLS Block 2 launches: one for the SEP system, four for the Mars spacecraft, and one for the MPCV.

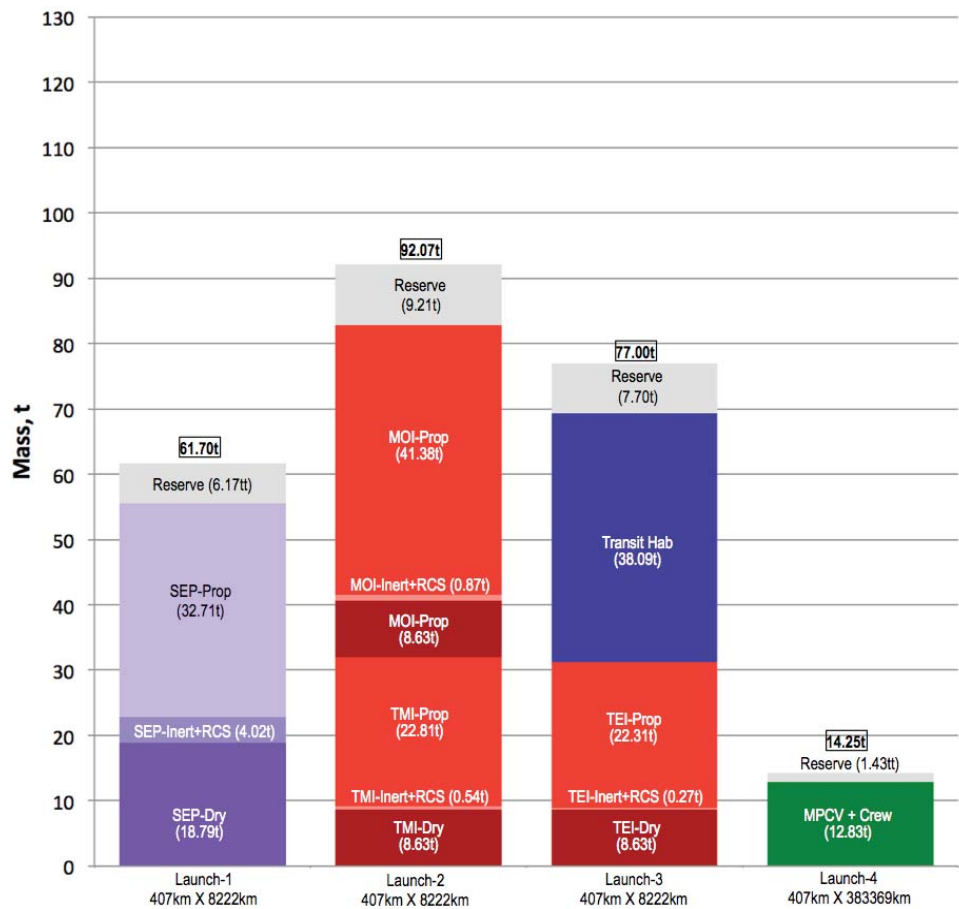


Figure 8: Conjunction Launch Requirements

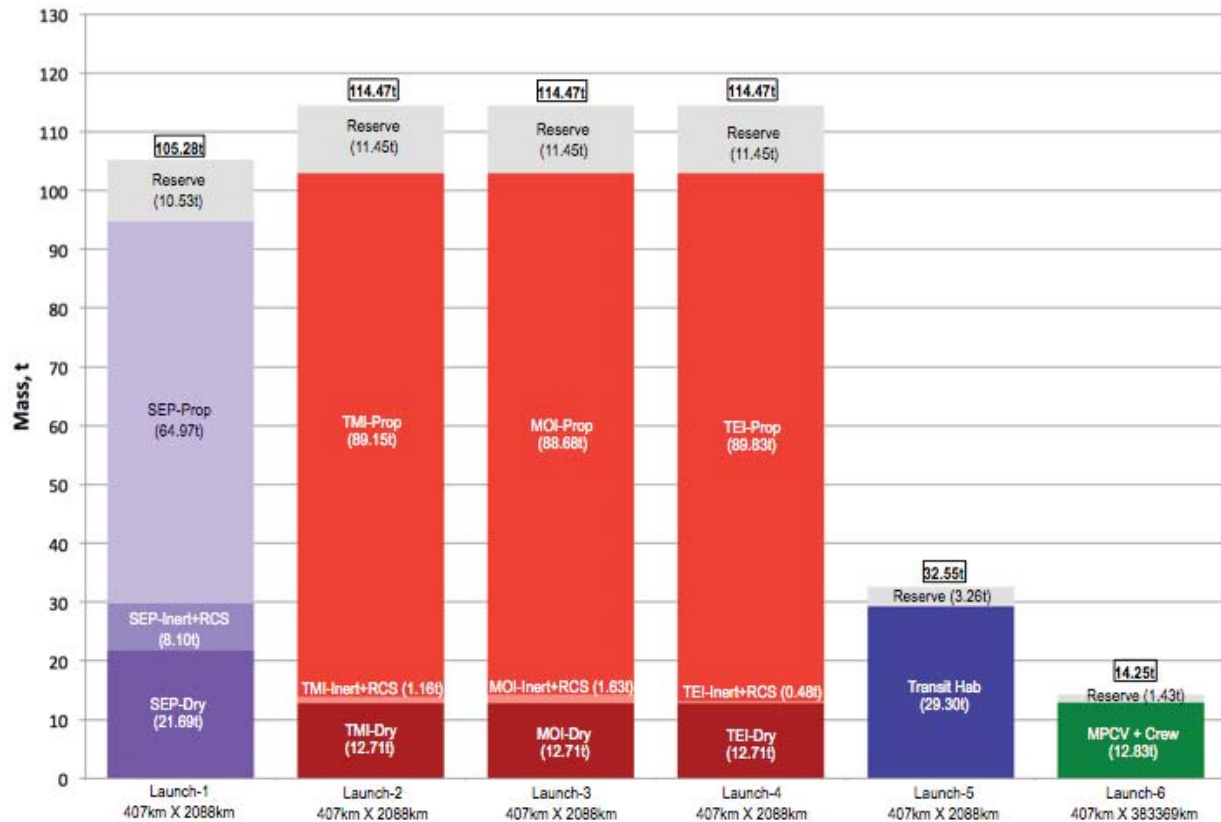


Figure 9. Opposition Launch Requirements

E. Risk Characterization

Before identifying the differences in risk between exploration trajectory cases, it is important to reiterate that the purpose of this analysis is to investigate opposition class missions as a viable alternative to conjunction class missions for initial human exploration of Mars space. Ultimately, as NASA gains experience with deep space exploration, much of the time-based risk associated with initial missions will be mitigated and conjunction-class missions may be preferable. It is within this context that a risk comparison was conducted.

Characterizing the risks associated with each mission class first involves defining the main differentiating factors inherent to each case. In this study, there are two critical variations in mission constructs that drive risk: mission duration and transit path. Individual risks were identified based on these factors and comparatively evaluated between the conjunction and opposition class missions. When evaluating mission risk, it is important to distinguish between transit duration and total mission duration. Periods on Mars surface present different risks to the mission and the crew than the periods in space. The potentially large risks associated with long durations of Mars surface habitation will likely preclude long surface stays, requiring much of the crew period in Mars vicinity to be spent in orbit and thus much of the mission risks to be duration dependent. For this analysis, which concentrates on initial exploration missions, the evaluation of risk assumes orbital missions and/or short stays on the Mars surface.

In a progressive campaign, gains in technological and operational experience will be vital to enabling sustainable human presence in Mars vicinity. Crewed exploration missions of the Mars surface and vicinity will potentially require significant technology maturation. Progress in the development and operational experience of high-closure ECLSS, radiation shielding and mitigation systems, cryogenic propellant management, crew diagnostic and health maintenance systems, and heavy launch capabilities will likely be critical to enabling human exploration capabilities. By evaluating both mission classes through a series of metrics related to capabilities, a better understanding can be gained as to the progressive increases in capabilities needed to enable each case. Table 6 provides an overview of key performance metrics as well as current demonstrated capabilities.

Table 6. Mission Capability Metrics

<i>Performance Metric</i>	Selected Mission Capability		
	Current	Opposition	Conjunction
CPS Operational Duration from Final Crew Checkout	N/A	210 Days	760 Days
Human Duration Beyond LEO	10 Days	560 Days	1005 Days
Human Exposure to Deep Space Radiation	10 Days	Maximum 560 Days (adjusted for protection at moons or on surface)	Maximum 1005 Days (adjusted for protection at moons or on surface)
Human Duration in Microgravity	6 Months	560 Days – Surface Duration	1005 Days – Surface Duration
Crewed Habitat Performance w/o Re-Supply	N/A	560 Days	1005 Days
Earth Entry		13.0 km/s	11.5 km/s

1. Spacecraft Systems Risk

Mission duration is the most prominent differentiating characteristic of opposition and conjunction class missions. Longer missions require extended durations for spacecraft systems, including habitation, propulsion, and support systems. DSH architecture design can potentially leverage evolutionary advances of ISS heritage habitation systems to achieve the necessary maintainability and closure to sustain a crew for the duration of a Mars mission. However, given the current ISS heritage component MTBFs and reliability histories, extended habitation system reliability is an area of substantial uncertainty. As mission durations extend, the uncertainties in system performance and maintenance capabilities are amplified, resulting in greater mission risk. Long-term, in-space habitation systems maintenance and repair has never been demonstrated without a continuous contingency chain back to Earth. Even with substantial spares manifesting prior to crew transit, the long exposure times present a significant uncertainty in mission safety.

2. Propulsion Systems Risk

The lifetime requirements for the propulsion stages likewise increase with mission duration. This includes both the lifetime of the stage and the duration required for cryogenic management of propellant once the crew has rendezvoused with the aggregated stack. In the selected opposition-class mission, there is a maximum duration of 210 days between final crew checkout prior to the initial Earth departure date and the firing of the TEI stage. The conjunction case, however, requires a quiescent period of 758 days after departure in which the TEI CPS system must maintain ZBO conditions. Within the architecture constructs provided in this analysis, a nearly 400% increase in the duration of CPS operation is required for the conjunction class mission over the opposition mission. The additional functional lifetime presents elevated CPS risk to the conjunction mission.

There is some potential added risk for the propulsion system due to the number of burns and the duration of those burns. However, because of the need to split the MOI burn between two stages, the total number of burns increased, and the amount of propellant required for each burn increased significantly. This would result in significantly longer burns for the opposition-class mission, and it would increase propulsion risk to some extent. Both evaluated mission concepts utilized the same number of propulsion stages, removing the number of stages as a differentiating risk factor between concepts.

3. Crew Autonomy Risk

Exploration missions into deep space imply a degree of crew autonomy not previously demonstrated during crewed occupations in space. Given ISS proximity in LEO, where almost instantaneous communication capabilities to Earth are available, few crew operations are conducted in full autonomy. However as part of a progressive campaign, ISS can provide an effective platform for gaining autonomous operations experience if desired. Communication lag in Mars vicinity can reach times greater than 20 minutes, requiring large periods of autonomous crew operations. The longer duration of conjunction-class missions requires the crew to operate autonomously for significantly longer periods of time.

4. *Crew Health Risks (non radiation related)*

Maintaining crew health while exposed to a deep space environment can be a critical challenge that significantly shapes the total mission. Health risks, both immediate and latent in nature, are sensitive to the durations and magnitudes of exposure. Exposure to the microgravity environment of deep space carries a fairly direct relationship with total mission duration. For initial exploration missions, crew will likely maintain orbital habitation for most if not all of their duration in Mars vicinity. Therefore, the opposition case provides an almost 50% reduction in crew microgravity exposure versus the conjunction case, assuming an orbital or short stay surface mission.

5. *Radiation Risk*

Another major consideration for crew health in deep space pertains to radiation exposure and mitigation. There are two main sources of radiation risk: solar particle events (SPEs) and galactic cosmic radiation (GCR). The magnitude of SPE exposure during an event period grows exponentially as the minimum spacecraft perihelion distance decreases. This presents concerns for an opposition trajectory that utilizes a Venus fly-by maneuver, such as the 0.72-AU minimum perihelion encountered during the short-stay case of this study. Conjunction missions naturally transit beyond the 1-AU of Earth orbit, greatly reducing SPE exposure relative to opposition trajectories. Exposure to SPEs can potentially present risk not only to the crew, but to equipment as well. Uncertainty of the impacts of DSH equipment exposure to high-flux SPEs present additional risks to system performance. It should be noted that given the discrete nature of SPEs, crew mitigation for exploration spacecraft is available in the form of internal radiation-safe enclosures that crew enter during event periods. Crew SPE exposure can be mitigated through architectural means, but it does become a driving factor in radiation protection sizing for opposition-class missions.

GCR radiation is a function primarily of in-space duration. For orbital and short-stay surface missions, the GCR risk will be a function almost entirely of total mission duration, and thus a greater concern for conjunction architectures. Extended visits to the Mars moons during orbital missions can reduce GCR exposure to some degree but the total reduction is limited. Opposition missions provide relief from GCR exposure by reducing overall mission times. However, as surface capabilities develop and Mars surface habitation periods expand, GCR risk will present greater threat to the opposition trajectories given the long transit durations and short periods of crew shelter in surface habitats. GCR risk also potentially presents a layer of uncertainty not present with SPEs, given the lack of human familiarity with deep space. Unlike SPEs, for which experience at near-Earth destinations can be leveraged to develop mitigation technologies, GCR requires exposure to deep space environments at a level that has not yet been demonstrated.

6. *Spacecraft Launch and Aggregation*

Because additional launches are required for the opposition-class mission, there is the potential of additional mission risk associated with the added SLS launches and docking events. In addition, if a SEP-based system is used to move the spacecraft stack to LDEO, then there will be additional in-space duration required for that transit, due to the larger mass. This will increase the exposure to failure for those systems. The launch and aggregation all relate to mission failure, rather than loss of crew, as they occur before the crew is launched.

7. *Earth Return and Re-Entry*

Increases in Earth re-entry velocity can present elevated risk for the opposition-class mission compared to conjunction-class missions. The trajectory on the return-leg of the opposition mission results in an expected re-entry velocity of 13 km/s, a significant increase of 1.5 km/s over the 11.5 km/s expected for the conjunction class mission. This increase in velocity at Earth entry will require more robust heat management and aerodynamic braking capabilities to enable the opposition-class mission, and potentially present additional risk to the crew during re-entry.

F. Mission Extensibility

A critical consideration for the viability of opposition-class missions as part of a progressive Mars campaign is in the extensibility of hardware elements and capabilities to eventual conjunction-class missions. In the proposed campaign construct, opposition missions serve as a stepping-stone for Mars exploration, buying down risk to enable eventual long duration missions to the Mars surface. It is anticipated that only a small number of opposition-class missions would be conducted; therefore, it is critical that elements can be used to conduct both types of missions without major modifications or penalties. It would be cost and time prohibitive to build elements just for opposition missions.

For both cases analyzed as part of this study, habitation systems with similar designs and capabilities were assumed. The total volume of the conjunction-class habitat was greater than for opposition, accounting for the added required storage volume. However, the difference was comparatively small and could be achieved through a relatively simple increase in the length of the barrel for the habitat. Alternatively, the full volume conjunction habitat could be used for the opposition with a slight mass penalty.

The cases presented in this study incorporate similar propulsive elements both in terms of engines and zero boil-off cryogenic propellant storage. The opposition and conjunction cases utilize engines of identical thrust sizing, 3x 30klbf with a LOX/CH₄ propellant. As previously presented, the high orbital energy at LDEO departure reduces the impact of finite gravity burn losses, which in turn allows similarly sized engines to be used for both mission cases.

However, there are significant differences in the required propellant tank sizes for each class of mission. Tank sizing was constrained to maintain feasible SLS loading, but the propellant tank requirements for the opposition class mission are significantly larger than for conjunction. The largest propulsion stage for the conjunction class requires a total of approximately 48 tons of propellant (with margin), and the largest stage for the conjunction class requires 101t of propellant. This doubling of propellant requirements will involve either an increase in tank sizing for the CPS or the use of drop tanks. This is a significant change to the mission architecture that must be evaluated. A common CPS could be extended across both cases by replacing the individual conjunction mission TMI and MOI stages with a single larger TMI/MOI stage that shared commonality with the opposition-class CPS architecture. The smaller conjunction-class TEI stage could then also be replaced with the opposition-sized CPS, but would be offloaded as needed to accomplish the mission. Incorporating this common CPS architecture would impart a mass penalty on the conjunction mission, as the conjunction TEI stage dry mass would be similar to that of the opposition-class CPS.

IV. Conclusions

Short duration opposition class trajectories have largely been dismissed as a viable alternative for human mission to Mars due to concerns over the increased propulsive requirements, short destination durations, and architecture extensibility. However, a more comprehensive analysis indicates that the relative penalties associated with opposition concepts may not be as severe as originally anticipated. Furthermore, short-stay missions could represent a stepping-stone to long-duration missions, reducing overall campaign risk and allowing for a more progressive build-up of capabilities. The investigation of propulsive requirements, element delivery, and mission risk provides a deeper understanding of the advantages and trade-offs associated with opposition trajectories, presenting new arguments towards their viability as part of a larger exploration campaign.

The analysis presented in this study suggests that the propulsive requirements for opposition class missions are not nearly as prohibitive as initially perceived. Opposition trajectories will always require greater propulsive loads than conjunction trajectories; however, the relative impact can be mitigated slightly through lower loaded element masses and optimized ΔV mission splits.

The total number of SLS Block 2 launches required to enable the crewed portion of the Mars mission increased from four for the conjunction class to six for the opposition class in this analysis. While the addition of two SLS launches is significant, it is likely not so prohibitive as to invalidate the mission. The increased launch mass, requiring the additional two launches, is associated entirely with added propellant load.

By evaluating the risks associated with each mission concept, trades in mission reliability can be compared, particularly for initial missions. The long total durations of conjunction class missions can likely result in increased risk for early conjunction class missions due to risk sensitivity to mission duration. Given the capabilities developments and investments required to reliably enable such missions, opposition concepts may present a better opportunity to progressively gain exploration experience, while maintaining a less drastic risk buy-down strategy.

V. Future Work

Maintaining consistent assumptions in the analysis and performing an in-depth assessment of each concept allowed for a detailed comparison of mission concepts. However, this level of analysis is time consuming and requires substantial resources. The set of missions that are presented in this paper represent one possible set of architectural assumptions, allowing for a detailed comparison of options. There are many potential changes to these assumptions that could be assessed in the future in order to evaluate the relative impacts on conjunction and opposition class missions. Specific topics for further evaluation include:

- Pre-positioning of TEI stage in Mars orbit
- Return to Earth orbit at the conclusion of the mission / No MPCV in spacecraft stack

- Use of Liquid Oxygen – Hydrogen propulsion
- Use of drop tanks or cross-fed propulsion stages
- Impacts of delivery method to and the location of aggregation on mission feasibility.

In addition, further assessment should be conducted on certain issues that impact the opposition mission, such as: required radiation protection and mass impacts for Venus fly-by, detailed assessment of viability of the “apotwist” maneuver at Mars, and an assessment of the cost impacts of CPS tank sizing. Further assessment of these factors will help define whether opposition-class missions play a role in an integrated Mars campaign

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