A One-year, Short-Stay Crewed Mars Mission using Bimodal Nuclear Thermal Electric Propulsion (BNTEP) - A Preliminary Assessment

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A crewed mission to Mars poses a significant challenge in dealing with the physiological issues that arise with the crew being exposed to a near zero-gravity environment as well as significant solar and galactic radiation for such a long duration. While long surface stay missions exceeding 500 days are the ultimate goal for human Mars exploration, short round trip, short surface stay missions could be an important intermediate step that would allow NASA to demonstrate technology as well as study the physiological effects on the crew. However, for a 1-year round trip mission, the outbound and inbound hyperbolic velocity at Earth and Mars can be very large resulting in a significant propellant requirement for a high thrust system like Nuclear Thermal Propulsion (NTP). Similarly, a low thrust Nuclear Electric Propulsion (NEP) system requires high electrical power levels (10 megawatts electric (MW_e) or more), plus advanced power conversion technology to achieve the lower specific mass values needed for such a mission. A Bimodal Nuclear Thermal Electric Propulsion (BNTEP) system is examined here that uses three high thrust Bimodal Nuclear Thermal Rocket (BNTR) engines allowing short departure and capture maneuvers. The engines also generate electrical power that drives a low thrust Electric Propulsion (EP) system used for efficient interplanetary transit. This combined system can help reduce the total launch mass, system and operational requirements that would otherwise be required for equivalent NEP or Solar Electric Propulsion (SEP) mission. The BNTEP system is a hybrid propulsion concept where the BNTR reactors operate in two separate modes. During high-thrust mode operation, each BNTR provides 10's of kilo-Newtons of thrust at reasonably high specific impulse (I_{sp}) of 900 seconds for impulsive trans-planetary injection and orbital insertion maneuvers. When in power generation / EP mode, the BNTR reactors are coupled to a Brayton power conversion system allowing each reactor to generate 100's of kW_e of electrical power to a very high I_{sp} (3000 s) EP thruster system for sustained vehicle acceleration and deceleration in heliocentric space.

Nomenclature

I_{sp}	Specific impulse, s
g	Earth standard gravity, 9.80665 m/s^2
V_∞	Hyperbolic Excess Velocity, km/s
C_3	Characteristic energy, km^2/s^2
ΔV	(Delta-V) Imparted Velocity Change km/s
$^T/_W$	Ratio of Thrust to Weight
$BNTEP$	Bimodal Nuclear Thermal Electric Propulsion
$BNTR$	Bimodal Nuclear Thermal Rocket
BRU	Brayton Rotating Unit

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DRA	Design Reference Architecture
EOI	Earth Orbit Insertion
EP	Electric Propulsion
$IMLEO$	Initial Mass in Low Earth Orbit
LEO	Low Earth Orbit
MLI	Multilayer Insulation
MOI	Mars Orbit Insertion
$MPCV$	Multi-Purpose Crew Vehicle
mt	Metric Ton (1 mt = 1000 kg)
MTV	Mars Transfer Vehicle
$NAIF$	Navigation and Ancillary Information Facility
NEP	Nuclear Electric Propulsion
NTR	Nuclear Thermal Rocket
PCU	Power Conversion Unit
$PMAD$	Power Management and Distribution
RCS	Reaction Control System
SEP	Solar Electric Propulsion
SLS	Space Launch System
TEI	Trans-Earth Injection
TMI	Trans-Mars Injection
ZBO	Zero Boil Off

I. Introduction

A crew health and performance assessment was done for the Mars DRA 5.0 concluded that for both conjunction and opposition class missions, exposure to solar proton events and galactic cosmic radiation during interplanetary transit and solar proton event effects during close perihelion passage are well outside current permissible exposure limits.[1] Limiting total mission time to 1-year can reduce interplanetary time by 75-300 days, significantly reducing exposure time.

The analysis presented in this paper covers a detailed trajectory design and mission architecture for a 2033 one-year round trip, 1 MW_e-class BNTEP mission with an outbound transit time of 126 days, a 30 day stay in a 24 hour elliptical Mars orbit and an inbound transfer time of 209 days with direct re-entry at Earth by the crewed MPCV. The dual-mode BNTEP vehicle enables a short round trip mission by reducing the use of the high thrust BNTR engines. Having an initial mass in LEO of 389.9 mt, this mission requires a total of 5 SLS Block-IB launches to deliver all the vehicle components for assembly in LEO. This is on-par with the stay time and IMLEO for NTR opposition-class mission and accomplishes the mission in 365 days instead of 400-600 days. Descriptions of the mission, propulsion and vehicle needed for this type of mission are included in the following text. A conceptual design of the vehicle and major components is provided in Figures 1 and 6.

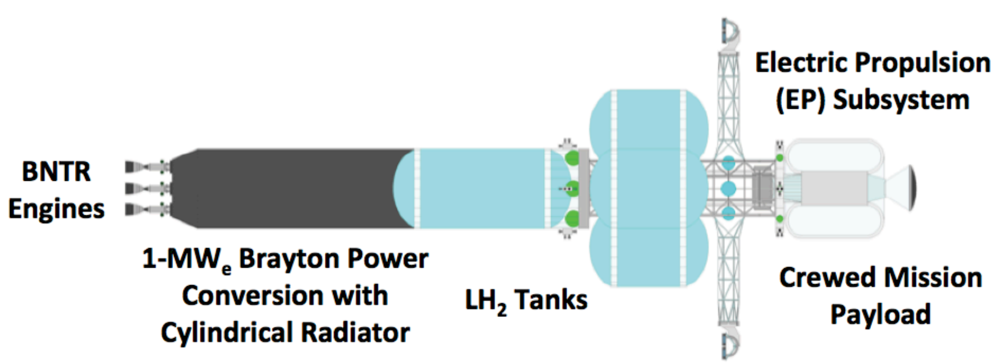


Figure 1. Key Components of BNTEP Mars Transfer Vehicle

II. 2033 1-Year Earth-Mars Roundtrip BNTEP Mission

II.A. Mission Definition

A 1-year mission during the 2033 opportunity requires a lower combined BNTR and low-thrust ΔV budget than other opportunities in the 2031-2041 time frame (Appendix A). Although 2033 is not the preferred mission opportunity for ballistic transfer NTR missions due to the high launch asymptote declination, the compressed mission timeline causes the launch date to move later than the ballistic optimal and out of the higher declination region. Plane change to adjust for declinations beyond 28.5° is performed during the low-thrust burns during the outbound transit.

This mission uses the BNTR engines in high-thrust mode to depart Earth on May 6, 2033. Following injection into the hyperbolic Earth escape trajectory, the BNTR engines are then powered down to power-generation mode to complete low-thrust EP burns during transit. The BNTR engines are powered up again just prior to Mars arrival for a high-thrust burn to injection into a 24 *hr* Mars orbit on September 8, 2033. The MTV stays in orbit around Mars for 30 days at which point the BNTR engines perform the last high-thrust burn to escape Mars. During the return leg of the trajectory the BNTR engines are switched to power-generation mode again to complete the return low-thrust EP burns. Upon arrival at Earth on May 6, 2034, the crew boards the MPCV, separates from the MTV and performs a direct re-entry into Earth's atmosphere. Over the course of the mission, the total time the BNTR engines are operating in high thrust mode is 1.75 hours.

II.B. Mission Design Analytical Methods

The trajectory optimization program COPERNICUS[2] was used to model and perform analysis for the 1-year BNTEP missions. Impulsive burns were used to model the BNTR propulsive maneuvers and finite burns were used to model the longer EP burns. Trajectories were optimized for the 2031-2041 opportunities. Earth departure and arrival dates were optimized parameters but the total time of flight was constrained to be no longer than 365 days. The MTV begins in an 407 *km* circular LEO orbit inclined at 28.5°. The BNTR engines perform TMI to put the MTV into a hyperbolic Earth-Mars transfer orbit. A minimum half-day coast is constrained to occur before and after each BNTR burn to allow for targeting and checkout operations. Following TMI and a half-day checkout period, the optimization is allowed to initiate the first EP burn. This burn usually occurs as early as possible in the transfer trajectory in order to reduce the burden on the BNTR system to provide all the energy required for Earth departure. A coast period separates this first EP burn from a second EP burn that occurs prior to Mars arrival. The second EP burn is terminated no later than a half-day prior to MOI. The second EP burn is used to slow down the MTV to reduce the MOI ΔV. MOI is performed using the BNTR engines to insert the MTV into a 300 *km* x 24 *hr* Mars orbit. The stay time at Mars is constrained to be a minimum of 30 days. Due to the geometry of this mission, stay time never extends past the 30 day lower bound. To depart Mars, the BNTR engines perform the TEI burn to put the MTV into a hyperbolic Mars-Earth transfer orbit. After a half-day checkout coast following TEI the optimization is allowed to initiate the third EP burn. A coast period separates this third EP burn from a fourth EP burn. Typically the fourth EP burn is removed, as it is deemed unnecessary by the optimizer. Unlike the other EP burns which occur as close to departure/arrival as possible, the fourth EP burn, if performed, occurs near the mid-point of the inbound trajectory. Since the MTV employs a direct entry at Earth rather than EOI to capture into an Earth orbit, the optimization uses the fourth EP burn to shape/correct the trajectory to return to Earth within 365 days.

Similar to ballistic Earth-Mars trajectories, optimal BNTEP Earth-Mars trajectories can have outbound legs that are either Type-I or Type-II trajectories. Type-I trajectories are characterized as having shorter trip times while Type-II trajectories are characterized as having longer trip times. Type-I and Type-II trajectories are identified as having heliocentric travel angles less than or greater than 180° respectively. While 2031, 2033 and 2035 are more optimal with Type-I outbound transfers, 2037, 2039 and 2041 are more optimal having a Type-II outbound trajectory leg. For this analysis, only the optimal trajectory type was analyzed for each opportunity.

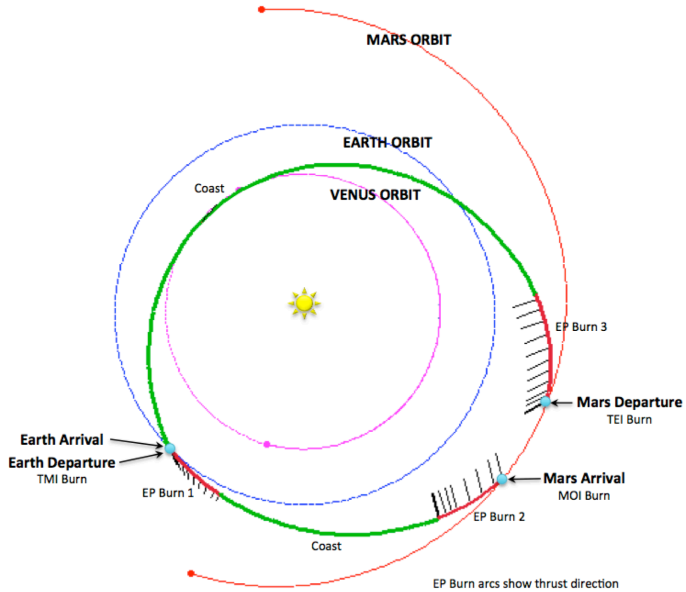


Figure 2. Ecliptic View of 2033 Reference 1-Year BNTEP Earth-Mars Roundtrip Mission

An ecliptic view of a 2033 BNTEP trajectory is showing in Figure 2. The green segments represent coasting phases while the red segments represent EP burns as well as the thrust direction during those burns. It should also be noted that although a minimum Spacecraft-Sun distance was not specified as a constraint, for all trajectories analyzed for this study the MTV did not approach closer than 0.7 AU to the Sun (Venus' orbit) and that these trajectories were modeled without requiring a Venus flyby on the outbound or return legs.

II.B.1. Analysis Tools

COPERNICUS was used to model the Earth-Mars BNTEP trajectories and perform the analysis presented in this paper. COPERNICUS is a 3-Degrees of Freedom spacecraft trajectory design and optimization program that was originally developed at the University of Texas with recent developments and maintenance being done by Johnson Space Center.[2] Trajectory models are built as a series of segments propagated in either a point-mass or higher order gravitational field. The segments can be connected and constrained with the addition of linear or non-linear constraints. COPERNICUS has the capability to model both low thrust burns as well as high thrust burns as either impulsively or with finite maneuvers for propulsion systems which can be based on BNTR, solar electric, or nuclear powered engines. SPICE files provided by Jet Propulsion Laboratory's NAIF is the basis of coordinate systems and ephemeris data.

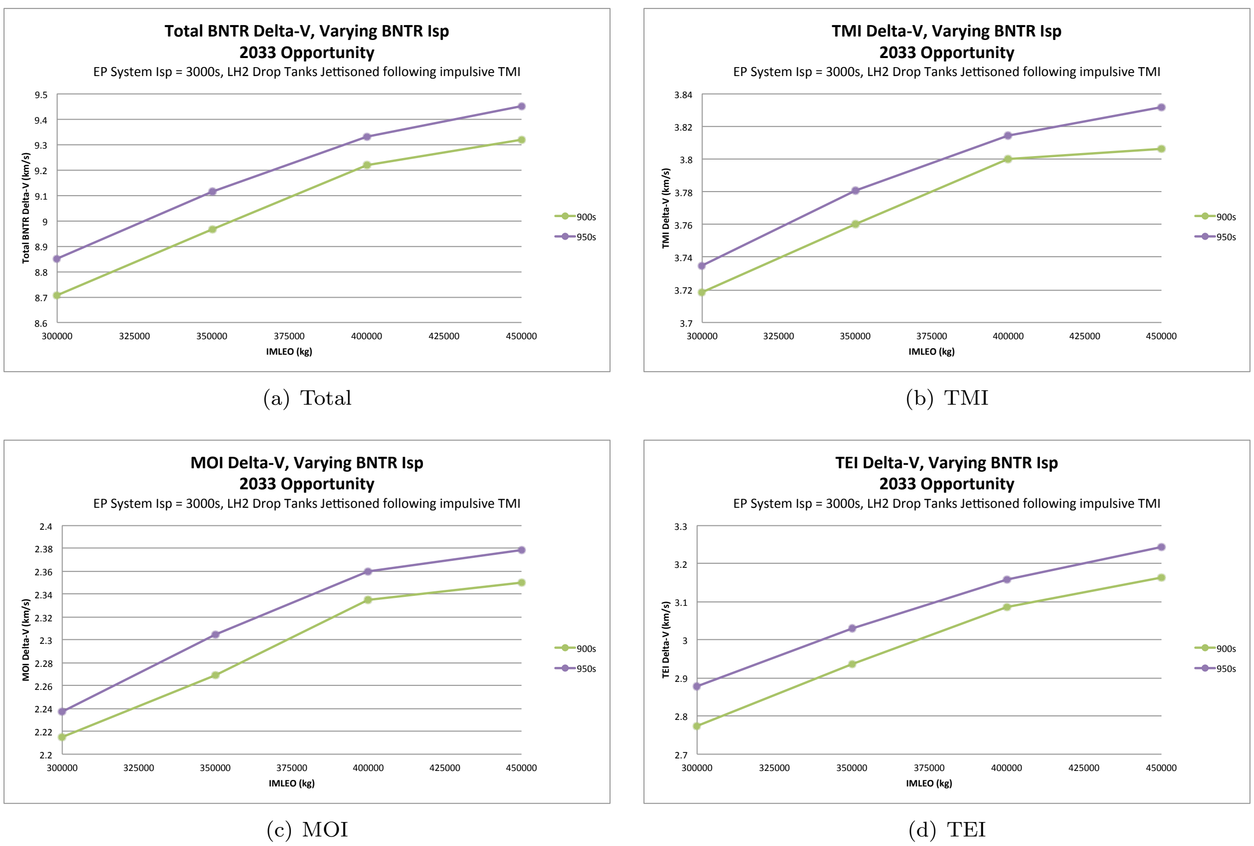
II.C. Assumptions and Constraints

- TOF = 365 $days$
- Mars Stay Time = 30 $days$
- EP system efficiency = 65%
- Earth departure orbit: 407 km circular orbit inclined at 28.5°
- Mars arrival orbit: 300 km x 24 hr elliptical orbit
- Maximum Earth arrival $V_\infty = 11.5\ km/s$
- EP system $I_{sp} = 3000\ s$
- NTR $I_{sp} = 900\ s$

- Propellant Constraints
  - Maximum drop tank propellant capacity is 39.2 *mt* (8.4 *m* outer diameter x 13 *m* length drop tank)
  - The TMI-1 burn is constrained to use no more than the full propellant capacity of 2 drop tanks
  - BNTR propellant required for TMI-2 beyond the capacity of the remaining 2 drop tanks will be stored in the inline tank
- Dropped Elements
  - Individual drop tank sets released after TMI-1 and TMI-2

II.D. Trajectory Details

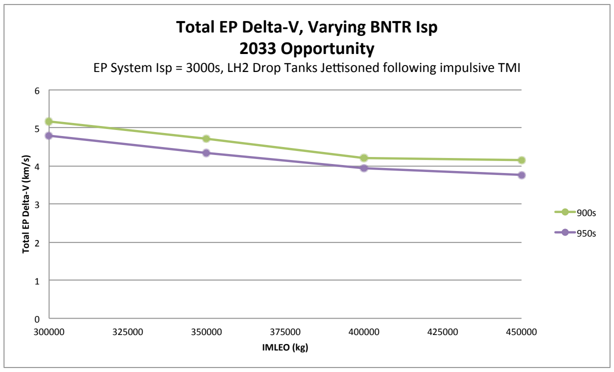
Trajectory analysis for the 2033 Opportunity was completed to determine the variations in BNTR and EP ΔV with the MTV IMLEO. As expected, as the IMLEO of the MTV increases, the effectiveness of the EP system to move the vehicle during the short transit time decreases. Hence, the amount of ΔV imparted by the EP system decreases since the high-thrust BNTR engines must be utilized to a greater degree in order to accomplish the mission in the constrained 1-year time period. Plots showing the relationship between IMLEO and ΔV are shown in Figure 3 and Figure 4.



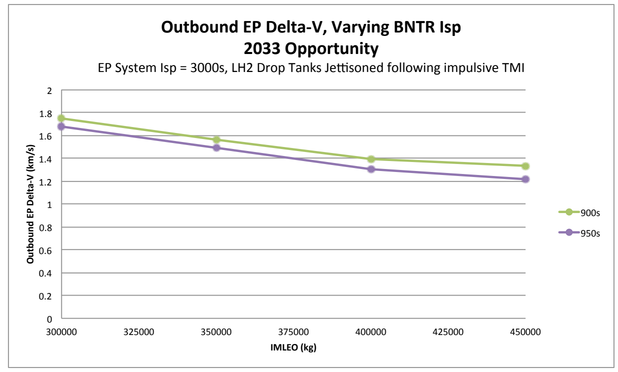
(a) Total (b) TMI

(c) MOI (d) TEI

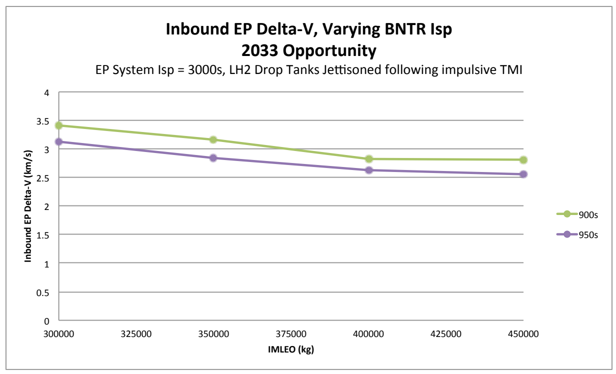
Figure 3. BNTR ΔVs for 2033 Mission



(a) Total



(b) Outbound, Earth-Mars



(c) Inbound, Mars-Earth

Figure 4. EP ΔVs for 2033 Mission

The data presented in these charts was interpolated for the IMLEO of the fully assembled MTV vehicle. Since these burns were modeled impulsively for the COPERNICUS analysis, a separate calculation of gravity loss for each of the BNTR burns was completed and added to the impulsive ΔV. The BNTR and EP ΔV values used in this analysis are presented in Table 1. The gravity loss calculations assume each of the three BNTR propulsive maneuvers are performed as a 2-perigee burn departure/capture maneuvers. For high-thrust burns of this magnitude, even with the high thrust BNTR engines there can be significant gravity losses. By utilizing a 2-burn maneuver sequence instead of a single burn, the gravity loss of each maneuver is minimized. In future assessments, to reduce complexity and risk the MOI and TEI maneuvers could be reduced to a single perigee burn without a substantial increase in gravity loss ΔV. Since no mass drops are performed during MOI and TEI, the ΔV in Table 1 is collective, representing the sum of the two perigee burns for each of these maneuvers.

Mission Delta-V Summary			
Phase Name	BNTR DV		EP DV
	Impulsive DV (m/s)	G-Loss DV (m/s)	(m/s)
TMI-1 Burn	1765		
TMI-2 Burn	2029	317	
EP Burn 1			639
EP Burn 2			781
MOI	2324	79	
TEI	3060	100	
EP Burn 3			2873
EP Burn 4			0

Table 1. BNTR and EP ΔVs for Reference 2033 1-Year BNTEP Earth-Mars Roundtrip Mission

Following assembly of the MTV in LEO, a 2-perigee burn TMI using the three 25 klb_f BNTR engines injects the MTV into a hyperbolic Earth-Mars transfer trajectory on May 6, 2033. TMI is separated into two burns in order to reduce gravity losses as well as to take advantage of the drop tank design of the MTV. In order to reduce the inert mass that needs to be accelerated throughout the mission, the MTV jettisons the depleted LH_2 drop tanks following each of the TMI burns. The first pair of empty LH_2 tanks are jettisoned following TMI-1 such that TMI-2 does not have to push the empty drop tank mass. Likewise, the second pair of LH_2 drop tanks are jettisoned following TMI-2 in order to further reduce the inert mass carried throughout the remainder of the mission. Figure 5 shows am image of how the four drop tanks separate from the star truss.

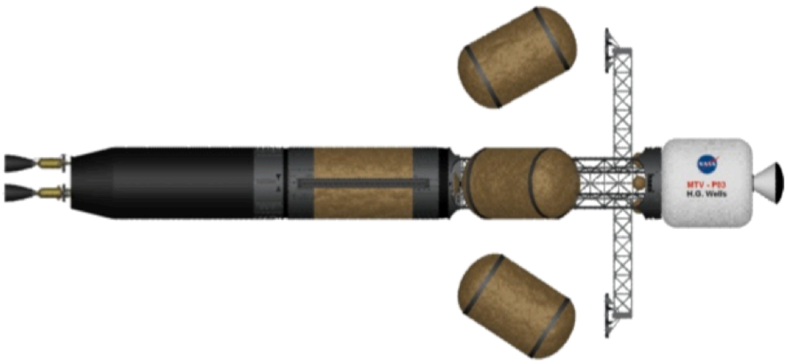


Figure 5. Jettison of Drop Tanks from Star Truss following TMI Burn

At the start of the in-transit phase to Mars, the BNTR engines are powered down from 545 MW_t (for the NTR/thermal propulsion mode) to 1.76 MW_t (for the EP/power generation mode). Energy generated in the reactor fuel assemblies is removed using a secondary closed gas loop that carries a helium-xenon (He-Xe) gas mixture. In a BNTR design derived from the Rover/NERVA technology program,[3] the existing regenerative-cooled core support tie tubes would carry recirculated He/Xe coolant gas. Power from the NERVA fuel elements surrounding the tie tubes enters the tubes via conduction. In the fast reactor BNTR design called ESCORT,[4] a closed loop, coaxial energy transport duct, integrated into each UO_2-W fuel element, carries the He-Xe coolant gas. The heated gas is then routed to a high power (500 kW_e) BRU consisting of a Turbine-Alternator-Compressor (TAC) assembly that generates electricity at approximately 20% energy conversion efficiency to power the EP system and spacecraft systems. Waste heat is rejected to space using a pumped-loop radiator.[5] A 36.7 day low thrust EP burn follows the half-day forced coast after TMI. This burn is used to add additional energy to the MTV such that the high thrust BNTR engines do not need to provide the full departure energy that would be necessary for a true ballistic transfer. A 44 day coast period separates this first EP burn from a second 43.8 day low thrust EP burn then ends a half-day prior to MOI.

Following completion of the last EP burn just prior to Mars arrival, the power level and fuel temperature of the BNTR engines are increased to full capability for the high thrust/high I_{sp} 2-perigee burns required to propulsively capture into a 24 hr elliptical Mars parking orbit on September 9, 2033. At this point the crew will be captured in a 300 km x 24 hr Mars orbit for 30 days.

The BNTR engines are used again to perform the 2-perigee burn TEI maneuver which injects the MTV into a Mars-Earth hyperbolic transfer trajectory on October 9, 2033. After a successful TEI, the BNTR engines are again powered down to 1.76 MW for a 80.8 day EP burn occurring a half-day after TEI completion. A 127.7 day coast returns the MTV to Earth and aligns for a direct re-entry. V_∞ at Earth was constrained to be less than 11.5 km/s. The optimization eliminated the need for a final EP burn near Earth on the return leg of the trajectory. One may be added if a case arises where Earth arrival V_∞ exceeds 11.5 km/s or when the trajectory needs to be corrected part way through the return coast to align properly to intercept Earth. Once the MTV has reached the Earth entry interface point, the crew boards the MPCV and separates from the MTV. Re-entry occurs on May 6, 2034 while the MTV flies by Earth and is disposed of in heliocentric space.

For the 1-year round trip BNTEP mission, the total operational time for the BNTR engines is 324 megawatt - days (MWD) which includes 1.75 hours of high thrust / high power mode operation totaling 40 MWD and 284 MWD of reduce power EP mode operation. Assuming 1.2 grams of U-235 consumed per MWD, the total U-235 fuel loss in each engine is 389 grams. Since each cermet fuel BNTR has in excess of

200 kg, the burn-up is less than 0.2% which is quite acceptable.

Table 2 shows the timeline for the 2033 reference mission, including pre-burn masses and propellant loads for each of the BNTR and EP burns. Similarly to Table 1,the ΔV and burn time in the mission timeline are collective for MOI and TEI, representing the sum of the two perigee burns.

Phase #	Event Name	BNTR DV (m/s)	EP DV (m/s)	Event Begin Date	Duration (hr)	Pre-Burn Mass (kg)	BNTR Prop Load (kg)	EP Prop Load (kg)
1	**Earth Departure**			5/6/33	0.00	389907.08	0.00	0.00
1.1	TMI-1 Burn	1765.0		5/6/33	0.52	389907.08	70671.04	0.00
1.2	Coast, drop 2 drop tanks			5/6/33	8.00	303236.05	0.00	0.00
1.3	TMI-2 Burn	2345.3		5/6/33	0.52	303236.05	70761.20	0.00
1.4	Coast, drop 2 drop tanks			5/6/33	0.00	216474.84	0.00	0.00
2	**Earth-Mars Transit**			5/6/33	0.00	216474.84	0.00	0.00
2.1	Coast			5/6/33	12.00	216474.84	0.00	0.00
2.2	EP Burn 1		638.8	5/6/33	881.93	216474.84	0.00	4649.45
2.3	Coast			6/12/33	1056.79	211825.39	0.00	0.00
2.4	EP Burn 2		780.7	7/26/33	1052.23	211825.39	0.00	5547.26
2.5	Coast			9/8/33	12.00	206278.13	0.00	0.00
2.6	MOI	2402.9		9/9/33	0.36	206278.13	49163.97	0.00
3	**Mars Stay**			9/9/33	720.00	157114.16	0.00	0.00
4	**Mars-Earth Transit**			10/9/33	0.00	157114.16	0.00	0.00
4.1	TEI	3160.4		10/9/33	0.35	157114.16	47288.69	0.00
4.2	Coast			10/9/33	12.00	109825.47	0.00	0.00
4.3	EP Burn 3		2873.2	10/9/33	1938.35	109825.47	0.00	10218.79
4.4	Coast			12/29/33	3064.94	99606.68	0.00	0.00
4.5	EP Burn 4		0.0	5/6/34	0.00	99606.68	0.00	0.00
4.6	Coast			5/6/34	0.00	99606.68	0.00	0.00
4.7	Direct Entry at Earth			5/6/34	0.00	99606.68	0.00	0.00

Table 2. Mission Timeline for 2033 Reference 1-Year BNTEP Earth-Mars Roundtrip Mission

II.E. Launch Summary

The Space Launch System (SLS) Block-IB configuration, a Shuttle-Derived Heavy Lift Vehicle capable of delivering 113.8 mt into orbit,[6] is used for delivering the MTV components to LEO for assembly. Vehicle integration is performed via autonomous rendezvous and docking of major elements, along with crew assisted orbital assembly to attach the four LH_2 drop tanks. Five SLS launches over 120 days deliver the MTV's major elements. A graphic showing the fully assembled MTV with the main components identified is shown in Figure 6.

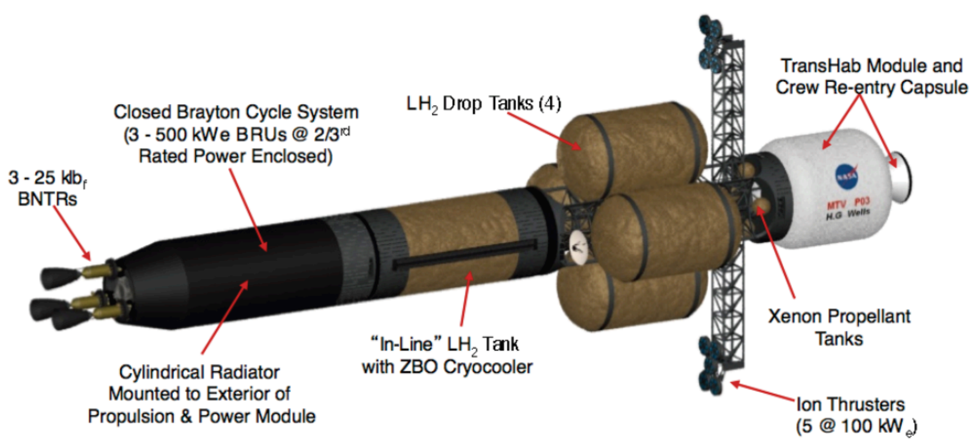


Figure 6. Concept Design of Mars Transfer Vehicle (MTV) Following Assembly in Low Earth Orbit

A launch summary giving the launch order as well as the total wet mass of each launch is provided in Table 3. The first launch carries up the core propulsion and power module. The second launch delivers the large in-line LH_2 propellant tank. The third launch delivers the 4-sided star truss and deployable, twin EP thruster arms with Xenon Hall engines, and the attached TransHab module. Launches 4 and 5 deploy four modular LH_2 propellant drop tanks manifested as twin tank sets. The MPCV and crew is launched on a Block-I SLS or commercial launch vehicle to the MTV after the third Block-IB SLS launch and assists in the attachment of the 4 LH_2 drop tanks to the MTV's star truss.

Launch Summary		
Launch	Elements	Launch Mass (t)
1	Core Power and Propulsion Module	37.40
2	In-line tank	104.55
3	TransHab, Startruss + EP System	56.15
4	Crew, Consumables, Re-entry Capsule	18.38
5	Drop Tanks 1,2	88.67
6	Drop Tanks 3,4	88.76
Total		**393.91**

Table 3. Launch Order and Wet Mass for 2033 Reference 1-Year BNTEP Earth-Mars Roundtrip Mission

Once fully assembled in LEO, the crewed MTV has an initial mass of 389.9 mt. The vehicles main components and their masses are provided in Table 4.

Element Masses			
		Unit Inert Mass (mt)	Total Inert Mass (mt)
Non-Dropped Elements			**99.61**
Core Propulsion and Power Module	1	37.40	37.40
In-line LH2 Tank	1	8.10	8.10
Star Truss+EP Subsystem	1	13.03	13.03
Crewed Payload Element	1	41.08	41.08
TransHab	1	22.70	22.70
Crew	1	0.80	0.80
Consumables	1	4.08	4.08
MPCV	1	13.50	13.50
Drop Tanks			**32.00**
Individual Tank	4	8.00	32.00

Table 4. Main Components of the Mars Transfer Vehicle

II.E.1. Launch 1

- Core Propulsion and Power Module

  The core stage uses a cluster of three 25 klb_f thrust BNTP engines each carrying an external radiation shield for crew protection. These engines have a T/W of approximately 4-5. Analysis in this paper assumed the use of cermet engines operating in the 1 MW_t range utilizing UO_2 in a tungsten metal matrix fuel. However, analysis of this fuel option has to date only been completed for BNTR engines operating at significantly lower electrical power levels, 10s of kW_e.

  The core propulsion and power module contains the following key components:

  - Three BNTR engines, each with its own external radiation shield
  - Three 500 kW_e-class recuperated Brayton PCUs (containing the BRU, heat exchanger, heat rejection and PMAD)
  - Combined thrust and cylindrical support structure (8.4 m outer diameter x 20 m length) which houses the Brayton PCUs and provides support for the shared, 1-sided 970 m^2 cylindrical radiator mounted to its exterior
  - Avionics
  - Auxiliary battery power
  - Docking system

  In order to provide the 1 MW_e of power needed by the EP system, each 500 kW_e BRU is operated at $^2/_3$ of the rated power, approximately 334 kW_e. Operating in this way provides BRU redundancy. Should a malfunction occur resulting in the loss of a BRU or loss of an engine during the mission, the remaining two units can be ramped up and operated at the full 500 kW_e power level.

  NTR Engine Performance Parameters:

– Fuel Type: UO_2 in a tungsten metal matrix cermet
– Engine Thrust Level: 25 klb_f
– Engine T/W: Approx. 4-5 for 25 klb_f engines
– Number of Engines: 3 engine cluster
– I_{sp}: 900 s
– Allowable Engine Thrust Mode Burn Time: 1.5 to 2.0 hrs
– Allowable Power Mode Operating Time: 1.0 to 1.5 yrs

Power Conversion System (PCS) Performance Parameters:

– Closed Brayton Cycle Total Electrical Power: 1 MW_e
– Brayton Engine Unit Size: up to 500 kW_e
– Turbine Inlet Temperature: 1300 K

Future launch vehicle assessments may determine that these components could be delivered using a Block-I SLS with a larger faring rather than the Block-IB SLS. The additional lift capability of the Block-II design is unnecessary for the 37.4 mt launch mass.

II.E.2. **Launch 2**

The in-line tank is sized to carry the BNTR propellant for the MOI and TEI burns as well as any excess propellant required for TMI beyond the drop tank capacity. For the 2033 reference case, the total propellant load carried in the in-line tank is 96.4 mt. The tanks are cylindrical with forward and rear cylindrical adaptor sections with docking attachments. A 920 kg ZBO Brayton-cycle cryocooler system is located in the forward adaptor section. The ZBO system removes heat penetrating the 60-layer MLI system throughout the mission with peak use occurring during MTV assembly in LEO where the tank heat flux is the highest. The shell of the tank is manufactured using an aluminum-lithium alloy, AlLi "Weldalite" T6E4. Assuming an exterior diameter of 8.4 m, the tank has a wall thickness of 0.3175 cm and a total inert mass of 8095.9 kg. Included in this mass is 600 kg to account for lines, valves, and fittings. Additional parameters and assumptions used for sizing the in-line tank are provided in Table 5. Avionics, RCS and auxiliary battery power are also carried on this launch.

In-line Tank Sizing Inputs		
Propellant Load	96452.66	kg
Additional Tank Masses	1520	kg
Pressure	30	psia
Tank Material	AlLi "Weldalite" T6E4	
Tank Interior Diameter	8.39365	m
Wall Thick.	0.3175	cm
Volume Margin	5.00%	%
Tank Shape: Sqrt(2)/2 Cylinder with End Caps		
Propellant Density	67.541	kg/m^3
Tank Material Density	2700	kg/m^3
Required Volume	1499.463	m^3
End Cap Volume	218.946	m^3
Cyl. Section Volume	1280.518	m^3
Cyl. Section Length	23.142	m
Total Tank Length	29.083	m
Tank Outer Diameter	8.400	m
Tank Shell Mass	6575.870	kg
Total Tank Inert Mass	8095.870	kg
Total Tank Wet Mass	104548.531	kg

Table 5. Inline Tank Sizing using Sizer Tool Parametrics

II.E.3. Launch 3

- Star Truss and EP Subsystem

  The EP subsystem consists of ten 100 kW_e Xenon Hall thrusters, having five thrusters located on each EP thruster arm. The EP system is used to gradually accelerate or decelerate the spacecraft in interplanetary space., allowing the mission to maintain relatively low ΔV BNTR departure and injection burns when compared to a 1-year all NTR mission. The electrical power generated by the BNTEP reactor system will also provide power to the other spacecraft subsystems, eliminating the need for photovoltaic arrays. Minimal attitude control will be required during interplanetary transit when the BNTR engines are in low-thrust mode since the EP system can correct for trajectory inaccuracies during the long burn periods. A RCS having thrusters and bipropellant located on the core bimodal propulsion and power stage as well as the star truss forward adaptor ring, will provide additional attitude control which will be required for initial vehicle assembly, larger mid-course corrections, vehicle orientation maneuvers, and attitude control while in high-thrust mode as well as during Mars stay.[5] The EP subsystem has a total inert mass of 10.5 mt. This analysis leveraged results for sizing EP subsystems for MW_e-class Earth-Mars missions done for other studies.[7] The EP mass for BNTEP missions is similar except any additional power subsystem mass for solar arrays is unnecessary. For the 2033 reference case, the total Xenon propellant load carried by the EP subsystem is 20.4 mt.

  The star truss is a rigid, 4-sided composite structure, with integrated docking, electrical and drop tank connections, and forward RCS and propellant. Mounted to the truss are two EP thruster arms each with five 100 kW_e ion thrusters plus the Xenon propellant and tankage. Truss sizing for the drop tank was done by interpolating parametric data generated from the Sizer Excel Tool developed at NASA GRC.[8] The hang-mass and propellant load of the drop tanks were used to interpolate parametric curves generated by the Sizer Tool. Star truss sizing parameters are provided in Table 6. The truss length is set such that it is 5 m longer than the length of the in-line tank.

Star Truss Sizing		
Truss Length	18.000	m
(Tank Wet Mass)*(T/W_{IMLEO})	15.127	mt
Truss Mass	2534.010	kg

Table 6. Truss Sizing using Sizer Tool Parametrics

- Crewed Payload Element

  The crewed payload element consists of the transit habitat, 4 crew members with suits, consumables, and the MPCV. The total initial mass of this payload element when delivered to LEO is 41.08 mt. The 4 person crew will reside within the transit habitat (TransHab) during interplanetary transit as well as throughout the stay in Mars orbit. Consumables are carried within the TransHab, amounting to 2.45 kg/d per crew member. An additional 51 days were added to the total crewed time to budget for consumables required for the period of time the crew will on-orbit assisting in final MTV assemble and checkout in LEO. The MPCV will be used as a re-entry capsule which the crew will enter just prior to arrival at Earth. At Earth entry interface, the crew and the MPCV will separate from the MTV, enter the atmosphere, and perform a water landing.

II.E.4. Launch 4, 5

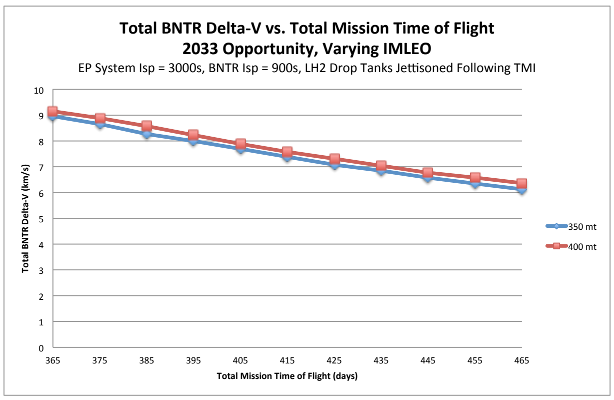
The final two SLS launches deliver twin sets of LH_2 drop tanks that will attach to the star truss. Each drop tank is 13 m long with an external diameter of 8.4 m and has an inert mass of 8 mt. Each drop tank is capable of carrying up to 39.2 mt of LH_2 propellant. For the 2033 reference case, the LH_2 propellant required for TMI does not fill the drop tanks so there is excess volume between the tanks to optimize the ΔV split between TMI-1 and TMI-2. For this analysis, TMI-1 and TMI-2 were sized in order to maintain an approximately equal propellant load between the tank pairs.

In addition to the wet mass of the drop tanks, each drop tank pair requires a 2 mt intertank adapter for launch. Once in orbit the intertank adapter is jettisoned prior to full vehicle assembly, hence, the total launch mass in Table 3 is 4 mt higher than the IMLEO of the fully assembled MTV.

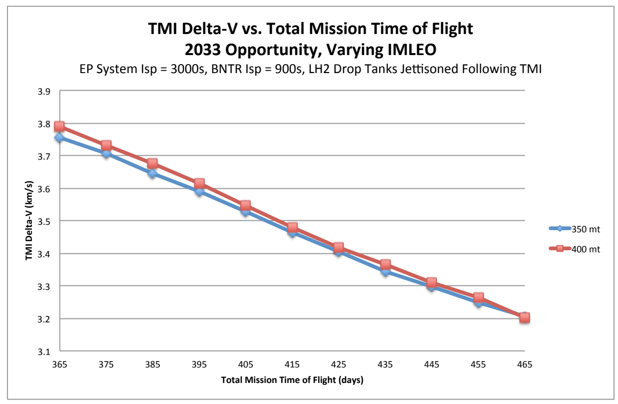
II.F. Variations in Total Time of Flight

Allowing the mission time to extend beyond 365 days can provide significant savings in propellant mass. Figure 7 and Figure 8 show the variation in BNTR and EP ΔV as total flight time is extended. The extra time for interplanetary transit allows the BNTEP system to reduce the amount of energy added to or removed from the MTV by the BNTR system. Specifically, the TMI maneuver can be reduced by approximately 110 m/s when 20 days are added to the mission time by allowing more of the required Earth departure acceleration of the vehicle to be performed with the high efficiency EP system, increasing the outbound EP ΔV by approximately 130 m/s. The reduction in LH_2 and Xenon propellant by extending the mission 20 days could reduce IMLEO of the MTV from 389.9 mt to 340.2 mt.

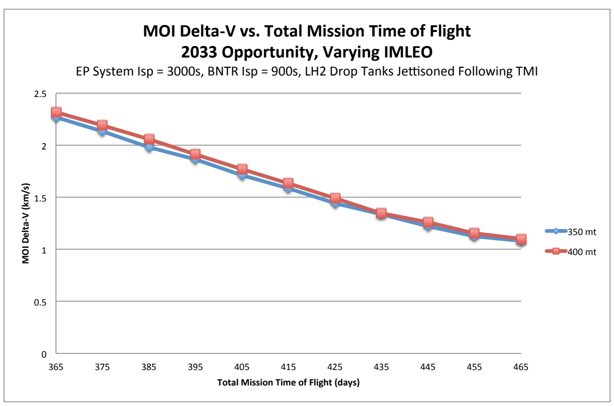
Although there may be significant mass savings, any mass savings made by extending the mission duration must be carefully weighed against the increased risk to the crew by extending exposure time to harmful radiation as well as the prolonging the period in a microgravity environment.



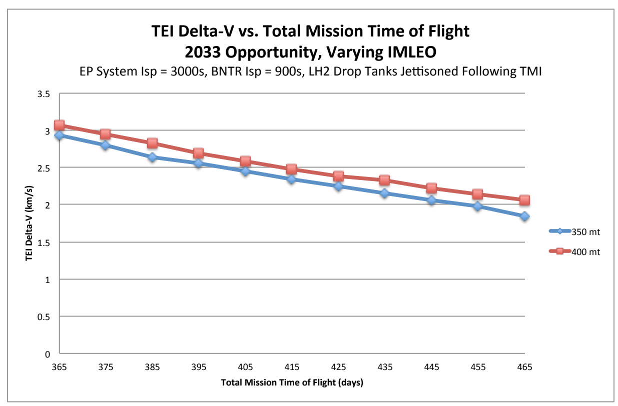
(a) Total



(b) TMI

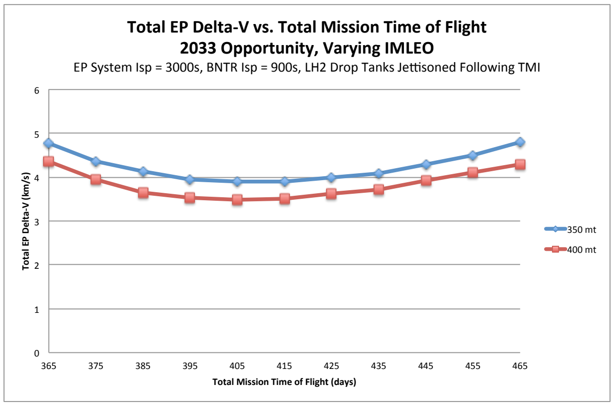


(c) MOI

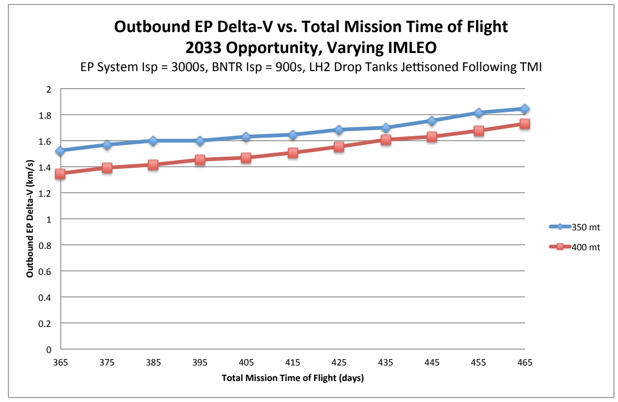


(d) TEI

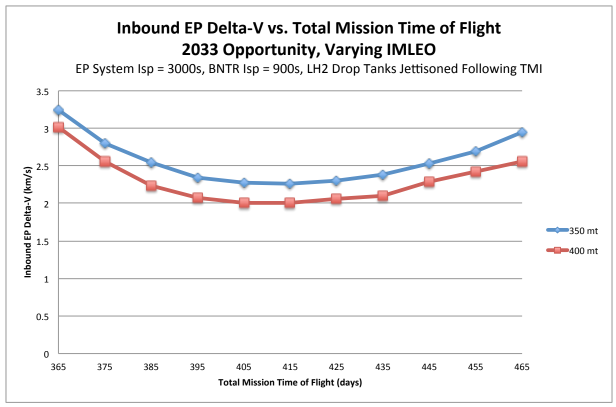
Figure 7. BNTR ΔVs vs Total Mission Time of Flight for 2033 Mission Opportunity



(a) Total



(b) Outbound, Earth-Mars



(c) Inbound, Mars-Earth

Figure 8. EP ΔVs vs Total Mission Time of Flight for 2033 Mission Opportunity

III. Conclusion

Ballistic opposition-class (short stay) Mars round trip missions are characterized by long in-space durations, shorter surface stays, and high ΔV requirements. Because of this, architectures for crewed Mars missions, including Mars DRA 5.0, often select a conjunction-class (long stay) trajectory. However, the overall shorter duration of an opposition-class mission is desirable for reducing risk associated with crew behavioral health and performance as well as medical capabilities.[1] Utilizing BNTEP technology for short duration Mars missions can reduce the in-space duration as well as the IMLEO for comparable NTR missions.[6] BNTEP technology enables a feasible 1-year Mars round trip mission by using the EP system during transits to maintain relatively low escape and arrival energy requirements for the high thrust BNTR engines. Reducing propulsive requirements for the BNTR engines allows the IMLEO of the MTV to remain relatively low. The analysis presented in this paper shows that the MTV of a 2033 BNTEP 1-year mission would have an IMLEO of 389.9 mt, requiring 5 SLS Block-IB launches to deliver all of the components. Future investigation into the use of BNTEP technology for conjunction-class and split mission architectures could potentially further reduce in-space time and potentially IMLEO for these missions.

Additional work in the future could also be done to assess vehicle reusability by capturing the MTV into a highly elliptic Earth orbit or halo orbit around the Earth-Moon L2 libration point following MPCV and crew separation. This would reduce cost and risk for future BNTEP missions by already having the main structure of the MTV assembled and only requiring refueling.

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The authors would like to thank John Taylor and Gary Kelm (NASA/GRC) and Mike Houts (NASA/MSFC) for their encouragement and interest in this work, as well as, Chris Moore and John Warren (NASA/HQ) for including the BNTEP concept in the Nuclear Cryogenic Propulsion Stage (NCPS) project funded under NASAs Advanced Exploration Systems (AES) program.

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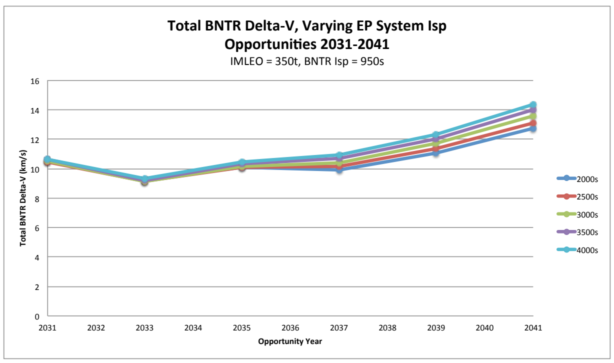
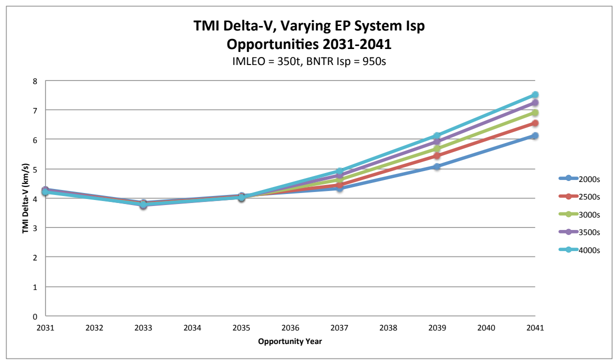
Appendix A - ΔVs for 2031-2041 Mission Opportunities

III.A. Assumptions and Constraints for General Analysis

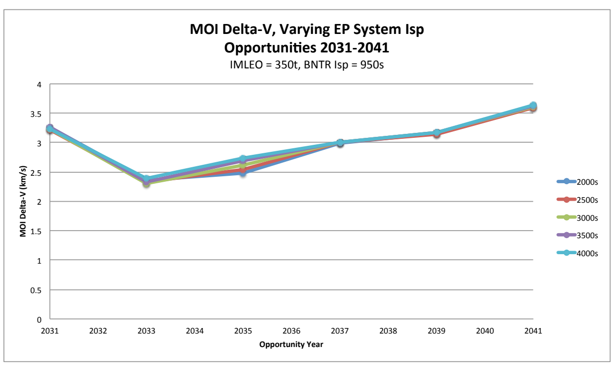
- TOF = 365 $days$
- Mars Stay Time = 30 $days$
- EP system efficiency = 65%
- NTR I_{sp} = 900 s
- Earth departure orbit: 407 km circular orbit inclined at 28.5°
- Mars arrival orbit: 300 km x 24 hr elliptical orbit
- Maximum Earth arrival V_∞ = 11.5 km/s
- Four 8 mt LH_2 drop tanks are jettisoned following TMI



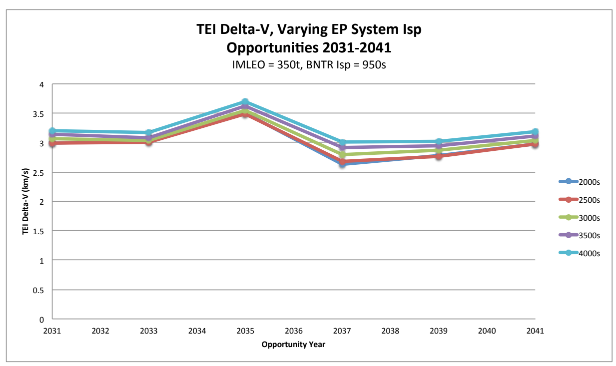
(a) Total



(b) TMI

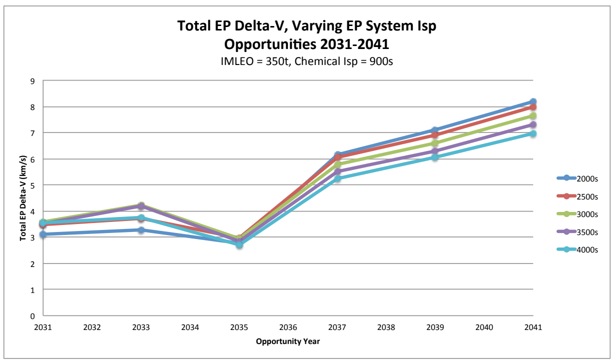


(c) MOI

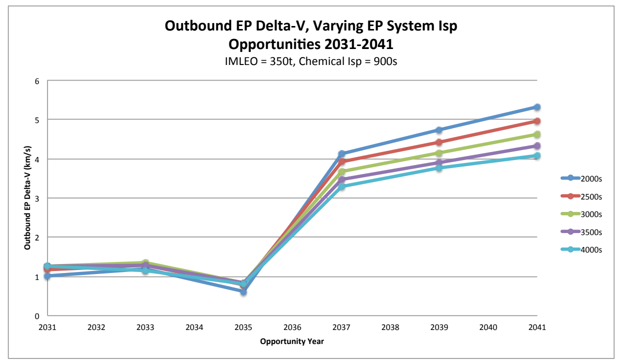


(d) TEI

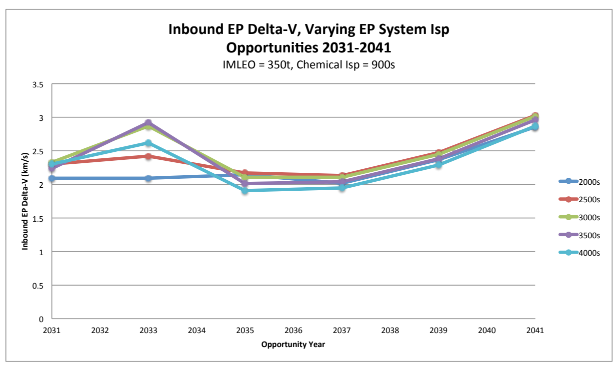
Figure 9. BNTR ΔVs for 2031-2041 Mission Opportunities



(a) Total



(b) Outbound, Earth-Mars



(c) Inbound, Mars-Earth

Figure 10. EP ΔV for 2031-2041 Mission Opportunities