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Nuclear Thermal Propulsion Mars Mission Systems Analysis and Requirements Definition

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Abstract – This paper describes the Mars transportation vehicle design concepts developed by the Marshall Space Flight Center (MSFC) Advanced Concepts Office. These vehicle design concepts provide an indication of the most demanding and least demanding potential requirements for nuclear thermal propulsion systems for human Mars exploration missions from years 2025 to 2035. Vehicle concept options vary from large "all-up" vehicle configurations that would transport all of the elements for a Mars mission on one vehicle, to "split" mission vehicle configurations that would consist of separate smaller vehicles that would transport cargo elements and human crew elements to Mars separately. Parametric trades and sensitivity studies show NTP stage and engine design options that provide the best balanced set of metrics based on safety, reliability, performance, cost and mission objectives. Trade studies include the sensitivity of vehicle performance to nuclear engine characteristics such as thrust, specific impulse and nuclear reactor type. The associated system requirements are aligned with the NASA Exploration Systems Mission Directorate (ESMD) Reference Mars mission as described in the Explorations Systems Architecture Study (ESAS) report. The focused trade studies include a detailed analysis of nuclear engine radiation shield requirements for human missions and analysis of nuclear thermal engine design options for the ESAS reference mission.

I. INTRODUCTION

The Nuclear Thermal Propulsion Mission and System Analysis (NTP MSA) Study was initiated in May 2005 by Marshall Space Flight Center's (MSFC) Advanced Concepts Office. The primary goal of the NTP MSA Study was to identify the range of potential nuclear thermal propulsion (NTP) engine and vehicle requirements for human Mars exploration missions. To achieve these goals, NTP vehicle and engine requirements were derived from analyses, trade studies, and conceptual designs to define point-of-departure design concepts and associated system requirements for human Mars missions. The vehicle concepts that were investigated represent a range from least demanding to most demanding requirements for the NTP systems. Vehicle options were analyzed to identify stage and engine concepts that offer the best balance of figures-of-merit (FOM) based on safety, reliability, performance, and cost. The second phase of this study focused on the development of point-of-departure concepts and associated system requirements for the NASA Exploration Systems Architecture Study (ESAS) Mars Exploration Design Reference Mission[1]. The vehicle concept design cases that were investigated are listed below:

Phase 1 Study:
NTP Mars Vehicle Design Concepts:

- Case 1: All-Propulsive NTP Vehicle - All-Up Mission
- Case 2: All-Propulsive NTP Vehicle - Split Mission
- Case 3: NTP/Aerocapture/Chemical Propulsion Vehicle - All-Up Mission
- Case 4: NTP/Aerocapture/Chemical Propulsion Vehicle – Split Mission

Phase 2 Study:
ESAS Mission Architecture Vehicle Design Concepts:

- Cargo Vehicle – NTP/Aerocapture Vehicle
- Piloted Mission – All-Propulsive NTP Vehicle.

II. NTP VEHICLE CONCEPTS

II A. Mars Mission Analysis

Phase 1 of this study considered short-stay Mars missions in which the Mars stay time varied from 30 to 70 days and total round trip mission was on the order of 600 days. Phase 2 considered long-stay missions in which the Mars stay time was on the order of 550 days and the total round trip mission was on the order of 900 days which is consistent with the ESAS Mars design reference mission.

The Phase 1 trajectory analysis identified short-stay (opposition class) trajectories for Earth departure dates ranging from 2025 to 2035. The total mission durations were restricted to less than 2 years. Both piloted (roundtrip) and cargo (one-way) trajectories were analyzed. All missions departed Earth from a 407 km circular parking orbit and were inserted into a 250 km by 33,793 km elliptical Mars orbit having a period of one Mars day. The mission analysis also considered trajectories with and without aerocapture at Mars. The Mars aerocapture altitude was assumed to be 125 km, and the maximum allowable arrival speed at this altitude was 7.350 km/s, which corresponds to a hyperbolic excess speed of 5.450 km/s. All missions assumed a direct atmospheric entry upon Earth return. The maximum allowable hyperbolic excess speed at Earth arrival was assumed to be 6.813 km/s. The aerocapture missions used NTP for the outbound leg of the mission and chemical propulsion for the inbound leg due to the packaging restrictions within the aeroshell. The non-aerocapture architectures used NTP for all propulsive maneuvers. The analysis showed that the minimum initial mass in low Earth orbit occurs for the 2033 mission opportunity, therefore that opportunity was used in for the design of the Phase 1 NTP vehicle. The trajectory data for the 2030 cargo mission and 2033 piloted mission is shown in Tables 1 and 2.

TABLE 1
Trajectory Data for Cargo Vehicles Supporting 2033 Piloted Mission

Earth Departure			Mars Arrival			
Date	V_∞ (km/s)	ΔV (km/s)	Time (days)	V_∞ (km/s)	ΔV (km/s)	V_{entry} (km/s)
All-propulsive						
12/26/2030	3.260	3.705	283.5	3.494	1.353	---
Aerocapture at Mars						
02/20/2031	2.871	3.630	318.9	5.450	0.000	7.350

TABLE 2
2033 Piloted Mission Trajectory Data

Earth Departure		Mars Arrival			Mars Orbit	Mars Departure	Venus Swing-by	Earth Arrival	
Date	$V_\infty/\Delta V$ (km/s)	Time (days)	$V_\infty/\Delta V$ (km/s)	V_{entry} (km/s)	Stay (days)	$V_\infty/\Delta V$ (km/s)	Time (days)	Time (days)	$V_\infty/\Delta V$ (km/s)
All-propulsive									
04/14/2033	2.979 3.667	195.4	3.357 1.274	---	30.0	5.867 3.015	414.0	566.6	4.858 0.000
Aerocapture at Mars									
04/10/2033	2.934	189.5	3.503	6.049	40.0	5.868	417.8	569.7	4.926

	3.650		0.000			3.064			0.000

II B. Phase 1 Design Case 1: All-Propulsive NTP Vehicle - All-up Mission

The all-propulsive NTP vehicle refers to a vehicle which uses NTP propulsion for all mission maneuvers, consisting of trans-Mars injection (TMI), Mars orbit insertion (MOI) and trans-Earth injection (TEI). The all-up mission refers to a mission in which everything required for the crew during both the in-space and surface-stay phases of the mission is transported on a single vehicle. The vehicle payload consists of a transit habitat and a lander contained within an atmospheric entry aeroshell. Artificial gravity is used on the outbound and inbound legs of the mission. The vehicle is spun about its center of gravity to create an artificial gravity of at least 0.3 g's. The main drivers in the configuration of this design case were the propellant tanks and the overall vehicle length required to generate the minimum level of artificial gravity.

II C. Phase 1 Design Case 2: All-Propulsive NTP Vehicle - Split Mission

The split mission refers to a mission in which a cargo vehicle transports the lander to a Mars parking orbit approximately 2.5 years before the crew travels to Mars. The cargo mission uses a one-way minimum energy trajectory. The piloted mission includes an outbound leg of 195 days, a 30 day stay time at Mars, and a 342-day return trip, which includes a Venus swing-by after 180 days on the inbound leg. This mission has a total duration of 540 days for the crew. In this study, the cargo vehicle payload consists of a lander contained within an atmospheric entry aeroshell. The aeroshell is used for aerocapture into the Mars parking orbit as well as the entry portion of the descent to the surface. The piloted all-propulsive NTP vehicle carries all the support equipment and supplies required for the outbound and inbound trajectories. Upon arrival at Mars, the piloted vehicle docks with the lander in Mars orbit. The piloted vehicle payload consists of the transit habitat, a transfer node, and a docked Crew Exploration Vehicle. The propellant tank configuration for the piloted vehicle optimizes the center of gravity location to allow artificial gravity by rotating the vehicle during the outbound and inbound legs of the mission.

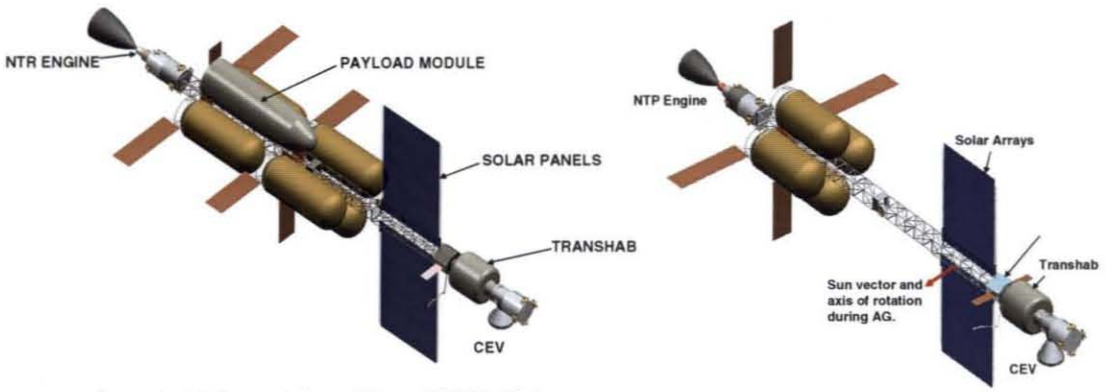
II D. Phase 1 Design Case 3: NTP/Aerocapture/Chemical Propulsion Vehicle – All-Up Mission

The NTP/aerocapture/chemical propulsion vehicle for this design case performs and all-up mission just as in design case 1. In this case the NTP stage performs only the TMI maneuver, the MOI is accomplished using aerocapture and the TEI maneuver is performed using a chemical stage. The vehicle payload consists of a transit habitat and a lander, contained within two atmospheric entry aeroshells. The transit habitat, a chemical TEI stage, and a docked CEV, are integrated into one of the aeroshells and the lander is integrated into the other. Prior to Mars arrival the two aeroshells separate from the vehicle and aerocapture into Mars orbit separately. They dock in Mars orbit prior to the descent to the surface. The lander aeroshell is used for aerocapture into the Mars parking orbit as well as the entry portion of the descent to the surface. The main drivers in the configuration of the vehicle are the number of propellant tanks and the length of the vehicle truss needed to allow the minimum artificial gravity, however, this configuration only allows artificial gravity on the outbound leg of the mission. To minimize the NTP engine radiation shielding requirement, the NTP engine and the transit habitat are located on opposite ends of the vehicle. The heavier components such as the fuel tanks and payload were located as far aft as possible to maximize the moment arm for the artificial gravity and keep them inside the engine radiation shield shadow cone of 26.5 degrees.

II E. Phase 1 Design Case 4: NTP/Aerocapture/Chemical Propulsion Vehicle - Split Mission

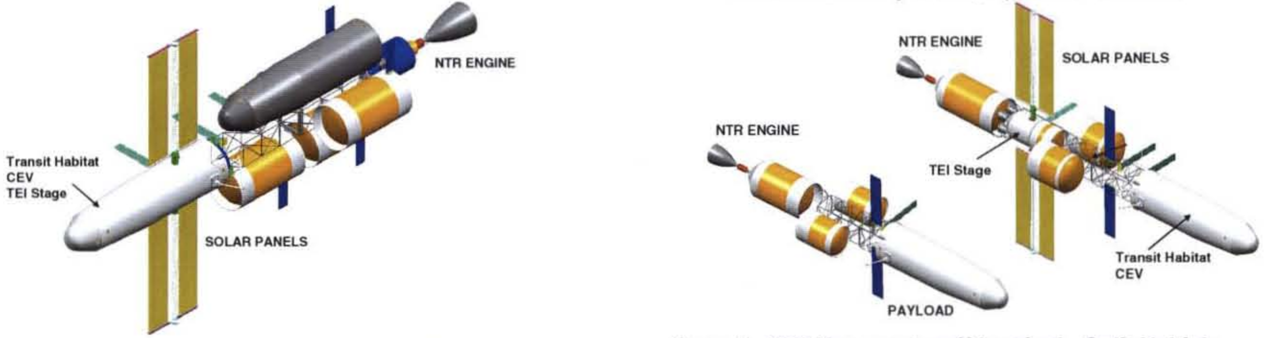
The NTP/aerocapture/chemical propulsion vehicles for this design case perform a split mission just as in case 2. The NTP stage performs only the TMI maneuver. The MOI is accomplished using aerocapture and the TEI maneuver is performed using a chemical stage. The cargo vehicle payload consists of a lander contained within an atmospheric entry aeroshell. The aeroshell is used for aerocapture into the Mars parking orbit as well as the entry portion of the descent to the surface. The piloted vehicle payload consists of the transit habitat, a docked CEV, and a chemical TEI stage which are integrated within an aeroshell used for aerocapture into Mars orbit. As in case 2, upon arrival at Mars, the piloted vehicle docks with the lander in Mars orbit. The main driver in the configuration of the piloted vehicle was positioning of the major components to allow the required artificial gravity. Similar to case 3, this configuration only allows artificial gravity on the outbound leg of the mission.

The configurations for the Phase 1 vehicle concepts are shown in Figure 1.



Case 1: All-Propulsive, All-up NTP Vehicle

Case 2: All-Propulsive, Split NTP Vehicle



Case 3: NTP/Aerocapture/Chemical - All-up Vehicle

Case 4: NTP/Aerocapture/Chemical - Split Vehicle

Figure 1. NTP MSA Phase 1 Vehicle Design Concepts

II F. Figure of Merit Assessment

The figures of merit (FOMs) for this study were based on the on the draft Exploration Systems Mission Directorate FOM descriptions[2]. Specific FOM titles and metrics were defined for 3 categories shown in Table 3.

TABLE 3
NTP MSA Figures of Merit

Safety, Reliability, and Operations Figures of Merit

FOM Title	FOM #	FOM Metric
Flight Crew Safety	S-1.1 S-1.2	Probability of Risk of Loss of Flight Crew (LOC) Probability of Flight Crew Health Hazard Exposure
Public Safety	S-2.1 S-2.2	Probability of Public Fatality Due to Flight Systems Probability of Public Health Hazard Exposure
Flight System Reliability	R-1.1 R-1.2	Probability of Catastrophic Loss of Flight System (LOV) Probability of Critical Loss of Flight System Function
Flight System Operational Readiness	O-1.1	Probability of Flight System Readiness for Scheduled Launch

Performance and Mission Objectives Figures of Merit

FOM Title	FOM #	FOM Metric

System Design	P-1.1 P-1.2 P-1.3	IMLEO Capability to perform mission aborts Risk of planetary biological or nuclear contamination
Mission Objectives	P-2.1 P-2.2 P-2.3	Capability to satisfy exploration objectives Technology Readiness Applicability to Multiple Exploration Missions

Affordability Figures of Merit

FOM Title	FOM #	FOM Metric
Technology Cost	A-1.1	Total cost to advance a technology to Technology Readiness Level 6 or 7
Unique Facilities Cost	A-2.1	Facilities required for the completion of the reference mission.
Non-Recurring Cost	A-3.1	Total system design, development, test, and evaluation (DDT&E) cost
Recurring Cost	A-4.1 A-4.2 A-4.3	Recurring Flight Hardware Cost Recurring Launch Cost Recurring Mission Operations Cost
Multi- Mission Economic Analysis	A-5.1	Total mission cost over several missions and the total estimated cost incurred between missions

The FOM analysis process used the Kepner-Tregoe scoring method[3]. This method uses a non-linear scoring set in which the design options are given scores of 9, 3, 1, or 0 (with 9 being the best). Using this scoring set allows the design concepts to be scored against a larger number of FOM's with less likelihood that the total aggregate scores will turn out with similar values (data smearing). The relative ranking of the FOM scores for the four Phase 1 design cases are shown in Figure 2.

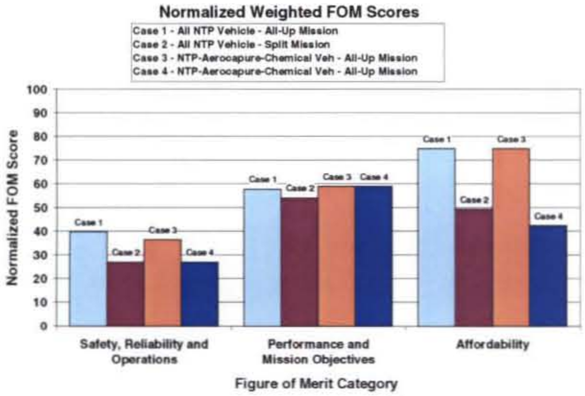
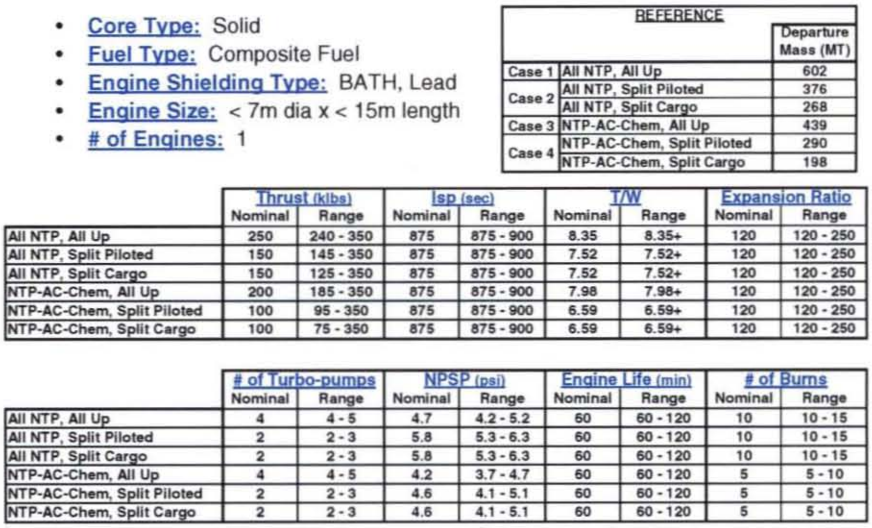


Figure 2.Weighted NTP FOM Scores

II G. Nuclear Thermal Propulsion Engine Requirements

The basic NTP engine requirements were derived from the systems analyses and sensitivity trades conducted during the study. Performance parameters were bound by minimum and maximum values. A minimum value represents the lowest possible performance level necessary to accomplish the mission objectives. A maximum value represents the highest level of performance that may be achieved before the bounds of other system parameters (such as launch vehicle shroud size or material thermal limitations) are reached. The "design goal" value is the performance level that represents the best balance between the numerous competing factors and constraints. The NTP requirements identified for the vehicle concepts considered in the Phase 1 study are shown in Table 4.

TABLE 4
NTP Engine Requirements



- **Core Type:** Solid
- **Fuel Type:** Composite Fuel
- **Engine Shielding Type:** BATH, Lead
- **Engine Size:** < 7m dia x < 15m length
- **# of Engines:** 1

REFERENCE		Departure Mass (MT)
Case 1	All NTP, All Up	602
Case 2	All NTP, Split Piloted	376
	All NTP, Split Cargo	268
Case 3	NTP-AC-Chem, All Up	439
Case 4	NTP-AC-Chem, Split Piloted	290
	NTP-AC-Chem, Split Cargo	198

	Thrust (klbs)		Isp (sec)		T/W		Expansion Ratio	
	Nominal	Range	Nominal	Range	Nominal	Range	Nominal	Range
All NTP, All Up	250	240 - 350	875	875 - 900	8.35	8.35+	120	120 - 250
All NTP, Split Piloted	150	145 - 350	875	875 - 900	7.52	7.52+	120	120 - 250
All NTP, Split Cargo	150	125 - 350	875	875 - 900	7.52	7.52+	120	120 - 250
NTP-AC-Chem, All Up	200	185 - 350	875	875 - 900	7.98	7.98+	120	120 - 250
NTP-AC-Chem, Split Piloted	100	95 - 350	875	875 - 900	6.59	6.59+	120	120 - 250
NTP-AC-Chem, Split Cargo	100	75 - 350	875	875 - 900	6.59	6.59+	120	120 - 250

	# of Turbo-pumps		NPSP (psi)		Engine Life (min)		# of Burns	
	Nominal	Range	Nominal	Range	Nominal	Range	Nominal	Range
All NTP, All Up	4	4 - 5	4.7	4.2 - 5.2	60	60 - 120	10	10 - 15
All NTP, Split Piloted	2	2 - 3	5.8	5.3 - 6.3	60	60 - 120	10	10 - 15
All NTP, Split Cargo	2	2 - 3	5.8	5.3 - 6.3	60	60 - 120	10	10 - 15
NTP-AC-Chem, All Up	4	4 - 5	4.2	3.7 - 4.7	60	60 - 120	5	5 - 10
NTP-AC-Chem, Split Piloted	2	2 - 3	4.6	4.1 - 5.1	60	60 - 120	5	5 - 10
NTP-AC-Chem, Split Cargo	2	2 - 3	4.6	4.1 - 5.1	60	60 - 120	5	5 - 10

III. ANALYSIS OF THE ESAS REFERENCE HUMAN MARS MISSION ARCHITECTURE

The goal of Phase 2 of the NTP MSA Study was to identify the range of potential NTP engine and vehicle requirements applicable to the NASA Exploration Systems Architecture Study (ESAS) Mars Exploration Design Reference Mission[1]. The most significant difference between Phase 1 and Phase 2 of this study is the change from short-stay missions to long-stay missions.

III A. Mars Mission Analysis

The objective of the Phase 2 mission analysis task was to determine Mars mission trajectories for the ESAS reference mission architecture. The mission architecture is based on long-stay (conjunction class) split-mission profiles. Two transfer opportunities spaced about two years apart, would be used for cargo and piloted missions. Two cargo delivery missions during the first opportunity would be used to deliver a surface habitat to the surface of Mars, and a lander to a Mars parking orbit. These missions would use aerocapture for Mars orbit insertion. The crew would travel to Mars during the following mission opportunity using a long Mars stay-time (conjunction-class) mission trajectory. The piloted mission uses an all-propulsive MOI maneuver.

One-way cargo mission and round-trip piloted mission trajectories were generated for mission opportunities between 2026 and 2039 (see Tables 5 and 6). For the purposes of this study, it was decided that the piloted missions would likely depart between the years 2030 and 2036. Therefore, worst-case delta-velocities were chosen for the vehicle designs from these opportunities, with the corresponding cargo departures ranging from 2028 to 2034. Also, the inclination of the low-Earth assembly orbit was restricted to less than 30 degrees, therefore a deep space, plane-change maneuver following Earth-departure was required for the 2033 opportunity. This maneuver is included in the TMI delta-velocity. Representative trajectories are illustrated in Figure 3.

TABLE 5
Cargo Opportunities with Aerocapture at Mars

Earth Departure Date	Transfer Time (days)	TMI ΔV (km/s)	Mars Arrival V_∞ (km/s)
10/5/2024	344.91	3.7538	2.5411
10/30/2026	294.72	3.6573	2.6993
12/1/2028	318.26	**3.6473**	3.2636
02/20/2031	318.91	3.6149	**5.4500**
04/28/2033	273.89	3.5930	4.3788
06/23/2035	195.49	3.7068	2.6959
09/6/2037	395.42	3.9249	3.3457

TABLE 6
All-propulsive, Piloted Opportunities

Earth Departure Date	Mars Stay Time (days)	ΔV (km/s)			
		TMI	MOI	TEI	Earth Return
12/12/2026	533.95	4.6170	2.7038	1.9633	0.0000
01/17/2029	531.18	4.4396	2.4934	1.3103	0.0000
02/27/2031	542.26	4.0651	**1.9497**	0.9087	0.0000
05/2/2033	**565.00**	**4.2641**	1.3039	1.0919	0.0000
07/3/2035	563.21	3.7482	0.9707	**1.5883**	0.0000
09/5/2037	535.26	4.1885	1.3606	1.8120	0.0000
10/22/2039	533.39	4.5108	2.1400	2.0583	0.1894

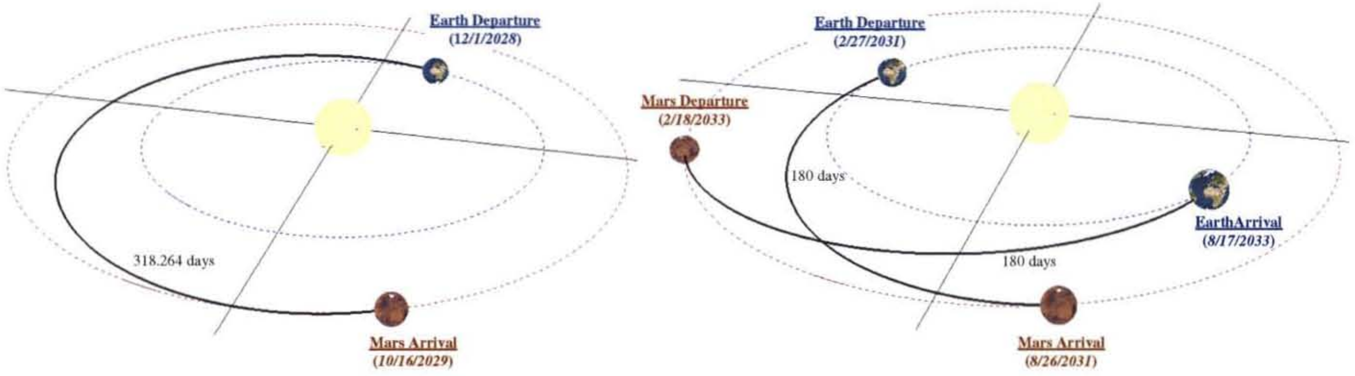


Figure 3: 2028 Cargo and Piloted Mission Trajectories

III B. NTP Vehicle Concepts

The vehicle concepts developed in this study were adapted from the NTP MSA Phase 1, Case 4. Vehicle sizing was performed using scaling equations developed in Phase 1 with updated NTP engine masses. The cargo vehicles utilize tri-conic aerobrakes for Mars Aerocapture. The all-propulsive piloted vehicle uses NTP propulsion for TMI, MOI and TEI. The propellant for the TMI maneuver is stored in two drop tanks attached to the central vehicle truss. The propellant for MOI and TEI is stored in the core tank at the aft end of the vehicle. Representative vehicle configurations for the cargo and piloted vehicles are shown in Figure 4.

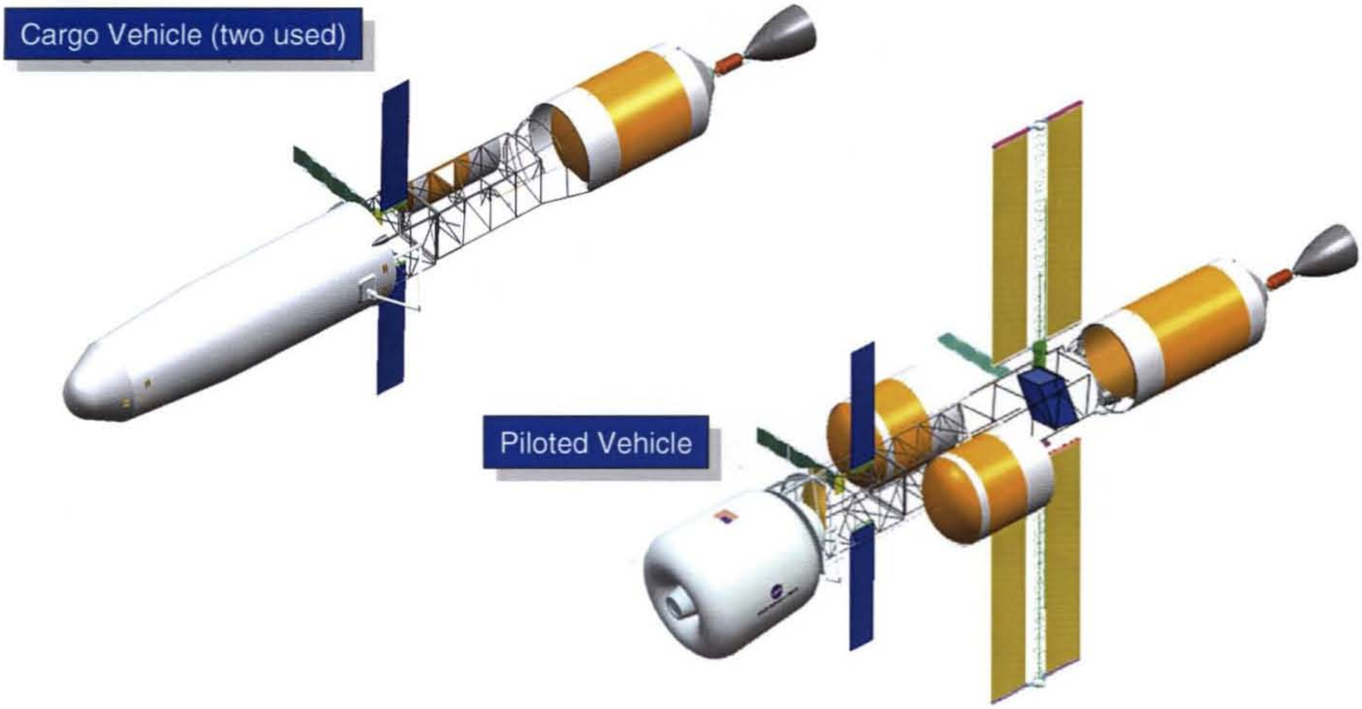


Figure 4. NTP MSA Phase 2 NTP Vehicle Concepts

Each mission to Mars requires a total of eight earth-to-orbit launches spread over two Mars mission opportunities. The elements of the Mars transportation systems are assembled in low Earth orbit. The two cargo missions require two launches each, and the piloted mission requires four launches. The required launch vehicle lift capability varies from 70 to 90 mt. The launch manifest and ETO requirements for the Cargo and Piloted missions are shown in Figure 5.

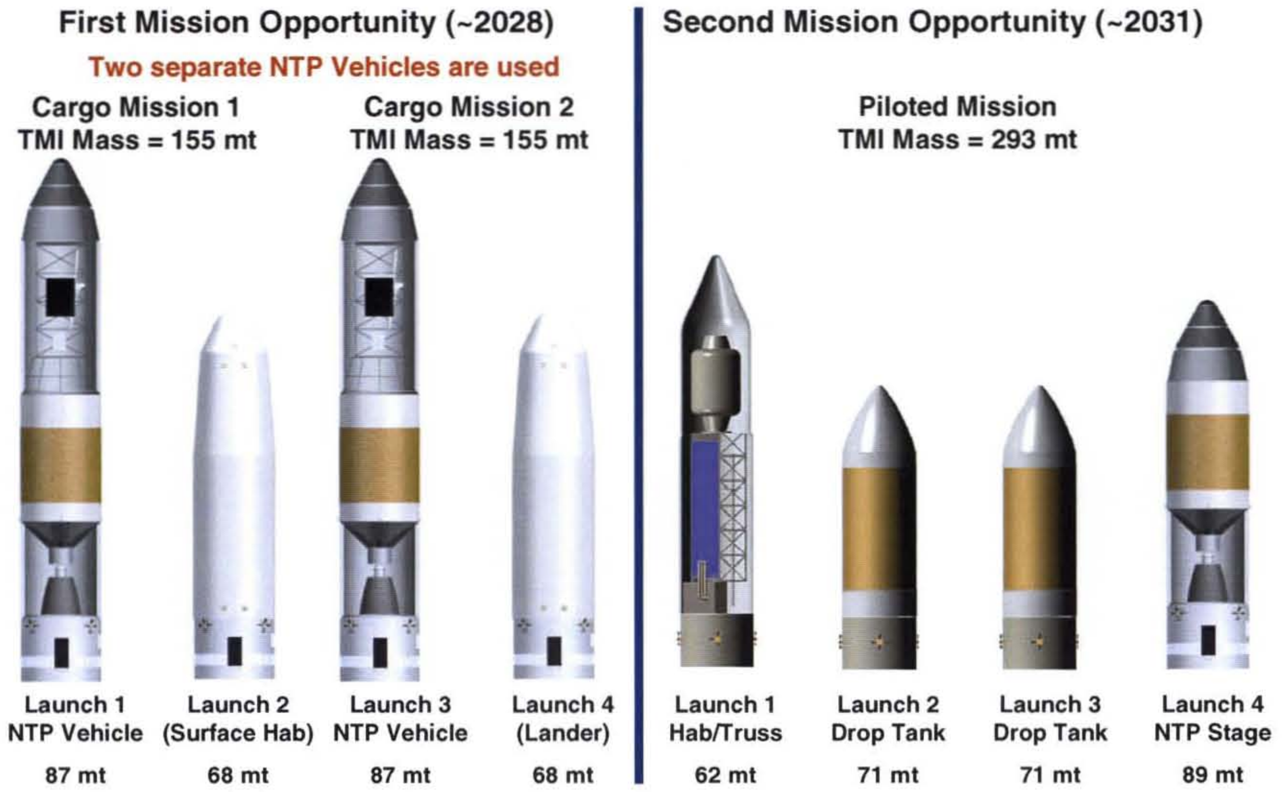


Figure 5. Piloted Mission ETO Launch Requirements

III C. Radiation Shielding Design Requirements and Limitations

Piloted and cargo space vehicles have different shielding requirements, which drive the shield design. Although there are known sensitivities to payload equipment, such as electronics and some structural devices, cargo missions will usually have less restrictive radiation dose criteria than missions involving human crews. Radiation exposure is critical and the reactor and local crew shielding should be optimized to minimize the total dose from natural radiation and the radiation from the reactor. For space missions, most of the radiation exposure is due to galactic cosmic radiation (GCR) and solar particle events (SPEs).

The most basic design for an NTR engine system utilizes a single, large reactor with several flow paths. For this configuration an external shadow shield is the default design option except in extreme cases requiring large shadow angles combined with close proximity of sensitive equipment and/or personnel. When considering clustering NTR engines several issues must be considered. Radiation emitted from the engines both during operation and during shutdown has the potential to scatter forward toward the crew and equipment unless blocked by an extended shadow shield or individual 2 Pi shields around each engine. Also, during operation, neutrons escaping one reactor have the potential of affecting the reactivity of the other reactors in the cluster unless they are shielded by individual 2 Pi shields. Between the two choices of shielding, the 2 Pi shield approach provides coverage for both scattering and reactivity interaction.

The overall results of the shielding study, assuming a 26.6° shadow shield half angle are provided in Figure 6, which shows the range of dose plane distance and thrust levels for the single, double and triple engine configurations for which a 2-Pi shield is lighter than a shadow shield.

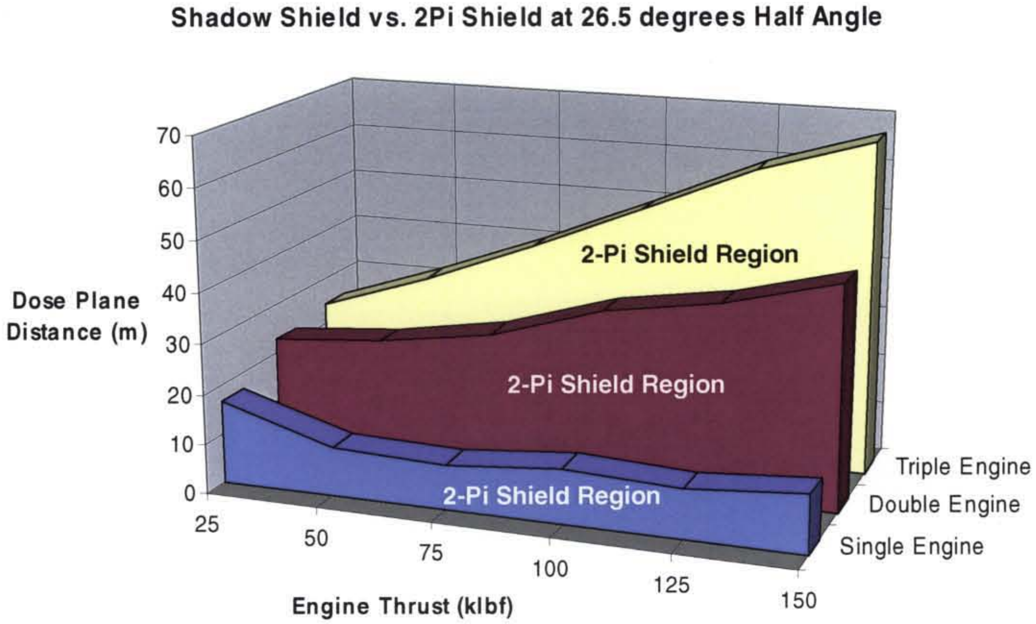


Figure 6. Range of 2 Pi Shield Preference for Minimum Mass (26.6° Half Angle)

III D. NTP Requirements for the ESAS Reference Mars Mission

Based on the mission analysis, vehicle concept definition and NTP sensitivity trade studies performed in Phase 2 of the NTP Mission and Systems Analysis study, recommended NTP requirements were defined as listed in Table 7.

TABLE 7
NTP MSA Phase 2 NTP Requirements Summary

NTP Engine Type
- **Core:** **Graphite Prismatic (Solid)**
- **Fuel Type:** **Composite**
- **Engine Shielding:** **BATH, Lead**
- **Engine Size:** **< 7m dia. X < 15m length**
- **Number of Engines:** **1**

Long Stay Mars Mission

ESAS Reference Architecture	
Mission	**Earth Departure Mass (mt)**
All NTP, Split Piloted	293
NTP-AC, Split Cargo	154

	Thrust (klbs)		Isp (sec)		Thrust / Weight		Expansion Ratio	
	Nominal	Range	Nominal	Range	Nominal	Range	Nominal	Range
All NTP, Split Piloted	75	50 - 100	875	875 - 900	6.59	6.59+	120	120 - 250
NTP-AC, Split Cargo	75	50 - 100	875	875 - 900	6.59	6.59+	120	120 - 250

	# of Turbo-pumps		NPSP (psi)		Engine Life (min)		# of Burns	
	Nominal	Range	Nominal	Range	Nominal	Range	Nominal	Range
All NTP, Split Piloted	2	2 - 3	4.6	4.1 - 5.1	60	60 - 120	5	5 - 10
NTP-AC, Split Cargo	2	2 - 3	4.6	4.1 - 5.1	60	60 - 120	5	5 - 10

IV. CONCLUSIONS

The Nuclear Thermal Propulsion Mission and System Analysis study results indicate that nuclear thermal propulsion provides many performance advantages for human Mars exploration missions. The study considered a broad range of vehicle designs and applications of nuclear thermal propulsion technologies. The significant conclusions of Phase 1 and Phase 2 of the study are listed below:

IV A. Phase 1 Conclusions (Short Stay Mars Mission)

- NTP provides the capability to achieve total mission durations of 520 – 650 days
- Mission times under 500 days require NTP specific impulse > 1200 seconds
- 8-12 Earth to orbit launches for LEO assembly of the Mars vehicles are required
    - Assuming 110 mt ETO delivery capability
- Advanced NERVA NTP Technology is sufficient for performing short-stay Mars missions
    - Single Engine configuration
    - Thrust: 100 – 250 klb thrust
    - Specific Impulse: 875 seconds
    - Thrust-to-Weight Ratio ~ 6 – 8
- Foreseeable improvements in NTP technology would have little vehicle performance benefit

IV B. Phase 2 Conclusions (Long Stay – ESAS Reference Human Mars Mission)

- NTP provides the capability to achieve outbound and inbound transit times as low as 140 days
- 8 Earth to orbit launches for LEO assembly of the Mars vehicles are required
    - Assuming 90 mt ETO delivery capability
- Advanced NERVA NTP Technology is sufficient for performing the ESAS reference Mars mission
    - Single Engine configuration
    - Thrust: 50-75 klb thrust (75 klb thrust selected as a baseline)
    - Specific Impulse: 875 seconds
    - Thrust-to-Weight Ratio ~ 6 – 8
- Foreseeable improvements in NTP technology would have little vehicle performance benefit

V. NOMENCLATURE

ΔV	- Delta Velocity (km/s)
ESAS	- Exploration Systems Architecture Study
ESMD	- Exploration Systems Mission Directorate (NASA Headquarters)
ISP	- Engine Specific Impulse (sec)
MOI	- Mars Orbit Insertion
NPSP	- Engine Net Positive Suction Pressure (psi)
NTP	- Nuclear Thermal Propulsion
NTP MSA	- Nuclear Thermal Propulsion Mission and Systems Analysis
T/W	- Engine Thrust-to-Weight Ratio
TEI	- Trans Earth Injection
TMI	- Trans Mars Injection
V_∞	- Hyperbolic Excess Velocity (km/s)
V_{entry}	- Atmospheric Entry Velocity (km/s)

VI. RERFERENCES

1. NASA, "NASA's Exploration Systems Architecture Study", Final Report, NASA-TM-2005-214062, November 2005.

2. NASA, "Exploration Systems Mission Directorate Figures of Merit", Draft-1, June 23, 2004.

3. Eberle, Bill, et al, "Selection and Prioritization of Advanced Propulsion Technologies for Future Space Missions," AIAA Joint Propulsion Conference, Paper 2180, 2002.