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# "7-Launch" NTR Space Transportation System for NASA's Mars Design Reference Architecture (DRA) 5.0

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**In NASA's recently completed Mars DRA 5.0 study, mission, payload and transportation system options and requirements for a human Mars mission in the post-2030 timeframe were re-examined. This paper summarizes the analysis and concept design results for a nuclear thermal rocket (NTR)-based mission strategy aimed at reducing the number of Ares-V heavy lift launches. The NTR was again selected over chemical propulsion as the preferred in-space transportation system because of its higher specific impulse ($I_{sp}$) capability, increased tolerance to payload mass growth and architecture changes, and lower initial mass in low Earth orbit (IMLEO) which is important for reducing the heavy lift launch count, overall mission cost and risk. DRA 5.0 features a long surface stay "split mission" using separate cargo and crewed Mars transfer vehicles (MTVs). All vehicles utilize a common "core" propulsion module with three 25 $klb_f$ "composite fuel" NERVA-derived engines ($T_{ex}$ ~2700 K, $p_{ch}$ ~1000 psia, $\varepsilon$ ~300:1, $I_{sp}$ ~900 s, engine thrust-to-weight ratio ~3.43) to perform all primary mission maneuvers. Two cargo flights, using "1-way" minimum energy trajectories, pre-deploy a cargo lander to the surface and a habitat lander into a 24-hour elliptical Mars parking orbit where it remains until the arrival of the crewed MTV during the next mission opportunity (~26 months later). The cargo payload elements aerocapture (AC) into Mars orbit and are enclosed within a large triconic-shaped aeroshell which functions as a payload shroud during launch, then as an aerobrake and thermal protection system during Mars orbit capture and subsequent entry, descent and landing (EDL) on Mars. The all-propulsive crewed MTV is a "0-$g_E$" vehicle design. It carries six crew and utilizes fast conjunction trajectories that allows ~6-7 month "1-way" transit times to and from Mars and ~18 months on the planet's surface. Four 12.5 $kW_e$ / 125 $m^2$ rectangular photovoltaic arrays provide the crewed MTV with ~50 $kW_e$ of electrical power in Mars orbit for crew life support and spacecraft subsystem needs. Vehicle assembly involves autonomous Earth orbit rendezvous and docking between the propulsion stages, in-line propellant tank and payload elements. Seven Ares-V launches -- four for the two cargo MTVs and three for the crewed MTV -- deliver the key components for the three vehicles. Details on mission, payload, engine and vehicle characteristics, and their impact on Ares-V lift and payload shroud requirements to support the "7-Launch" NTR Mars strategy are presented and discussed.**

## Nomenclature

*DRM* = Design Reference Mission
*ESMD* = NASA's Exploration Systems Mission Directorate
*GRC* = Glenn Research Center
*JSC* = Johnson Space Center
*K* = temperature (degrees Kelvin)
$klb_f$ = thrust (1000's of pounds force)
*LEO* = Low Earth Orbit (= 407 km circular)
*NERVA* = Nuclear Engine for Rocket Vehicle Applications
*SDHLV* = Shuttle-derived Heavy Lift Vehicle
*t* = metric ton (1 t = 1000 kg)
$\Delta V$ = velocity change increment (km/s)

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## I. Introduction

In 2007, NASA conducted a multi-center, agency-wide study that re-examined the mission, payload and transportation system options and requirements for landing humans on Mars in the post-2030 timeframe. The *Mars Design Reference Architecture (DRA) 5.0* study[1] is an update to NASA's earlier DRM 3.0 and 4.0 studies[2,3,4,5] and was conducted in two phases. In Phase I, key architectural approaches, mission drivers and technology options were evaluated to support a down-selection process. Selected architectural approaches and systems concepts were then further refined in Phase II while also evaluating different surface exploration strategies. A three mission set of Mars landing missions over an ~10 year period was baselined. A crew of six would be sent on each mission and would explore a different location on Mars each time to sample the planet's rich geological diversity and maximize scientific return. A "fast conjunction" long surface stay mission was chosen to provide the crew with adequate time to explore, and because these missions have lower energy requirements than the short stay "opposition-class" missions, less propellant and in-space transportation system mass is needed.

DRA 5.0 also features a "split mission" approach with two cargo vehicles pre-deploying assets to Mars ahead of the crew. Aerocapture is used on the cargo missions while propulsive Mars orbit capture is baselined for the crewed mission. A surface exploration strategy referred to as the "Commuter" option, uses a habitat lander for the crew's primary living space. Two small pressurized and unpressurized rovers provide capability for extended and local exploration sorties, respectively. A fission surface power system (FSPS) manifested on the cargo lander supplies "24/7" electrical power to the cargo and habitat lander systems and an "in-situ" resource utilization (ISRU) plant supplies liquid oxygen (LOX) propellant for the Mars ascent vehicle (MAV). Phase I and II analysis[6] again determined the nuclear thermal rocket (NTR) to be the propulsion system of choice for the in-space transportation system. For delivery of the major Mars transfer vehicle and payload elements to LEO, several modified versions of the Ares-V heavy launch vehicle with ~110-120 t lift capability were examined.

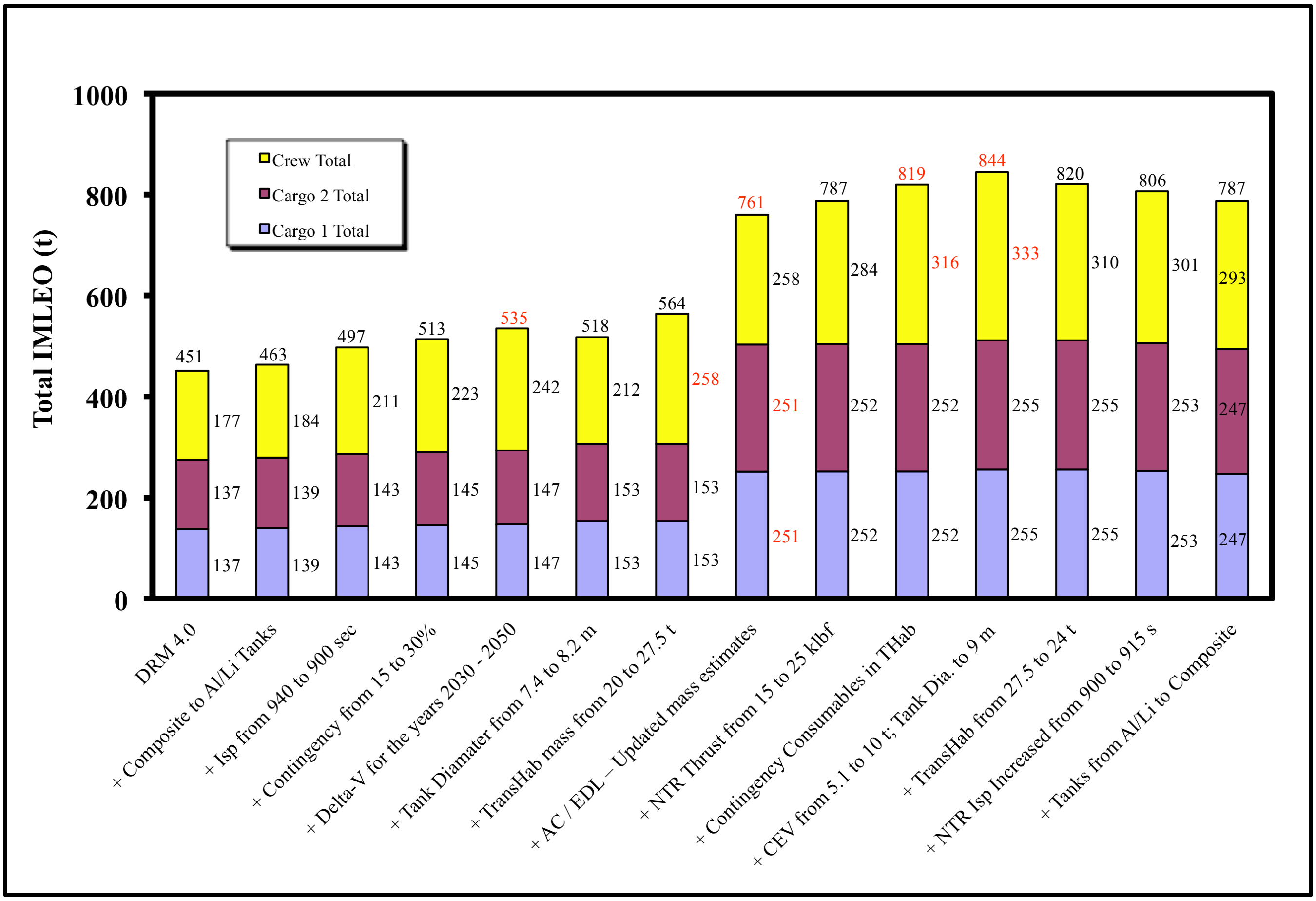


Figure 1. Trace Analysis Results Detailing Reasons for IMLEO Increase between DRM 4.0 and DRA 5.0

Phase II analysis results showed that NTR provides an IMLEO savings over chemical propulsion of ~400 t, the equivalent of 3–4 Ares-V launches. However, despite an ~50% greater lift capability for the Ares-V, DRA 5.0 required 9 Ares-V launches to deliver the cargo and crewed MTV components needed for the mission compared to 6–80 t SDHLVs plus a Shuttle launch (for TransHab and crew delivery) used in DRM 4.0[4,5]. To better understand the causes for the mission mass growth between DRM 4.0 and DRA 5.0, ESMD and JSC tasked GRC to identify the "cause and effect" of specific changes in the transportation system and mission payloads between the two studies. Furthermore, because large numbers of heavy lift launches has been identified as a major mission risk area, ESMD tasked GRC to identify solutions for getting the number of Ares-V launches down.

Figure 1 traces the growth in total IMLEO associated with key transportation, mission and payload changes from DRM 4.0. DRA 5.0 baselined Al/Li over composite propellant tanks, lower Isp "composite" NERVA fuel, higher dry weight contingency, and slightly higher Mars mission $\Delta$Vs over the timeframe of interest. To accommodate the increased $LH_2$ propellant loads needed to push heavier mission payloads, larger diameter tanks were required. Besides an ~37.5% increase in the TransHab mass, the mass of the AC/EDL aeroshell used on the cargo flights increased by ~400% (from ~10 t to 40 t) increasing the mass of each cargo vehicle by over 100 t. To accommodate this significant mass growth, the NTR engine thrust level was increased to 25 $klb_f$. The addition of the contingency consumables and doubling of the CEV mass led to further increases in tank diameter. The net result is an IMLEO increase of ~392 t (from ~451 t to 844 t) with each cargo MTV accounting for ~118 t and the crewed MTV for ~156 t. With an assumed lift capability of ~110 t, 8 Ares-V launches were required with NTR. To reduce the launch count further and also accommodate design deficiencies in the crewed mission payload mass identified at the end of the Phase II analysis cycle, GRC developed the "7-Launch" NTR Mars mission strategy which is the subject of this paper.

The paper addresses the following key areas. First, the operational principles and characteristics of the 25 $klb_f$ NTR engine baselined in DRA 5.0 are discussed along with performance projections using recent MCNP transport models of the engine's reactor core. Also included is a brief summary of the technical accomplishments of Rover/NERVA nuclear rocket programs. Mission and transportation system ground rules and assumptions are then presented, followed by a discussion of NTR stage and mission payload sizing issues and their impact on the Ares-V lift and payload shroud requirements. The overall mission scenario, including assembly activities, is discussed next followed by a description of the key features and characteristics of the cargo and crewed MTVs. The paper ends with a summary of our findings and a brief discussion of benefits of NTP for future NASA exploration missions and its significant growth potential.

## II. NTR System Description and Performance Characteristics

The NTR uses a compact fission reactor core containing 93% "enriched" uranium (U)-235 fuel to generate the large quantities of thermal power (100's of $MW_t$) required to heat the $LH_2$ propellant to high exhaust temperatures for rocket thrust. In an "expander cycle" NERVA-type engine (Fig. 1), high pressure $LH_2$ flowing from twin turbopump assemblies (TPAs) cools the engine's nozzle, pressure vessel, neutron reflector, and control drums, and in the process picks up heat to drive the turbines. The turbine exhaust is then routed through the core support structure, internal radiation shield, and coolant channels in the reactor core's fuel elements where it absorbs energy from the fissioning U-235 atoms, is superheated to high exhaust temperatures ($T_{ex}$ ~2650-2800 K depending on fuel type and uranium loading), then expanded out a high area ratio ($\varepsilon$ ~300:1-500:1) nozzle for thrust generation. Controlling the NTR during its various operational phases (startup, full thrust and shutdown) is accomplished by matching the TPA-supplied $LH_2$ flow to the reactor power level. Multiple control drums, located in the reflector region surrounding the reactor core, regulate the neutron population and reactor power level over the NTR's operational lifetime. The internal neutron and gamma radiation shield, located within the engine's pressure vessel, contains its own interior coolant channels. It is placed between the reactor core and key engine components (e.g., TPAs) to prevent excessive radiation heating and material damage.

The NERVA-derived engine assumed in DRA 5.0 uses a "graphite matrix" material fuel element (FE) containing the U-235 fuel in the form of a dispersion of uranium and zirconium carbide (UC-ZrC) within the matrix material, referred to as "composite" fuel. It utilizes an epithermal neutron energy spectrum. A typical NERVA FE has a hexagonal cross section (~0.75" across the flats), is 52" long and produces ~1 megawatt of thermal power[7]. Each FE has 19 axial coolant channels, which along with the element's exterior surfaces, are coated with ZrC using chemical vapor deposition to reduce hydrogen erosion of the graphite. Composite fuel, with its higher exhaust temperature potential ($T_{ex}$~2550-2800 K for ~4-6 hours[8]), was the preferred fuel form at the end of Rover/NERVA program. An alternative fast energy spectrum NTR fuel is a ceramic-metallic or "cermet" fuel consisting of uranium dioxide ($UO_2$) in a tungsten (W) metal matrix. It was developed during the GE-710 and ANL nuclear rocket programs[9,10] as a backup to the carbide-based fuels of the Rover/NERVA programs. While no integrated reactor/engine tests were conducted, a large number of fuel specimens were produced and exposed to non-nuclear hot $H_2$ and irradiation testing with promising results.

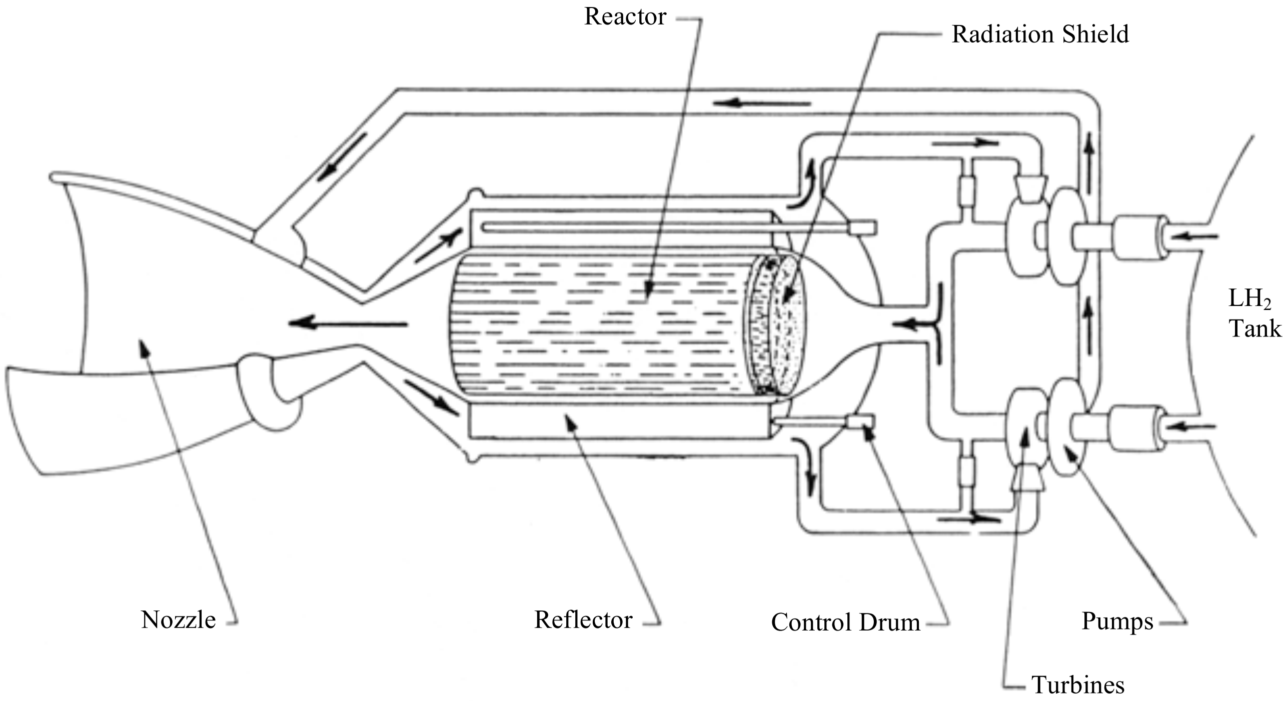


Figure 2. Schematic of "Expander Cycle" NTR Engine with Dual $LH_2$ Turbopumps

The performance parameters for the 25 $klb_f$ dual TPA expander cycle engine baselined in DRA 5.0 include: $T_{ex}$ ~2700 K, chamber pressure ($p_{ch}$) ~1000 psi, ε ~300:1, and $I_{sp}$ ~900 s. At $I_{sp}$ ~900 s, the $LH_2$ flow rate is ~12.6 kg/s. The engine thrust-to-weight ratio is ~3.43. The overall engine length is ~7.01 m, which includes an ~2.16 m long, retractable radiation-cooled nozzle skirt extension. The corresponding nozzle exit diameter is ~1.87 m.

Recent detailed MCNP Monte Carlo transport modeling of the engine's reactor core[11], not yet optimized, indicates that an $I_{sp}$ range of ~905 s to 940 s is achievable by lowering the U-235 fuel loading in the core from ~0.60 to 0.25 grams /$cm^3$ which allows the peak fuel temperature to increase while staying safely below the melt temperature. The engine thrust-to-weight ratio also improves to ~3.50.

Finally, it should be remembered that NTR technology is not new! It was demonstrated to high technology readiness levels (TRL~5-6) during the Rover / NERVA nuclear rocket programs[7] (1955-1973). Twenty rocket reactors were designed, built and ground tested in integrated reactor/ engine tests that demonstrated: (1) a wide range of thrust levels (~25, 50, 75 and 250 $klb_f$); (2) high temperature nuclear fuels that provided hydrogen exhaust temperatures up to 2550 K (achieved in the small 25 $klb_f$ Pewee engine); (3) sustained engine operation (*over 62 minutes for a single burn on the NRX-A6*); as well as; (4) accumulated lifetime; and (5) restart capability *(>2 hours during 28 startup and shutdown cycles*) on the NRX-XE experimental engine in 1969.

## III. Mission and Transportation System Ground Rules and Assumptions

NTR-specific mission and transportation system ground rules and assumptions used in DRA 5.0 are summarized in Tables I and II, respectively. Table I provides information about the assumed parking orbits at Earth and Mars, along with representative ΔV budgets for the "1-way" minimum energy cargo missions and the round trip "fast conjunction" crewed mission. In order to size the cargo MTV components to accommodate all mission opportunities, the largest total ΔV across the 15-year synodic cycle (~2028–2043) was selected for both the propulsive capture and aerocapture options. For the crewed mission, both short and long surface stay opportunities, occurring in the 2030-2046 timeframe, were examined during the Phase I analysis period[1,6]. Long surface stay missions were selected because of their lower energy requirements and ΔV budgets, and their relatively short "1-way" transit times (~130-210 days) out to Mars and back. The crewed mission profile also assumed only propulsive capture at Mars. Besides the large ΔV requirements shown for the primary mission maneuvers [trans-Mars injection (TMI), Mars orbit capture (MOC) and trans-Earth injection (TEI)], additional smaller ΔV maneuvers are needed for rendezvous and docking (R&D) of MTV components during the LEO assembly phase, for spacecraft attitude during interplanetary coast, and for Mars orbital operations and maintenance.

Table 1. NTR Mission Ground Rules and Assumptions

| | |
|---|---|
| Mission Profile | • Split mission; cargo pre-deployed to Mars before crew leaves Earth<br>• Cargo missions use "1-way" minimum energy trajectories<br>• Round trip crewed missions use "fast conjunction" trajectories |
| Earth and Mars Parking Orbits | • Earth: 407 km circular<br>• Mars: 250 km x 33,793 km |
| Cargo Mission $\Delta V$ Budget: Largest total $\Delta V$ across 15 year synodic cycle (~2028 - 2045) used for both propulsive (PC) and aerocapture (AC) options | • Propulsive MOC: Earth Departure $C_3$ ~10.794 $km^2/s^2$, $\Delta V_{TMI}$ ~3.662 km/s, arrival $V_{inf}$ ~3.480 km/s, $\Delta V_{MOC}$ ~1.341 km/s<br>• AC at Mars: Earth Departure $C_3$ ~14.849 $km^2/s^2$, $\Delta V_{TMI}$ ~3.839 km/s<br>• NOTE: Gravity losses added to above Ideal $\Delta V$s (value of g-loss depends on $C_3$, vehicle T/W, $I_{sp}$) |
| Crewed Mission $\Delta V$ Budget: An "all propulsive" mission profile with long surface stay times at Mars is the baselined approach | • Propulsive MOC: Earth Departure $C_3$ ~18.40 $km^2/s^2$, $\Delta V_{TMI}$ ~3.992 km/s, arrival $V_{inf}$ ~4.176 km/s, $\Delta V_{MOC}$ ~1.771 km/s<br>• Mars Departure $C_3$ ~14.80 $km^2/s^2$, $\Delta V_{TEI}$ ~1.562 km/s<br>• NOTE: Gravity losses added to above Ideal $\Delta V$s |
| Additional $\Delta V$ Requirements | • LEO R&D between orbital elements: ~100 m/s<br>• Coast attitude control and mid-course correction: ~15 m/s and ~50 m/s, respectively<br>• Mars orbit maintenance: ~100 m/s |
| Surface Power System (SPS) Options and Use of ISRU | • Nuclear fission and solar SPS options compared; Fission Surface Power System (FSPS) selected for baseline<br>• ISRU selected for MAV LOX ascent propellant production |
| Cargo Mission Payload Masses: | • Aerocapture (AC): 103 t - 133 t<br>• Propulsive MOC: 99.5 t - 122 t (Alternative option) |
| Crewed Mission Payload Mass: Total crew consumables based on 900 day mission that includes 180 day transit times to and from Mars and 540 days at Mars. Payload also includes short saddle truss (ST), a second docking module (DM) and jettisonable contingency consumables with canister | • Transit Habitat: 27.5 t<br>• Short ST, DM & Canister 8.67 t<br>• Total Crew Consumables: 13.23 t; ~5.29 t (transit to and from Mars), ~7.94 t (contingency); assumes crew consumption rate of ~2.45 kg/person/day)<br>• CEV/SM & 6 crew: 10.6 t<br>• Returned Mars Samples: 0.5 t |
| Mission Abort Strategy | • Outbound: Abort to Mars Surface<br>• At Mars: Abort to orbiting crew MTV which carries contingency consumables |

A range of cargo payload masses were developed during Phases I and II, which established the physical size and overall mass for the cargo MTVs. In Phase I, the use of ISRU for MAV propellant production was not considered. This led to a heavier MAV, EDL system and aeroshell (~110.9 t) for the propulsive capture (PC) option. The need for additional TPS mass on the aeroshell for the aerocapture option increased the cargo payload mass further (~138.2 t). In Phase II, reductions in the aeroshell and TPS masses, and the use of a fission surface power system and ISRU-produced ascent propellant, decreased the payload masses to ~99.5 t and 103 t for the PC and AC options, respectively.

For the crewed mission, the outbound payload mass is fixed at ~60 t not including the forward RCS & propellant. For long surface stay Mars missions, the crewed MTV carries contingency consumables equivalent to that found on the habitat lander. This allows the crew MTV to function as an orbital "safe haven" in the event of a major failure of a key surface system. In the case of a nominal surface mission, the contingency consumables are jettisoned prior to the TEI maneuver. Assuming the crew collects and returns with ~0.5 t of Mars samples, the total return payload mass for the crewed mission is ~53.8 t.

Table II lists the key transportation system ground rules and assumptions used in this study. The NTR engine and fuel type, thrust level and operating characteristics are summarized first. The 25 $klb_f$ NERVA-derived engine design baselined here uses composite fuel, operates with $T_{ex}$ ~2700 K, and an $I_{sp}$ of ~900 s, although higher $I_{sp}$ values are achievable by lowering the fissile fuel loading or using a larger area ratio nozzle. The total $LH_2$ propellant loading for a Mars mission consists of the usable propellant plus performance reserve, post-burn engine cooldown, and tank trapped residuals. For the smaller auxiliary maneuvers, an established storable bipropellant RCS system is used.

**Table 2. NTR Transportation System Ground Rules and Assumptions**

| | |
|---|---|
| NTR System Characteristics | • Engine / Fuel Type: NERVA-derived / UC-ZrC in graphite “Composite” fuel<br>• Propellant: $LH_2$<br>• Thrust Level: 25 $klb_f$/ engine (3 engine cluster on “Core” Propulsion Stage)<br>• Exhaust Temp: $T_{ex}$ ~2650 - 2800 K<br>• Chamber Pressure: $p_{ch}$ ~1000 psi<br>• Nozzle Area Ratio: ε~300:1 to 500:1<br>• $I_{sp}$ Range: 900 s (2650 K) - 910 s (2700 K) at ε ~300:1, 925 s (2750 K) at ε ~500:1 |
| Propellant Margins | • Cooldown: 3% of usable $LH_2$ propellant<br>• Performance reserve: 1% on ΔV<br>• Tank trapped residuals: 2% of total tank capacity |
| Reaction Control System (LEO R&D, Settling, Attitude Coast Control, and Mid-course Correction Burns) | • Propulsion Type: Chemical<br>• Propellant: NTO / MMH<br>• Nominal $I_{sp}$: 320 seconds |
| $LH_2$ Cryogenic Tanks and Passive Thermal Protection System (TPS) | • Material: Aluminum-Lithium (Al/Li)<br>• Tank ID / OD: ~9.8 m / 10.0 m<br>• Tank L: ~19.7 m (propulsion stage) – 21.2 m (“in-line” drop tank)<br>• Geometry: cylindrical with root 2/2 ellipsoidal domes<br>• Insulation: 1” SOFI (~0.78 kg/$m^2$) + 60 layers of MLI (~0.90 kg/$m^2$) |
| Active Cryo-Fluid Management / Zero Boil-Off (ZBO) $LH_2$ Propellant System | • ZBO Brayton-cycle cryocooler system powered by PVAs<br>• ZBO mass and power requirements for NTR core stage are 1130 kg and ~7.37 $kW_e$, respectively |
| Photovoltaic Array (PVA) Primary Power System | • PVA sized for ~7 $kW_e$ at 1 A.U. has mass of ~455 kg and array area of ~25 $m^2$; to supply 1 $kW_e$ at Mars requires ~10 $m^2$ of array area<br>• “Keep-alive” power supplied by battery / fuel cell combination |
| Dry Weight Contingency Factors | • 30% on NTR system and composite structures<br>• 15% on established propulsion, propellant tanks, spacecraft systems |
| Ares-V LEO Lift Requirements | • ~103 t - 133 t (AC), 99.5 t -122 t (PC); cargo lander / aeroshell mass ranges<br>• ~139 t; NTR propulsion stage with external crew radiation shields |
| Launch Shroud Size<br>Cylindrical Payload (PL) Envelope | • ~12 m D x 42.5 m L<br>• ~10 m D x 33.5 m L (crewed mission PL element) |

The $LH_2$ propellant used in the NTR cargo and crewed MTVs will be stored in the same “state-of-the-art” Al/Li $LH_2$ propellant tank that will be developed and used in the Ares-V heavy lift launch vehicle. Tank sizing assumes a 30 psi ullage pressure, 5 $g_E$ axial / 2.5 $g_E$ lateral launch loads, and a safety factor of 1.5. A 3% ullage factor is also assumed. All tanks use a combination foam / multilayer insulation (MLI) system for passive thermal protection. A ZBO “Brayton-cycle” cryocooler system is used on each common propulsion module $LH_2$ tank to eliminate boiloff during LEO assembly and the long duration Mars mission. The propellant tank heat load is largest in LEO and sizes the ZBO cryocooler system. Because non-“bimodal”

NTR engines are assumed in this study, it is necessary to use solar photovoltaic arrays to supply needed primary electrical power for the MTV systems. Because of the decreased solar intensity at Mars (~486 W/m$^2$), array areas can become quite large (~10 m$^2$/kW$_e$) necessitating multiple arrays. Lastly, Table II provides information on the assumed "dry weight contingency" (DWC) factors, along with the Ares-V LEO lift requirements and shroud cylindrical payload envelope required to support the "7-Launch" NTR mission option. A 30% DWC is used on the NTR system and advanced composite structures (e.g., stage adaptors, trusses) and 15% on heritage systems (e.g., Al/Li tanks, RCS, etc.,). The maximum Ares-V lift and shroud size are determined by the core propulsion module and total payload (PL) envelope for the crewed MTV, respectively.

## IV. Spacecraft Component Sizing and Impact on Ares-V Requirements

In 1991, the Synthesis Group[12] identified heavy lift launch capability as a basic necessity for efficiently undertaking human Moon / Mars exploration. A "minimum lift" capability of ~150 t and large payload envelopes (~10 m D x ~30 m L) were recommended to reduce launch count and simplify vehicle assembly in LEO. During the DRA 5.0 Phase II analysis cycle, the maximum lift and PL dimensions needed for the NTR architecture was ~110 t and ~9 m D x ~30 m L, respectively. With this capability, 9 Ares-V launches were required to launch the spacecraft and payload components for the mission. To achieve a "7-Launch" architecture, further increases in lift and payload diameter are required. Figure 3 shows the variation in propellant loading and NTR stage launch mass with increasing tank diameter. The stage length is fixed at ~32.2 m (~30 m with nozzles on the clustered 25 klb$_f$ NTR engines retracted for launch) along with other stage lengths resulting in a total available LH$_2$ tank length of ~19.7 m. By increasing the stage tank D from 8.4 m to 10 m, the LH$_2$ propellant loading can be increased by ~40% provided the Ares-V lift capability can be increased to ~140 t. By increasing the length of the tank's

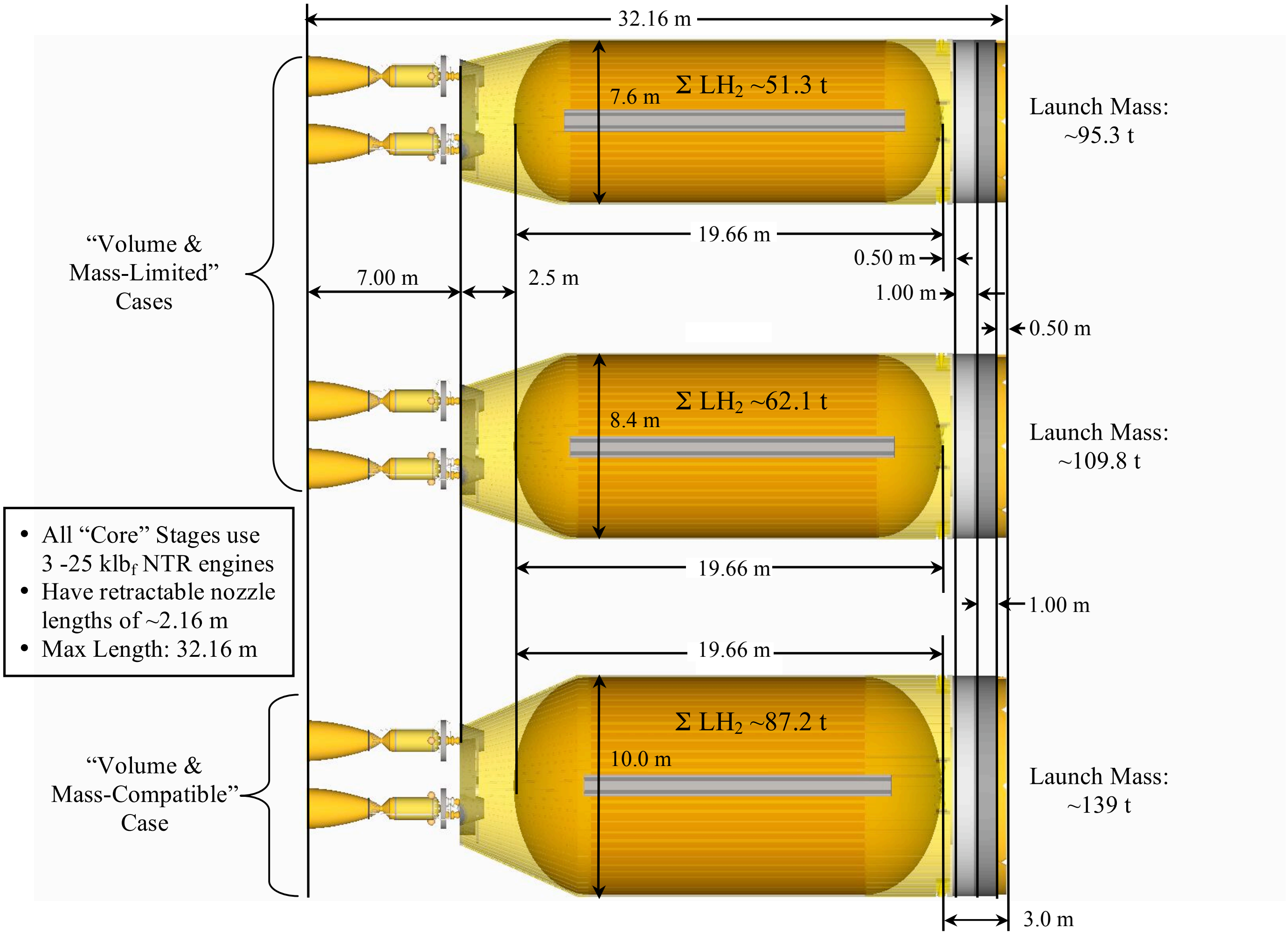


Figure 3. NTR "Core" Stage Sizing: Fixed Stage Length and Increasing Tank Diameter

cylindrical barrel section by ~1.5 m and the overall tank length to ~21.2 m, the propellant loading and lift requirement is increased to ~92.5 t and ~150 t, respectively.

The cargo and habitat landers baselined in DRA 5.0 also have considerable size and mass. Each lander occupies a PL envelope of ~9 m D x ~28 m L and is enclosed in a large triconic-shaped aeroshell that has dimensions of ~10 m D x 33 m L. A horizontal lander configuration was baselined in Mars DRM 4.0 [4,5] because of its attractive packaging efficiency and unloading features, and is again required in DRA 5.0 to accommodate all of the payload elements identified on the cargo and habitat lander flights. Key components of the cargo lander supporting the "commuter" surface exploration option are shown in Fig. 4. They include the lander descent stage, Mars ascent vehicle (MAV), small pressurized rover (SPR), dynamic isotope power system (DIPS), fission surface power system (FSPS), and in-situ resource utilization (ISRU) plant, plus additional surface payload stored in cargo containers located in the front and back ends of the lander. The total lander mass is ~103 t which includes the aeroshell (~40 t), "wet" lander stage (23 t) and surface payload elements (~40 t). In Fig. 4, the MAV's four ascent engines are assumed to be supplied with descent propellant from adjacent tank sets and also used for EDL.

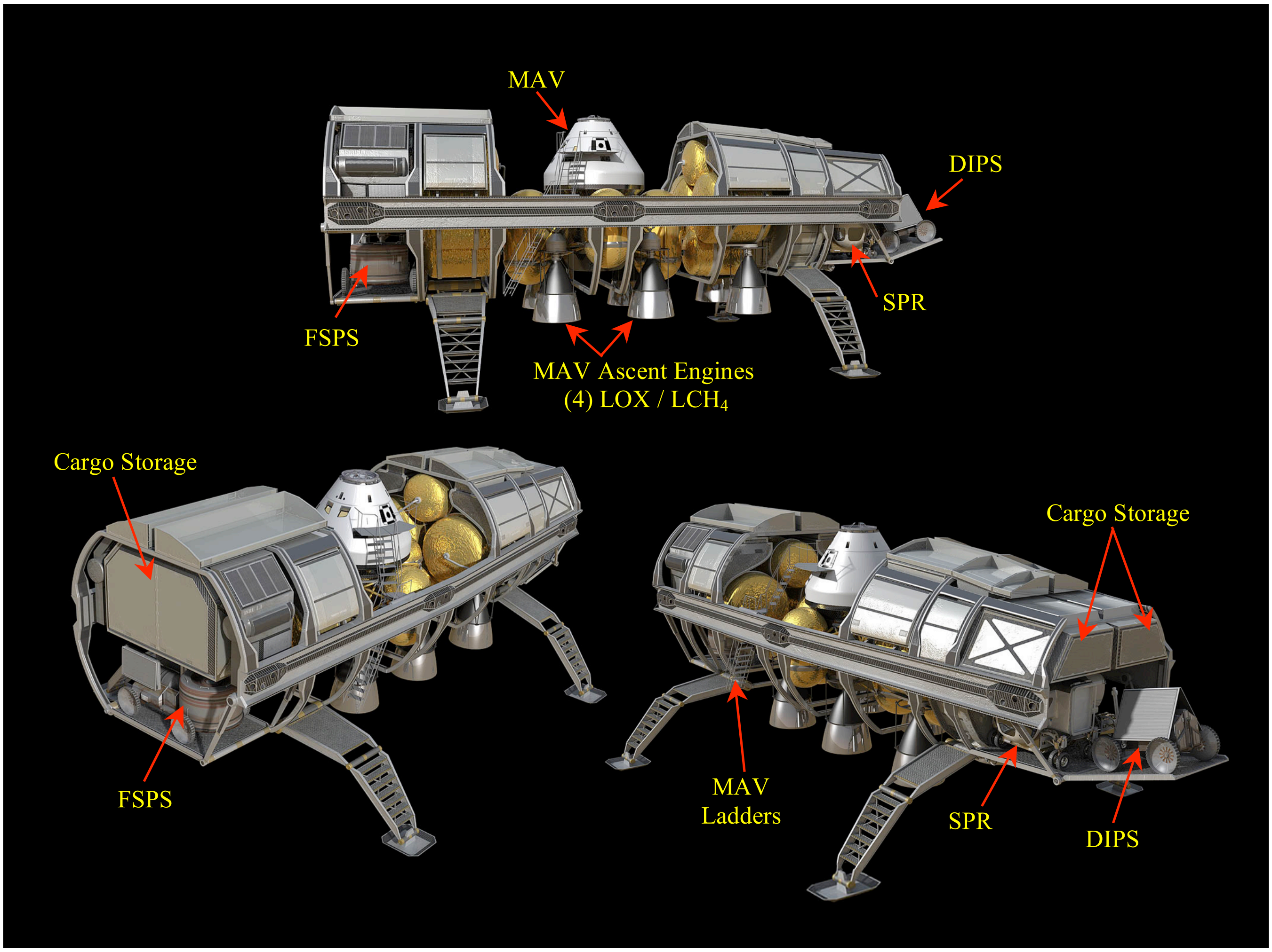
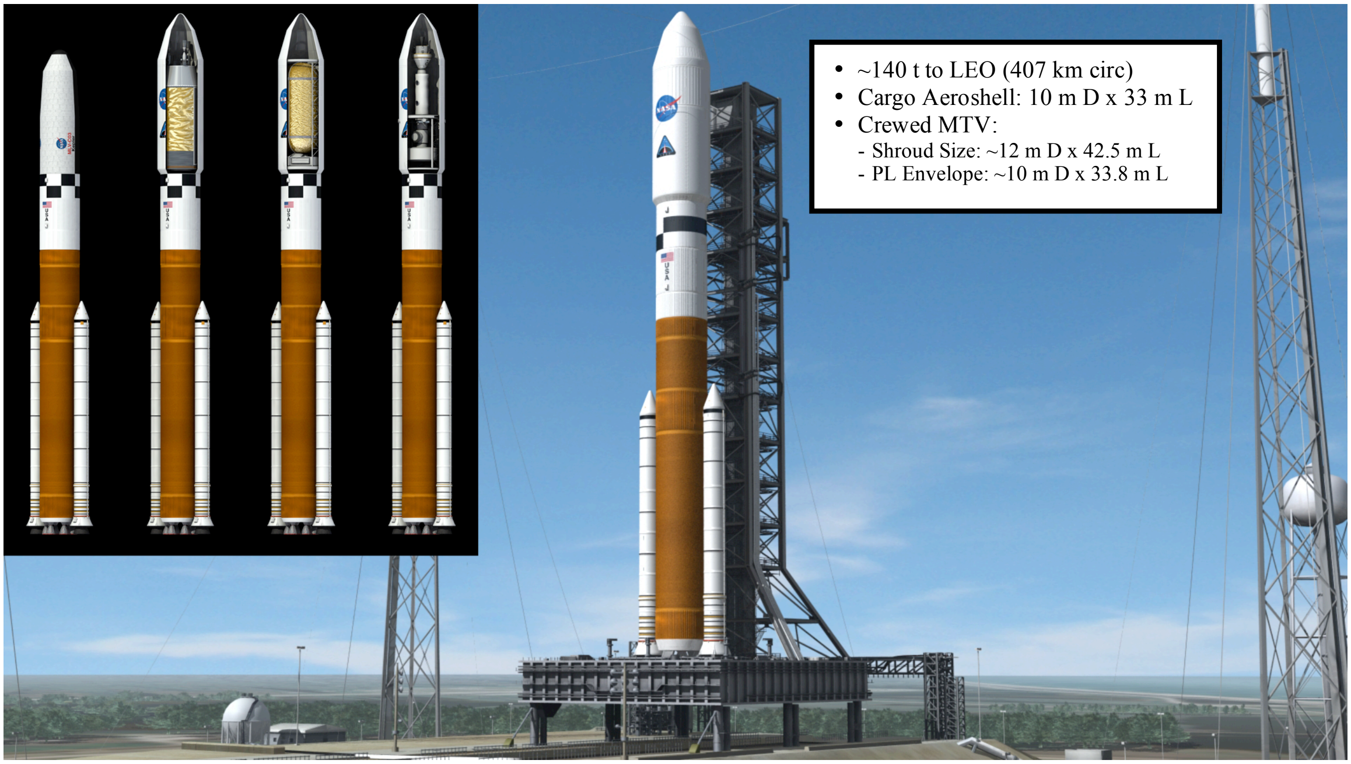


Figure 4. Conceptual Layout of Horizontal Cargo Lander and Surface Payload Elements

For EDL, the cargo and habitat landers use a combination of hypersonic aeroassist and supersonic retro-propulsive braking. The lander's triconic aeroshell provides lift and deceleration through the hypersonic regime. At low supersonic Mach number, exhaust outlets in the "bottom" of the aeroshell are opened or blown out and propulsive braking begins. The upper half of the aeroshell is then jettisoned and parachutes are deployed briefly to help pull the lander away from the bottom portion of the aeroshell allowing it to free fall to the surface while the lander continues its propulsive descent towards the targeted landing location.



- ~140 t to LEO (407 km circ)
- Cargo Aeroshell: 10 m D x 33 m L
- Crewed MTV:
  - Shroud Size: ~12 m D x 42.5 m L
  - PL Envelope: ~10 m D x 33.8 m L

Figure 5. Ares-V Lift and Payload Shroud Requirements to Support “7-Launch” NTR Mars Strategy

The crewed MTV’s NTR propulsion stage and crewed payload element dictate the Ares-V lift capability and shroud size (see Figs. 5 and 6). The crewed payload element includes the “packaged” TransHab module, short saddle truss, contingency consumables canister, secondary docking module and Orion / Service Module (SM) and has a maximum OD of ~11 m and a total length of ~33.8 m. The 10 m D propulsion stage (shown in Fig. 3) dictates the ~140 t lift requirement.

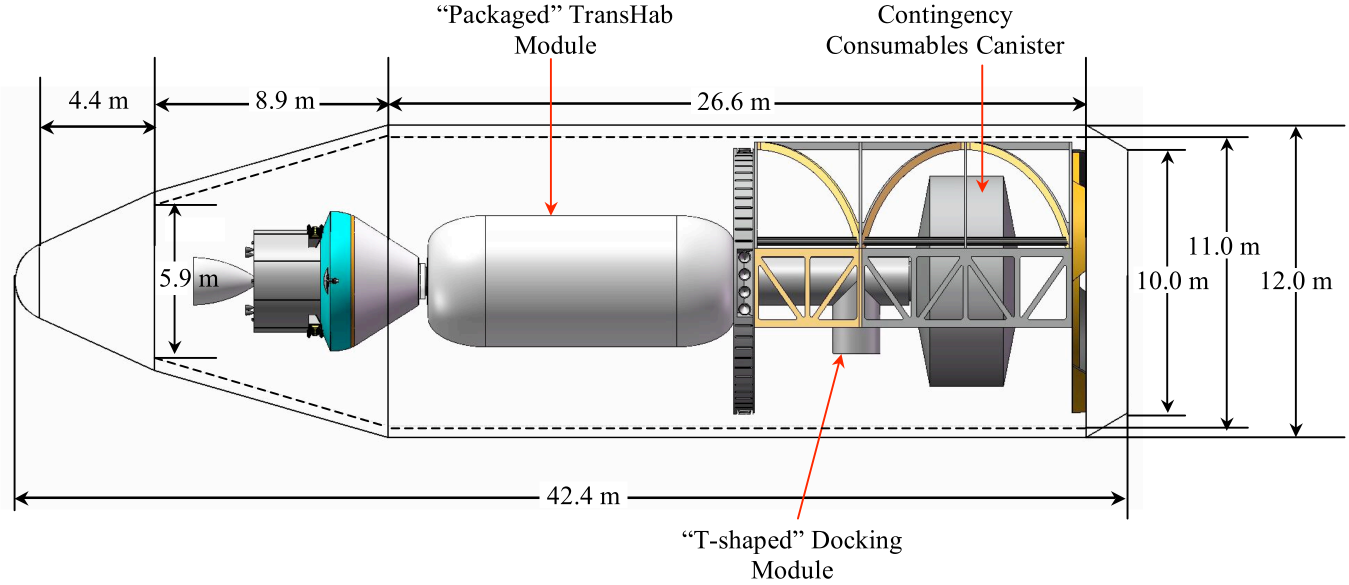


Figure 6. Crewed Payload Element Shown in Packaged Configuration within Hammerhead Shroud

## V. Mars DRA 5.0: “7-Launch” NTR Mission Description

As mentioned above, Mars DRA 5.0 is centered around long surface stay, split cargo / piloted mission approach shown in Fig. 7. Two cargo flights are used to pre-deploy a cargo lander to the surface and a habitat lander into Mars orbit where it remains until the arrival of the crew on the next mission opportunity (~26 months later). The cargo flights utilize “1-way” minimum energy, long transit time trajectories. Four Ares-V flights carried out over 90 days (~30 days between launches), deliver the required components for the two cargo vehicles. The first two launches deliver the NTR core propulsion stages, each with a 10 m D $LH_2$ propellant tank and three 25 $klb_f$ NTR engines operating with a $I_{sp}$ of ~900 s. Because of the significant increase in the current aeroshell mass (~40 t versus ~10 t used to the earlier DRM studies), larger D tanks are required to accommodate the additional propellant needed for the TMI maneuver. The next two launches deliver the cargo and habitat lander payload elements which are enclosed within a large biconic- or triconic-shaped aeroshell that functions as payload shroud during launch, then as an aerobrake and thermal protection system during Mars orbit capture and subsequent entry, descent and landing (EDL) on Mars. Vehicle assembly involves Earth orbit rendezvous and docking (R&D) between the propulsion stages and payload elements with the NTR stages functioning as the active element in the R&D maneuver.

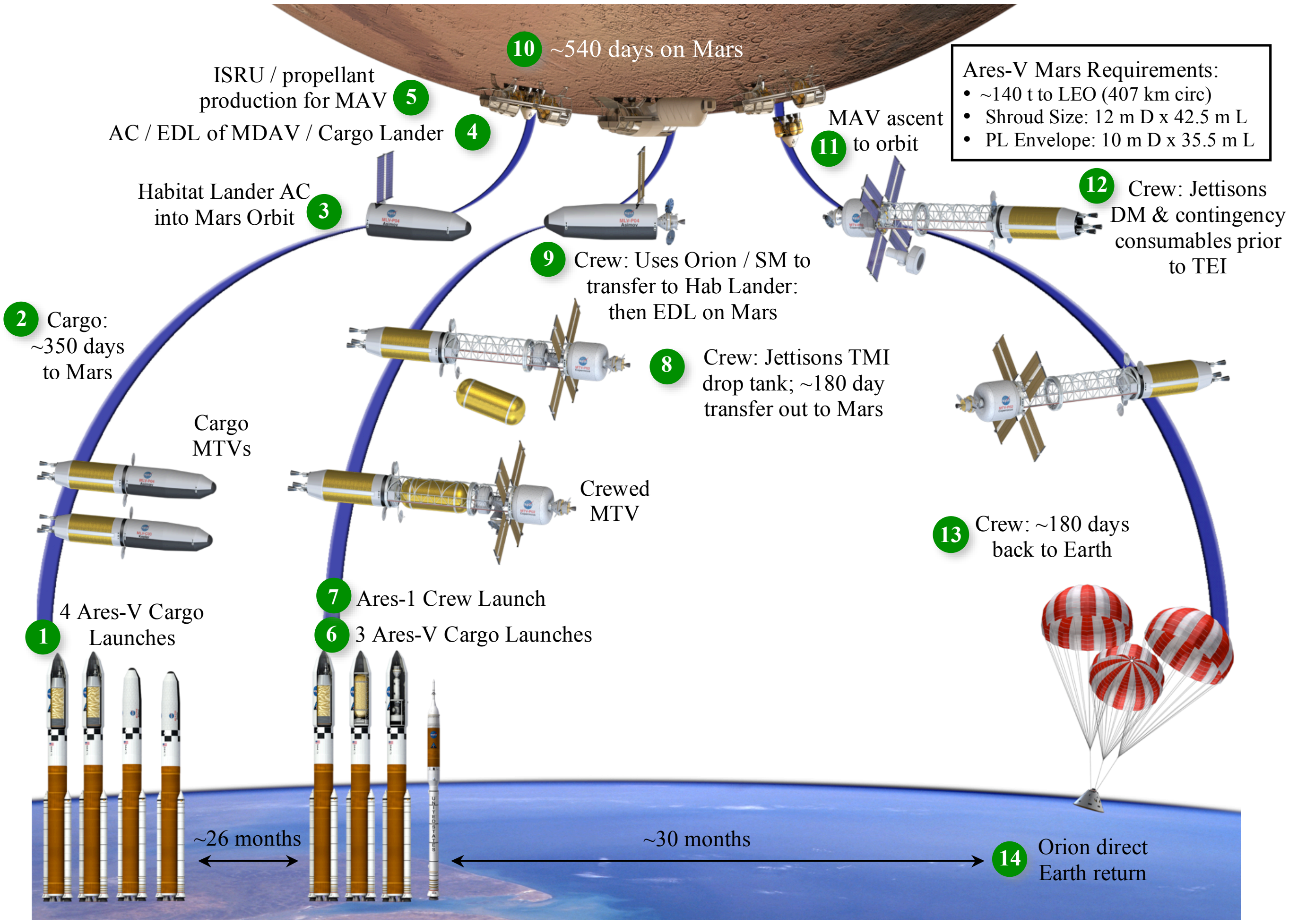


Figure 7. DRA 5.0 Long-Stay Mars Mission Overview: “7-Launch” NTR Strategy

Following the TMI maneuver, the NTR propulsion stage is not jettisoned but remains with the payload using its onboard RCS to provide mid-course correction and attitude control during the coast out to Mars. The stage also uses its two small circular PVAs to supply kilowatts of electrical power to the payload up to the point of stage–payload separation near Mars. The AC’ed cargo and habitat landers also carry their own multi-kilowatt ($kW_e$) deployable/retractable PVA to supply electrical power during transit, and also while in Mars orbit prior to landing and while awaiting the arrival of the crew.

Once the operational functions of the orbiting habitat and surface cargo landers are verified, and the MAV is supplied with ISRU-produced ascent propellant, the crewed mission will be cleared to go on the next available mission opportunity. The all-propulsive crewed MTV is a “0-$g_E$” vehicle design that utilizes fast conjunction trajectories that allow ~6-7 month “1-way” transit times to and from Mars. Like the cargo MTV, it is an “in-line” configuration that uses Earth orbit R&D to simplify vehicle assembly. It uses the same “common” NTR propulsion stage but includes additional external radiation shielding on each engine for crew protection during engine operation. Three Ares-V launches over 60 days are used to deliver the vehicle’s key components which include: (1) the NTR “core” stage; (2) a “saddle truss” and $LH_2$ drop tank; and (3) the supporting crewed payload. The crewed payload component includes the TransHab module with its six crew, a long-lived Orion/SM for vehicle-to-vehicle transfer and “end of mission” Earth entry, a secondary T-shaped docking module (DM), contingency consumables canister and connecting structure. Four 12.5 $kW_e$ / 125 $m^2$ rectangular PVAs provide the crewed MTV with ~50 $kW_e$ of electrical power at Mars for crew life-support and spacecraft subsystem needs. When assembly is complete, the Mars crew is launched on the Ares-I and the Orion/SM docks with the underside of the orbiting MTV using the secondary DM that connects the TransHab crew module and contingency consumables canister (shown below in Fig. 8).

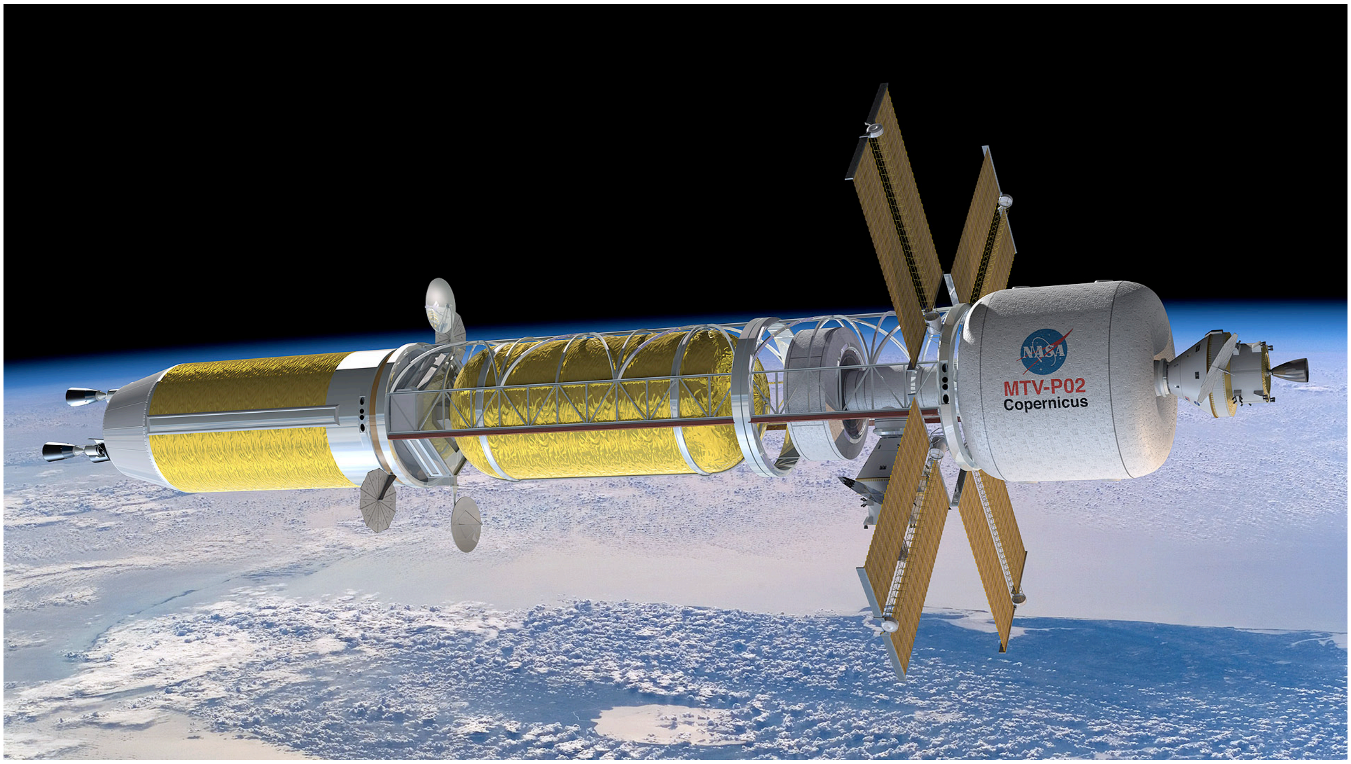


**Figure 8. Crew Delivery to Orbiting Mars Transfer Vehicle Prior to Earth Departure**

Following the TMI maneuver, the drained $LH_2$ drop tank, attached to the central saddle truss, is jettisoned and the crewed MTV coasts to Mars under 0-$g_E$ conditions and with its four PVAs tracking the Sun. Attitude control, mid-course correction and vehicle orientation maneuvers are provided by a split RCS with thrusters and bipropellant located on the rear NTR propulsion module and the short saddle truss forward adaptor ring just behind the TransHab module. After propulsively capturing into Mars orbit, the crewed MTV rendezvouses with the orbiting Hab lander using engine cooldown thrust and the vehicle’s RCS. The crew then transfers over to the lander using the Orion/SM that subsequently returns and docks to the TransHab autonomously. The crew then initiates EDL near the cargo lander and begins the surface exploration phase of the mission. After ~533 days on the surface, the crew lifts off and returns to the MTV using the MAV. Following the transfer of the crew and samples to the MTV, the MAV is jettisoned. The crew then begins a weeklong checkout and verification of all MTV systems, jettisons the DM and contingency consumables and performs the TEI burn to begin the journey back to Earth. After an ~6 month trip time, the crew enters the Orion/SM, separates from the MTV and subsequently re-enters the atmosphere while the MTV flies by Earth at a “sufficiently high altitude” and is disposed of into heliocentric space.

## VI. Mars Transfer Vehicle Design Features and Characteristics

The cargo and crewed MTVs comprising the “7-Launch” NTR Mars architecture are shown in Figs. 9 and 10. Each cargo vehicle has an IMLEO of ~236.2 t consisting of a “common” NTR propulsion module (PM) and an aerocaptured (AC’ed) PL (aeroshell, propulsive lander and surface payload). The later has a launch mass of ~103 t which is consistent with a surface exploration strategy using FSP and ISRU, similar to that used in DRM 4.0. The PM on each cargo vehicle uses three 25 klb$_f$ NTR engines with a thrust-to-weight ratio of 3.43. Each PM has launch mass of ~133.2 t and carries ~87.2 t of LH$_2$ in its 10 m D x ~19.7 m L Al/Li propellant tank. Because the PM is used only for TMI, the fuel elements in the engine’s reactor core can be operated at higher temperatures to increase I$_{sp}$ or tank length can be increased by an additional meter (to ~20.7 m) to accommodate a range of AC’ed PL masses. Four ~140 t-class Ares-V flights deliver the components for the 2 cargo vehicles to LEO for assembly via rendezvous and docking. The length of each cargo vehicle is a little over 65 meters as shown in Fig. 10.

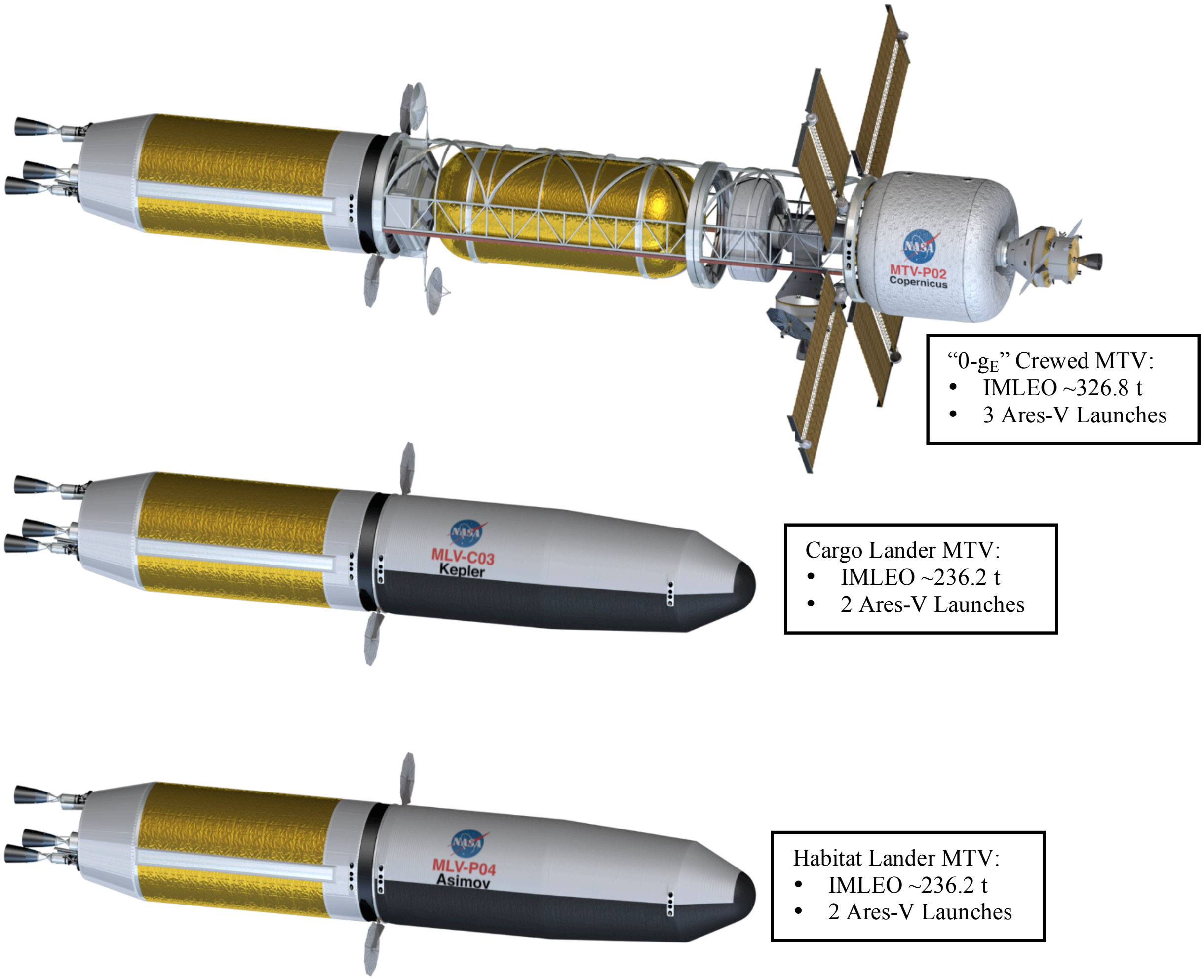


**Figure 9.** Size, Mass and Key Features of Crewed and Cargo NTR Mars Transfer Vehicle

The PM on each cargo vehicle also carries ~3.3 t of RCS propellant in its forward cylindrical adaptor section used during LEO assembly operations, coast attitude control, and mid-course correction on the way to Mars. The forward adaptor section also carries avionics, batteries, twin Orion-type circular PVAs, and docking system along with a “Brayton-cycle” ZBO cryocooler system to eliminate LH$_2$ propellant boil-off during the assembly period (~90 days) and subsequent TMI window allowance (~30-60 days). The cryocooler’s cylindrical band radiator is located at the front end of the PM’s forward adaptor section. Approximately 85 t of LH$_2$ is used during the TMI maneuver (including the “post-burn” cooldown propellant). The corresponding engine burn time is ~38 minutes, well within the 62 minute single burn duration demonstrated by the NERVA program’s NRX-A6 engine[7].

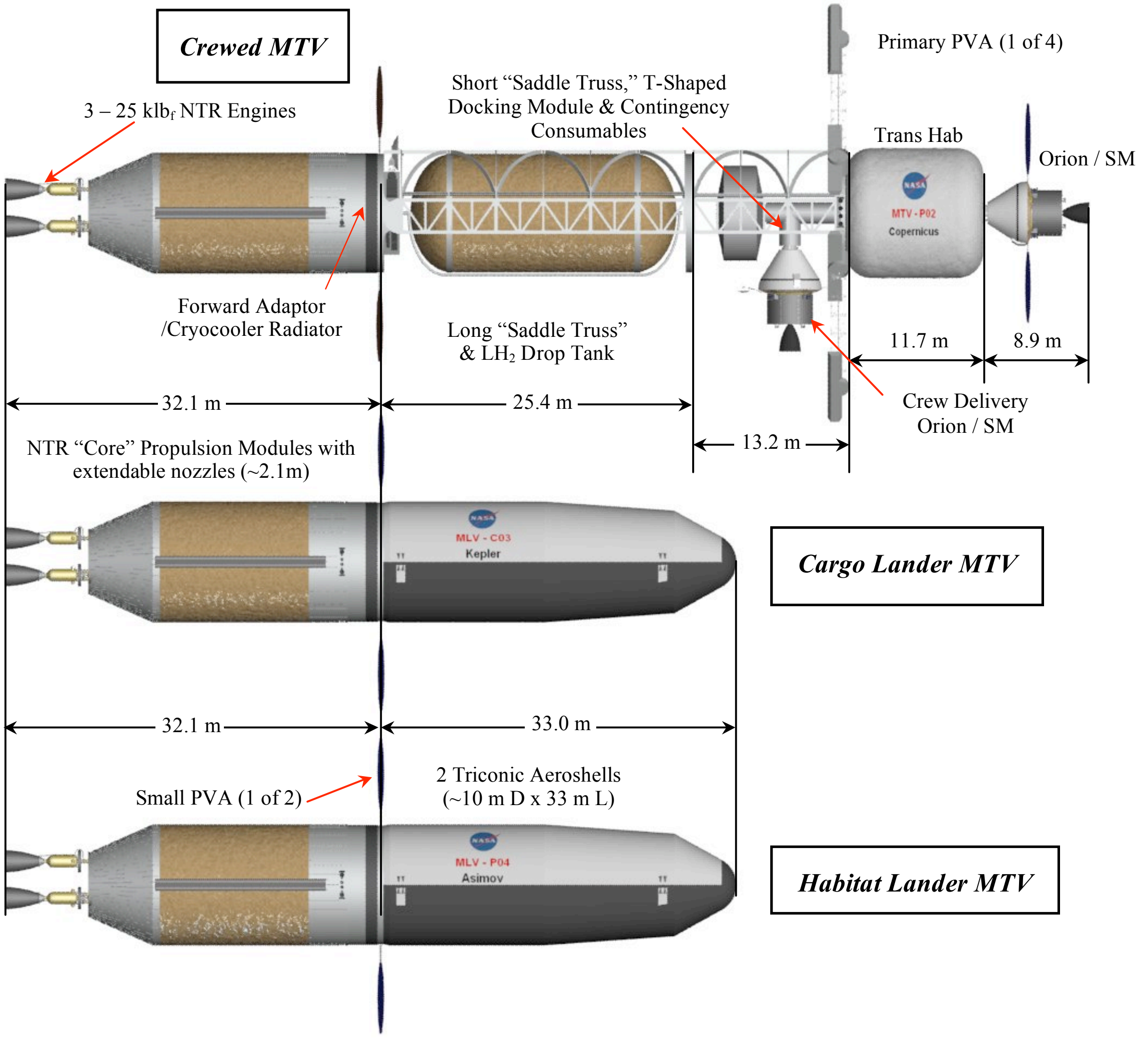


**Figure 10.** Key Features and Component Lengths of Crewed and Cargo NTR Mars Transfer Vehicles

The crewed MTV requires three "140 t-class" Ares-V flights over 60 days to deliver its key components. It has an IMLEO of ~327 t and an overall vehicle length is ~91.3 m. The vehicle's main components include: (1) the "core" NTR propulsion module (~139 t); (2) a saddle truss and LH$_2$ drop tank (124 t); and (3) the crew payload section (~64 t). Like the cargo vehicle, the crewed MTV uses the same PM and three engine cluster of 25 klb$_f$ NTR engines. However, for the crewed mission, the PM also carries additional external radiation shield mass (~5.7 t) for crew protection. The PM's LH$_2$ tank size and propellant capacity are 10 m D x 19.7 m L and ~87.2 t like on the cargo MTV. The Al/Li propellant tank on the PM has the same 10 m D as that used on the Ares-V core stage but is less than half its total length of ~44.5 m. The PM also carries the same avionics, RCS, auxiliary battery and PVA power, docking and Brayton-cycle ZBO cryocooler systems in its forward cylindrical adaptor section. To remove the ~74 watts of heat penetrating the 60 layer MLI system while in LEO (where the highest tank heat flux occurs), the Brayton refrigeration system requires ~7.4 kW$_e$ for its operation (~100 W$_e$ for each W$_t$ removed). Also, because the core PM on the crewed MTV carries the propellant needed for the MOC and TEI maneuvers, and has the longest storage time (~840 days from launch to TEI), a second backup Brayton ZBO system is carried. The twin circular Orion-type PVAs on the PM provide the electrical power for the ZBO system in LEO until the four primary PVAs on the crewed PL section are deployed just before TMI.

The second major component on the crewed MTV is the saddle truss and LH$_2$ drop tank assembly. The "saddle truss" is a rigid, spine-like composite structure that wraps around the upper half of the LH$_2$ drop tank and connects the core PM to the forward payload section. It is ~25.4 m long and has a mass of ~8.9 t. The saddle truss is open underneath allowing the drained $LH_2$ drop tank to be jettisoned after the TMI burn is completed.

The third and final component of the crewed MTV is the payload section that is designed for launch as a single integrated unit and determines the overall shroud size (12 m OD x ~42.5 m L). During the Phase I and II analysis cycles for DRA 5.0, payload mass limits were established but operational implementation issues where somewhat ill-defined. For example, the operational strategy for the crewed mission did not address where nearly 8 t of contingency consumables would be stored and how they would be jettisoned from the TransHab module prior to TEI. Also not addressed was how and where a second crew delivery Orion/SM or the MAV would dock to the TransHab module with a long-lived Orion/SM-type vehicle (part of the assumed crewed payload) already attached to its front docking port.

A preliminary design for an integrated crewed payload that addresses these issues was developed by GRC in the later stages of Phase II for the NTR design reference[1,6]. It requires a dedicated Ares-V launch due to its size (Fig. 6) but it is substantially off-loaded in terms of launch mass and therefore has substantial mass margin available for structural launch load supports for the front-mounted Orion/SM whether launched inverted (Fig. 6) or in capsule forward position. The same integrated payload element is also used on the crewed MTV design for the "7-Launch" NTR option. The integrated payload element is ~33.4 m long (see Fig. 10) and includes a short saddle truss with a "T-shaped" docking module (DM) attached to its forward adaptor ring. This second DM provides access to the TransHab module to the right and the jettisonable contingency consumables canister mounted at the left. It also provides docking access for the crew delivery Orion/SM and the MAV. Following the crew's return for Mars and MAV separation, the DM and attached contingency consumables canister are both jettisoned to reduce vehicle mass prior to TEI (see Fig. 7).

The mass of the integrated crewed payload at TMI is ~64 t and includes the following items: (1) a short saddle truss (~5.1 t); (2) a second DM and transfer tunnel (~1.8 t); (3) contingency consumables and jettisonable container (~9.7 t); (4) TransHab module (~27.5 t); (5) transit consumables (~5.3 t); (6) crew (~0.6 t); (7) a long-lived Orion/SM (~10 t); and (8) forward RCS and propellant (~4 t). The crewed MTV's total RCS propellant loading is ~9.6 t with the "post-TMI" RCS propellant load split between the core stage (~5.9 t) and short saddle truss forward cylindrical adaptor ring (~4 t).

Lastly, it is noteworthy to comment on the total operating time for the NTR engines. For the round trip crewed mission, the total usable $LH_2$ propellant loading is ~170 t and the corresponding total mission engine burn duration is ~75 minutes (~53 minutes total for the "2-perigee" TMI burn, ~13.5 minutes for MOC, and ~8.3 minutes for TEI), well within the ~2 hour accumulated engine burn time demonstrated by the NERVA eXperimental Engine (the NRX-XE) 40 years ago!

## VII. Summary and Conclusions

Despite a very significant increase in payload mass plus a 400% increase in the mass of the AC/EDL aeroshell (from ~10 t to 40 t), the NTR option still offers the potential for a "7-Launch" human Mars mission campaign. This option will require a cargo heavy lift vehicle (HLV) capable of delivering ~140 t of usable payload to LEO and a large payload shroud to accommodate the basic vehicle and mission payload elements discussed above. These conclusions are not new! Similar findings and recommendations were contained in the Synthesis Group report and in subsequent SEI studies conducted by the NASA centers in the early 1990's. In fact, the Synthesis Group report specifically recommended a HLV with an ~150 t lift capability and large PL shroud as a minimum requirement to carry out efficient human Moon / Mars exploration.

The "7-Launch" NTR Mars strategy uses a common propulsion module with three 25 $klb_f$ "Pewee-class" NTR engines, the smallest thrust and highest performing engine built and ground tested during the Rover/NERVA program. Our "Model T" NTR engine also uses graphite matrix composite fuel and a hydrogen exhaust temperature of ~2700 K to achieve a conservative 900 s specific impulse value. Each of the three engines on the PM carries dual $LH_2$ TPAs that provides both a "pump-out" and "engine-out" capability that can increase crew safety and reduce mission risk. A smaller thrust engine is also expected to help reduce the time and cost to develop, ground- and flight-test these engines. Lastly, the total engine operating time and number of restarts for a round trip crewed Mars mission is 75 minutes and 3 restarts, substantially less than the ~2 hours of accumulated lifetime and 28 restarts demonstrated on the NRE-XE engine 40 years ago this year!

It is also important to realize that NTR and stage technologies have much in common with today's cryogenic $LOX/LH_2$ engine (e.g., RL10B-2) and stage hardware like $LH_2$ TPAs, regenerative- and radiation-cooled nozzles and skirt extensions, avionics and thrust vector control system. Even more important to realize is the fact that the large Al/Li $LH_2$ propellant tank (10 m D x ~44.5 m L) in the Ares-V core stage is almost tailor-made for use on the NTR Mars transfer vehicles. *Two Ares-V $LH_2$ core tanks cut in approximately half with 4 extra domes provides the propellant tanks needed for the two Mars cargo vehicles and the crewed MTV.* The ability to exploit the tooling, manufacturing and transportation infrastructure for Ares-V should help reduce development cost, as well as, the recurring cost for the NTR propulsion modules.

From a mission and operations perspective, the NTR Mars transportation system has fewer vehicle elements and simpler space operations. No complex orbital assembly (or refueling operations currently being proposed) are required as with chemical propulsion, just Earth orbit R&D of several vehicle elements – one for each cargo vehicle and two for the crewed

MTV. A higher performance NTR Mars space transportation system is also more tolerant of unexpected mass growth and provides NASA planners greater mission flexibility, such as a propulsive capture option for cargo missions should technical difficulties arise with the aerocapture approach.

Finally, one should consider the "return" on scarce investment dollars. Are we investing in "short shelf life / limited growth" technologies or those that can help extend human presence into the Solar System? Nuclear thermal propulsion allows greater future growth capability including use of higher temperature fuels and "bimodal" engine operation, which can eliminate the need for deploying and operating large Sun-tracking PVAs. The configuration of a NTR-powered MTV (long and linear) is also naturally compatible with artificial gravity operations[4,5] that can help maintain crew fitness during the transit out to Mars and back, also while in Mars orbit in the event of an "abort-to-orbit" scenario as exists in the current DRA 5.0. Lastly, by adding a "LOX-afterburner" nozzle[13], the monopropellant NTR can transition to bipropellant LANTR (LOX-augmented NTR) operation with an engine that now has a variable thrust and $I_{sp}$ capability achieved by varying the oxygen-to-hydrogen mixture ratio used in the afterburner nozzle. The improvements to the basic NTR outlined here offer the potential for significant downstream growth capability, well beyond that of chemical propulsion, and can lead to revolutionary performance advancements[14] in an evolutionary manner – *"Revolution through Evolution"*.

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