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NUCLEAR THERMAL ROCKET/VEHICLE CHARACTERISTICS AND SENSITIVITY TRADES FOR NASA's MARS DESIGN REFERENCE ARCHITECTURE (DRA) 5.0 STUDY

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Abstract - *This paper summarizes Phase I and II analysis results from NASA's recent Mars DRA 5.0 study which re-examined mission, payload and transportation system requirements for a human Mars landing mission in the post-2030 timeframe. Nuclear thermal rocket (NTR) propulsion was again identified as the preferred in-space transportation system over chemical/aerobrake because of its higher specific impulse (I_{sp}) capability, increased tolerance to payload mass growth and architecture changes, and lower total initial mass in low Earth orbit (IMLEO) which is important for reducing the number of Ares-V heavy lift launches and overall mission cost. DRA 5.0 features a long surface stay (~500 days) "split mission" using separate cargo and crewed Mars transfer vehicles (MTVs). All vehicles utilize a common "core" propulsion stage with three 25 klb_f "composite fuel" NERVA-derived NTR engines (T_{ex} ~2650 - 2700 K, p_{ch} ~1000 psia, ε ~300:1, I_{sp} ~900 - 910 s, engine thrust-to-weight ratio ~3.43) to perform all primary mission maneuvers. Two cargo flights, utilizing "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 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 that utilizes a "fast conjunction" trajectory that allows ~6-7 month "1-way" transit times to and from Mars. 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 tanks and payload elements. Nine Ares-V launches -- five for the two cargo MTVs and four for the crewed MTV -- deliver the key components for the three MTVs. Details on mission, payload, engine and vehicle characteristics and requirements are presented and the results of key trade studies are discussed.*

I. INTRODUCTION

The nuclear thermal rocket (NTR) is a leading propulsion system option for human Mars missions because of its high thrust (10's of klb_f) / high specific impulse (I_{sp} ~875-950 s) capability which is twice that of today's LOX/LH_2 chemical rocket engines. Demonstrated in twenty rocket/reactor ground tests during the Rover/NERVA (Nuclear Engine for Rocket Vehicle Applications) Programs[1], the NTR utilizes fission-reactor-generated thermal power rather than chemical combustion of an oxidizer-fuel mixture to directly heat liquid hydrogen (LH_2) propellant for rocket thrust. NASA's previous Mars Design Reference Mission (DRM) studies, DRM 3.0 in 1998[2,3] and DRM 4.0 in 1999[4,5], utilized a "common" propulsion module with three 15,000 pounds force (klb_f) NTR engines. The use of clustered, lower thrust (~15-25 klb_f) engines provides an "engine-out" capability that can increase crew safety and reduce mission risk. The time and cost to develop and ground test these smaller engines is also expected to be less then that required for higher thrust engines. Both conventional NTR engines (thrust only) and "bimodal" engines (BNTR), capable of producing both thrust and modest amounts of electrical power (few 10's of kW_e) during the mission coast phase, were examined in addition to $0\text{-}g_E$ and artificial gravity (AG) crewed Mars Transfer Vehicle (MTV) design concepts. The recent Mars DRA 5.0 Phase I and II study considered "thrust only" NTR engines, $0\text{-}g_E$ crewed MTV designs and photovoltaic arrays (PVAs) to supply spacecraft electrical power.

This paper reviews mission, engine and vehicle design considerations and assumptions used in the DRA 5.0 study, then presents Phase I and II study results and summarizes findings. The operating principles of a NERVA-based engine are outlined first, then the performance characteristics of a 25 klb_f "Pewee-class" engine[1], baselined in this study, are presented. NTP-specific mission and transportation system ground rules and assumptions are reviewed next, followed by a brief description of the "reference" NTP long surface stay Mars mission scenario and MTV LEO assembly operations. Design features and operating characteristics for Phase I and II cargo and crewed MTVs are discussed next along with proposed design changes for the crewed vehicle that could help to reduce the number of Ares-V launches. The section concludes with a summary of key findings and recommendations on required future work.

II. SYSTEM DESCRIPTION AND PERFORMANCE CHARACTERISTICS

As mentioned in the introduction, 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} ~2550-2800 K depending on fuel type and uranium loading), then expanded out a high area ratio (ε ~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

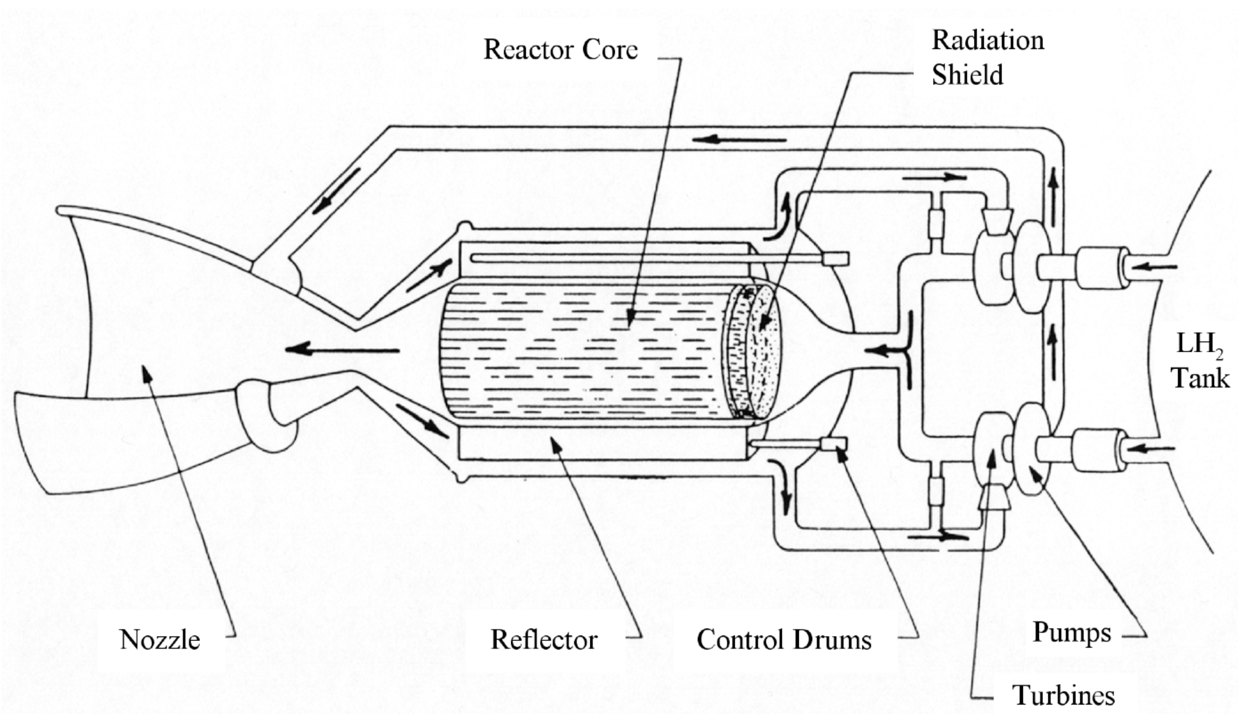

Fig. 1. Schematic of Expander Cycle, Dual LH_2 Turbopump Nuclear Thermal Rocket Engine.

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.

A NERVA-derived engine uses a "graphite matrix" material fuel element (FE) containing the U-235 fuel in the form of uranium-carbide (UC_2) microspheres or as a dispersion of uranium and zirconium carbide (UC-ZrC) within the matrix material, referred to as "composite" fuel. The typical NERVA FE has a hexagonal cross section (~0.75" across the flats), is 52" long and produces ~1 megawatt of thermal power. Each FE has 19 axial coolant channels, which along with the element's exterior surfaces, are CVD coated with ZrC to reduce hydrogen erosion of the graphite. Composite fuel, with its higher exhaust temperature range (T_{ex}~2550-2800 K), was the preferred fuel form at the end of Rover/NERVA program, and is used here. The performance characteristics for the 25 klb_f NTR baselined in this study include: T_{ex}~2650 – 2700 K, p_{ch} ~1000 psi, ε ~300:1, and I_{sp} ~900 - 910 s. At I_{sp} ~900 s, the LH_2 flow rate is ~12.6 kg/s. The thrust-to-weight ratio for a dual TPA, expander cycle 25 klb_f engine 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.

III. MISSION AND TRANSPORTATION SYSTEM GROUND RULES AND ASSUMPTIONS

NTP-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. 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 (TMI, MOC and TEI), additional smaller ΔV maneuvers are needed for rendezvous and docking (R&D) of MTV components during the LEO assembly phase, for spacecraft attitude control during interplanetary coast, and for Mars orbital operations and maintenance.

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 Mars ascent vehicle (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 nuclear surface power system (NSPS) 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 remained fixed at ~51.3 t during Phases I and II. 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 ~43.9 t.

Table II lists the key transportation system ground rules and assumptions used in this study. The NTP 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 has a I_{sp} of ~910 s, although 900 s was used in the majority of Phase I and II analysis for conservatism. 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.

The LH_2 propellant used in the NTP 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 LH_2 tanks have a combination foam / multilayer insulation (MLI) system for passive thermal protection. An active zero-boiloff (ZBO) cryocooler

TABLE I. NTP-Specific Mission Ground Rules and Assumptions

Mission Profile	• Split mission; cargo pre-deployed to Mars before crew leaves Earth • Cargo missions use “1-way” minimum energy trajectories • Round trip crewed missions use “fast conjunction” trajectories
Earth and Mars Parking Orbits	• Earth: 407 km circular • Mars: 250 km x 33,793 km
Cargo Mission ΔV Budget: Largest total ΔV 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, ΔV_{TMI} ~3.662 km/s, arrival V_{inf} ~3.480 km/s, ΔV_{MOC} ~1.341 km/s • AC at Mars: Earth Departure C_3 ~14.849 km^2/s^2, ΔV_{TMI} ~3.839 km/s • NOTE: Gravity losses added to above Ideal ΔVs (value of g-loss depends on C_3, vehicle T/W, I_{sp})
Crewed Mission ΔV 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, ΔV_{TMI} ~3.992 km/s, arrival V_{inf} ~4.176 km/s, ΔV_{MOC} ~1.771 km/s • Mars Departure C_3 ~14.80 km^2/s^2, ΔV_{TEI} ~1.562 km/s • NOTE: Gravity losses added to above Ideal ΔVs
Additional ΔV Requirements	• LEO R&D between orbital elements: ~100 m/s • Coast attitude control and mid-course correction: ~15 m/s and ~50 m/s, respectively • Mars orbit maintenance: ~100 m/s
Surface Power System (SPS) Options and Use of ISRU	• Phase I: SPS unspecified, no ISRU, MAV carries its own propellant • Phase II: Nuclear and solar SPS options compared along with benefits of ISRU
Cargo Mission Payload Masses:	• Propulsive MOC: 110.9 t (Phase I) / 99.5 t - 122 t (Phase II) • Aerocapture (AC): 138.2 t (Phase I) / 103 t - 133 t (Phase II)
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	• Transit Habitat: 27.5 t • Crew (6): 0.6 t • 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) • CEV / SM: 10.0 t • Returned Mars Samples: 0.5 t
Mission Abort Strategy	• Outbound: Abort to Mars Surface • At Mars: Abort to orbiting crew MTV which carries contingency consumables

system is used on all tanks (except drop tanks) to minimize/eliminate LH_2 boiloff during the long duration Mars missions. The heat load into the propellant tanks is largest in LEO during the vehicle assembly phase. 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, Ares-V LEO lift requirements, and shroud cylindrical payload envelope dimensions used during the Phase I and II analysis cycles. A 30% DWC is used on the NTP 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 requirement was determined primarily by the mass of the various cargo payload elements used in the study.

TABLE II. NTP-Specific Transportation System Ground Rules and Assumptions

NTR System Characteristics	• Engine / Fuel Type: NERVA-derived / UC-ZrC in graphite "Composite" fuel • Propellant: LH_2 • Thrust Level: 25 klb_f/ engine (3 engine cluster on "Core" Propulsion Stage) • Exhaust Temp: T_{ex} ~2650 - 2800 K • Chamber Pressure: p_{ch} ~1000 psi • Nozzle Area Ratio: ε~300:1 to 500:1 • 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 • Performance reserve: 1% on ΔV • 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 • Propellant: NTO / MMH • Nominal I_{sp}: 320 seconds
LH_2 Cryogenic Tanks and Passive Thermal Protection System (TPS)	• Material: Aluminum-Lithium (Al/Li) • Tank ID: ~8.2 m (Phase I), ~8.9 m (Phase II) • Geometry: cylindrical with root 2/2 ellipsoidal domes • Insulation: 1" SOFI (~0.78 kg/m^2) + 60 layers of MLI (~0.90 kg/m^2)
Active Cryo-Fluid Management (CFM) System	• Zero boil-off (ZBO) cryocooler system powered by PVAs • ZBO mass and power requirements for NTR core stage are 742 kg and ~6.75 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 • "Keep-alive" power supplied by battery / fuel cell combination
Dry Weight Contingency Factors	• 30% on NTR system and composite structures • 15% on established propulsion, propellant tanks, spacecraft systems
Max. Ares-V LEO Lift Requirements (Determined by the cargo payload elements)	• Phase I: 110.9 t (PC) - 138.2 t (AC) • Phase II: 103 t - 133 t (AC), 122 t (PC)
Launch Shroud Cylindrical Payload Envelope	• 8.4 m ID x 30 m L (Phase I), 9.1 m ID x 26.6 m L (Phase II)

IV. NTP SYSTEM MISSION DESCRIPTION

The current Mars Design Reference Architecture (DRA 5.0) is again centered around a long surface stay, split cargo / piloted mission approach (Fig. 2). 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. The cargo flights utilize 1-way minimum energy, long transit time trajectories. Each cargo vehicle is assembled in LEO via autonomous R&D with vehicle and payload components delivered on Ares-V cargo heavy lift launch vehicles. Each cargo vehicle uses a common core propulsion stage with 3 - 25 klb_f NTR engines operating with a I_{sp} of ~900 s. Assembling both cargo vehicles requires ~5–6 Ares-V launches depending on the assumed payload mass and whether PC or AC option is used at Mars. Figure 2 illustrates the 5-launch AC option. The first two Ares-V launches deliver the NTR core propulsion stages, while the third launch delivers two short "in-line" LH_2 tanks packaged end-to-end. Because of the significant increase in the current aeroshell mass (~40-45 t versus ~10 t used to the earlier DRM studies), additional propellant is required for the trans-Mars injection maneuver. The in-line tanks supply extra propellant to augment that contained in the core propulsion stages. Once in orbit, the in-line tanks separate and dock with the propulsion stages which function as the active element in this R&D maneuver. The cargo transfer vehicles then R&D with the two AC'ed payload elements

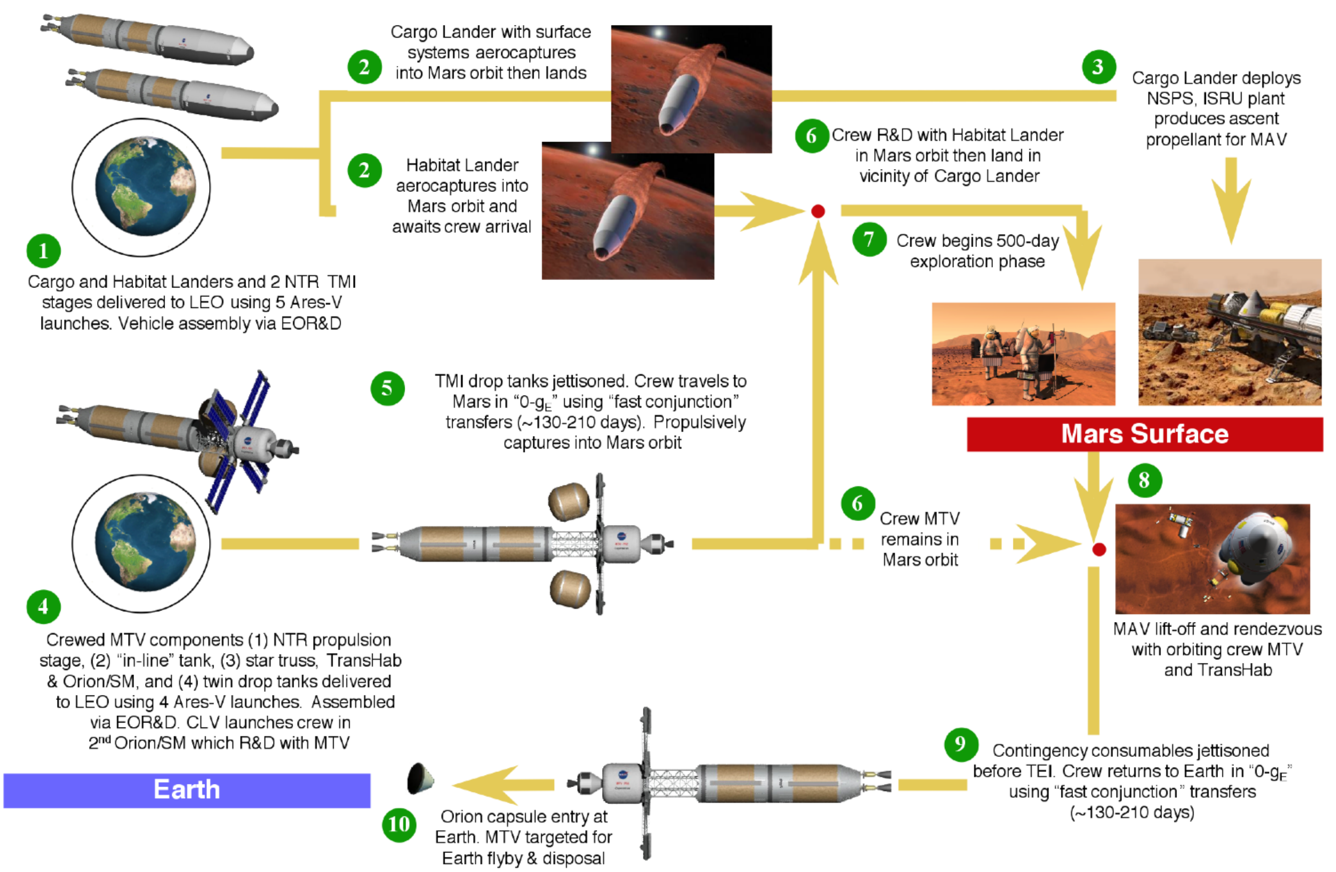

Fig. 2. DRA 5.0 Long-Stay Mars Mission Overview: Phase II NTR Option.

delivered on the last two Ares-V launches. For the AC option, the large aeroshell (configured as either a triconic or ellipsled geometry) has multiple functions that include a payload shroud during launch, and an aerobrake and thermal protection system during AC into Mars orbit and subsequent EDL on Mars.

Following the TMI maneuver, the NTR transfer vehicle remains with the payload using its onboard RCS to provide mid-course correction and attitude control during the coast out to Mars. The core propulsion stage can also use its small PVA to supply kilowatts of electrical power to the payload up to the point of vehicle–payload separation near Mars. The AC'ed habitat lander must carry its own multi-kW$_e$, deployable/retractable PVA for use in Mars orbit while awaiting the arrival of the crew, and possibly later, for use on the Mars surface.

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 (~26 months later). The "all propulsive" crewed MTV uses the same common NTR propulsion stage but includes additional external radiation shielding on each engine for crew protection during engine operation. Four 12.5 kW$_e$ / 125 m^2 rectangular PVAs provide the crewed MTV with ~50 kW$_e$ of electrical power for crew life-support (~30 kW$_e$), ZBO cryocoolers (~15 kW$_e$) and high data-rate communications (~5 kW$_e$) with Earth. Four Ares-V flights are required to deliver the main MTV components which are launched in the following preferred order: (1) a 4-sided "star truss" with deployable PVAs, TransHab module containing consumables for the 6 crew, and a long-lived Orion/SM for vehicle-to-vehicle transfer and "end of mission" Earth entry; (2) an in-line LH_2 propellant tank with ZBO system; (3) the NTR propulsion stage, also with a ZBO system; and (4) twin LH_2 drop tanks which are attached to the integrated star truss / propellant feed line assembly and launched last to reduce LEO boiloff. When assembly is complete, the Mars crew is launched on the CLV and the Orion/SM is used for R&D with the crewed MTV.

Following the TMI maneuver, the two drained drop tanks are 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 stage and the star truss forward adaptor ring. After propulsively capturing into Mars orbit, the crewed MTV rendezvous 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. At the end of the Mars exploration phase, 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. After checkout and verification of all MTV systems, the crew then jettisons the contingency consumables, performs the TEI burn and begins 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.

V. MTV DESIGN FEATURES / CHARACTERISTICS

Phase I Vehicle Concepts: A variety of MTV designs were developed during the recent Phase I and II analysis periods. Figure 3 shows a sampling of cargo and crewed vehicle options evaluated during Phase I. Higher ΔV "short stay" missions require larger amounts of propellant resulting in increased vehicle size and mass. For the difficult 2039 mission opportunity (547 day round trip time with "30-day" stay), the crewed MTV initial mass in low Earth orbit is ~501 t and requires 7 Ares-V launches, each with a lift capability of ~109 t and cylindrical payload volume of ~8.4 m D x 30 m L. The NTR core propulsion stage, in-line tank, star truss and crewed payload, and 4 large drop tanks each use a separate launch but only the core propulsion stage and in-line tank are near the lift and payload length limits. For the "generic" long surface stay mission (~180 day transits to and from Mars with ~540 days at Mars), the total mission ΔV is reduced by more than 3 km/s thereby lowering the IMLEO of the crewed MTV to ~315 t and the number of Ares-V launches to 4. The propulsion stage, in-line tank, star truss and crewed payload, and twin drop tanks (packaged end-to-end inside the payload shroud) each use a separate Ares-V launch. The truss and crewed payload launch is only at 55% of capacity.

The PC and AC cargo MTV concepts have comparable IMLEO values (~319 t and 311 t, respectively). Both options utilize EOR&D for assembly and require 3 Ares-V launches. The PC cargo vehicle employs a "saddle truss" (with attached inside drop tank) that connects the NTR propulsion stage to the payload (~111 t). The "saddle truss" configuration allows the drop tank to be easily jettisoned after the TMI maneuver reducing vehicle mass and the propellant requirements for the MOC burn. Although the cargo payload mass is larger (~138 t) for the AC option (because of increased aeroshell structure and TPS mass), the cargo vehicle is only used for the TMI maneuver. To augment the propellant capacity of the core propulsion stage, an "in-line" propellant tank is added to the vehicle configuration.

Phase II Vehicle Concepts: During the Phase II analysis cycle, AC was selected over PC for the cargo mission. A common 10 m outer diameter (D) shroud/aeroshell used for launch, AC and EDL was also analyzed, and a range of surface payload masses were established that reflected different surface exploration strategies (e.g., the "commuter" option), power systems (nuclear or solar), as well as, the impact of ISRU. Additional analysis and refinements of the crewed mission payload was postponed until a later Phase III effort.

The Phase II cargo and crewed MTV concepts are shown in Fig. 4. Five Ares-V flights are required for LEO assembly of the two cargo vehicles. Each vehicle has an IMLEO of ~246.2 t and an overall length (L) of ~72.6 m which includes the 30 m long AC'ed payload. The total payload mass (aeroshell, propulsive lander and surface payload) is ~103 t and is consistent with a surface strategy using nuclear power and ISRU, similar to that used in DRM 4.0. The NTR propulsion stage has an overall L of ~28.8 m (~26.6 m with retracted nozzles for launch) and a launch mass of ~96.6 t. The stage LH_2 tank has an inner diameter (ID) and L of ~8.9 m and ~16.3 m, respectively, and a propellant capacity of ~59.4 t. The in-line tank (1 of 2 delivered on the third Ares-V launch) has a launch mass of 46.6 t and overall L of ~15.5 m including the forward and rear adaptor sections. The 8.9 m ID tank has an ~10.23 m L and holds an additional ~34.1 t of LH_2. The NTR cargo vehicle also carries ~4.5 t of RCS propellant for LEO assembly operations, coast attitude control, MCC and Mars orbit maintenance. Approximately 91 t of LH_2 is used during the TMI maneuver (including the "post-burn" cooldown propellant). The corresponding engine burn time was ~39 minutes, well within the 62 minute single burn duration demonstrated by the NRX-A6 engine during the NERVA program.

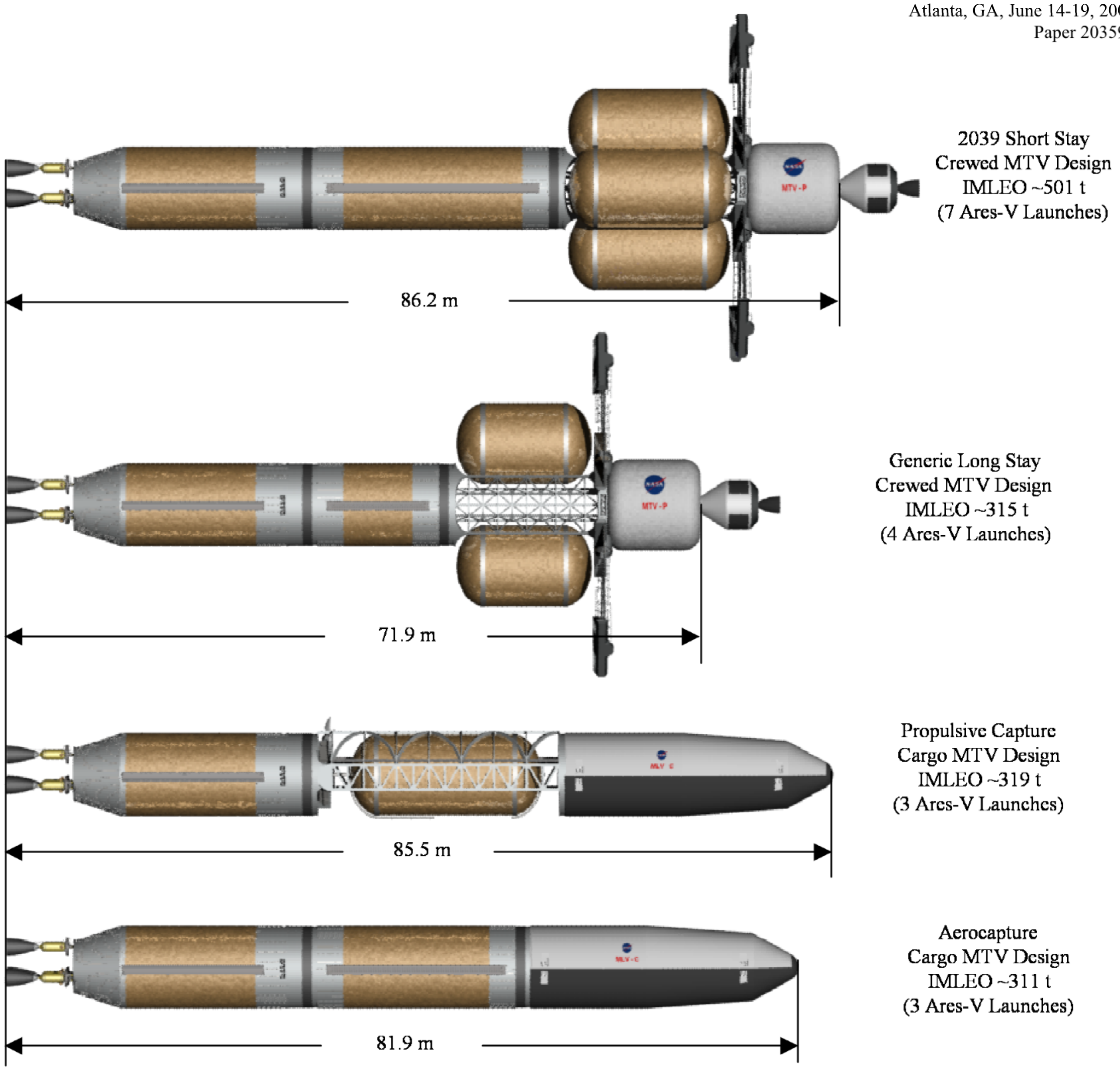

Fig. 3. Phase I NTP Crewed and Cargo Mars Transfer Vehicle (MTV) Design Concepts.

The crewed MTV requires four Ares-V flights to deliver its key components. It has an IMLEO of ~333 t and an overall vehicle length is ~67.2 m as compared to ~315 t and ~71.9 m for the equivalent Phase I configuration. In the Phase II analysis, a larger D (~9.1 m) but shorter L (~26.6 m) cylindrical payload enveloped was used. The use of shorter (~10.23 m) drop tanks on the crewed MTV (to achieve commonality with the cargo vehicle in-line tank) required a longer (~12 m) in-line tank increasing the vehicle dry mass and resulting in the larger IMLEO value. The core NTR propulsion stage has a larger launch mass (~106.3 t) than that used on the cargo vehicle due to the addition of external radiation shield on the engines. The LH_2 tank size and propellant capacity was approximately the same however. The in-line tank launch mass was ~68.1 t, which included ~50.9 t of LH_2 propellant. The 4-sided star truss and crewed payload had a combined mass of ~58.9 t. Lastly, the twin drop tanks had a combined launch mass of ~99.7. The total RCS propellant loading (~8 t) was split between the core stage and truss forward cylindrical adaptor ring. For the round trip crewed mission, the total usable LH_2 propellant loading was ~180.2 t and the corresponding total mission engine burn duration was ~80 minutes (~55 minutes for TMI, ~15 minutes for MOC, and ~9.8 minutes for TEI), well within the ~2 hour accumulated engine burn time demonstrated by the NERVA eXperimental Engine, the NRX-XE.

Looking back at the Phase I and II crewed vehicle assumptions, they were somewhat ill-defined. They did not address how nearly 8 t of contingency consumable would be jettisoned from the crewed MTV prior to TEI, or how and where a second Orion/SM or the MAV would dock to the TransHab module with an Orion/SM-type vehicle (part of the assumed crewed payload) already attached to the TransHab's front docking port. Figure 4 shows an "in-line" crewed vehicle configuration that addresses these issues. Like the "twin drop tank" option, it is also a "4-Launch" configuration that uses the following elements: (1) the NTR propulsion stage; (2) a longer in-line propellant tank (used for parts of the TMI and MOC maneuvers); (3) a saddle truss with single large drop tank (used for TMI only); and (4) a "revised" crew payload. The revised payload manifest includes the addition of a short saddle truss with a "T-shaped" docking module (DM) attached to the saddle truss forward adaptor ring. The new DM provides access to the TransHab to the right and the jettisonable contingency consumables canister mounted at the left. In the middle of the DM is a third hatch that provides docking access for a second Orion/SM or the MAV. Following the crew's return from Mars and MAV separation, the DM and attached contingency consumables canister are both jettisoned to reduce vehicle mass prior to TEI (Fig. 5).

Including the short saddle truss (~4.7 t), DM (~1.8 t) and consumables canister (~1.9 t) increases the total crewed payload mass by ~8.4 t; from ~51.3 t to ~59.7 t. With the added payload, the crewed vehicle IMLEO increases by ~23.5 t; from ~333 t to ~356.5 t. The launch

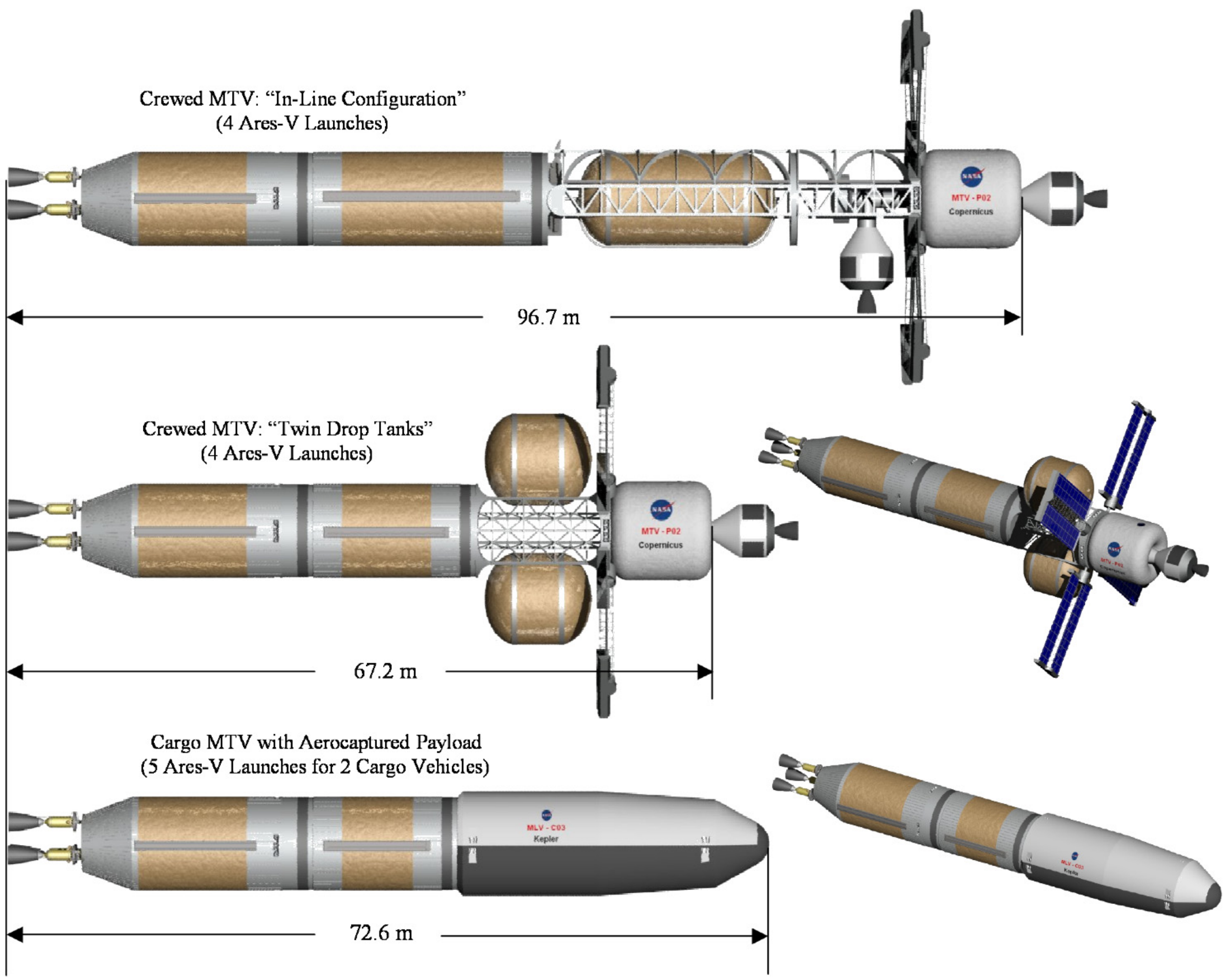

Fig. 4. Phase II NTP Crewed and Cargo MTV Design Concepts.

mass of the individual vehicle elements is as follows: (1) NTR propulsion stage ~106.2 t; (2) in-line tank ~94.6 t; (3) saddle truss and drop tank ~96 t; and (4) short saddle truss, DM and remaining payload ~59.7 t. With the additional payload mass, the total usable LH_2 propellant loading for the crewed mission increases to ~191.7 t and the total mission burn time for the engines to ~84.5 minutes (~57.8 minutes for TMI, ~16 minutes for MOC, and ~10.7 minutes for TEI).

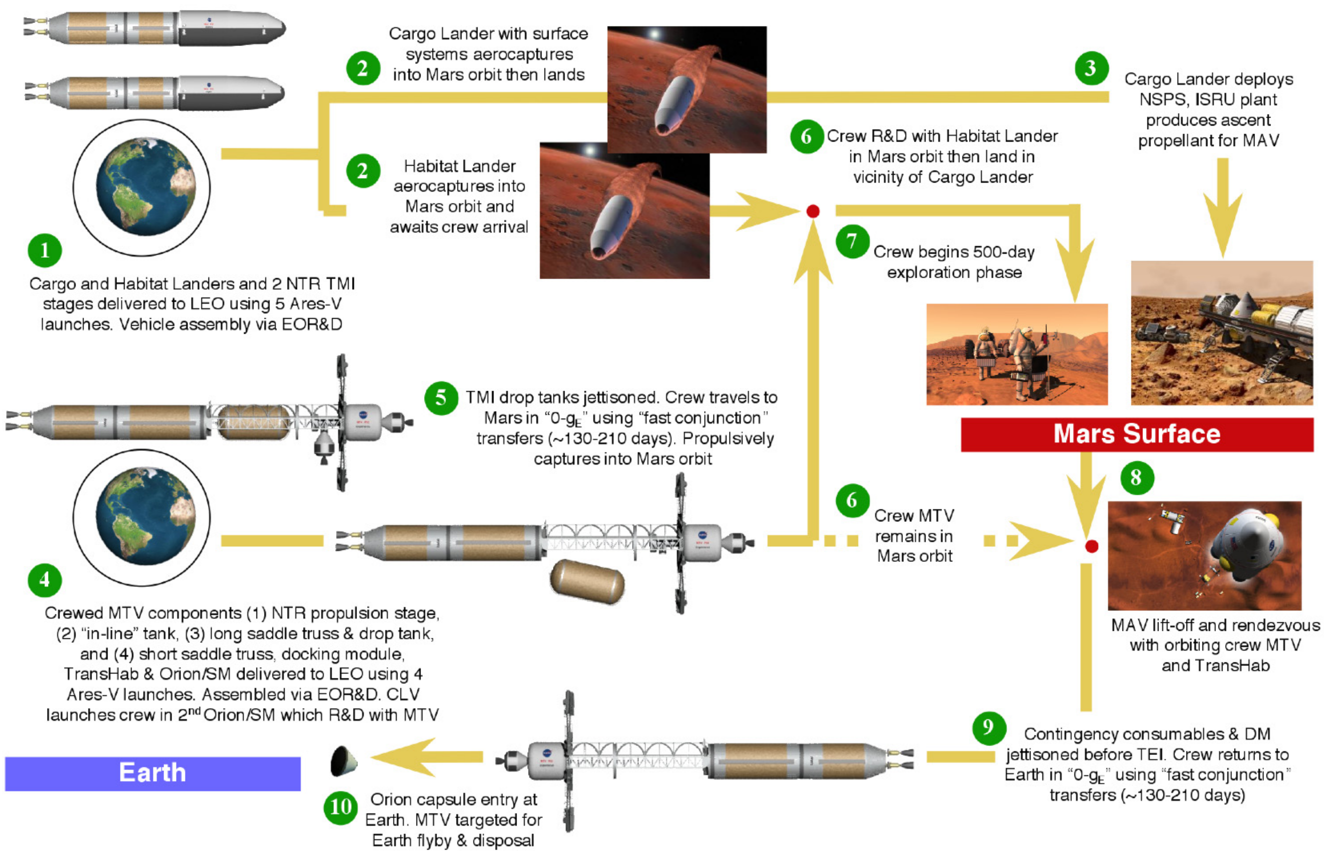

Fig. 5. DRA 5.0 Long-Stay Mars Mission Overview: "In-Line" NTP Crewed MTV Configuration.

VI. CONCLUSIONS AND RECOMMENDATIONS

Phase I and II analysis efforts to date show that there are many performance, system, mission and operational benefits to using NTP. Its high thrust and high I_{sp} (~2x chemical) means short burn durations, reduced propellant mass, and lower total IMLEO (~403 t less than that of the chemical/aerobrake system) which translates into ~3-4 fewer Ares-V launches. At launch, NTR engines contain negligible amounts of radioactivity thus simplifying shipping and handling, as well as, the engine, stage, payload, launch vehicle integration function at KSC. The use of multiple, smaller thrust 25 klb_f engines, each with dual LH_2 TPAs, provides a "pump-out" and "engine-out" capability that can increase crew safety and reduce mission risk. Small engine size is also expected to help reduce the time and cost to develop, ground and flight test these engines. The strong technology synergy between NTP and chemical systems (e.g., LH_2 TPAs, radiation-cooled nozzle extensions, and large Al/Li propellant tanks) should provide further cost savings.

From a mission and operations perspective, the NTP-based space transportation system has fewer vehicle elements and simpler space operations. No complex orbital assembly is required as with chemical propulsion, just Earth orbit R&D of several vehicle elements – two for each cargo vehicle and three for the crewed MTV. A higher performance NTP-based space transportation system is also more tolerant of 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, the use of NTP 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 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.

Recommendations for future work include the need to select and mature the designs for the different surface systems, their packaging on the Mars lander, plus the lander's configuration design (vertical or horizontal) and volume to help define payload mass and volume sizing requirements for a Mars-relevant Ares-V launch vehicle. Higher fidelity payload masses are also required to improve performance and sizing estimates for the NTP transportation system. Lastly, the large number of Ares-V flights has been identified as a mission risk area. Increasing the LH_2 tank D to 10 m, using larger payload shrouds (~12 m D x ~43 m L), and increasing the Ares-V lift capability to LEO (~407 km circular) to ~140 t can help reduce the launch count and enable a "7-Launch" NTR Mars mission architecture.

NOMENCLATURE

Al /Li	=	Aluminum/Lithium
Ares-V	=	Cargo Heavy Lift Vehicle
CLV	=	Crew Launch Vehicle
ε	=	Nozzle Area Ratio
g_E	=	Earth gravity; 9.80665 m/s^2
0-g_E	=	Zero-gravity
ISRU	=	In-Situ Resource Utilization
LEO	=	Low Earth Orbit
MAV	=	Mars Ascent Vehicle
MCC	=	Mid-Course Correction
MOC	=	Mars Orbit Capture
Orion	=	Crew Capsule
p_{ch}	=	Engine Chamber Pressure
RCS	=	Reaction Control System
SM	=	Service Module
SOFI	=	Spray On Foam Insulation
t	=	metric ton; 1000 kg
TEI	=	Trans-Earth Injection
TMI	=	Trans-Mars Injection
TPS	=	Thermal Protection System
ΔV	=	Delta Velocity Increment

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