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NUCLEAR THERMAL ROCKET (NTR) PROPULSION: A PROVEN GAME-CHANGING TECHNOLOGY FOR FUTURE HUMAN EXPLORATION MISSIONS

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The NTR represents the next "evolutionary step" in high performance rocket propulsion. It generates high thrust and has a specific impulse (I_{sp}) of ~900 seconds (s) or more – twice that of today's best chemical rockets. The technology is also proven. During the previous Rover and NERVA (Nuclear Engine for Rocket Vehicle Applications) nuclear rocket programs, 20 rocket reactors were designed, built and ground tested. These tests demonstrated: (1) a wide range of thrust; (2) high temperature carbide-based nuclear fuel; (3) sustained engine operation; (4) accumulated lifetime; and (5) restart capability – all the requirements needed for a human mission to Mars. Ceramic metal "cermet" fuel was also pursued, as a backup option. The NTR also has significant "growth and evolution" potential. Configured as a "bimodal" system, it can generate electrical power for the spacecraft. Adding an oxygen "afterburner" nozzle introduces a variable thrust and I_{sp} capability and allows bipropellant operation. In NASA's recent Mars Design Reference Architecture (DRA) 5.0 study, the NTR was selected as the preferred propulsion option because of its proven technology, higher performance, lower launch mass, simple assembly and mission operations. In contrast to other advanced propulsion options, NTP requires no large technology scale-ups. In fact, the smallest engine tested during the Rover program – the 25,000 lb_f (25 klb_f) "Pewee" engine is sufficient for human Mars missions when used in a clustered engine arrangement. The "Copernicus" crewed spacecraft design developed in DRA 5.0 has significant capability and a human exploration strategy is outlined here that uses Copernicus and its key components for precursor near Earth asteroid (NEA) and Mars orbital missions prior to a Mars landing mission. Initially, the basic Copernicus vehicle can enable reusable "1-year" round trip human missions to candidate NEAs like 1991 JW and Apophis in the late 2020's to check out vehicle systems. Afterwards, the Copernicus spacecraft and its 2 key components, now configured as an Earth Return Vehicle / propellant tanker, would be used for a short round trip (~18 – 20 months) / short orbital stay (60 days) Mars / Phobos survey mission in 2033 using a split mission approach. The paper also discusses NASA's current Foundational Technology Development activities and its "pre-decisional" plans for future system-level Technology Demonstrations that include ground testing a small (~7.5 klb_f) scalable NTR "before the decade is out" with a flight test shortly thereafter.

I. INTRODUCTION

The United States' National Space Policy [1] specifies that NASA shall: *By 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth.* In NASA's recent Mars DRA 5.0 study [2], both short and long surface stay landing missions were considered. The "fast conjunction" long stay option was selected for the design reference because it provided adequate time at Mars (~540 days) for the crew to explore the planet's rich geological diversity while also reducing the crew "1-way" transit times to and from Mars to ~6 months, or ~1 year in deep space. Long surface stay missions also have lower energy requirements than the short round trip time, short surface stay "opposition-class" missions, and therefore require less propellant and less mass delivered to low Earth orbit (LEO).

The NTR was again selected as the propulsion system of choice in DRA 5.0 because of its high thrust (10's of klb_f) and high specific impulse (I_{sp} ~900 – 950 s), its increased tolerance to payload mass growth and architecture changes, and its lower initial mass in low Earth orbit (IMLEO) which is important for reducing the heavy lift vehicle (HLV) launch count, overall mission cost and risk. With a 100% higher I_{sp} than today's best chemical rockets, the use of NTP in DRA 5.0 reduced the required launch mass by over 400 metric tons (1 t = 1000 kg) – the equivalent mass of the International Space Station. For the higher energy, short round trip time opposition-class missions examined, the mass savings using NTP were even greater – over 530 t compared to chemical propulsion. Most importantly, the NTR is proven technology and the only advanced propulsion option to be successfully ground tested at the performance levels required for a human mission to

Mars. No large technology or performance scale-ups are needed as with other propulsion options. In fact, the smallest and highest performing engine tested during the Rover / NERVA programs [3] – the 25 klb$_f$ "Pewee" engine is sufficient for a human mission to Mars when used in a clustered engine arrangement.

DRA 5.0 featured a "split mission" approach using separate cargo and crewed Mars transfer vehicles (MTVs). Both vehicle types utilized a common "core" propulsion stage each with three 25 klb$_f$ "composite fuel" Pewee-class engines. Two cargo vehicles were used to pre-deploy surface and orbital assets to Mars ahead of the crew who arrived during the next mission opportunity (~26 months later). The crewed MTV "Copernicus" (Fig. 1) is a zero-gravity (0-g$_E$) vehicle design [4] consisting of three basic components: (1) the crewed payload element; (2) the NTR propulsion stage; and (3) an integrated "saddle truss" and liquid hydrogen (LH_2) propellant drop tank assembly that connects the payload and propulsion elements. The Copernicus spacecraft was sized to allow it to perform all of the fast-conjunction missions over the 15-year synodic cycle. It therefore has significant capability that can be utilized for near Earth asteroid (NEA) and Mars orbital missions currently under study by NASA.

Over the last several years, the study efforts of NASA's Human Architecture Team (HAT) have been following a serial approach to exploration focused on nearer-term mission objectives (Earth-Moon libration points and NEAs) and technologies (chemical and solar electric propulsion) first, before moving on to develop the technologies and systems needed for Mars. Such an approach could be short-sighted and jeopardize NASA's ability to orbit Mars by 2035 by diverting scarce resources away from more capable technologies like NTP towards nearer-term, short shelf life, less capable systems that are operationally complex to use. Furthermore, a short (~18 month) round trip / short (~60 day) orbital stay mission to Mars is best performed in the 2033-2035 timeframe when the mission ΔV budgets are near their minimum values over the 15-year synodic cycle. After that, the ΔV budgets for successive short round trip missions increase significantly with the next minimum occurring in 2045.

This paper presents analysis supporting an alternative human exploration strategy focused on developing "Mars-relevant" technologies and in-space transportation system elements initially – specifically those used on the Copernicus MTV, then validating these systems on "1-year" round trip NEA missions in the late 2020's in preparation for an orbital Mars mission in 2033. By focusing NASA resources on developing the key technologies found in Copernicus' two key elements, its propulsion stage and integrated saddle truss / drop tank assembly, and exploiting the technology synergies that exist on Copernicus, the HLV (e.g., large aluminum / lithium (Al/Li) LH_2 tanks) and existing flight-tested chemical rocket hardware (e.g., LH_2 turbpumps, regenerative- and radiation-cooled nozzles and skirt extensions), substantial savings in development time and cost savings are expected.

This paper addresses the following key areas. The operational principles and performance characteristics of the baseline 25 klb$_f$ NTR engine are presented first. Next, the technical accomplishments of Rover/NERVA programs are summarized and the growth potential of NTP is discussed. After summarizing the "7-Launch" NTR Mars Mission Strategy [4] for DRA 5.0, candidate NEA and Mars orbital missions using Copernicus and its components are presented including descriptions of the different missions, key features of the crewed asteroid survey and MTV systems and their operational characteristics. Also discussed are NASA's current Foundational Technology Development activities and its "pre-decisional" plans for future system-level Technology Demonstrations that include ground, then flight testing, a small scalable NTR over the next 10 years. The paper ends with a summary of our findings and some concluding remarks.

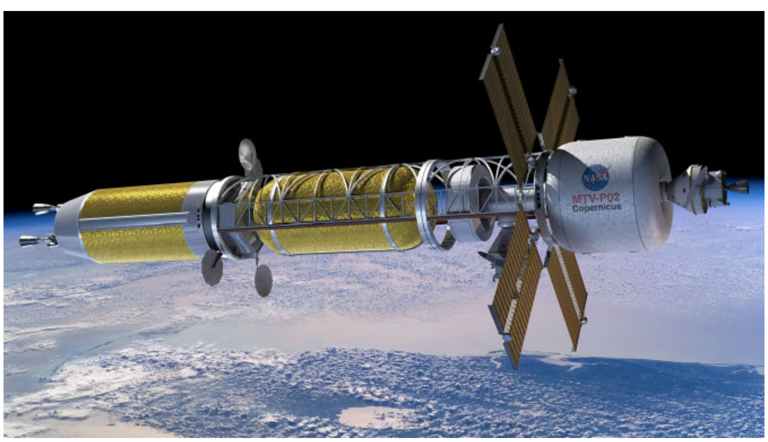

Fig. 1: Crewed NTR Mars Transfer Vehicle Allows NEA Survey and Short Orbital Stay Mars Missions.

2. NTR SYSTEM DESCRIPTION, TECHNOLOGY STATUS AND OPERATING CHARACTERISTICS

The NTR uses a compact fission reactor core containing 93% "enriched" Uranium (U)-235 fuel to generate 100's of megawatts of thermal power (MW_t) required to heat the LH_2 propellant to high exhaust temperatures for rocket thrust. In an "expander cycle" NERVA-type engine (Fig. 2), high pressure LH_2 flowing from twin turbopump assemblies (TPAs) cool 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 produced from the fission of U-235 atoms, is superheated to high exhaust temperatures (T_{ex} ~2550-3000 degrees Kelvin (K) depending on fuel type and uranium loading), then expanded out a high area ratio nozzle (ε ~300:1-500:1) 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 to prevent excessive radiation heating and material damage.

A Rover / NERVA-derived engine uses a "graphite matrix" material fuel element (FE) containing the U-235 fuel in the form of either coated particles of uranium carbide (UC_2) or as a dispersion of uranium and zirconium carbide (UC-ZrC) within the matrix material, referred to as "composite" fuel (shown in Fig. 3). The basic FE [3] has a hexagonal cross section (~0.75" across the flats), is 52" long and produces ~1 MW_t. Each FE has 19 axial coolant channels, which along with the element's exterior surfaces, are coated with ZrC using chemical vapor deposition (CVD) to reduce hydrogen erosion of the graphite. This basic shape was introduced in the KIWI-B4E and became the standard used in the 75 klb_f Phoebus-1B, 250 klb_f Phoebus-2A, 25 klb_f Pewee and the 55 klb_f NERVA NRX series of engines. These elements were bundled around and supported by cooled coaxial core support tie tubes. Six elements per tie tube were used in the higher power Phoebus and NRX reactor series. In the smaller Pewee engine, the ratio was reduced to three elements per tie tube. To provide sufficient neutron moderation and criticality in the smaller Pewee core, sleeves of zirconium hydride moderator material were added to the core support tie tubes (shown in Fig. 3).

The Rover program's 25 klb_f Pewee engine [3] was designed and built to evaluate higher temperature, longer life fuel elements with improved coatings, and in the process Pewee set several performance records. The Pewee full power test consisted of two 20-minute-long burns at the design power level of ~503 MW_t and an average fuel element exit gas temperature of ~2550 K, the highest achieved in the Rover/NERVA nuclear rocket programs. The peak fuel temperature also reached a record level of ~2750 K. Other performance records included average and peak power densities in the reactor core of ~2340 MW_t/m^3 and ~5200 MW_t/m^3, respectively. A new CVD coating of ZrC was also introduced and used in Pewee that showed performance superior to the niobium carbide (NbC) coating used in previous reactor tests.

In follow on tests in the "Nuclear Furnace" fuel element test reactor [3], higher temperature composite fuel elements with ZrC coating were evaluated. They withstood peak power densities of ~4500-5000 MW_t/m^3 and also demonstrated better corrosion resistance than the standard coated particle graphite matrix fuel element used in the previous Rover/NERVA reactor tests. Composite fuel's improved corrosion resistance is attributed to its higher coefficient of thermal expansion

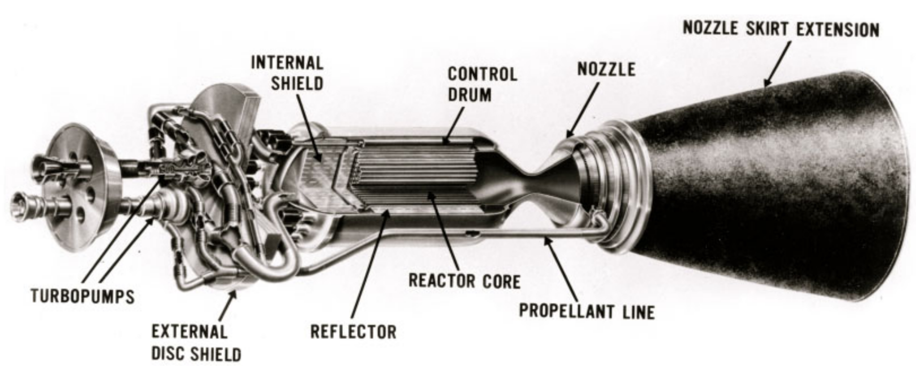

Fig. 2: Schematic of NERVA-derived "Expander Cycle" NTR Engine With Dual LH_2 Turbopumps.

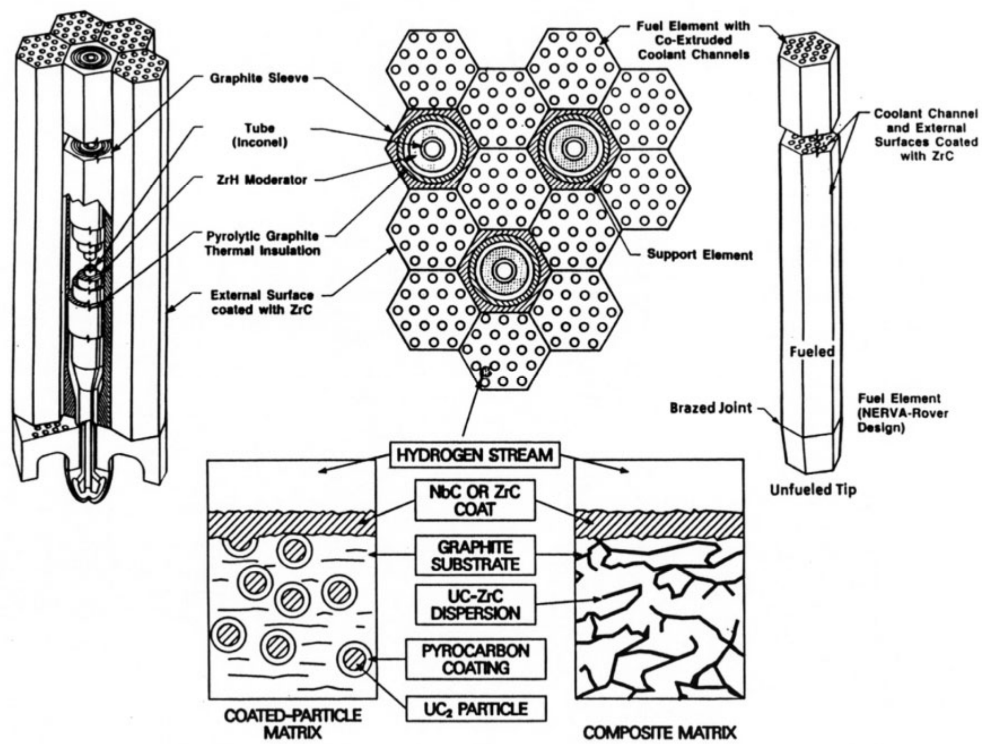

Fig. 3: Coated Particle and Composite Rover / NERVA Fuel Element and Tie Tube Bundle Arrangement.

(CTE) that more closely matches that of the protective ZrC coating, thereby helping to reduce coating cracking. Electrical-heated composite fuel elements were also tested by Westinghouse in hot hydrogen at 2700 K for ~600 minutes – ten 1-hour cycles. At the end of Rover/NERVA, composite fuel performance projections [5] were estimated at ~2-6 hours at full power for hydrogen exhaust temperatures of ~2500-2800 K and fuel loadings in the range of ~0.60 to 0.45 grams/cm^3.

The NERVA-derived engine baselined in DRA 5.0 and in this analysis is a 25 klb$_f$ Pewee-class dual TPA expander cycle engine with the following performance parameters: T_{ex} ~2790 K, chamber pressure ~1000 psia, ε ~300:1, and I_{sp}~906 s. The LH_2 flow rate is ~12.5 kg/s and the engine thrust-to-weight ratio is ~3.50. 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 Monte Carlo N-Particle (MCNP) transport modeling of the engine's reactor core [6], indicates that an I_{sp} range of ~894 s to 940 s is achievable by increasing the FE length from 0.89 m to 1.32 m and lowering the U-235 fuel loading in the core from ~0.45 to 0.25 grams/cm^3 which allows the peak fuel temperature to increase while still staying safely below the melt temperature.

The state-of-the-art for NTP can be summarized as follows: It is a proven technology! A high technology readiness level (TRL~5-6) was demonstrated during the Rover / NERVA programs (1955-1972) [3]. 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 carbide-based nuclear fuels that provided hydrogen exhaust temperatures up to 2550 K (*achieved in the 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*) – all the requirements needed for a human Mars mission.

3. NTP FUEL OPTIONS AND GROWTH POTENTIAL

The NTR has significant "growth and evolution" potential not possible with chemical propulsion. For thermal and epithermal neutron energy spectrum reactor designs, one can transition from NERVA composite fuel to higher performance tricarbide fuels or to a fast neutron spectrum reactor using "cermet" fuel. Cermet fuel was the primary backup option to the carbide-based fuels developed in Rover/NERVA. The fuel consists of uranium dioxide (UO_2) fuel embedded in a high temperature tungsten (W) metal matrix. Cermet fuel underwent extensive nuclear/non-nuclear testing in the 1960's under the GE-710 and Argonne National Laboratory (ANL) nuclear rocket programs [7, 8] but no integrated reactor/engine tests were conducted. Fuel elements were designed and fabricated that were axial flow and hexagonal in geometry. A large number of fuel samples were produced and evaluated in a variety of separate effects tests. Non-nuclear, hot hydrogen exposure tests at temperatures up to 3000 K, including temperature cycling to demonstrate restart, established the viability of cermet fuel for NTP use. Irradiation tests, conducted under both transient and steady-state conditions, further indicated the fuel was robust and had the potential for high burn-up and improved fission product retention using a W-alloy cladding similar to the matrix material.

Binary carbide fuels were produced at the end of the Rover/NERVA program and even higher temperature ternary or "tricarbide" fuel was developed in the former Soviet Union's (FSU) nuclear rocket program that began after the Rover/NERVA program started and continued up until 1986. The FSU's ternary fuel [9] consisted of a solid solution of uranium, zirconium and niobium carbide (UC-ZrC-NbC) having a maximum operating temperature of ~3200 K. The basic fuel element assembly was an axial flow design that contained a series of stacked 45 mm diameter bundles of thin (~1 mm) "twisted fuel ribbons" ~2 mm wide by ~100 mm long. The number of fuel bundles per assembly and the number of assemblies in the reactor core were determined by the desired engine thrust level and associated power output. Although full-scale integrated engine tests were not conducted, hydrogen exhaust temperatures of ~3100 K for more than 1 hour were reported in reactor tests at the Semipalatinsk facility in Kazakhstan using bundled fuel elements individually fed with high pressure H_2. Replacing NbC with higher melting point carbides like tungsten (WC), tantalum (TaC) or hafnium (HfC) could increase the maximum operating temperature beyond 3100 K allowing even higher specific impulse capability.

Engine specific impulse versus hydrogen exhaust temperature for a 1000 psia chamber pressure and nozzle area ratios from 100:1 to 500:1 are shown in Fig. 4 for the various fuel types. The anticipated temperature range for coated particle, composite, cermet, binary and ternary carbides, and advanced tricarbides are also shown. These fuels can be operated at near maximum temperature or at lower temperature levels to extend fuel lifetime or to increase the engine's operational margins.

Besides providing high thrust and high I_{sp}, the NTR also represents a "rich energy source" because it contains substantially more U-235 fuel in its reactor core than is consumed during the primary propulsion maneuvers performed in a typical human Mars mission. By reconfiguring the NTR for "bimodal" operation [9] (both thrust and power production), the BNTR can generate 10's of kilowatts of electrical power (kW_e) for crew life support, high data-rate communications, and zero-boiloff (ZBO) LH_2 propellant storage using an active refrigeration system. By adding electric thrusters, a "hybrid" bimodal nuclear thermal and electric propulsion (BNTEP) system is also possible (shown in Fig. 5).

In the "low tech" BNTR option without EP, the reactor produces 100's of MW_t that is removed using LH_2 propellant pumped through the engine's reactor core during the high thrust "propulsion phase". During the "mission coast / power generation phase," the BNTR's reactor continues to operate but in an "idle mode" at greatly reduced power levels (~125 kW_t to produce ~25 kW_e). Energy generated in the reactor fuel assemblies is removed using a secondary "closed" gas loop that carries a helium-xenon (He-Xe) gas mixture. In a NERVA-derived BNTR design, the existing regenerative-cooled core support tie tubes would carry the recirculated He-Xe coolant gas. Power from the

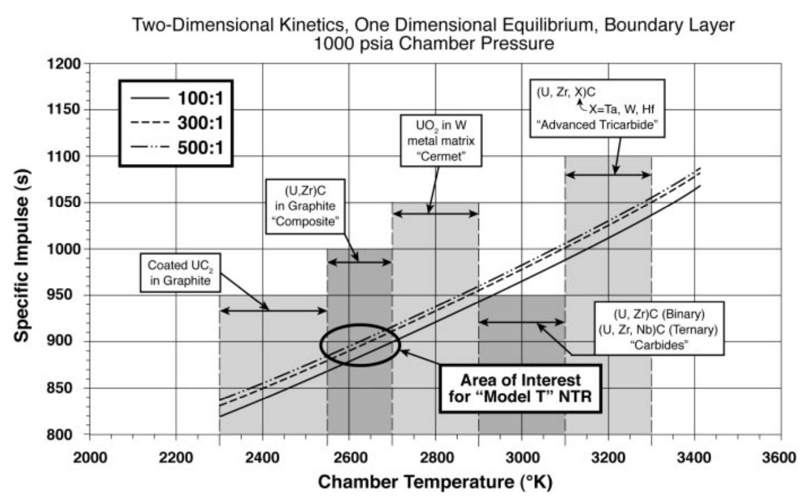

Fig 4: NTP Specific Impulse vs. Chamber Temperature for Different Fuels and Nozzle Area Ratios.

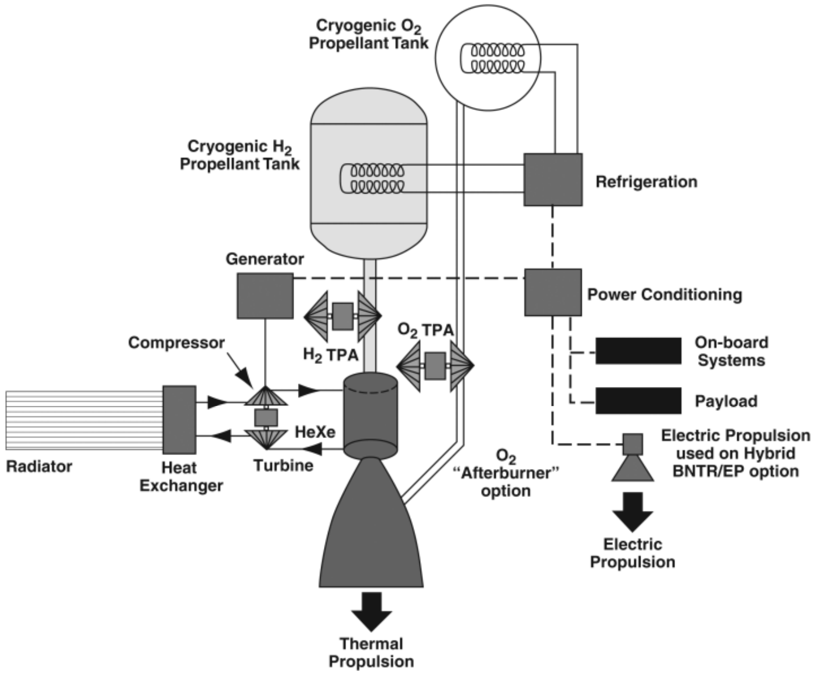

Fig 5: NTR Growth Paths: Bimodal Operation for Electricity With O_2 Afterburner for Augmented Thrust.

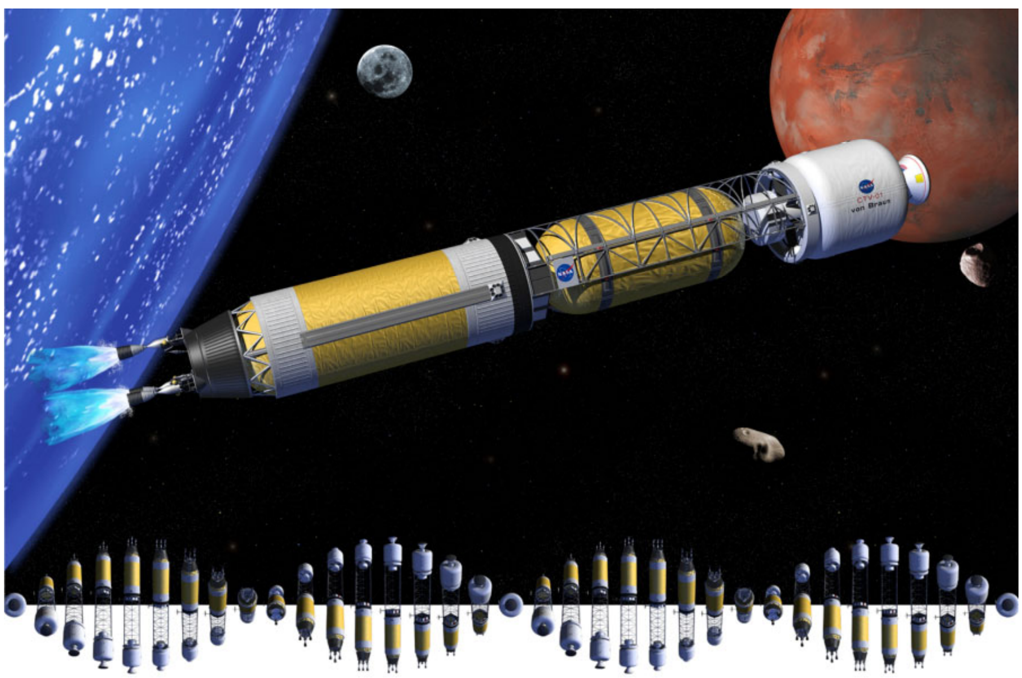

Fig. 6: Artificial Gravity "Bimodal" NTR Crewed MTV With Conical Radiator on Aft Thrust Structure.

NERVA fuel elements surrounding the tie tubes enters the tubes via conduction (see Fig. 3). In the fast reactor BNTR design called ESCORT [10], a closed loop, coaxial energy transport duct (ETD), integrated into each UO_2 – W fuel element, carries the He-Xe coolant. The heated gas is then routed to a 25 kW_e-class Brayton rotating unit using a turbine-alternator-compressor assembly that generates electricity at ~20% conversion efficiency. Waste heat is rejected to space using a conical pumped-loop radiator that is mounted to the exterior of the propulsion stage thrust structure (Fig. 6). The radiator also helps remove low level decay heat power from the engines following high thrust operation.

Because a BNTR-powered spacecraft generates its own "24/7" power, the need to deploy and operate large Sun-tracking photovoltaic arrays (PVAs) is eliminated.

The configuration of the BNTR-powered MTV (long and linear) is also compatible with artificial gravity (AG) operations [11,12]. By rotating the vehicle about its center-of-mass and perpendicular to its flight vector, (illustrated at the bottom of Fig. 6), a centrifugal force and AG environment can be established to help maintain crew fitness during the transit out to Mars and back, also while in Mars orbit in the event of a surface accident requiring an "abort-to-orbit" [12].

The performance and versatility of the basic NTR/BNTR engine can be further improved by adding an oxygen "afterburner" nozzle, storage and feed system to augment thrust and reduce the need for developing large, more costly engines. In the "LOX-augmented" NTR (LANTR) option [13, 14], oxygen is injected into the divergent section of the nozzle downstream of the sonic throat. Here it mixes with reactor-heated H_2 and undergoes supersonic combustion adding both mass and chemical energy to the rocket exhaust (see Fig. 5). By controlling the "oxygen-to-hydrogen" mixture ratio, the LANTR can operate over a wide range of thrust and I_{sp} levels while the reactor core power level remains relatively constant. Downstream nozzle injection also isolates the reactor core from oxygen interaction and possible damage.

The NTR improvements outlined above 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"*.

4. MARS DRA 5.0: "7-LAUNCH" NTR MISSION OVERVIEW

The 7-Launch NTR Mars mission strategy [4] for a human landing mission is illustrated in Fig. 7 and is centered around the long surface stay, split cargo / piloted mission approach. Two cargo flights 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 HLV 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 propulsion stages each with three 25 klb$_f$ NTR engines. The next two launches deliver the cargo and habitat lander payload elements which are enclosed within a large triconic-shaped aeroshell that functions as a payload shroud during launch, then as an aerobrake and thermal protection system during Mars aerocapture (AC) 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.

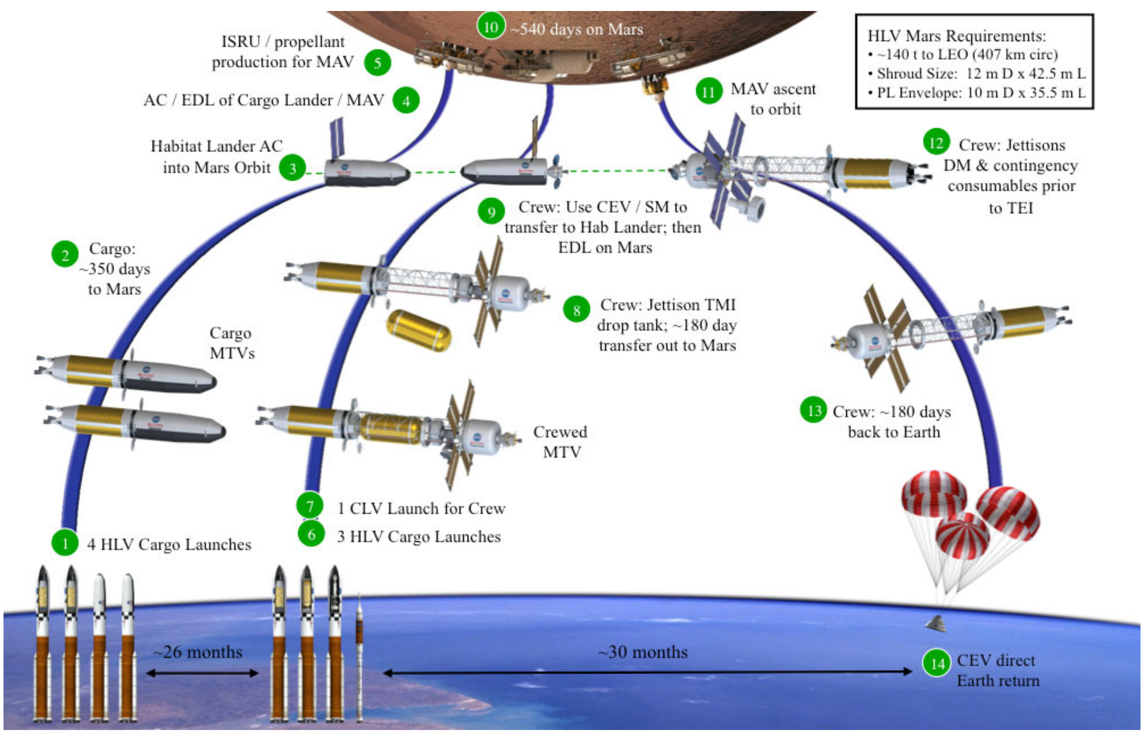

Fig 7: DRA 5.0 Long-Stay Mars Mission Overview: "7-Launch" NTR Strategy.

Once the operational functions of the orbiting habitat and surface cargo landers are verified, and the Mars Ascent Vehicle (MAV) is supplied with ISRU-produced ascent propellant, the crewed MTV is readied and departs on the next mission opportunity. The crewed MTV is a "0-g_E" vehicle design that utilizes a fast conjunction trajectory with ~6 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 HLV launches over 60 days are used to deliver the vehicle's key components which include: (1) the NTR propulsion stage; (2) integrated "saddle truss" and LH_2 drop tank assembly; and (3) supporting crewed payload. The crewed payload component includes the TransHab module with its six crew, a long-lived Crew Entry Vehicle (CEV) / Service Module (SM) for vehicle-to-vehicle transfer and "end of mission" Earth entry, a secondary T-shaped docking module (DM), contingency consumables container and connecting structure. Four 12.5 kW_e/125 m^2 rectangular PVAs provide ~50 kW_e of electrical power at Mars for crew life-support (~30 kW_e), a ZBO Brayton cryocooler system (~10 kW_e), and high data-rate communications (~10 kW_e) with Earth. When assembly is complete, the crew launch vehicle (CLV) delivers the Mars crew. The CEV/SM docks on the underside of the orbiting MTV using the secondary DM that connects the TransHab crew module and contingency consumables container (shown in Fig. 8).

After trans-Mars injection (TMI), the drained LH_2 drop tank, attached to the saddle truss, is jettisoned and the crewed MTV coasts to Mars under 0-g_E conditions with its four PVAs tracking the Sun. Attitude control and mid-course correction maneuvers are provided by a split Reaction Control System (RCS) that uses small storable bipropellant thrusters located on the rear NTR propulsion module and the short saddle truss forward adaptor ring just behind the TransHab module. After propulsive Mars orbit capture (MOC), 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 CEV/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

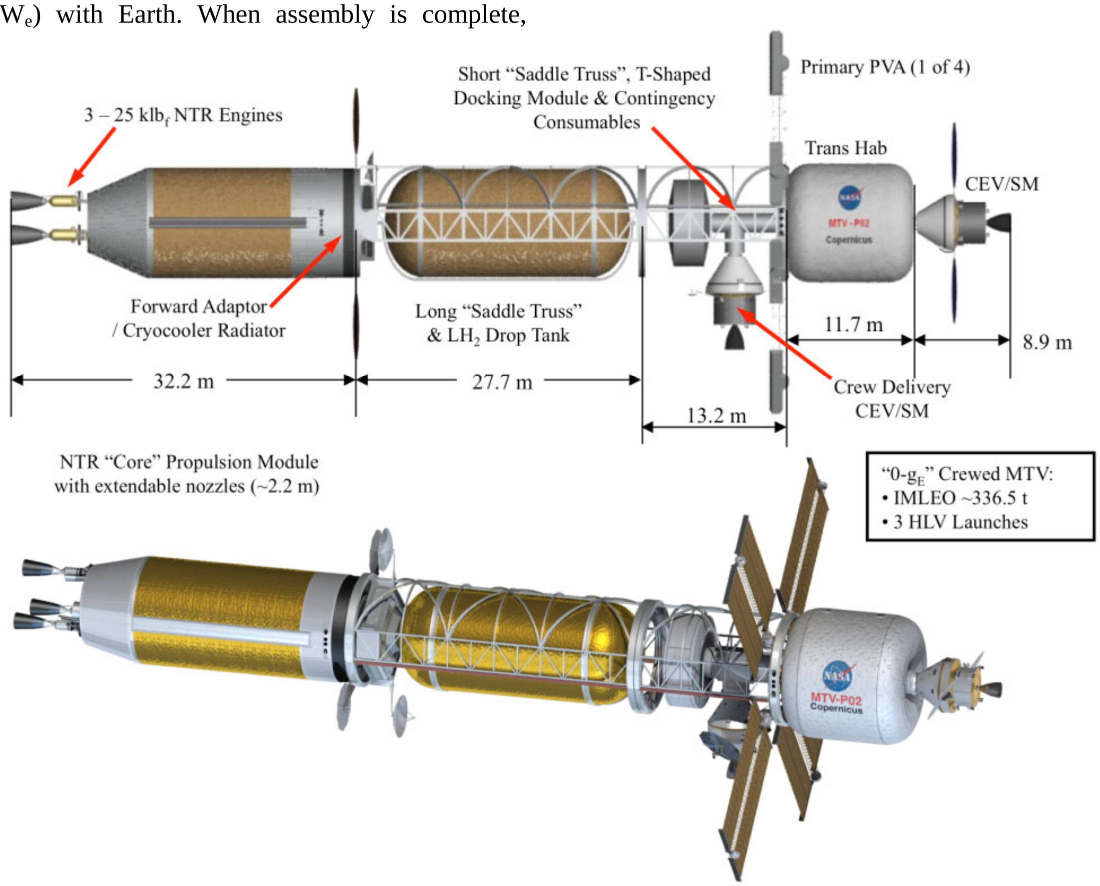

Fig. 8: Key Features and Component Lengths of the Crewed NTR Mars Transfer Vehicle.

systems, jettisons the DM and contingency consumables and performs the trans-Earth injection (TEI) burn to begin the journey back to Earth. After an ~6 month trip time, the crew enters the CEV/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.

The "Copernicus" crewed MTV has an overall length of ~93.7 m and an IMLEO of ~336.5 t consisting of: (1) the NTR propulsion stage (~138.1 t); (2) the saddle truss and LH_2 drop tank (133.4 t); and (3) the crew payload section (~65 t). The propulsion module (PM) uses a three-engine cluster of 25 klb_f NTR engines and also carries additional external radiation shield mass (~7.3 t) for crew protection. The PM's Al/Li LH_2 tank size and propellant capacity are 10 m D x 19.7 m L and ~87.2 t, respectively. It also carries avionics, RCS, auxiliary battery and PVA power, docking and Brayton-cycle ZBO refrigeration systems located in the forward cylindrical adaptor section. To remove ~78 watts of heat penetrating the 60 layer MLI system in LEO (where the highest tank heat flux occurs), the Brayton cryocooler system needs ~8.9 kW_e for its operation (~114 W_e for each W_t removed). Twin circular 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 prior to TMI.

The second major component 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 NTR stage to the forward payload section. It is ~27.7 m long and has a mass of ~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 ~22.7 m long LH_2 drop tank has a mass of ~22 t and carries ~102.4 t of propellant.

Copernicus' third and final component is its payload section that is designed for launch as a single integrated unit and determines the overall shroud size discussed above. The integrated payload element is ~33.8 m long and includes a short saddle truss with a "T-shaped" docking module (DM) and transfer tunnel connecting the TransHab module to the jettisonable contingency consumables container (shown in Fig. 8). The second DM also provides docking access for the crew delivery CEV/SM and the MAV. Following the crew's return from Mars and MAV separation, the DM and attached consumables container are both jettisoned to reduce vehicle mass prior to TEI (see Fig. 7).

The total crewed payload mass at TMI is ~65 t distributed as follows: (1) short saddle truss (~5.1 t); (2) second DM and transfer tunnel (~1.8 t); (3) contingency consumables and jettisonable container (~9.7 t); (4) TransHab with its primary PVAs (~27.5 t); (5) transit consumables (~5.3 t); (6) crew (~0.6 t); (7) long-lived CEV/SM (~10 t); and (8) forward RCS and propellant (~5 t). The crewed MTV's total RCS propellant loading is ~9.1 t with the "post-TMI" RCS propellant load split between the core stage (~5.1 t) and the short saddle truss forward cylindrical adaptor ring (~4 t).

Lastly, for DRA 5.0, the performance requirements on operating time and restart for Copernicus' 3 – 25 klb_f NTR engines are quite reasonable. For the round trip mission, there are 4 primary burns (3 restarts) that use ~178.4 t of LH_2 propellant. With 75 klb_f of total thrust and a I_{sp} of 906 s the total engine burn time for the mission is ~79.2 minutes (~55 minutes for the "2-perigee" TMI burns, ~14.5 minutes for MOC, and ~9.7 minutes for TEI), well under the ~2 hour accumulated engine burn time and 27 restarts demonstrated by the NERVA eXperimental Engine (the NRX-XE) in 1969.

5. USE OF COPERNICUS FOR NEA AND MARS / PHOBOS ORBITAL MISSIONS

Crewed Asteroid Missions to 1991 JW and Apophis

The performance capability of Copernicus has been evaluated for reusable "1-year" round trip missions to 1991 JW in 2027 and Apophis in 2028. The trajectory and the ΔV budget details for 1991 JW are shown in Fig. 9. The total mission ΔV is ~7.2 km/s and the round trip time is ~362 days which includes an outbound transit time of 112 days, a 30-day stay at 1991 JW and an inbound transit time of 220 days. For Apophis, the total mission ΔV is ~7.38 km/s (with ~3.78 km/s for Earth departure on May 8, 2028, and 1.54, 0.34 and 1.71 km/s for NEA arrival, departure, and capture back at Earth). The round trip time is ~344 days which includes an outbound transit time of 268 days, a 7-day stay at Apophis and an inbound transit time of 69 days.

Outfitted as an Asteroid Survey Vehicle (ASV), a reconnaissance mission to either of these NEAs can serve as a "check out" mission for Copernicus' key elements (its propulsion module, TransHab and life support systems, etc.) in a "deep space" environment prior to undertaking a longer duration Mars orbital mission. The Apollo 8 orbital mission of the Moon in December 1968 provided a similar check out for the Apollo Command and Service module and its primary propulsion system. A 1-year round trip mission time is also comparable to the Venus swing-by leg of a short round trip, short orbital stay Mars mission and is within the current Russian and US astronaut experience base in 0-g_E on Mir and the ISS. Finally, such a mission can also provide valuable scientific data on asteroid composition plus experience in proximity operations needed for extracting future resources or for executing

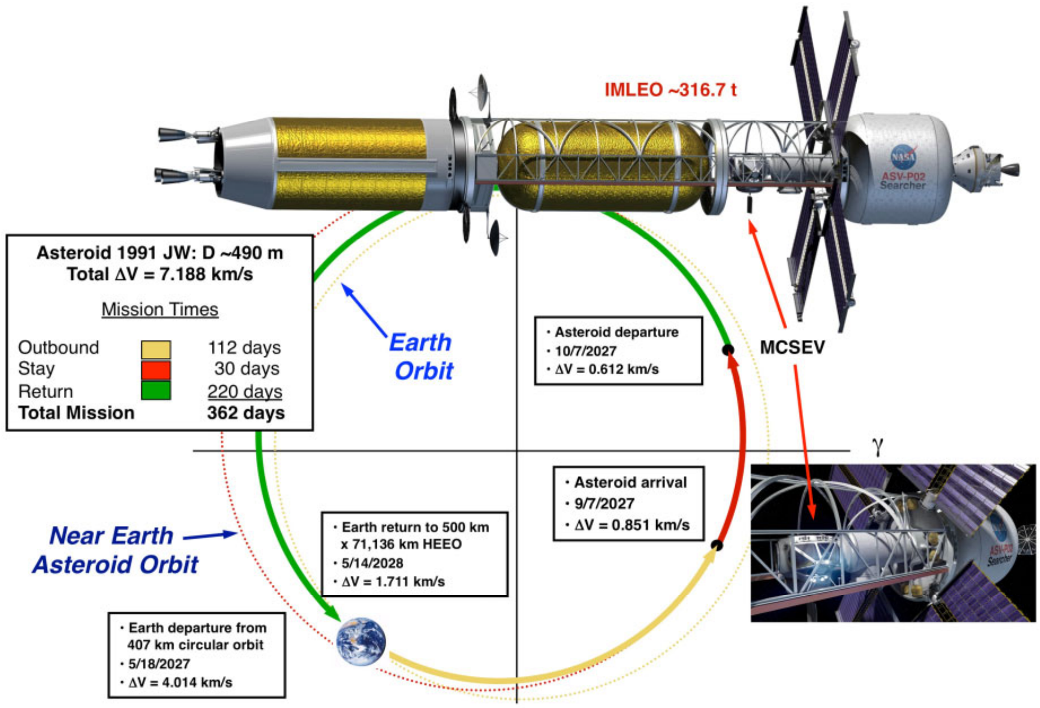

Fig. 9: Trajectory and Vehicle Details for Reusable NTR Asteroid Survey Mission to NEA 1991 JW.

potential threat mitigation techniques against a possible Earth impacting NEA.

The ASV "Searcher" (shown in Fig. 9) has an IMLEO of ~316.7 t comprising the NTR propulsion module (~137.7 t), the saddle truss and ~21.1 m long LH_2 drop tank (~116.7 t), and the crew PL section (~62.3 t). The PL element includes the TransHab (27.5 t) and 6 crew (0.6 t), their consumables (5.4 t), the CEV/SM (10 t) used for crew re-entry, the short saddle truss (~5.1 t) and forward RCS (~5.2 t), plus the DM / transfer tunnel (~1.8 t) that connects the TransHab to the multi-crew space excursion vehicle (MCSEV). The MCSEV (~6.7 t) is used for close-up NEA examination and sample gathering and is returned to Earth along with 100 kg of samples. The total LH_2 propellant load for the 1991 JW mission is ~175.2 t (96.4% of the maximum available capacity of ~181.7 t). The total burn time on the three 25 klb_f engines operating at I_{sp} ~906 s is ~73.8 minutes and there are 4 restarts, well below the 2 hours and 27 restarts demonstrated on the NRX-XE. For Apophis, the IMLEO is ~323.1 t, the LH_2 propellant loading is ~181.1 t (near maximum capacity) and the total engine burn time is ~76.2 minutes with 4 restarts.

As mentioned above, the ASV is fully reusable and captures into a 24-hour elliptical Earth parking orbit upon its return. It subsequently returns to LEO for refurbishment and resupply at a servicing node/ propellant depot and is then available for reuse (e.g., to other NEOs, the Moon or Mars).

2033 Short Round Trip / Orbital Stay Mars Mission

Using the Copernicus / Searcher spacecraft and its two key components, configured as an Earth Return Vehicle (ERV) / propellant tanker, a 545-day round trip / 60-day stay crewed mission to Mars is possible in 2033 using the "split mission" approach [15] depicted in Fig. 10. The ERV / propellant tanker is pre-deployed to Mars orbit in advance of the crew. It departs from LEO (~407 km circular) in December 2030 on a 283-day "minimum-energy" trajectory out to Mars. The ERV then propulsively captures into a 250 km x 33,793 km "24-hour" elliptical parking orbit in October 2031 where it remains until the Mars Survey Vehicle (MSV) with its 6-person crew arrives on the next opportunity ~2 years later.

The MSV departs LEO in May 2033. It uses a higher energy, opposition-class trajectory out to Mars taking ~159 days, then propulsively captures into the same parking orbit as the ERV in October 2033 [15]. In the process, the crewed MSV uses a substantial percentage of the vehicle's available propellant. To return to Earth, the MSV rendezvouses with the ERV and the forward crewed PL element is switched over to the ERV (shown in Fig. 11). No propellant transfer is required just a R&D maneuver. Before the ERV performs the trans-Earth injection (TEI) maneuver, the exterior consumables container and connecting tunnel (~6.2 t) are jettisoned from the PL element to reduce propellant consumption. The ERV utilizes an inbound Venus swing-by on the 326-day transfer back to Earth.

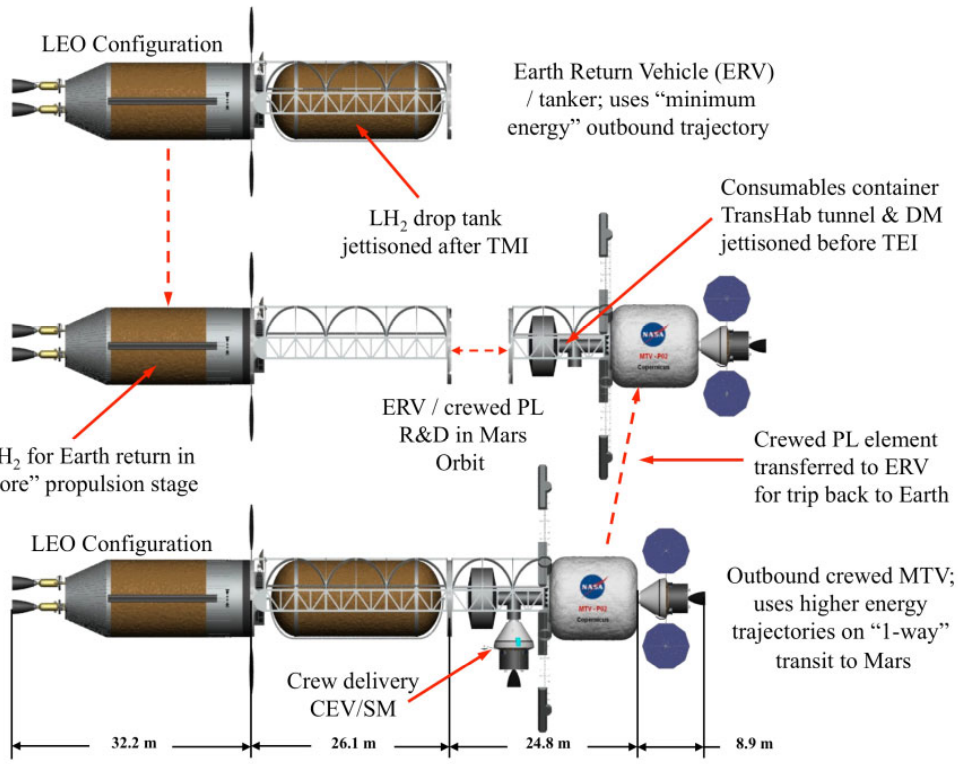

Fig. 10: Crewed MTV and Components Configured for Short Orbital Stay Mars / Phobos Missions.

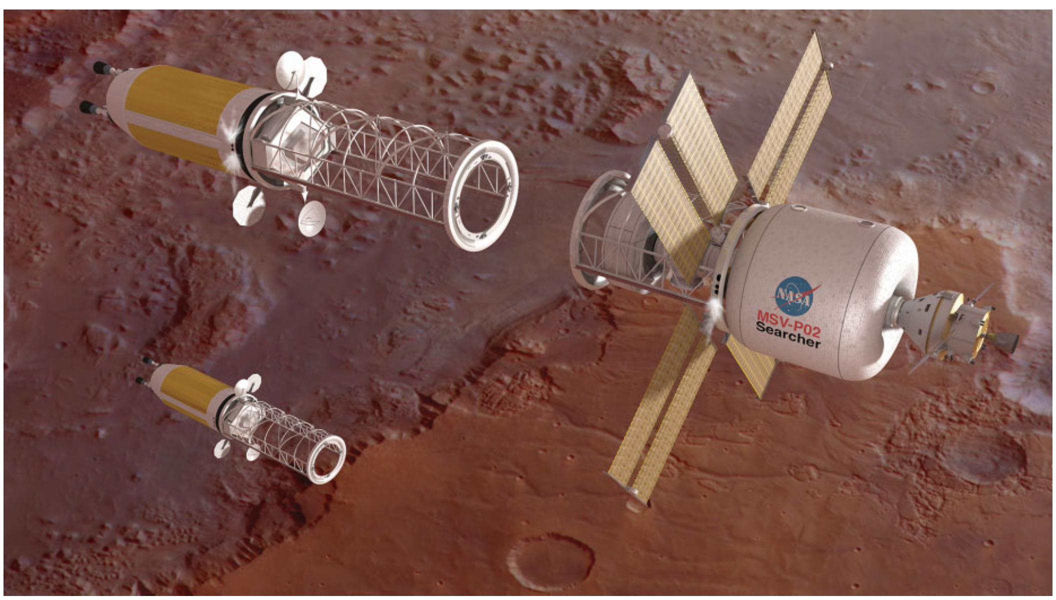

Fig. 11: "Switch-over" - Crewed PL Element Transfer to ERV in Mars Orbit for Trip Back to Earth.

At mission end, the crew re-enters in the CEV capsule, while the MSV flies by Earth and is disposed of into heliocentric space.

The outbound crewed MSV has an IMLEO of ~251.1 t consisting of NTR propulsion module (~107 t), the integrated saddle truss / LH_2 drop tank assembly (~84.3 t), and the crewed PL element (~59.8 t). The PM and ~21.1 m long LH_2 drop tank are substantially off-loaded in propellant (~ 66.8% and 59.6%, respectively), with ~114.5 t of LH_2 propellant carried on the outbound crew mission (~63% of the maximum available capacity of ~181.7 t). In addition to 3 restarts, the total burn time on the MSV's three 25 klb$_f$ engines is ~47.7 minutes, substantially lower than that needed for DRA 5.0 and the reusable NEA missions, and well below the capabilities demonstrated on the NRX-XE.

The "round trip" ERV / tanker has an IMLEO of ~237.4 t consisting of NTR propulsion stage (~127.6 t) and the integrated saddle truss / LH_2 drop tank assembly (~109.8 t). The ERV carries a larger LH_2 propellant loading in its propulsion stage and forward drop tank totaling ~153.6 t (~84.5% of the maximum available capacity of ~181.7 t) which is needed to return the crewed PL back to Earth. In addition to 3 restarts, the total burn time on the ERV's three 25 klb$_f$ engines is ~64.2 minutes (~35.2 minutes for the "2-perigee" burn TMI maneuver, ~7.9 minutes for MOC, and ~21.1 minutes for TEI), again well below the capabilities demonstrated on the NRX-XE. The ERV's longer TEI burn duration is attributed to the addition of the ~51.2 t crewed PL plus the higher TEI ΔV requirement (~3.12 km/s versus ~1.56 km/s for DRA 5.0). Lastly, the total mission IMLEO for the outbound crewed MSV and the ERV is ~488.5 t.

2033 Combined Mars / Phobos Orbital Mission Option

The performance capability of the Copernicus / Searcher spacecraft design can be extended further to include a combined orbital reconnaissance mission of Mars and its moon, Phobos (shown in Fig. 12), by reducing the crew size to 4 and extending the mission round trip time to 600 days (183 days outbound, 60 days at Mars / Phobos, and 357 days inbound). As before, the mission begins with the ERV / tanker departing LEO in December 2030 on a 283-day, minimum-energy trajectory to Mars then propulsively capturing into a 24-hour elliptical parking orbit in October 2031. The crewed mission follows with the outbound MSV departing LEO in April 2033 and propulsively capturing into the same Mars parking orbit in October 2033, 183 days later.

The crewed MSV has an IMLEO of ~312.1 t consisting of the NTR propulsion module (~136.6 t), the integrated saddle truss / drop tank assembly (~119.2 t), plus the crewed PL section (~56.2 t). The later includes the smaller TransHab (22.7 t), 4 crew (0.4 t), consumables (~6 t), the short saddle truss (~5.1 t), and the transfer tunnel (~1.8 t) connecting the TransHab to the exterior consumables container (~0.5 t) plus the forward RCS (~6.2 t). Also included is a "3-port" docking module (1.5 t) located at the front of the TransHab that accommodates the CEV/SM (10 t) plus two 1-person "ManCans" (2 t) used for up-close inspection and sample collection at Phobos (shown in Fig. 12 insert).

After ~30 days of Mars orbital reconnaissance, the crewed MSV performs three short propulsive maneuvers (for plane change, periapse raising and apoapse lowering totaling ~1105 m/s of extra ΔV) necessary to rendezvous with Phobos which has an ~6000 km circular equatorial orbit about Mars. Over the next 3 weeks the crew explores Phobos using the 2 ManCans to collect ~250 kg of samples. The crew then jettisons waste and unneeded payload mass (~6.8 t) and returns to its original 24-hour elliptical parking orbit (requiring an additional ~1105 m/s of ΔV). Here the remaining crewed PL element (~46.3 t) and Phobos samples are transferred to the waiting ERV for the return to Earth. The combined Mars/Phobos mission better utilizes the Copernicus / Searcher-class vehicle's capabilities than a "Mars only" orbital mission requiring a total LH_2 propellant loading of ~177.4 t (~97.6% of Copernicus' maximum available capacity of ~181.7 t). The total engine burn time is ~74.4 minutes and there are 8 engine restarts – 6 of these associated with the

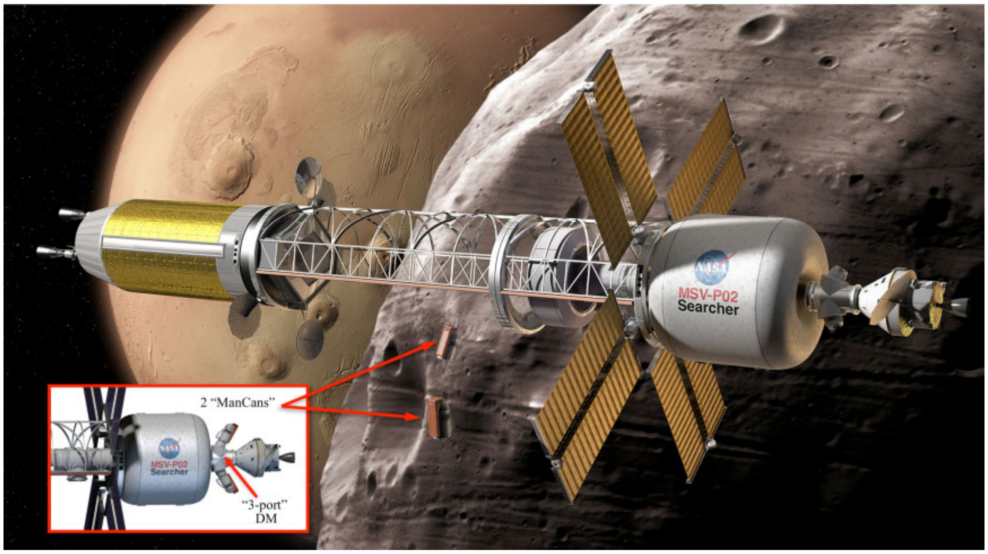

Fig. 12: Combined Mars / Phobos Orbital Mission is Possible Using NTR Crewed MSV and ERV.

"3-burn" Phobos rendezvous and departure maneuver sequence. The ERV has an IMLEO of ~236 t consisting of the NTR propulsion module (~126.7 t) and the integrated saddle truss / LH_2 drop tank assembly (~109.3 t). The total LH_2 propellant load for the round trip ERV mission is ~151.8 t (~83.6% of the maximum available capacity). Three engine restarts are required and the total engine burn time is ~63.4 minutes. For the combined Mars/Phobos orbital mission, the total IMLEO for the crewed MSV and the ERV is ~548.1 t.

6. NOTIONAL PLANS FOR NTP TECHNOLOGY DEVELOPMENT AND DEMONSTRATION

In FY'11, NASA started a technology development effort in NTP under the Advanced In-Space Propulsion (AISP) component of its Exploration Technology Development and Demonstration (ETDD) program. The NTP effort included two key tracks – "Foundational Technology Development" followed by "Technology Demonstration" projects (shown in Fig. 13). Near-term activities initiated under Foundational Technology Development (now part of NASA's new Nuclear Cryogenic Propulsion Stage project [16]), included five key tasks and objectives:

Task 1. Mission Analysis, Engine/Stage System Characterization and Requirements Definition to help establish performance goals for fuel development and guide concept designs for small, scalable demonstration engines and the full size engines needed for future human NEA and Mars missions;

Task 2. NTP Fuels and Coatings Assessment and Technology Development aimed at recapturing fabrication techniques, maturing and testing fuel, then selecting between the two primary fuel forms previously identified by DOE and NASA – NERVA "composite" and UO_2 in tungsten "cermet" fuel [17]. Partial, then full-length fuel elements will be tested in the NTR Element Environmental Simulator (NTREES) [18] at the MSFC using up to ~1.2 MW of RF heating to simulate the NTP thermal environment that includes exposure to hot H_2. Candidate fuels and fuel element designs will be screened in NTREES prior to irradiation testing and final selections;

Task 3. Engine Conceptual Design, Analysis, and Modeling aimed at developing conceptual designs of small demonstration engines and the full size 25 klb_f-class engines utilizing the candidate fuels discussed above. State-of-the-art numerical models are being used to determine reactor core criticality, detailed energy deposition and control rod worth within the reactor subsystem [19], provide thermal, fluid and stress analysis of fuel element geometries [20], and predict engine operating characteristics and overall mass [21];

Task 4. Demonstration of Affordable Ground Testing focused on "proof-of-concept" validation of the SAFE (Subsurface Active Filtration of Exhaust) [22] or "bore-hole" test option at the Nevada Test Site (NTS). Non-nuclear, subscale hot gas injection tests, some with a radioactive tracer gas, will be conducted in a vertical

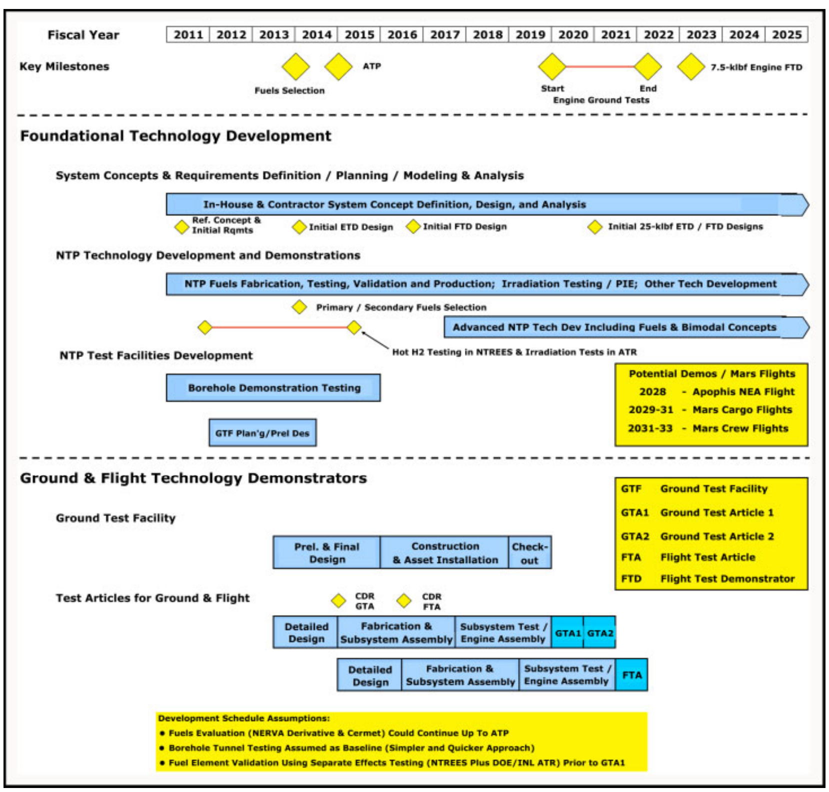

Fig. 13: Notional NTP Development Plan includes Foundational, Ground and Flight Technology Demonstrations.

bore-hole to obtain valuable test data on the effectiveness of the porous rock (alluvium) to capture, holdup and filter the engine exhaust. The data will also help calibrate design codes needed by DOE to design the SAFE test facility and support infrastructure needed for the small engine ground technology demonstration tests and the larger 25 klb_f-class engine tests to follow; and

<u>Task 5</u>. *Formulation of an Affordable and Sustainable NTP Development Strategy* aimed at outlining the content of an affordable development plan that utilizes separate effects tests (e.g., NTREES and irradiation tests), existing assets and innovative SAFE testing at the NTS, and small scalable engines for ground and flight technology demonstrations.

The above tasks, successfully carried out over the next 3 years under the NCPS project, could provide the basis for “authority to proceed” (ATP) in ~2015 with ground technology demonstration (GTD) tests at the NTS in late 2019, followed by a flight technology demonstration (FTD) mission in 2023. To reduce development costs, the GTD and FTD tests would use a small, lower thrust (~7.5 klb_f) engine with a “common” fuel element design that is scalable to higher thrust levels by increasing the number of elements in a larger diameter core producing a greater thermal power output. The small engine demonstration tests would also maximize the use of existing and proven liquid rocket components [23] to further ensure affordability.

The GTD effort would build and test two ground test articles (GTA1, GTA2) and one flight test article (FTA) that provide system-level technology demonstration and design validation for a follow-on FTD mission. The FTD will also provide the technical foundation for an “accelerated approach” to design, fabrication, ground then flight testing of a 25 klb_f-class engine by ~2026. The Rover program used a common fuel element/tie tube design and similar approach to test the 50 klb_f Kiwi-B4E, the 75 klb_f Phoebus-1B, the 250 klb_f Phoebus-2A, and 25 klb_f Pewee engines, in that order, between 1964 and 1968. Flight testing a stage with clustered 25 klb_f engines would follow next in time to support 1-year round trip human NEA missions in the late 2020’s and short round trip / short orbital stay Mars missions using the “split cargo and crew” mission approach outlined above in the early 2030’s.

7. SUMMARY AND CONCLUSIONS

The NTR represents the next major evolutionary step in high performance liquid rocket engines and can correctly be called a “game-changing” technology. It was developed to a high TRL in twenty rocket / reactor tests that demonstrated a wide range of thrust levels, high-temperature fuel, sustained engine operation, accumulated time at full power, and restart capability – everything required for a human mission to Mars. Important developmental work on a second fuel option, UO_2 – W cermet, was also conducted under the ANL and GE-710 programs, and even higher temperature UC-ZrC-NbC ternary carbide fuels were reported in the Russian NTP program.

NTP also has significant “evolution and growth” potential. Designed as a “bimodal” system, the BNTR can generate its own electrical power eliminating the need for deploying and operating large Sun-tracking PVAs. The configuration of a BNTR-powered MTV (long and linear) is also compatible with AG operation that could help maintain crew fitness on long duration space flights. Adding an oxygen “afterburner” nozzle introduces a variable thrust and Isp capability and allows bipropellant operation plus the ability to utilize extraterrestrial sources of hydrogen and oxygen that exist throughout the Solar System. These improvements to the basic NTR can lead to revolutionary performance advancements in an evolutionary manner – “*Revolution through Evolution*”.

With its high thrust and high specific impulse (twice that of chemical propulsion), NTP is the preferred propulsion option for human missions to Mars. Compared to chemical propulsion, the use of NTP in NASA’s recent Mars DRA 5.0 study, helped reduce the required launch mass by over 400 t – the equivalent mass of the International Space Station. Furthermore, NTP requires no large technology or performance scale-ups. In fact, the smallest engine tested during the Rover program – the 25 klb_f “Pewee” engine is sufficient for Mars when used in a clustered engine arrangement.

The “Copernicus” crewed MTV design developed for DRA 5.0 was sized to allow it to perform all of the fast-conjunction missions over the 15-year synodic cycle. It therefore has significant capability that can be utilized for NEA and Mars orbital missions currently under study by NASA. Copernicus can perform reusable 1-year round trip missions to NEAs 1991 JW and Apophis in the late 2020’s that can also be used to check out vehicle systems. Afterwards, the Copernicus spacecraft and its 2 key components, configured as an ERV/tanker, would be used for a short round trip/short orbital stay Mars mission in 2033 using the split mission approach. Also noteworthy is the fact that the total engine operating time and required restarts for all missions analyzed are well below the capabilities demonstrated on the NRX-XE ~43 years ago!

Finally, and most importantly, NASA restarted an NTP development and demonstration effort in FY’11 that includes Foundational Technology Development work in the five key task areas. The results from these tasks will provide the basis for continuing work in these same areas under the NCPS project over the next three years. If successful, this effort could be followed by system-level Technology Demonstrations that include ground testing a small, scalable NTR before 2020, with a flight test shortly thereafter.

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