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LEU NTP Engine System Trades and Mission Options

C. Russell Joyner II[1], Michael Eades[4], James Horton[4], Tyler Jennings[1], Timothy Kokan[3], Daniel J. H. Levack[4], Brian J. Muzek[3], and Christopher B. Reynolds[3]

[1]*Aerojet Rocketdyne, West Palm Beach, Florida 33410, USA,*
[2]*Ultra-Safe Nuclear Corporation, Seattle, Washington 98199, USA,*
[3]*Aerojet Rocketdyne, Huntsville, Alabama 35806, USA,*
[4]*Aerojet Rocketdyne, Canoga Park, California 91309, USA,*
561-882-5349; claude.joyner-ii@rocket.com

The future of human exploration missions to Mars are dependent on solutions to the technology challenges being worked by NASA and industry. One of the key architecture technologies involves propulsion that can transport the human crew from Earth orbit to other planets and back to Earth with the lowest risk to crew and the mission. Nuclear Thermal Propulsion (NTP) is a proven technology that provides the performance required to enable benefits in greater payload mass, shorter transit time, wider launch windows, and rapid mission aborts due to its high specific impulse (Isp)and high thrust.

Aerojet Rocketdyne (AR) has stayed engaged for several decades in working NTP engine systems and has worked with NASA recently to perform an extensive study on using Low Enriched Uranium (LEU) NTP engine systems for a Mars campaign involving crewed missions from the 2030s through the 2050's. AR has used a consistent set of NASA ground rules and they are constantly updated as NASA adjusts its sights on obtaining a path to Mars, now via the Lunar "Gateway." Building on NASA work, AR has assessed NTP as the high-thrust propulsion option to transport the crew looking at how it can provide more mission capability than chemical or other propulsion systems.

The impacts of the NTP engine system on the Mars transfer vehicle (MTV) configuration have been assessed via several trade studies since 2016, including thrust size, number of engine systems, liquid hydrogen stage size, reaction control system sizing, propellant losses, NASA Space Launch System (SLS) payload fairing (PLF) size impact, and aggregation orbit.

AR study activity in 2018 included examining NTP stages derived from Mars crew mission elements to deliver extremely large cargo via multiple launches or directly off the NASA Space Launch System (SLS). This paper provides an update on the results of the on-going engine system and mission trade studies.

INTRODUCTION

Since 2013, AR has been working with NASA and Ultra-Safe Nuclear Corporation (USNC) to examine NTP configurations and determine the optimum reactor design. In 2016, AR started performing architecture trades with a notional LEU NTP design based on legacy LEU NTP work performed by AR and USNC in 2015 and early 2016. AR and USNC during 2017 started examining in more detail the design variables that have a strong impact on LEU NTP designs. Past studies have looked at discrete LEU NTP designs to compare LEU to High Enriched Uranium (HEU) core designs for NTP. Those efforts identified LEU NTP design characteristics for further examination to improve the LEU core designs based on CERMET fuel operating in the thermal spectrum via neutron moderation. Those designs were moderated using materials in a structural assembly (tie-tubes) similar to the Nuclear Engine for Rocket Vehicle Applications (NERVA) design [1].

Future exploration human and robotic missions will require maturation of many technologies to successfully place humans on any planet's surface and return them to Earth. Cis-lunar space and the Lunar Operations Platform-Gateway (LOP-G) are one option to assemble, test, and mature the NTP propulsion technologies and vehicle elements. Cis-lunar space and the Lunar Orbital Platform-Gateway enhance this option by allowing tests of mission elements in a near-Earth domain where missions can last months instead of years and allow the hardware to be examined after the mission. These attributes can improve the schedule and cost characteristics for a Mars mission. Some of the NTP mission elements, when aggregated in Lunar vicinity, can be tested, modified, and matured at the Lunar-Gateway, testing both stage connections and interfaces and the prox ops of stage assembly even if they are ultimately to be aggregated for Mars missions in a different orbit.

Short duration missions can be used to test propulsion in a deep space environment with short communication and control times. Autonomous fueling and refueling procedures can be tested [2,3].

The same NTP stage elements have applicability to other exploration missions. This includes moving heavy cargo within 200 days to Mars (e.g., large landers), larger orbiter spacecraft to Jupiter (e.g., 2-3X size Juno), and placing orbiters (versus simply a fly-by) the size of the New Horizons spacecraft or larger at the outer planets with transit times less than 10 years. Examples of possible missions using core stages with and without additional propellant stages are core stages flown directly off the NASA Space Launch System (SLS) directly on escape trajectories to the Jupiter and the outer planets.

I. LEU NTP CORE AND ENGINE SYSTEM DEFINTION

AR and USNC in 2017 went through several design iterations to define the most optimum LEU NTP core designs. This effort was undertaken to ensure that the best core designs and a wider range of interactions were being captured for later integration into the engine thermodynamic analysis. LEU core configurations were optimized for maximum specific impulse (Isp) and minimum core reactor mass while being designed to assure that the core could achieve criticality for continuous operation. AR and USNC, along with input from subject matter experts at NASA, Department of Energy, and the nuclear fuels industry, discussed and looked at the most effective way to extend the design variables and examine how to capture the effects from larger multivariate design sets. New updated LEU core designs were defined in 2018 that would then include fuel elements that presented the best approaches for lowest cost development, testing, and manufacturing.

The primary difference in the LEU NTP core designs worked in 2018 was a transtion to a Uranium Nitride (UN) fuel matrix that included optimized content of Molybdeum and Tungsten (MoW). The moderator element or tie-tube (ME,T/T) to fuel element (FE) ratio for the NTP engine cycle remained near 2:1. The updated core design differed from enriched CERMET core designs studied in 2017 that considered fuels comprised of Uranium Dioxide, Tungsten, and Rhenium. The ME remained composed of Zircaloy, Zirconium Hydride, and Zirconium Carbide.

As before in the LEU NTP designs optimized in 2017, the LEU NTP reactor cores data was then used in the thermodynamic mass and power balance NTP model to determine operability of the engine system and the final thrust and Isp performance.

The schematic shown in Figure 1 illustrates the type of engineering attributes that result from the thermodynamic analysis using the AR NTP cycle model. As reported in the paper at NETS 2018, the AR NTP cycle model captures the effects of the power density distribution and heat transfer variations for any LEU NTP reactor core FE and ME design approach. This example shows a design with the hydrogen coolant flow path, turbopump integration approach with the hydrogen coolant flow-path, the use of a turbopump flow control by-pass valve based on an liquid rocket expander-cycle type operation, and typical chamber-nozzle exit conditions [4].

Figure 1 shows an LEU NTP engine design at 25,000 lbf thrust and operating at a 1,000 psia reactor exit condition. The LEU NTP reactor exit temperature of 4,770 deg-Rankine (2,650 deg-Kelvin) was a design target for this thermodynamic cycle analysis. The exit temperature for the LEU NTP was reduced as a results of analysis in 2018 that indicated more margin in the design was possible by reducing the temperature by 50 to 100 degrees. The LEU NTP core design illustrated in Figure 1 reflects an optimized LEU NTP core design with the FE and ME arrangement producing adequate heating to drive the turbopump in the engine cycle and heat the hydrogen to the 2,650 deg-K exit temperature. The NTP is capable of 900+ seconds of Isp with a nozzle similar in size to the AR RL10B-2 and a engine system thrust to weight of 3.0 to 1. AR has been analyzing all mission and vehicle architecture trades at 875 seconds Isp to keep design margin on the Mars architecture planning for all the mission options.

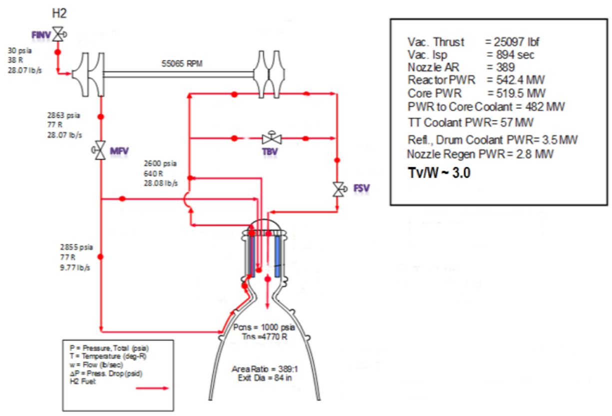


FIGURE 1. *A Schematic of a NTP Engine System with LEU UN Fuel Elements – 25,000-lbf Thrust Class.*

AR NTP and architecture studies, as well as NASA studies, have continued to show three NTP engines around 25,000-lbf (~111 KN) thrust each are near optimum for a Mars crew vehicle. As mentioned in the previous section, the LEU NTP has evolved to considering UN-based fuel elements but still at 25,000-lbf thrust level operating with a ~550 MWt (megawatt-thermal) reactor to superheat the hydrogen propellant to greater than 2,600-K to obtain 890+ seconds of ISP. This is still considered a moderate size core NTP needing 50 to 100 kilograms of LEU as defined from the LEU NTP core/engine cycle optimization studies. As a reference, the former NERVA/Rover program had reactors operating at 1,000 to 2,000 MWt and 50 to 200 kilograms of HEU. Figure 2 illustrates a typical arrangement of the three LEU NTP engines mounted on the core stage element of the Mars crew vehicle stack.

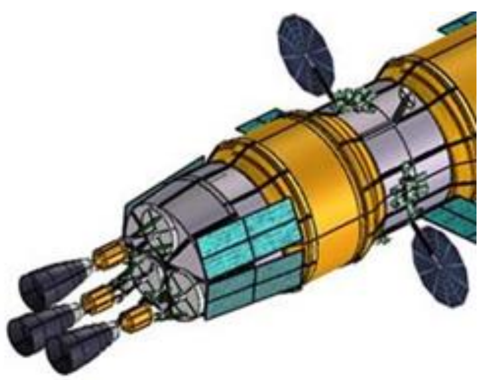


Figure 2: NTP Mars Transfer Vehicle Concept Update with 3 x 25,000 lbf NTP Engines.

Work has continued in 2018 to understand the mechanical design and mass breakdown of the LEU NTP engine systems. Detailed configuration geometry and placement of components has been progressing to ensure that engine assessories are placed in optimal locations around the NTP reactor core to lessen any impact of secondary external radiation during reactor operation. Figure 3 provides one perspective on an arrangement being evaluated by AR for placement of components. It can be seen that the physical size of a single 25,000-lbf LEU NTP is not much larger than an AR RL10B-2 liquid oxygen/liquid hydrogen chemical rocket engine. The LEU NTP basic engine is roughly the same size as the RL10B-2 and when arranged with an optional external shield to reduce any excess neutron and gamma radiation, it remains at ~7.6 meters in total length with the external shield. The radiation (thermal) cooled nozzle extension is small enough to be manufactured in a similar manner as the RL10B-2 nozzle as shown in Figure 3.

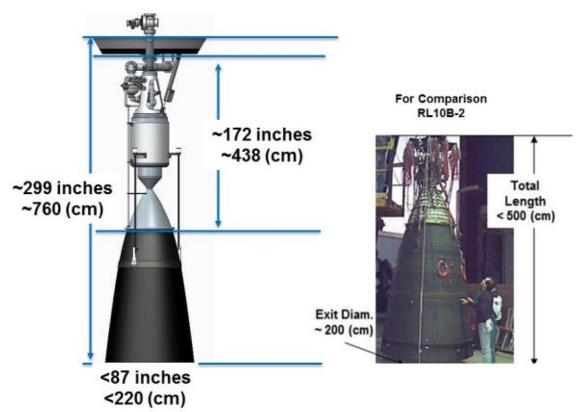


Figure 3: Example LEU NTP Engine System Configuration with Single Turbopump.

II. LEU NTP MISSION TRADE STUDIES

Since 2016 AR has continued to conduct trade studies on a NTP-based Mars architecture based on the human Mars mission ground rules defined by the NASA Evolvable Mars campaign (EMC) and recently updated in 2018 using information from the Mars Capability Studies (MSC) Team [5,6].

Many of the benefits for using the LEU NTP on Mars crew mission architectures has been reported in previous AR papers. The trade studies from 2016 and 2017 showed that using a cis-lunar aggregation orbit and LDHEO type orbit for Earth departure (at perigee) and return was beneficial to reducing the

NTP Mars crew vehicle mass while still providing a space transportation system with 5 to 6 months transit capability from Earth to Mars. This Mars NTP vehicle can be assembled in four to five NASA SLS Block 2 launches using the 8.4m PLF (payload fairing), including the crew habitat. The NTP MTV is a robust solution for a Mars vehicle and using the various stage elements in different approaches can provide an even more versatile exploration system approach.

A key benefit to reducing the health risk for the astronauts on a Mars mission, as discussed in many NASA reports, is to reduce in-space mission transit times. The primary reason to reduce Earth to Mars to Earth transit times is shown in Figure 4. The shorter trip times reduce the Mars crew health risk by reducing cumulative exposure to deep space radiation (e.g., Galactic Cosmic Rays (GCR)) which damages human tissue, especially blood forming organs (BFO). GCR cannot be totally shielded against because the required types of material (high density) needed result in a higher mass Mars vehicle that becomes higher technical risk and less affordable. Thus using the materials needed for mitigating all GCR has a major impact on the MTV gross stack mass. The only documented approach to reduce total Mars crew dose rates is to reduce exposure time. The only way to reduce exposure time is to use planetary bodies as partial shielding and reduce the time accumulated in space. Figure 4 compares trying to use a low thrust propulsion system similar to high power Solar Electric Propulsion (SEP) versus NTP for the Mars crew transportation system. Using data from a previous NASA JPL Mars crew mission radiation assessment report, it can be seen that the NTP MTV reduces the crew radiation exposure by nearly 25% for optimized long-stay missions. When the NTP MTV is optimized for only a 360-day total in-space and 500-day surface mission, the total dose exposure is reduced by nearly 30%, similar to an opposition type short-stay mission. The NTP MTV reduces total crew radiation exposure and provides an approach to reduce some of the risk associated with a Mars crew mission [7].

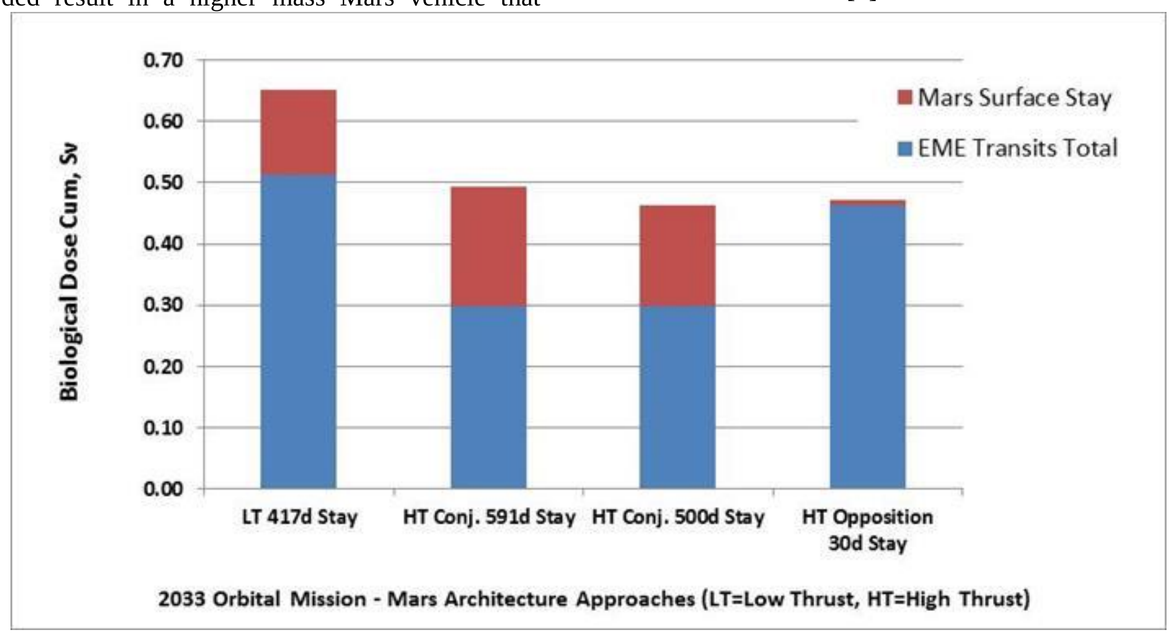


Figure 4: Mars Crew GCR Dose Rate Reduction with High Thrust NTP.

In 2018, AR updated the Mars architecture study results using studies performed by NASA and others reducing the conductive heat loads into the cryogenic hydrogen tanks by a factor of 2 or more, improving packaging optimization of each NTP stage element, and updating mission opportunities and payloads from the NASA MSC studies. The updates to the NTP Mars vehicle included attaching the cryo-tanks to the interstages via low-mass struts and placement of the RCS system. The changes had very little impact on the stage element masses. Each stage element was still able to stay within the 45 mT NASA SLS throw capability defined in the previous architecture trades. Figure 4 shows the updated NTP Mars crew vehicle configuration with a three NTP engine system core and hydrogen tank, three in-line hydrogen tank stage elements and the crew habitat sized for 1,000+ day missions.

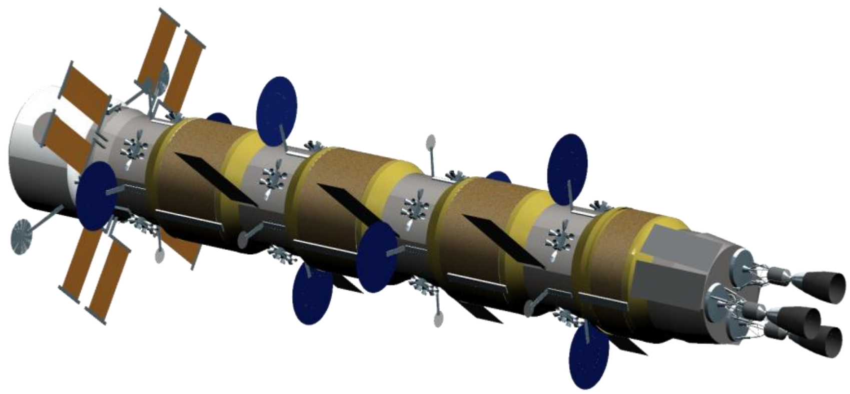
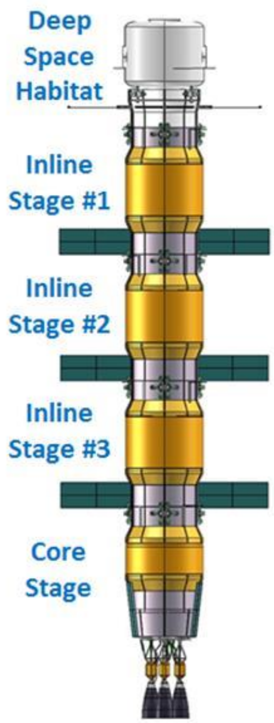


Figure 5: LEU NTP Mars Crew Vehicle Point of Departure Configuration.

Mission: 2033 Fast Conjunction

Mission Times	
Earth-Mars	163 days
Mars Stay	618 days
Mars-Earth	163 days
Earth Sphere of Influence	
Aggregation Orbit	NRHO
Departure / Arrival Orbit	LDHEO
Mars Sphere of Influence	
Arrival / Departure Orbit	1 SOL
NTP Primary Burns (4)*	
TMI ΔV / Time	610 m/s / 363 sec
MOI ΔV / Time	1,648 m/s / 842 sec
TEI ΔV / Time	1,324 m/s / 487 sec
EOI ΔV / Time	571 m/s / 183 sec
**Primary burn ΔV values do not include 4% FPR*	
Earth Sphere of Influence ΔVs (RCS)	
Launch to NRHO	125 m/s
NRHO to LDHEO	195 m/s
LDHEO to NRHO	116 m/s
Mars Sphere of Influence ΔVs (RCS)	
Plane Changes, Apotwist	250 m/s



Vehicle Concept Characteristics

Payload: Deep Space Habitat	
Gross Mass	43,679 kg (At TMI)
Inline (each)	
Propellants	LH2 Main; NTO/Hydrazine RCS
Main Usable Propellant‡	18,813 kg of LH2
RCS Usable Propellant	12,000 kg of NTO/Hydrazine
Dry Mass	10,524 kg
Inert Mass‡	13,062 kg
Gross Mass	43,875 kg
Stage Length	11.1 m
Stage Diameter	7.5 m (7.0 m Tank Diameter)
Core	
Propellants	LH2 Main; NTO/Hydrazine RCS
Main Usable Propellant‡	13,539 kg of LH2
RCS Usable Propellant	3,000 kg of NTO/Hydrazine
Dry Mass	25,674 kg
Inert Mass‡	27,336 kg
Gross Mass	43,875 kg
Stage Length	19.2 m
Stage Diameter	7.5 m (7.0 m Tank Diameter)
# of NTP Engines	3
NTP Engine Thrust	25,000 lb_f
NTP Engine Isp	875 sec

‡Main Usable Propellant does not include 4% FPR. Inert Mass does.

Figure 6: 2018 LEU NTP Mars Crew Vehicle Point of Departure (PoD) Configuration.

The NASA MSC mission architecture trades focused on the opportunities in 2033, 2037, 2041, and 2045. AR proceeded in 2018 to examine the impact on the mission capability of the Point of Departure (PoD) Trade studies were performed for the other MSC opportunities using the PoD LEU NTP Mars vehicle in Figure 6. The MSC 2037, 2041, and 2045 mission opportunities had significant variations in the delta-V's for the primary NTP burns versus those shown in Figure 6. Depending on whether the trajectories were Type I or Type II to achieve the minimum energy

Mars crew vehicle architecture for all the MSC missions. Figure 6 shows the PoD LEU NTP Mars crew vehicle performance and vehicle characteristics that is conceptualized based on the 2033 opportunity. trajectory between Earth and Mars, the delta-V values can be twice the value for the 2033 opportunity year. Figure 7 illustrates a typical Earth Departure/Mars Arrival energy (delta-V versus trip time) contour where the lower right contour series is a Type I trajectory set and the upper left contour series is a Type II trajectory set. These type of trajectory contours can be generated for every Earth to Mars mission opportunity year and show the sensitivity to launch window dates and transit times. Similar trajectory energy contours were generated for the Mars to Earth departure and return opportunities.

AR has created a mission data book with all the “ballistic” type trajectory contours for every opportunity between 2028 to 2052 including the NASA MSC mission opportunities. These trajectory energy (delta-V) contours were used to identify how sensitive the trajectories were relative to transit times for the 2033, 2037, 2041, and 2045 mission opportunities. AR uses the NASA Copernicus program to calculate the trajectories for all the LEU NTP Mars mission trades. That Copernicus trajectory data is used to calculate the mission delta-V values that are then used to determine the performance capability of the LEU NTP Mars crew vehicle.

AR is preparing a paper to be released in 2019 that will provide more details on the Earth-Mars-Earth mission data book compilation used for the LEU NTP mission analysis.

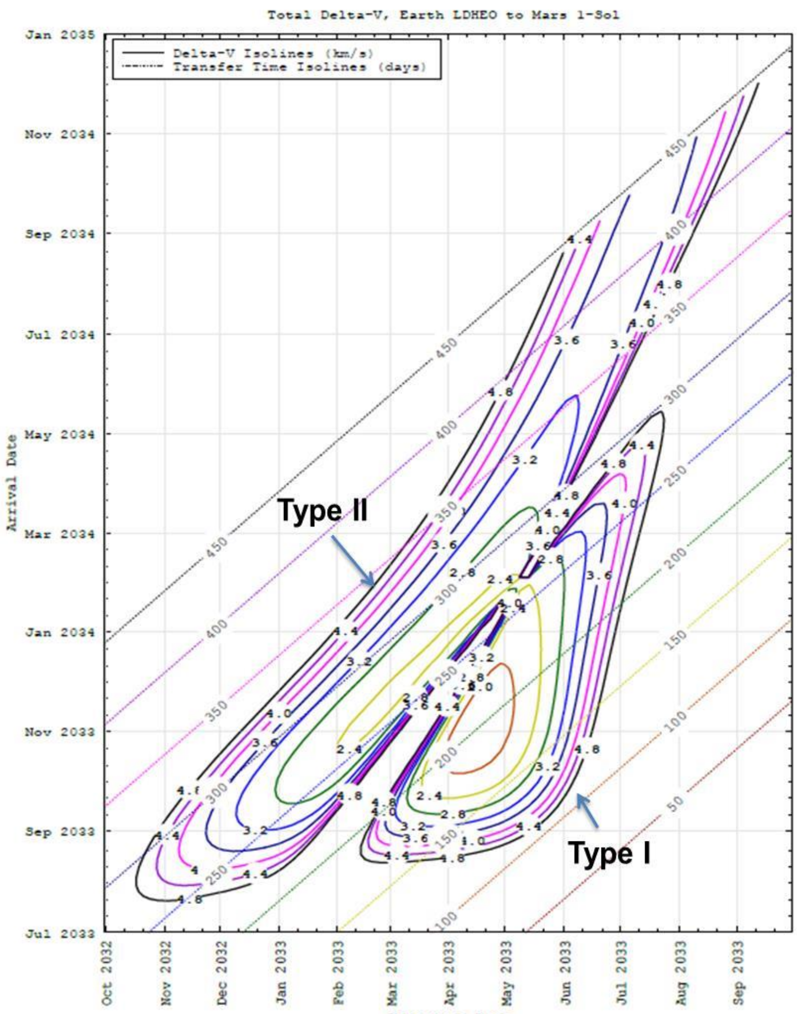


Figure 7: Earth to Mars Trajectory Energy Contour - 2033 Opportunity.

Trades were performed in 2018 on the LEU NTP Mars crew vehicle and missions that used elements of the PoD Mars crew vehicle. These included examining increased core exit temperature to achieve Isp values at or higher than 900 seconds, using a orbital manuevering system (OMS) set tied to LEU NTP engine cycle providing an augmented RCS Isp near 500 seconds, and staging of one or more of the empty in-line tank elements at Mars before return to Earth. The LEU NTP Mars vehicle sensitivity tracked changes to mission delta-V capability for each opportunity for all these trades. The one-way transit time was allowed to vary for fixed NTP stage element masses (fixed Mars crew vehicle mass). The aggregation orbit was held from the past mission studies in 2016 and 2017 which had shown the capability of one-way transit times of ~160-170 days each way for the 2033 mission. Depending on the MSC long-stay mission opportunity flown, the transit times can vary from 150 to 250 days each way depending on the NTP performance. Using the NTP-based OMS system or dropping/staging an in-line stage before return to Earth can greatly increase the delta-V capability. The flexibility of the LEU NTP Mars vehicle PoD configuration can be illustrated with moderate enhancements to the architecture as a Mars mission campaign evolves. As the mission opportunites go from 2033 out to 2045, larger delta-V capabilities are required for the "harder" missions. Figure 8 illustrates how the LEU NTP PoD can perform all the MSC 2033 to 2045 missions using a Type I trajectory with the longest transit times each way being ~250 days for the worst Earth-Mars-Earth mission opportunities.

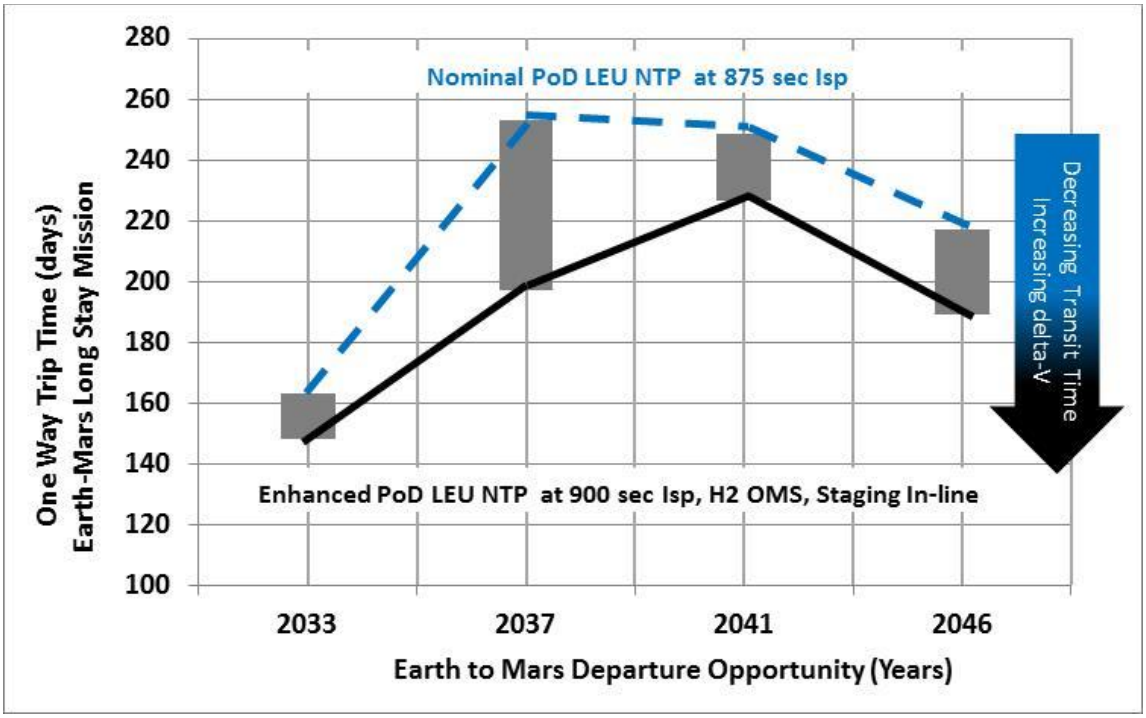


Figure 8: LEU NTP Mars Crew Vehicle Mission Trip Time Variation for MSC Mars Opportunity Year.

The LEU NTP PoD core and three in-line configuration is faster on the MSC opportunities than a LOX/CH_4 vehicle architecture, that pre-postions return propellant, by 16 to 29% with no modification to the PoD. When adding the features such as higher Isp, H_2 OMS, and staging an in-line tank stage the LEU NTP is 26 to 46% faster in transit time. The same LEU NTP architectures out-perform a "Hybrid" propulsion approach by 33 to 57% in reduced transit times. Architectures that use the LEU NTP PoD configuration shown in Figure 5 or the LEU NTP PoD with enhancements will keep astronauts at a lower risk in regards to GCR exposure on all Mars mission opportunities with reduced transit times.

III. MISSION OPTIONS – NTP CORE + IN-LINE STAGE ELEMENTS

The mission architecture trades have been conducted assuming the NASA SLS Block 2 cargo vehicle is the launch system to get the elements to either a lunar distant highly elliptical orbit (LDHEO) or a highly elliptical Earth orbit (HEO). It is also important to note that all the LEU NTP stage elements use the NASA SLS 8.4 meter long PLF.

Before embarking on a Mars mission, the in-space transportation elements must be tested and checked out most likely in the aggregation orbit. The elements sent to space for testing may not be identical to the elements flown in the first Mars crew missions. First, they will probably have more instrumentation and be flown as test units. Second, data from the testing may suggest or require changes to the full-up Mars crew mission flight elements.

The ultimate Mars mission aggregation orbit could probably be the LOP-G (Gateway) orbit. The elements will stay in the aggregation orbit for several months as the Mars vehicle assembly is completed. Consequently the testing, particularly thermal loads and propellant tank response and performance, will benefit from testing at the Gateway. The availability of personnel to examine the elements both pre and post-test and to troubleshoot any problems is also a benefit of using the Gateway. Short communication time delays for some tests are also potentially beneficial. A specific example unique to the NTP is to verify any "stay-out" zones around the NTP crew and cargo stages after the NTP engine has been operated. These will have been modeled and mapped out in ground testing but should be verified for the fielded elements in space.

Figure 9 illustrates a set of potential missions that could be conducted from the Gateway to demonstrate and/or shakedown the NTP Mars crew vehicle system. The core stage could eventually be validated and evolve to be used for a "fast" 24 to 48 hour cargo taxi from Lunar vicinity to the Earth, refueled at a 6-12 hour elliptical orbit and then re-flown back to Lunar vicinity, like a "Fed-Ex" delivery system between the Earth and the moon. Running the LEU NTP core stage at lower temperatures likely will enable many missions before the Uranium-based fuel in the NTP core has exhausted its fission capability.

Missions	1	2	3	4	5	6
Mission Description	Shakedown Cruise in Cislunar Space	Shakedown Cruise in Cislunar Space	Mars Trajectory Fast Abort to Earth (Limited ΔV)	Shakedown Cruise in Cislunar Space	Mars Orbit Insertion or Flyby	Mars Trajectory Fast Abort to Earth (Full ΔV)
Purpose	Ops test of single inline stage	Ops test of single core stage	Limited ops test of core stage with abort test	Full test of assembly and operations	Full test of single core stage	Extensive ops test of core and inline stages with abort test with full ΔV
Payload	Deep Space Hab or simulator	Deep Space Hab or simulator	Deep Space Hab or simulator	Deep Space Hab or simulator	Deep Space Hab	Deep Space Hab or simulator
Human Mars Mission Elements Demonstrated						
Crew Vehicle Core Stage (3-engine)		x	x	x	x	x
Crew Vehicle Inline Stage	x (1 inline)			x (1 inline)		x (3 inline)
Cargo Vehicle Core Stage (1-engine)						
Deep Space Habitat or simulator	x	x	x	x	x	x
Human Mars Mission Capabilities Demonstrated (1,3,9 : where 1=Weakly demonstrates capability,9=Strongly demonstrates capability)						
Autonomous Rendezvous and Docking	3	3	3	9	3	9
Stage-to-Stage Propellant Transfer				9		9
Stage Refueling	9*	9*	9*	9*		9*
Cryofluid Management	3	3	3	3	9	3
NTP Engine In-Space Operation		3	3	9	3	3
NTP Engine Life		3	3	9	9	9
NTP Engine Starts		3	3	9	9	3
Deep Space Comm						
G&C						
Radiation Levels vs Models		3	3	9	3	9
CONOPS	1	3	3	9	3	9
NTP Prox OPS						
Pre-fire		3	3	9	3	9
Post-fire		3	3	9	3	9
Cost	Low	Low	Low	Medium	Medium	Medium
Mission Time	Months	Months	Months	Months	Months	Year
Notes	1	1, 2	1	1, 2	3	1

Notes:
1. Where Habitat is used instead of simulator, the Habitat is also tested separately while these other missions occur.
2. System exercised through multiple returns to Gateway vicinity.
3. Useful mission performed in addition to NTP vehicle testing
* If reused for other missions

Figure 9. NTP Core and In-line Stages Shakedown Cruise / Demonstration Flight Options from the Gateway.

Several mission options are available using the LEU NTP Mars vehicle stage elements. The first mission is an operations and system checkout of a single inline stage. The stage is launched into LDHEO and then uses its RCS to transfer to the Gateway orbit. It then positions itself in a preplanned relation to the Gateway. The potential checkouts include autonomous rendezvous and docking with the habitat or a simulator, cryo fluid management (CFM) data gathering (recording actual fluences and actual H_2 losses versus models), and communication and control. This is also a test of the Con-Ops procedures for the later multi-stage aggregation for the Mars missions. The inline stage is then available for use in other test missions.

The second mission is an operations and checkout of a NTP core stage. This is a propulsive stage with three NTP engines and RCS/ACS. The stage is launched into LDHEO and then uses its RCS to transfer to the Gateway orbit. It then positions itself in a preplanned relation to the Gateway. The potential checkouts include autonomous rendezvous and docking with the habitat or a simulator, cryo fluid management (CFM) data gathering (recording actual fluences and actual H_2 losses versus models), and communication and control. This is also a test of the Con-Ops procedures for the later multi-stage aggregation for the Mars missions. The core stage is then available for use. The core stage would then be flown with at least two relatively short (a few minutes) burns that checkout the engine operation and the cooldown performance. The core stage is then returned to the Gateway where any "stay-out" zones around the NTP core stage after the NTP engine has been operated will be mapped and verified. These will have been modeled and mapped out in ground testing but should be verified for the fielded elements in space.

Mission 3 would occur after the core stage was refueled, which itself is a checkout of capability. This mission demonstrates the use of both the NTP engines and the RCS engines used to start a mission and then abort the mission back to the Gateway. The is the same capability that the full Mars vehicle (a core stage and three inline stages) would have but demonstrated with less ΔV because only a core stage is used. This demonstrates the Con-Ops of that capability. The mission also puts more time on the NTP and the RCS engines.

Mission 4, combines the core stage and the inline stage to demonstrate most of the operations of the full Mars vehicle stack. Besides adding more time and experience with the engines, it also demonstrates autonomous rendezvous and docking of the core stage, the habitat or simulator, and the inline stage. It demonstrates propellant transfer between the inline stage and the core stage while the NTP engine is running. Data will be acquired on thermal loads on the multi-element stack. When the vehicle returns to the Gateway any changes to the "stay-out" zones produced by a multi-element stack can be examined.

Missions 1 through 4 could be accomplished with only two elements: an inline stage and a core stage. The performance of these four missions demonstrates all the capabilities needed for the ultimate space transportation part of the Mars crewed mission and only requires two pieces of hardware.

If it is deemed necessary to run a full ΔV mission as a final checkout of the transportation system, but retain the hardware, mission 6 can be performed. This mission uses all elements of the full Mars transportation system, runs the engines for the full ΔV, and shows full aggregation of the elements, but require that two additional inline stages be sent to the Gateway.

None of the inline stages is wasted. The single inline stage used in missions 1, 4, and possibly 6, and the two additional inline stages used if mission 6 is performed are all available for further use. All stage elements are available for further use after the missions. The NTP crew core stage is also available for further use. All of the hardware used in the checkout missions could be refueled and used for the first vehicle on the first crewed Mars mission.

If it is instead chosen to not use the checkout hardware for the first Mars mission, the hardware can be held near the Gateway as a backup for future Mars missions, disposed of, or disposed of by being used for a useful mission such as mission 5 – a Mars orbit insertion or flyby.

Mission 5 is a method of disposing of the core stage, if disposal is chosen, in a way that gathers further data on the stage and its engines and performs a useful mission. Figure 10 shows the Con-Ops for the two options for delivering useful payload for mission 5.

Figure 11 shows the payload that can be carried to a 1 Sol Mars orbit by a fully fueled PoD core stage. Also shown is the amount of payload that can be dropped off at Mars by a fully fueled PoD core stage. This payload is dropped off at a low C3 (orbital specific energy) that allows for aerocapture. The large amount of payload for a flyby drop off is because the crew core stage is only required to make a TMI burn. Figure 11 assumes the payload is already at the Gateway. If it is in a lower energy orbit and the crew core stage must maneuver to the payload orbit and then perform an escape burn to Mars from there, the payload will be less.

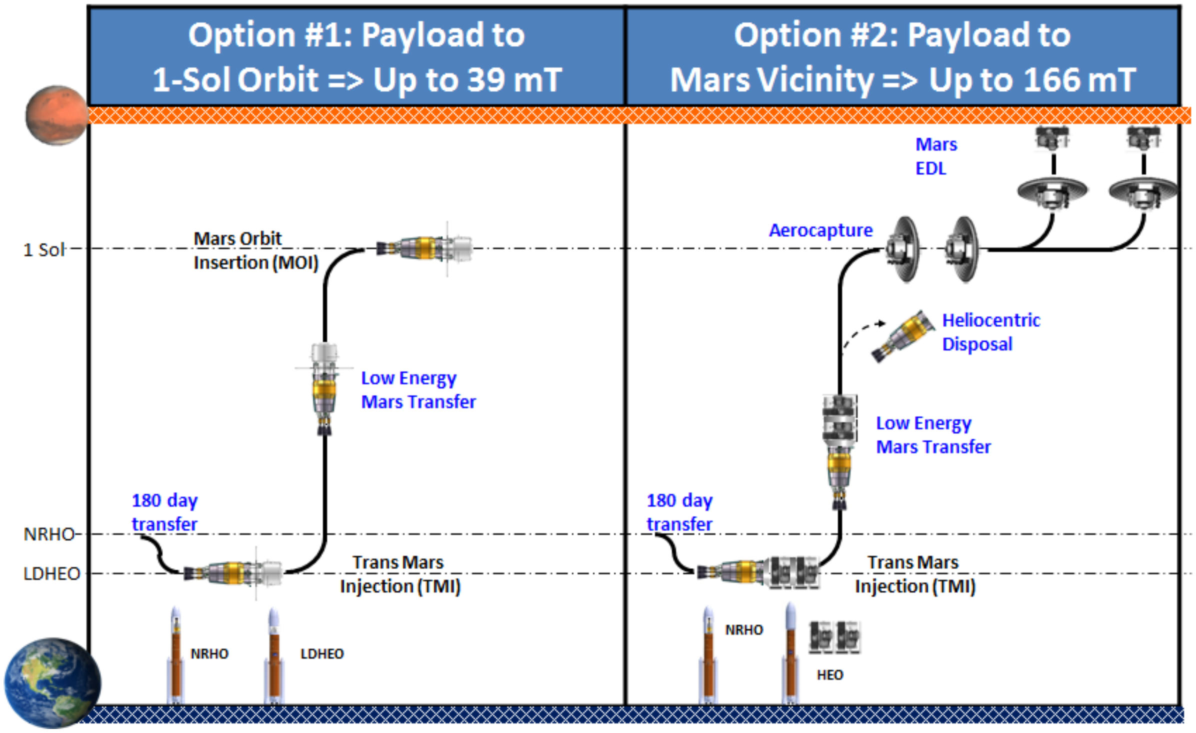


Figure 10. Useful Cargo via NTP Crew Core Stage Element Demonstration - Mission 5.

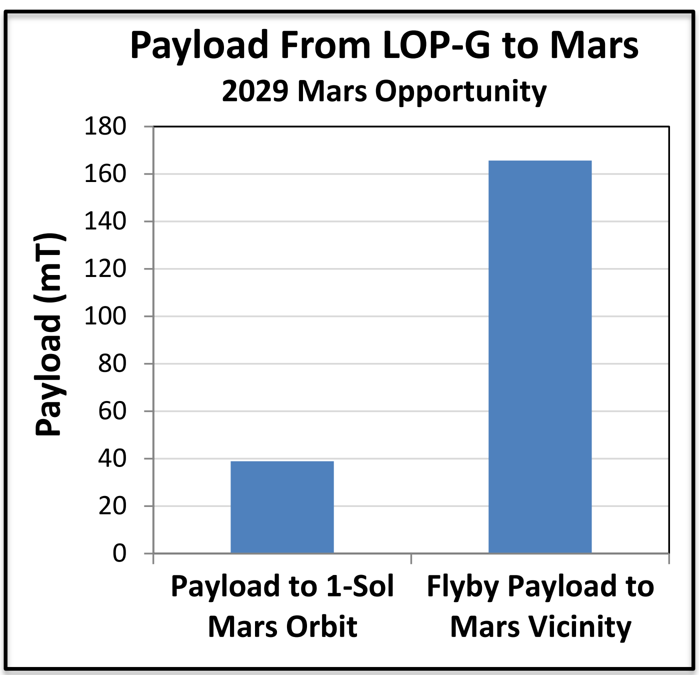


Figure 11. Payload Capability for a Mars Mission with Crew Core Stage Only.

Missions	7	8	9
Mission Description	Payload Delivery to Lunar Orbit / Surface	Payload Delivery to Mars Orbit / Surface	Deep Space Science Mission
Purpose	Full test of single cargo stage operations plus useful mission	Full cargo test plus useful mission	Limited ops test of cargo stage plus useful mission
Payload	Cargo (robotic lander, DSG elements / logistics)	Cargo (orbiter, comm relay, sample return lander)	Cargo (large outer planet or icy moons flyby / orbiter / lander)
Human Mars Mission Elements Demonstrated			
Crew Vehicle Core Stage (3-engine)			
Crew Vehicle Inline Stage			
Cargo Vehicle Core Stage (1-engine)	x	x	x
Deep Space Habitat or simulator			
Human Mars Mission Capabilities Demonstrated (1,3,9 : where 1=Weakly demonstrates capability,9=Strongly demonstrates capability)			
Autonomous Rendezvous and Docking	1	3	1
Stage-to-Stage Propellant Transfer			
Stage Refueling	9*		
Cryofluid Management	3	9	1
NTP Engine In-Space Operation	3	3	3
NTP Engine Life	3	3	1
NTP Engine Starts	9	3	1
Deep Space Comm			
G&C			
Radiation Levels vs Models	3	3	3
CONOPS	3	3	1
NTP Prox OPS			
Pre-fire	3	3	3
Post-fire	3	3	
Cost	Low	Medium	Medium
Mission Time	Months	Year	Years
Notes	3	3	3

Notes:
1. Where Habitat is used instead of simulator, the Habitat is also tested separately while these other missions occur.
2. System exercised through multiple returns to Gateway vicinity.
3. Useful mission performed in addition to NTP vehicle testing
* If reused for other missions

Figure 12. NTP Cargo Vehicle Shakedown Cruise / Demonstration Flight Options from the Gateway.

IV. MISSION OPTIONS – CREW NTP CORE SIZED FOR CARGO CAPABILITY USING LOP-G AGGREGATED HARDWARE

Because a cargo stage uses only one engine instead of the three engines on a crew stage, the cargo stage may be available prior to the crew stage. Consequently, missions 7 through 9 may occur before, during, or after missions 1 through 6. Figure 12 details the mission options using a core stage sized for cargo capability.

The cargo core stage is launched into LDHEO and then uses its RCS to transfer to the Gateway orbit. It then positions itself in a preplanned relation to the Gateway. The potential checkouts include autonomous rendezvous and docking with a payload or a payload simulator, cryo fluid management (CFM) data gathering (recording actual fluences and actual H_2 losses versus models), and communication and control. The cargo core stage is then available for checkout missions.

Mission 7, payload delivery to lunar orbit or the lunar surface, is suggested as a first checkout mission. The payload can be a real payload or a mass simulator. If it is a real payload, then this mission has a dual purpose and is useful in NASA's lunar campaign. If the mission is to lunar orbit only, then the cargo core stage is returned to the Gateway and the cargo core stage is available to be further checked out post mission with the additional resources available at the Gateway. The cargo core stage is then available for further checkouts through mission 8 or mission 9. For missions 8 and 9 the cargo core stage is not returned to the Gateway. Consequently, only one or the other of these missions can be performed if only one cargo core stage is used. Mission 8 is essentially a regular cargo mission to Mars. If performed prior to the Mars campaign, it can be used to preposition assets for other Mars missions; if performed as the Mars campaign is beginning; it is simply one of the scheduled Mars cargo missions.

An alternate use and checkout of the cargo core stage is to perform mission 9. Mission 9 is a deep space science mission and would benefit from the large payload capability of the NTP cargo stage. If the inline stage that was checked out in mission 1 is still available and not being used for the first Mars mission, then the inline stage can be attached to the cargo stage and a significantly larger ΔV, or a significantly heavier payload, or a significantly shorter trip time, or some combination of these, is available for the deep space mission. Figure 13 shows the Con-Ops for two deep space science missions (mission 9). Figure 14 shows example deep space science mission performance using either the NTP cargo core stage alone or the NTP cargo core stage and one inline stage. For the two examples shown, the payload performs the orbit insertion maneuvers at the destination. The departure burns are from the Periapse at LDHEO taking the payloads to hyperbolic escape for various trip times.

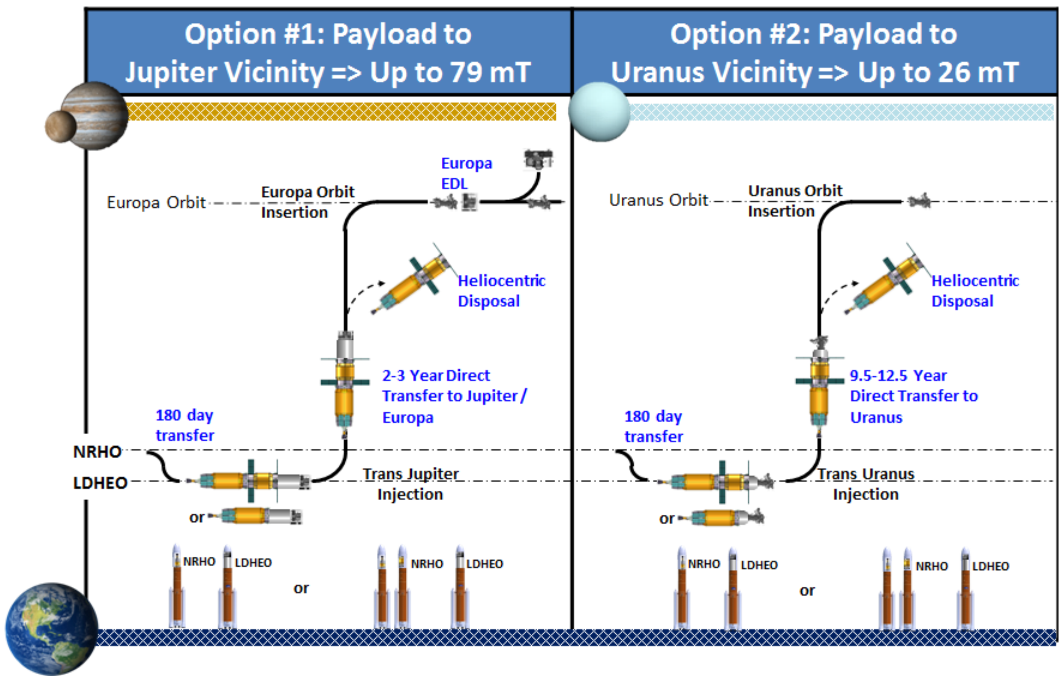


Figure 13. NTP Cargo Deep Space Missions.

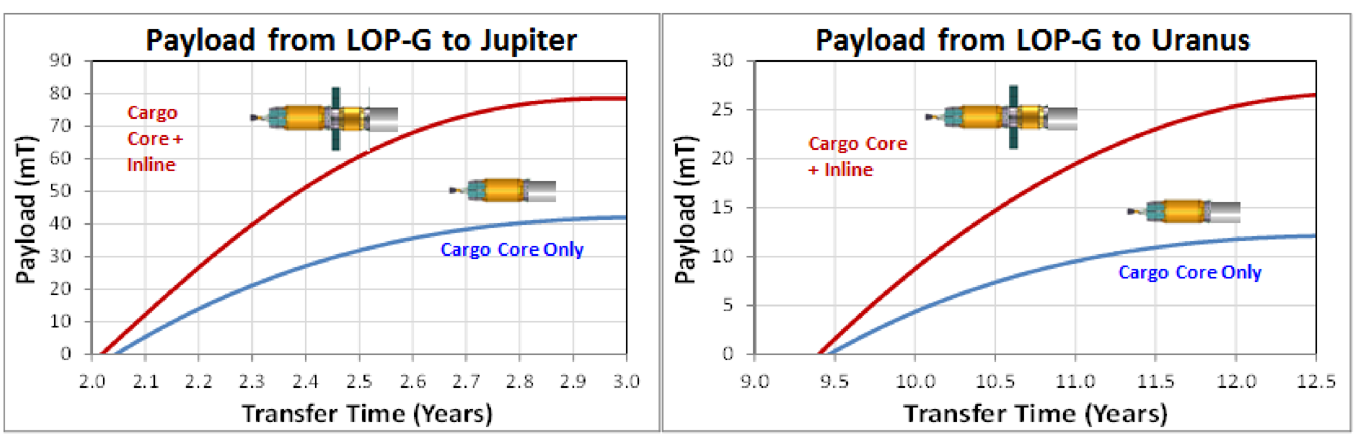


Figure 14. Example Deep Space Missions with NTP Cargo Stage.

V. NTP CORE CAPABILITY LAUNCHED OFF NASA SLS TO OUTER PLANETS DIRECTLY

AR in 2018 examined using the LEU NTP core stage from the Mars crew vehicle as a high-energy Earth escape stage flown off the NASA SLS Block 2 using a 8.4m PLF. The core stage was a duplicate of the Mars crew core stage with the exception of using only one 25,000-lbf NTP engine system and no external shield. Trajectory studies focused on examining how much payload increase would be possible and how payload and transit time traded. Figure 15 shows an example of the LEU NTP deep-space core stage with one LEU NTP engine system. The stage tank diameter was maintained at 7 meters, the LH_2 propellant load was held at ~14 mT useable and the stage total wet mass was ~31 mT.

Figure 15. Deep Space NTP Stage for Direct Missions off NASA SLS Block 2.

Figure 16 illustrates the combined LEU NTP core stage and how the deep space payload can fit within the NASA SLS 8.4 meter PLF. Note that the Juno spacecraft had an approximate cylindrical volume around 4 meters by 4 meters when launched.

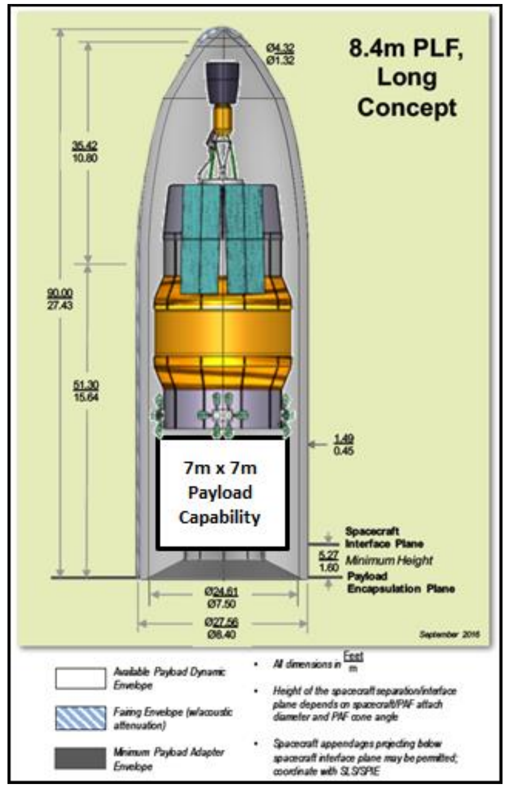


Figure 16. Deep Space NTP Stage in the NASA SLS Block 2 8.4meter PLF.

Example missions to Jupiter and Uranus were used to examine the payload and transit time trades with the LEU NTP core stage. The NASA SLS Block 2 put the stage and payload into an escape orbit Periapse. The LEU NTP core stage then performed an escape (e.g., TJI or TUI - single burn) maneuver from that Periapse immediately.

Figure 17 shows the performance variations for a Jupiter orbiter mission and the Con-ops scenarios using the NASA SLS. Figure 18 shows the performance variations for the Uranus orbiter mission and the Con-ops scenario using the NASA SLS.

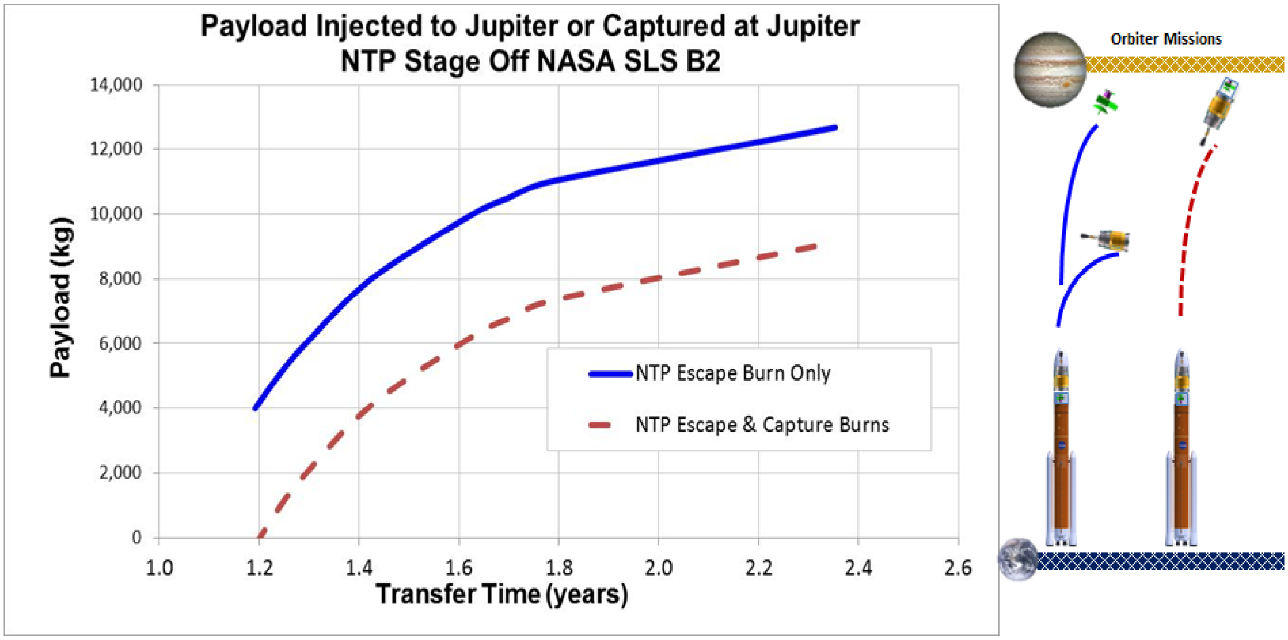


Figure 17. Deep Space NTP Stage for Jupiter Orbiter Missions using NASA SLS Block 2.

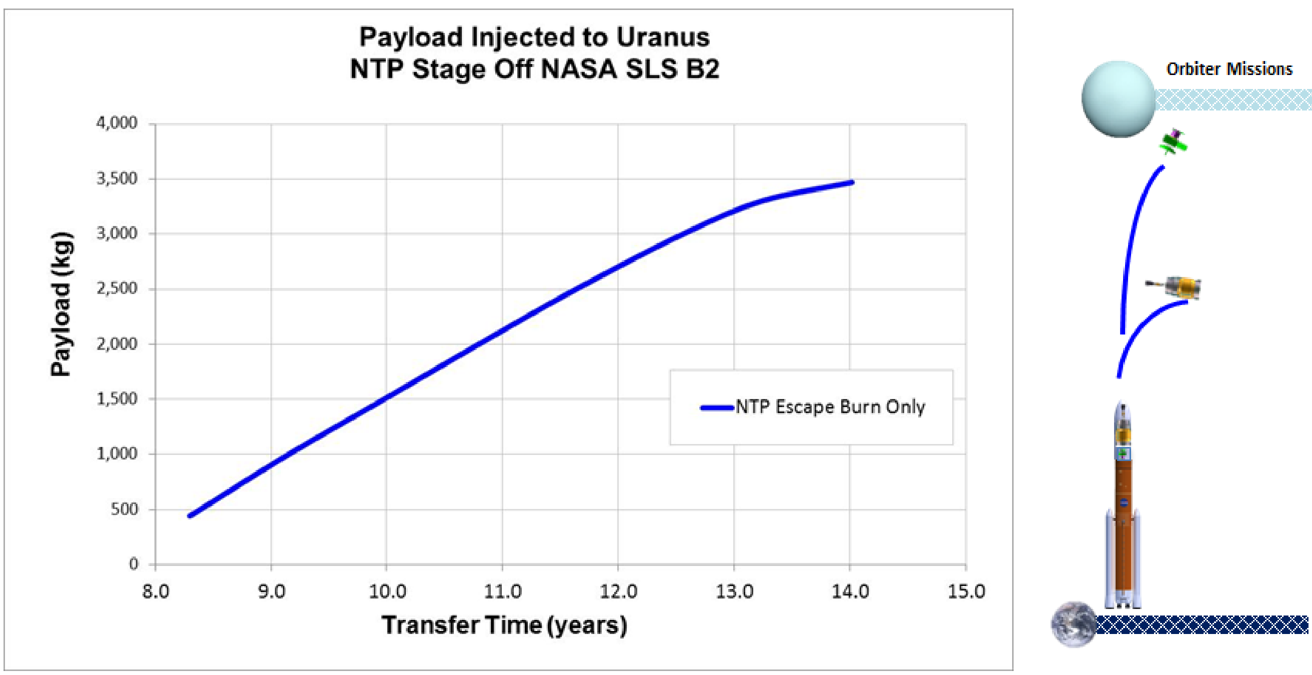


Figure 18. Deep Space NTP Stage Uranus Orbiter Missions using NASA SLS Block 2.

Figure 17 shows two scenarios for the Jupiter missions. The top curve (blue solid) shows a variation from quick ~1.2 year missions to a typical low energy Holmann-type transfer to Jupiter where the LEU NTP stage lets the orbiter perform the capture burn at Jupiter. The shortest transit time to Jupiter orbit insertion (~60-day period) shows a payload capability slightly larger than the Juno spacecraft but the orbiter gets to Jupiter nearly 4 years sooner. The typical low energy trajectory shows a NTP mission capability over 12 mT, about 2.5 times the mass of Juno (~3.6 mT) and still 2 years sooner and no major deep space maneuvers, Earth fly-bys, or gravity assist are required. If the LEU NTP core stage keeps the hardware on-board (e.g., cryo-cooler, additional RCS, etc.) to hold the hydrogen propellant at the cryogenic state, the stage can perform both the escape and capture burns. This full-up core stage can deliver a Juno-size (3.6 mT) spacecraft at Jupiter within 1.4 years (dotted red line). This ~4 mT spacecraft is now able to carry more instrumentation due to needing less propellant. The trade is between more investigation time at Jupiter or getting to Jupiter sooner, CFM technology versus more scientific instruments on the spacecraft, or additional probes that could be studying more about Jupiter and the moons. These are missions direct to Jupiter in at least one-third the typical lowest energy direct mission off a single NASA SLS Block 2.

Figure 18 provides a similar comparison but due to the extreme distance to the Uranus system, only injection of a spacecraft that could perform the capture burns was considered. A typical low energy direct transfer to the vicinity of Uranus can take 14 to 16 years. Using the LEU NTP core stage modified for only performing escape burns, a Juno size orbiter can be put into orbit (~20-day period) around Uranus in less than 14 years. If a faster mission is needed, the LEU NTP stage can inject a New Horizon size orbiter toward Uranus with a mission transit time near 8.5 years. These are orbiter missions to the icy giant Uranus, not fly-bys. All this mission capability allows more data faster, leading to spending the mission funding on getting more science and providing the opportunity to fly more science missions to the outer planets off the NASA SLS launch system.

VI. FUTURE WORK

Future work will continue on the reactor cores and examine other materials to improve the life and operability for crew and cargo missions using LEU NTP. This work will build off the previous design work performed with NASA, USNC and other team members on the LEU NTP program.

AR is continuing the LEU NTP work in 2019 with industry teammates and NASA to add increased fidelity and further evolve the NTP design with more mechanical and aerothermal design efforts and examining the transient start and stop performance of specific designs. Work is expected to continue in 2019 on examining various Lunar and Mars mission architectures, examining more about how using the Gateway can provide early NTP vehicle demonstration opportunities, and optimizing the core stage design for alternative stand-alone missions like asteroid mining and interstellar precursor opportunities. Detailed concept of operations with NASA SLS and commercial launch systems is continuing and will examine other propulsion technology opportunities to create a more robust LEU NTP system. The 2019 architecture trade studies will provide more data on the LEU NTP design sensitivities to enable more accurate cost estimates for developing a prototype.

VII. SUMMARY

As has been shown the Lunar Orbital Platform-Gateway is a useful location for the development and maturation of an NTP for Mars exploration. The ability to have personnel available to conduct and manage tests and to examine hardware after testing, along with the location in deep space provides many advantages.

The LEU NTP approach has been shown to be technically feasible based on work from 2016 to 2018. Significant conceptual design evaluations have been completed for the LEU NTP design approach at 25,000-lbf thrust and have shown high Isp potential, and can have thrust to weight ratios at or above 3.0:1.

Trades have been performed showing that a NTP can be used for Mars architectures for crewed missions using a 25,000-lbf (111 kN) NTP engine system. LEU NTP MTV stage elements create a flexible robust capability that can create affordable stage configurations for multiple missions.

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REFERENCES

[1] Joyner II, C. R., Jennings, T., Levack, D. J. H., "An Examination of the Engine Cycle Trends for a HEU and LEU NTP", ANS Proceedings of Nuclear and Emerging Technologies for Space, Huntsville, Alabama, February 22-25 2015.

[2] Horton, J. F., Joyner II, C. R., Kokan, T., Levack, D. J. H., Muzek, B. J., Widman, F., "Mars NTP Elements Using Lunar Orbital Platform-Gateway", AIAA Space 2018 Conference and Exposition, September 17-19, 2018, Orlando, Florida, AIAA 2018-5105.

[3] Anonymous, "NASA Lunar Orbital Platform-Gateway",https://www.nasa.gov/topics/moon-to-mars/lunar-outpost, Reference obtained 07/05/2018.

[4] Joyner II, C. R., Eades, M., Horton, J., Jennings, T., Kokan, T., Levack, D. J. H., Long, M., Widman, F., "Update on Approaches for LEU NTP Engine Systems and Exploration Implications", ANS Proceedings of Nuclear and Emerging Technologies for Space, Las Vegas, Nevada, February 26-March 1, 2018.

[5] Percy, T. K., Melissa, M., Polsgrove, T., "In-Space Transportation for NASA's Evolvable Mars Campaign", AIAA Space 2015 Conference and Exposition, August 31-September 2, 2015, Pasadena, California, AIAA 2015-4519.

[6] Polsgrove, T. P., Waggoner, J. D., Smitherman, D. V., Percy, T. K., "Transit habitat Design for Mars Exploration", AIAA Space 2018 Conference and Exposition, September 17-19, 2018, Orlando, Florida, AIAA 2018-5143.

[7] Cucinotta, F. A., Myung-Hee, Y. K., Ren, L., "Managing Lunar and Mars Mission Radiation Risks-Part I: Cancer Risks, Uncertainties, and Shielding Effectiveness", NASA TP-2005-213164, July 2005.