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Robotic Planetary Science Missions Enabled With Small NTR Engine/ Stage Technologies

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ROBOTIC PLANETARY SCIENCE MISSIONS ENABLED WITH SMALL NTR ENGINE/STAGE TECHNOLOGIES

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Abstract

The high specific impulse (Isp) and engine thrust-to-weight ratio of liquid hydrogen (LH_2)-cooled nuclear thermal rocket (NTR) engines makes them ideal for upper stage applications to difficult robotic planetary science missions. A small 15 thousand pound force (klbf) NTR engine using a uranium-zirconium-niobium "ternary carbide" fuel (Isp ~960 seconds at ~3025 K) developed in the Commonwealth of Independent States (CIS) is examined and its use on an expendable injection stage is shown to provide major increases in payload delivered to the outer planets (Saturn, Uranus, Neptune and Pluto). Using a single "Titan IV-class" launch vehicle, with a lift capability to low Earth orbit (LEO) of ~20 metric tons (t), an expendable NTR upper stage can inject two Pluto "Fast Flyby" spacecraft (PFF/SC) plus support equipment--combined mass of ~508 kg--on high energy, "6.5-9.2 year" direct trajectory missions to Pluto. A conventional chemical propulsion mission would use a liquid oxygen (LOX)/LH_2 "Centaur" upper stage and two solid rocket "kick motors" to inject a single PFF/SC on the same Titan IV launch vehicle. For follow on Pluto missions, the NTR injection stage would utilize a Jupiter "gravity assist" (JGA) maneuver to launch a LOX/liquid methane (CH_4) capture stage (Isp ~375 seconds) and a Pluto "orbiter" spacecraft weighing between ~167-312 kg. With chemical propulsion, a Pluto orbiter mission is not a viable option because of inadequate delivered mass. Using a "standardized" NTR injection stage and the same single Titan IV launch scenario, "direct flight" (no gravity assist) orbiter missions to Saturn, Uranus and Neptune are also enabled with transit times of 2.3, 6.6, and 12.6 years, respectively. Injected mass includes a storable, nitrogen tetroxide/monomethyl hydrazine (N_2O_4/MMH) capture stage (Isp ~330 seconds) and orbiter payloads 340 to 820% larger than that achievable using a LOX/LH_2-fueled injection stage. The paper discusses NTR technology and mission characteristics, shows NTR stage and payload accommodations within the 26.2 m long Titan IV payload fairing, and discusses NTR stage performance as a function of assumed cryogenic tank technology.

INTRODUCTION

The NTR has been identified in both the "90-Day Study Report" (NASA 1989) and the "Synthesis Group Report" (Synthesis Group 1991) as a critical technology enabling reduced trip time/minimum initial mass in LEO (IMLEO) missions to Mars. The benefits of NTR propulsion for human lunar exploration missions was also documented by NASA Lewis Research Center (Borowski 1991), and an integrated Moon/Mars exploration strategy was proposed (Borowski et al. 1992 and 1993) to reduce space transportation system (STS) development time and cost. In the integrated approach, a "modular" NTR-based STS would be developed which used "standardized" engine and stage components in a "building block" fashion to configure a wide variety of single and multi-engine lunar and Mars vehicles. Clusters of two to four 15 to 25 klbf NTR engines were shown to be sufficient for most of the lunar and "multi-perigee burn" Mars mission scenarios then under consideration by NASA.

In this paper, the benefits of using a single engine, 15 klbf NTR-powered injection stage and Titan IV launch vehicle combination to improve "robotic" science missions to the outer planets (Saturn, Uranus, Neptune and Pluto) is examined. An "expendable mission mode" is baselined here with the NTR upper stage providing primary propulsion for payload injection only. The expendable scenario: (1) reduces engine burn time requirements; (2) eliminates the need for reactor restart and cooldown propellant; (3) allows higher fuel operating temperatures when necessary; and (4) reduces stage thermal protection system (TPS) complexity because long term LH_2 propellant storage is no longer a requirement. The ground facilities for testing a 15 klbf NTR with closed effluent treatment system are also expected to be developed more quickly and at lower cost (<$200 million) due to the reduced engine size, burn duration and effluent throughput (Buden et al. 1993).

US/CIS NTR ENGINE CONCEPT/OPERATING CHARACTERISTICS

The NTR functions by raising low molecular weight hydrogen propellant to high pressure in a turbopump assembly, passing it through a high power reactor where it is heated to high temperature, and then exhausting it through a nozzle at high velocity (twice that of conventional LOX/LH_2-fueled chemical rockets) to generate thrust. Between 1955 and 1973, the United States' Rover/NERVA (Nuclear Engine for Rocket Vehicle Application) nuclear rocket programs conducted numerous reactor and integrated engine system tests which demonstrated the operational characteristics required for robotic, as well as, human exploration missions. The majority of experimental tests were performed using a "graphite" fuel consisting of pyrocarbon coated uranium carbide fuel particles dispersed in a graphite substrate, and operated at hydrogen exhaust temperatures as high as 2550 K (Koenig 1986).

Four years after NERVA program initiation, a NTR technology program was started in the former Soviet Union known today as the Commonwealth of Independent States (CIS). The CIS has conducted extensive nuclear and non-nuclear tests, including fuel element and reactor tests at the Semipalatinsk facility in Kazakhstan (Clark et al. 1993). Although integrated engine system tests were not conducted, a high performance ternary carbide fuel element (with maximum temperature capability of ~3200 K) was developed and a hydrogen exhaust temperature (T_{ex}) of ~3100 K for over one hour was demonstrated (Clark et al. 1993) in reactor tests. By contrast, the NRX-A6 NERVA developmental reactor operated at ~2350 K during its one hour endurance burn.

A joint US/CIS industry team of Aerojet, Energopool and Babcock and Wilcox developed a CIS NTR engine design (Culver et al. 1993) under NASA funding which utilizes a heterogeneous reactor core design with hydrogen-cooled zirconium hydride moderator and ternary carbide fuel materials. The CIS fuel assembly is an axial flow design containing a series of stacked 47 mm diameter bundles of thin (~1 mm) "twisted ribbon" fuel elements ~2 mm in width by 100 mm in length. The "fueled length" and power output from each assembly is determined by specifying the engine thrust level and hydrogen exhaust temperature (or desired Isp). For a 15 klbf engine, 34 fuel assemblies (with 6 fuel bundles each) are used to generate the required 340 MWt of reactor power at an Isp of ~960 seconds.

The US/CIS NTR engine (NTRE) design utilizes a recuperated topping cycle (Culver et al. 1993) with a combination recuperator/gamma radiation shield, located atop the engine to provide the necessary turbine drive power. The 15 klbf CIS engine baselined in this study has a chamber pressure of 2000 psia, a nozzle area ratio of 300 to 1, and a 110% bell length nozzle. With today's demonstrated CIS fuel technology, a steady state vacuum Isp of ~960 seconds should be maintainable for ~1 hour at T_{ex} ~3025 K. The engine thrust-to-weight ratio, total length and nozzle exit diameter for the 15 klbf US/CIS NTRE are ~3.0, 4.3 m and 1.0 m, respectively.

OUTER PLANET MISSION APPLICATIONS

Pluto Fast Flyby (PFF) Mission

Considerable interest presently exists at NASA and the Jet Propulsion Laboratory (JPL) in a flyby mission of Pluto and its large moon Charon (Asker 1993). In addition to Pluto being the outermost and only planet in our solar system not yet visited by robotic spacecraft, it also appears to be the only world with an atmosphere that forms and decays during its orbital cycle. Planetary scientists predict that Pluto's thin, largely methane atmosphere (discovered in 1988) will condense out on the planet's surface in the 2015 to 2020 timeframe as Pluto journeys outward from the Sun. Pluto's last perihelion was in 1989 and with a 248 year period of revolution its atmosphere is not expected to reappear until approximately the year 2237.

Initial JPL plans for a PFF mission envision two lightweight spacecraft (each ~164 kg) launched separately on "fast" direct trajectories to the Pluto-Charon system. Each spacecraft would require a Titan IV/Centaur launch vehicle and utilize two solid-fuel "kick motors" (Star 48B and Star 27) to achieve the high injection ΔV of ~12 km/s required for an 8 year trip time. With a 2001 launch date, Pluto flyby would occur in ~2009-2010. The two spacecraft are scheduled to encounter Pluto ~3.2 days apart, albeit at very high speed, and with Pluto's rotational period of 6.4 days, a "two spacecraft strategy" permits mapping of the entire planet. Initial costs for the PFF mission were estimated to be ~$1.35 billion which included $400 million for the spacecraft pair, $800 million for the two launch vehicles and $150 million for mission operations (Asker 1993). Using a 15 klbf CIS/NTRE injection stage, ~508 kg of payload mass (both PFF/SC and more) can be launched on a single Titan IV (see Table 1) eliminating the need for two Centaur upper stages, four solid fuel kick motors and an additional Titan IV. The single mission cost savings of ~$550 million would also provide a significant down payment toward US/CIS NTRE development and ground test facility construction which are estimated to cost ~$1.5 billion.

Table 1 illustrates the mission performance benefits of using lighter weight, higher strength materials, such as graphite/epoxy (Gr/Ep) and aluminum-lithium (Al/Li) in place of traditional aluminum (Al) alloys, for fabrication of LH_2 tank and stage structural components. Aluminum alloy 2219-T87 (F_{tu} = 62 ksi) is used extensively today in cryogenic tank construction. It has a relatively high strength-to-density ratio, good toughness and is weldable. It is also presently used in the LOX/LH_2 external tank of NASA's Space Shuttle. Aluminum-lithium alloy 2195 (F_{tu} = 90 ksi) is a candidate Al/Li alloy for cryogenic tank construction. It is a high strength, weldable alloy and has good fracture toughness. IM7/977-2 is a graphite/epoxy composite (F_{tu} ~91 ksi) consisting of carbon fiber and thermoplastically toughened epoxy. The chemical composition and structure of the IM7/977-2 laminate make it cryogenically tough and should make it resistant to radiation damage. Composite LH_2 tanks of graphite/epoxy have been developed and tested as part of the National AeroSpace Plane (NASP) program. The much lower density and increased strength of graphite/epoxy offers the potential for truly significant weight savings over Al and Al/Li LH_2 tanks sized for the same conditions. This weight savings can be leveraged to carry either more payload or more propellant allowing higher energy, shorter transit time missions to Pluto as shown in Table 1. Tank wall thickness and weight estimates were calculated assuming a maximum internal pressure of 35 psi (241.3 kPa) and included hydrostatic loads using a "4-g" launch load and a safety factor of 1.5. A 2.5% ullage was also assumed.

Using 2219-T87 Al for the NTR injection stage tankage and structure, two PFF/SC plus support equipment (~508 kg in all) can be launched in 2001 with a Pluto flyby occurring ~9.15 years later. The injection C_3 and ΔV requirements for this mission option are ~215.56 km²/s² and ~11.55 km/s, respectively. Included in the ΔV estimate are gravity losses amounting to ~985 m/s (~8.5% of the total ΔV) based on the conditions shown in Figure 1. The total injection stage length is ~19.7 m and includes the 13.5 m long LH_2 tank and the 4.3 m long 15 klbf CIS/NTRE. With ~3.0 m required for the two PFF/SC and support equipment, the total vehicle length is ~22.7 m which is within the ~23.9 m limit of the extended (86 ft/26.2 m) Titan IV fairing. The NTR injection stage TPS also includes 1.5 inches of PVC closed cell foam (at 1.0 inch) and multilayer insulation (MLI at 0.5 inches) required for "ground hold" thermal protection of "wet-launched" LH_2 tanks. The installed density of the TPS is ~1.625 kg/m² of LH_2 tank surface area. The total mass of the "wet" injection stage (minus its ~0.51 t payload) is ~19.49 t and includes the ~5.21 t "dry" injection stage (of which 2.56 t is the NTRE) and ~14.28 t of LH_2 propellant. A 15% contingency factor is also included in the weight estimates of both the engine and stage components.

TABLE 1. Pluto "Fast Flyby" (PFF) Mission Capability Using CIS/NTRE Injection Stage.

Tankage / Structural Material	Flight Time to Pluto (yrs.)/Injection C_3 (km²/s²)/ LH_2 Tank Length (m) / Total Vehicle Length (m)
2219 - T87 Al (ρ = 2821 kg/m³)	9.15 / 215.56 / 13.5 / 22.7
Al/Li Alloy 2195 (ρ = 2711 kg/m³)	8.30 / 233.21 / 13.8 / 23.0
IM7/977 - 2 Gr/Ep (ρ = 1577 kg/m³)	6.50 / 297.90 / 14.7 / 23.9

Assumptions:

1. Single Titan IV launch w/20 t to LEO (100 n. mi./185 km circular)
2. CIS/NTRE (Isp = 960 s @ 3025 K, F = 15 klbf, F/W_{eng} = 3.06, F/W_i = 0.34)
3. Payload: 508 kg (2 - PFF/SC w/adaptors + 173 kg for separation propulsion unit)
4. NTR stage TPS: 1" PVC foam + 0.5" MLI @ 1.625 kg/m²
5. Tank geometry: 4.6 m dia. cylinder √ 2/2 domes (includes 2.5% ullage)
6. Max. total vehicle length: ~ 23.9 m available w/86' Titan IV fairing

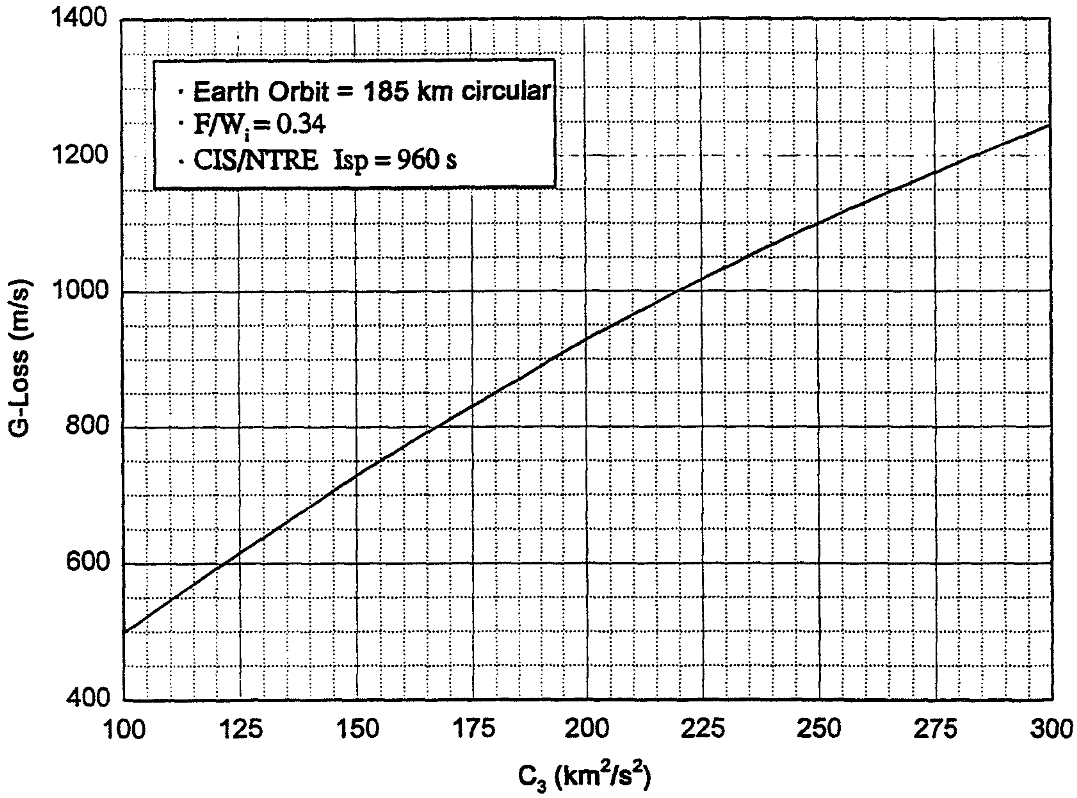

FIGURE 1. Gravity Loss Variation With Injection C_3 for Outer Planet Missions.

For the same IMLEO, payload and 2001 launch date, shorter Pluto transit times of 8.3 and 6.5 years are achievable using Al/Li and Gr/Ep tankage and structure, respectively. With Al/Li, the stage "dry" mass decreases to 4.89 t while the LH_2 propellant load increases to ~14.60 t. Similarly for Gr/Ep, the stage "dry" mass drops to ~3.89 t while the LH_2 propellant load increases to ~15.60 t. The stage mass fractions (minus the NTRE) for the Al, Al/Li and Gr/Ep systems are ~15.7, 13.8 and 7.9%, respectively, and the corresponding engine burn times for the Pluto injection maneuver are ~33.3, 34.0 and 36.2 minutes.

Pluto Orbiter Mission

While a flyby mission to Pluto will provide extremely valuable initial data, the small size of the PFF/SC and their short encounter time will impose significant limitations on their data gathering ability. Follow-up orbiter missions in the 2015 to 2020 timeframe with larger scientific payloads would provide a more comprehensive and detailed look at the Pluto/Charon system. The use of NTR propulsion for a Pluto orbiter mission has been examined previously by Zubrin and Sulmeisters (1992) assuming NERVA-derivative reactor (NDR) technology and by Venetoklis and Nelson (1993) with particle bed reactor (PBR) technology. Of the three NTR technologies, PBR, NDR, and now CIS, only the NDR and CIS concepts have undergone "proof-of-concept" validation and significant nuclear testing.

Pluto orbiter mission data using an expendable 15 klbf CIS/NTRE injection stage, a LOX/CH_4 capture stage and single Titan IV launch is summarized in Table 2 for different tank material and trip time combinations. With a December 2004 launch and a JGA maneuver at ~15 Jupiter radii, spacecraft can be in orbit around Pluto in the 2017 to 2018 timeframe--13 to 14 years after launch. The injection C_3, total ΔV and gravity losses for the 13 year mission are 108.26 km^2/s^2, 7.902 km/s, and 0.538 km/s (~6.8% of the total ΔV), respectively, and decrease to 106.4 km^2/s^2, 7.831 km/s and 0.529 m/s for the 14 year mission. A "2 stage" LOX/CH_4 capture system ("core" stage plus drop tanks) with 10% stage mass fraction and Isp = 375 seconds is used to place the scientific payload into a 1650 km by 3000 km parking orbit around Pluto (~1.1 by 2 Pluto radii). For 13 and 14 year transit times the arrival V-infinity values are 9.693 and 8.767 km/s, respectively, and the corresponding capture ΔV values are 8.870 and 7.951 km/s. An extra 200 m/s is also added to the capture ΔV budget to accommodate midcourse corrections.

TABLE 2. Pluto "Orbiter" Mission Capability Using CIS/NTRE Injection Stage.

Tankage / Structural Material	Pluto Orbiter / "Dry" Capture Stage / LOX/CH_4 Propellant Mass (kg)	
	13 yrs.	14 yrs.
2219 - T87 Al (ρ = 2821 kg/m^3)	167 / 351 / 3159	244 / 350 /3149
Al/Li Alloy 2195 (ρ = 2711 kg/m^3)	177 / 376 / 3384	262 /374 / 3367
IM7/977-2 Gr/Ep (ρ = 1577 kg/m^3)	212 / 450 / 4043	312 / 446 / 4013

Assumptions:

1. Single Titan IV launch w/20 t to LEO (100 n.mi./185 km circular)
2. CIS/NTRE (Isp = 960 s @ 3025 K, F = 15 klbf, F/W_{eng} = 3.06, F/W_i = 0.34)
3. NTR stage TPS: 1" PVC foam + 0.5" MLI @ 1.625 kg/m^2
4. Tank dimensions: 4.6 m dia. x 11.1 m length (includes 2.5% ullage)
5. NTR stage length: 17.3 m w/6.6 m available for LOX/CH_4 capture stage (w/10% stage mass fraction / Isp = 375 s) + orbiter

An expendable NTR-powered injection stage with its Pluto orbiter spacecraft and LOX/CH_4 capture stage payload is depicted within the 26.2 m Titan IV fairing in Figure 2. The injection stage LH_2 tank has a 4.6 m diameter, an ~11.1 m length with √2/2 ellipsoidal domes and a propellant capacity of ~11.47 t including a 1% reserve. It also includes: (1) a forward conical payload adaptor housing avionics, power and an attitude control system (ACS) for orientation control during the trans-Jupiter injection (TJI) burn; (2) forward and aft cylindrical band skirts; and (3) a rear conical adaptor or "thrust structure" for transferring in-space thrust loads from the 15 klbf CIS/NTRE to the injection stage. The overall NTR stage length is ~17.3 m. The LOX/CH_4 capture stage consists of an "in-line" 2-tank "core vehicle" and 6 "drop" tanks which are jettisoned half way through the Pluto capture burn. With an oxygen-to-methane propellant ratio of 3.6, three CH_4 tanks and five LOX tanks are required each having a height equal to 3 tank radii. The overall length of the capture stage and orbiter spacecraft (assumed here to be ~1.2 m) is <4.8 m and can grow to as much as 6.6 m before reaching the 23.9 m maximum payload length limit.

Table 2 shows the distribution of total injected payload mass between the orbiter spacecraft, the "dry" capture stage and LOX/CH_4 propellant load for different Pluto trip times and tank material combinations. With an injection stage of 2219-T87 Al, ~3.68 t of payload can be sent to Pluto in 13 years using a JGA maneuver. The payload includes a 167 kg orbiter SC and a 3510 kg "wet" capture stage containing 3159 kg of LOX/CH_4 propellant. Extending the transit time to 14 years increases the injected payload and reduces the capture ΔV requirements resulting in an ~46% increase in orbiter SC mass to 244 kg. With a Gr/Ep injection stage, the orbiter mass can be increased an additional 27% to 212 kg and 312 kg for 13 and 14 year trip times, respectively. By contrast, a LOX/LH_2-fueled Centaur upper stage can only inject enough mass to allow placement of 35 kg in orbit around Pluto. This mass is considered too small for a viable orbiter spacecraft. Table 2 demonstrates, rather convincingly, that a Pluto orbiter mission is enabled by NTR propulsion.

For the 13 year mission and Al tank option, the mass of the "wet" injection stage (minus payload) is ~16.32 t which includes the ~4.85 t "dry" stage (with 2.56 t NTRE) and ~11.47 t of LH_2 propellant. The same stage is used for the 14 year mission since it requires a comparable amount of propellant (~11.41 t). For Al/Li, the stage "dry" mass is ~4.59 t with mass decreasing to ~3.82 t for the Gr/Ep option. The corresponding stage mass fraction (minus the NTRE) for the Al, Al/Li and Gr/Ep systems are ~16.6, 15.0 and 9.9%, respectively, and the engine burn time requirement for the injection maneuver is ~26.7 minutes.

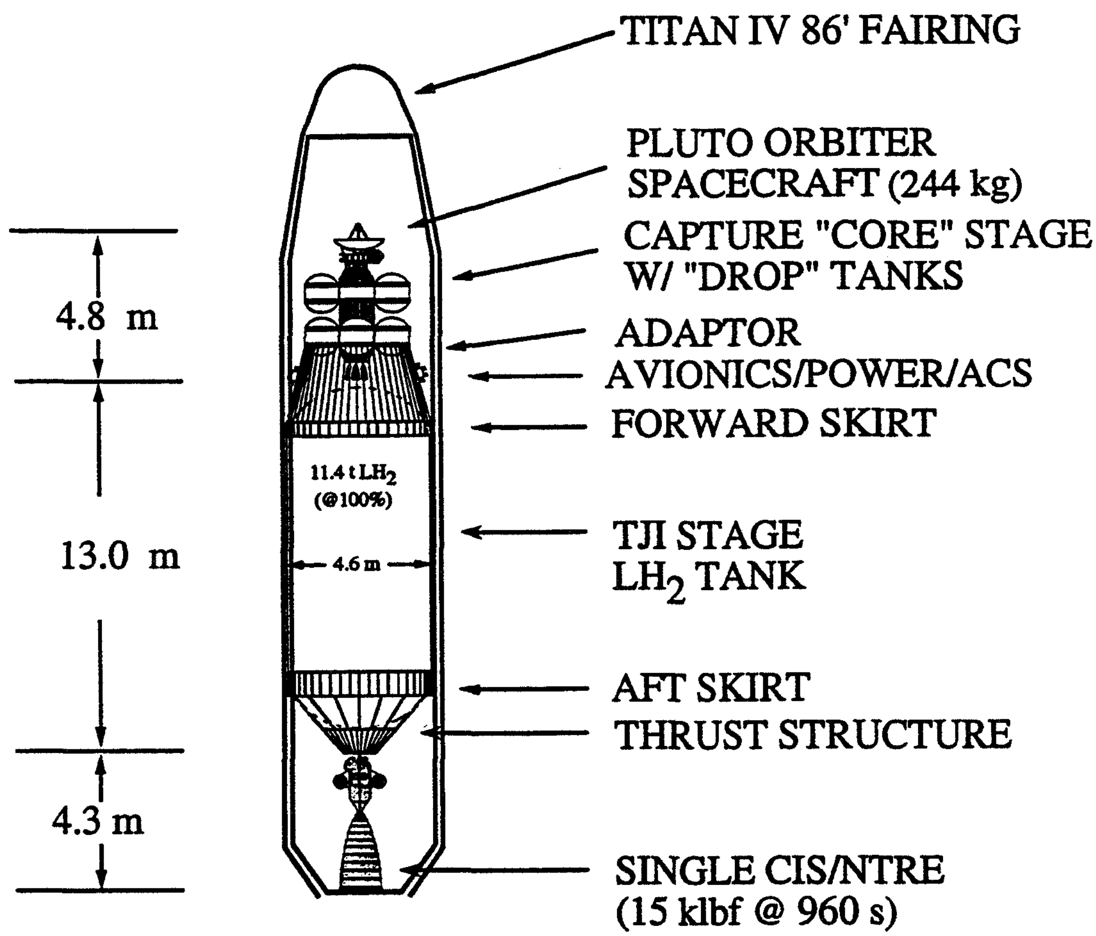

FIGURE 2. Packaging of NTR Injection Stage and Pluto Orbiter Payload in Titan IV Launch Vehicle.

Saturn, Uranus and Neptune Orbiter Missions

An NTR-powered injection stage can also enable high energy, "fast transit time" direct trajectory missions to the other planets of the outer solar system--Saturn, Uranus and Neptune. Direct orbiter missions (without gravity assists) are extremely difficult to accomplish with chemical propulsion because of the high injection ΔV requirements (>9.5 km/s) and the limited amount of payload mass (<100 kg) which can be delivered to orbit. Direct trajectories also offer the mission designer continuous access to the outer planets with yearly launch opportunities, whereas Jupiter is only properly positioned to provide an outer planet trajectory assist for a certain period of time every 11.9 years.

Table 3 summarizes results for orbiter missions to Saturn, Uranus and Neptune using a common "fixed size" NTR injection stage, a storable propellant N_2O_4/MMH capture stage and a single Titan IV launch. The trip times examined here were reported previously by Zubrin and Sulmeisters (1992) assuming a circular orbit trajectory approximation, a constant injection C_3 of ~152 km²/s² and a 5% gravity loss. In this work, detailed trajectory analysis and "single burn" gravity loss estimates (shown in Figure 1) are included. For the same trip times, the injection C_3, total ΔV and gravity loss are: (1) 159.12 km^2/s^2, 9.726 km/s and 0.768 km/s, respectively, for Saturn; (2) 162.8 km^2/s^2, 9.850 km/s and 0.783 km/s for Uranus; and (3) 156.9 km^2/s^2, 9.649 km/s and 0.758 km/s for Neptune. Gravity losses account for ~8% of the total departure ΔV budget and the mission C_3 values, while higher, are approximately constant showing little variation with launch date. A single stage N_2O_4/MMH capture system with 8% stage mass fraction and Isp = 330 seconds is used to place the orbiter payloads into highly elliptical parking orbits (~2 x 500 planet radii). For arrival V-infinity values at Saturn, Uranus and Neptune of 14.61, 11.54 and

TABLE 3. "Outer Planet" Orbiter Mission Capability Using CIS/NTRE Injection Stage.

Tankage / Structural Material	Planetary Orbiter / "Dry" Capture Stage / N_2O_4/MMH Mass (kg)		
	Saturn (2.3 yrs.)	Uranus (6.6 yrs.)	Neptune (12.6 yrs.)
2219 - T87 Al (ρ = 2821 kg/m3)	341 / 126 / 1454	334 / 119 / 1374	779 / 96 /1105
Al/Li Alloy 2195 (ρ = 2711 kg/m3)	392 / 146 / 1674	387 / 138 / 1593	894 / 110 / 1267
IM7/977 - 2 Gr/Ep (ρ = 1577 kg/m3)	543 / 201 / 2317	542 / 194 / 2231	1228 / 151 / 1741

Assumptions:

1. Single Titan IV Launch w/20 t to LEO (100 n. mi./185 km circular)
2. CIS/NTRE (Isp = 960 s @ 3025 K, F = 15 klbf, F/W_{eng} = 3.06, F/W_i = 0.34)
3. Direct missions to Saturn, Uranus and Neptune w/injection C_3 = 159, 163 and 157 km^2/s^2, respectively
4. NTR Stage TPS: 1" PVC foam + 0.5" MLI @ 1.625 kg/m^2
5. Tank dimensions: 4.6 m dia. x 12.5 m length (includes 2.5% ullage)
6. NTR stage length: 18.7 m w/5.2 m available for N_2O_4/MMH capture stage (w/8% stage mass fraction / Isp = 330 s) + orbiter

8.85 km/s, respectively, the corresponding "ideal" capture ΔV values are 3.98, 3.92 and 2.22 km/s. These ideal values are increased by 10% to account for orbital capture gravity losses and an extra 200 m/s is also added to the capture ΔV budget to accommodate midcourse corrections.

Each mission class uses a "standardized" NTR injection stage which is sized by the Uranus orbiter mission. The LH_2 tank length and propellant capacity are ~12.5 m and ~13.1 t, respectively, and the overall NTR stage length is ~18.7 m. Table 3 again shows the distribution of injected payload mass between the orbiter spacecraft, the "dry" capture stage and the N_2O_4/MMH propellant load for the different outer planet missions and assumed stage materials. For the 2.3 year mission to Saturn, orbiter SC mass increases from ~341 kg to 543 kg in going from Al to Gr/Ep stage construction with similar results obtained for the 6.6 year Uranus mission. The "standardized" NTR stage also allows orbiter SC masses ranging from ~779 kg (with Al) to ~1228 kg (with Gr/Ep) to be placed in Neptune orbit after a 12.6 year transit time. By comparison, the use of a LOX/LH_2 chemical injection system (with a 15% stage mass fraction and Isp = 460 seconds) allows <100 kg to be delivered to Saturn and Uranus and <150 kg to Neptune for the same trip times.

The N_2O_4/MMH capture vehicle is a single stage four tank configuration with equal numbers of oxidizer and fuel tanks. The combined length of the capture stage and orbiter spacecraft is estimated to be between 3.2 and 3.5 m (assuming an ~1.2 m orbiter length) but can grow to as much as 5.2 m. Including the 18.7 m NTR injection stage, the maximum total vehicle length is estimated to be ~22.2 m. With a LH_2 propellant load of ~13 t for each of the missions considered, the stage mass fractions (minus NTRE) for the Al, Al/Li and Gr/Ep systems are ~16.2, 14.6 and 9.5%, respectively, and are ~0.4% less than that required for the Pluto orbiter mission. Finally, the engine burn time requirements for the trans-Saturn, -Uranus, and -Neptune injection maneuvers are relatively constant at ~30.3, 30.5 and 30.2 minutes, respectively.

SUMMARY AND CONCLUSIONS

This paper demonstrates quite dramatically that "exciting" orbiter missions to the outer planets can be "enabled" using NTR propulsion and further "enhanced" through the use of lightweight, high strength Al/Li and Gr/Ep materials for fabrication of LH_2 tank and stage structural components. With an expendable upper stage powered by a 15 klbf CIS/NTRE, over 500 kg of payload (the weight of two PFF/SC and more) can be delivered to Pluto in 6.5

to 9.2 years using a single "Titan-IV-class" launch vehicle. A NTR-powered upper stage can also inject sufficient payload to enable a Pluto orbiter mission in the 2015 to 2020 timeframe, with spacecraft weight between ~167 and 312 kg. Fast transit time, direct missions to Saturn, Uranus and Neptune are also possible with orbiter payloads 340 to 820% larger than those achievable using a LOX/LH_2-fueled Centaur upper stage. The operational requirements imposed by the above missions on the CIS/NTRE's hydrogen exhaust temperature and burn duration have already been exceeded in reactor tests in the CIS, and provide confidence that a NTR-powered upper stage can be developed faster, cheaper and better through a joint US/CIS development effort. Beyond the "scientifically robust" Galileo and Cassini orbiter missions to Jupiter and Saturn, and a possible fast flyby mission to Pluto, there await orbiter missions to Uranus, Neptune and Pluto. With the development of NTR and Gr/Ep tank technologies, continuous access to the outer solar system will become a reality and the next "great age" of planetary exploration reminiscent of the Voyager program will begin.

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13. ABSTRACT ***(Maximum 200 words)***

The high specific impulse (Isp) and engine thrust-to-weight ratio of liquid hydrogen (LH_2)-cooled nuclear thermal rocket (NTR) engines makes them ideal for upper stage applications to difficult robotic planetary science missions. A small 15 thousand pound force (klbf) NTR engine using a uranium-zirconium-niobium "ternary carbide" fuel (Isp ~960 seconds at ~3025K) developed in the Commonwealth of Independent States (CIS) is examined and its use on an expendable injection stage is shown to provide major increases in payload delivered to the outer planets (Saturn, Uranus, Neptune and Pluto). Using a single "Titan IV-class" launch vehicle, with a lift capability to low Earth orbit (LEO) of ~20 metric tons (t), an expendable NTR upper stage can inject two Pluto "Fast Flyby" spacecraft (PFF/SC) plus support equipment--combined mass of ~508 kg--on high energy, "6.5-9.2 year" direct trajectory missions to Pluto. A conventional chemical propulsion mission would use a liquid oxygen (LOX)/LH_2 "Centaur" upper stage and two solid rocket "kick motors" to inject a single PFF/SC on the same Titan IV launch vehicle. For follow on Pluto missions, the NTR injection stage would utilize a Jupiter "gravity assist" (JGA) maneuver to launch a LOX/liquid methane (CH_4) capture stage (Isp ~375 seconds) and a Pluto "orbiter" spacecraft weighing between ~167-312 kg. With chemical propulsion, a Pluto orbiter mission is not a viable option because of inadequate delivered mass. Using a "standardized" NTR injection stage and the same single Titan IV launch scenario, "direct flight" (no gravity assist) orbiter missions to Saturn, Uranus and Neptune are also enabled with transit times of 2.3, 6.6, and 12.6 years, respectively. Injected mass includes a storable, nitrogen tetroxide/monomethyl hydrazine (N_2O_4/MMH) capture stage (Isp ~330 seconds) and orbiter payloads 340 to 820% larger than that achievable using a LOX/LH_2-fueled injection stage. The paper discusses NTR technology and mission characteristics, shows NTR stage and payload accommodations within the 26.2 m long Titan IV payload fairing, and discusses NTR stage performance as a function of assumed cryogenic tank technology.

14. SUBJECT TERMS

Nuclear thermal rocket; NTR; Robotic science missions; Orbiter; Pluto fast flyby; Titan IV; Saturn; Uranus; Neptune

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