NTR Performance Parameters for Science, Cargo Delivery and Crewed Exploration Missions.

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Introduction: The Nuclear Cryogenic Propulsion Stage (NCPS) project funded under NASA's Advanced Exploration Systems (AES) program is focused on 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. By the end of FY'14, partial-length fuel elements will be fabricated and tested in the NTR Element Environmental Simulator (NTREES) [1] located at NASA's MSFC. NTREES will provide up to ~1.2 MW of RF heating to simulate the NTP thermal environment that includes exposure to hot H_2. NTREES will be used to screen candidate fuels and fuel element (FE) designs prior to beginning irradiation testing at the DOE.

In FY'13, NASA GRC and DOE's Idaho National Laboratory developed "Point-of-Departure" (POD) designs for small "criticality-limited" and full-size (~25 klb_f) engines using "heritage" FE designs for both fuel types. This analysis also included the expected axial power distribution along the FE length that can be used to tailor the RF heating profiles in NTREES when this testing begins. Engine performance parameters for robotic science, cargo delivery and crewed exploration missions were also developed using three different thrust-class composite fuel engines: 7.4 klb_f (criticality-limited), 16.7 klb_f (SNRE-class) and 25 klb_f (Pewee-class). These performance parameters are summarized in Table 1 and provide important information to help guide future non-nuclear and nuclear testing. A brief description of each engine type and the mission application are provided below.

Robotic Science: A key assumption in the NCPS project is that a "common" fuel element design will be developed that is scalable to higher thrust engines by increasing the number of elements in a larger diameter core that can produce greater thermal power output. Building and ground testing a small engine initially is seen as an affordable and sustainable strategy for NTP development. A small NTP engine and stage can also enhance the payload delivery capability for robotic science missions while also serving as a flight technology demonstration mission. The small ~7.4 klb_f engine has 14 hexagonal rows of FEs and tie-tubes (TTs), produces ~161 MW_t of thermal power and has a maximum fuel temperature of 2860 K [2]. The engine chamber pressure and nozzle area ratio (NAR) are assumed to be 6.89 MPa and 300:1, respectively. A small NTP stage using this class engine can deliver ~4 t of science payload to the near Earth asteroid (NEA) 2000 SG344. Launched on 10/6/23 on a Delta 4M (5,4), the IMLEO would be ~13.6 t [3]. Engine burn times and other key parameters are shown in Table 1.

Lunar Cargo Delivery: Cargo delivery missions using a reusable NTP stage were envisioned by Wernher von Braun in his "post-Apollo" Integrated Space Plan. A NCPS using three ~16.7 klb_f SNRE-class engines together with a supplemental in-line LH_2 tank can deliver ~60 t of cargo to LLO on each round trip mission [4]. Each SNRE-class engine has a FE to TT ratio of 2 to 1, produces ~367 MW_t of thermal power and has a maximum fuel temperature of 2860 K. The engine chamber pressure and NAR are assumed to be ~3.1 MPa and 300:1, respectively. With a fuel loading of ~0.6 g/cm^3, the total inventory of 93% enriched U-235 in the engine core is ~60 kilograms. Assuming ~1.2 grams of U-235 are consumed per megawatt-day of operation, the U-235 burn-up on each round trip mission is only ~15 grams indicating that significant reuse capability exists with these vehicles.

Crewed Lunar Landing: Using NTP can enable a fully reusable lunar architecture with all valuable in-space assets, including the single stage lunar descent / ascent vehicle (LDAV), being returned Earth orbit for refurbishment and reuse thereby reducing the cost of space travel not only for NASA but for future private sector endeavors as well. The crewed lunar NCPS uses the same three SNRE-class engines, has additional radiation shielding for crew protection, and includes a longer in-line LH_2 tank to carry the required propellant loading needed to transport the crewed MPCV/SM and LDAV out to the Moon and back [4]. The total engine burn time is also ~6 minutes longer than on the cargo mission because the crewed mission returns more payload back Earth orbit. Both missions require 5 engine burns with 4 restarts. Other key parameters are shown in Table 1.

Crewed NEA Mission: NTP can also be used for difficult, high energy NEA missions like Apophis in 2028. Apophis is of particular interest to NASA because on Friday, April 13, 2029, it will pass Earth's surface at an altitude of ~18,300 miles – within the orbits of geosynchronous communications satellites – and will return for another close Earth approach in

2036. Both expendable and reusable asteroid survey missions have been examined [3]. The NCPSs for these missions use three 25 klb_f "Pewee-class" engines based on an "axial growth" version of the SNRE [5]. The FEs are longer (1.32 m) than those used in the lower thrust engines (0.89 m) discussed above. The fuel loading is also reduced to 0.25 g/cm^3 allowing the maximum fuel tempearature to increase from 2860 K to ~3010 K and the engines' specific impulse to increase from 906 s to ~940 s. These values are based on an engine chamber pressure and NAR of ~6.89 MPa and 300:1, respectively. Also, with longer FEs and additional moderation resulting from using the SNRE's FE to TT ratio of ~2 to 1, the amount of U-235 mass in each engine core is reduced to just under 37 kilograms. For the expendable mission scenario, the total burn time on the engines is just under 44 minutes for the 4 required burns. For the reusable scenario, the total burn time increases to just over 77 minutes with 5 burns required as shown in Table 1.

Mars Cargo: For NASA's "7-Launch" Mars Design Reference Architecture (DRA) 5.0 study [6], two NTP cargo vehicles were used to pre-deploy surface and orbital assets to Mars before the crewed arrived. Each cargo vehicle used a single NCPS again with three 25 klb_f Pewee-class engines – like those used in the Apophis mission – to inject 103 t of payload plus aerobrake to Mars. The engines operated at a maximum fuel temperature of 2860 K, a chamber pressure of 6.89 MPa and a NAR of 300:1. The corresponding hydrogen exhaust temperature and engine specific impulse were 2790 K and 906 s, although higher performance levels are available if required as shown in Table 1. The total engine burn time for the "2-perigee burn" Earth departure is ~38 minutes.

Mars Piloted: The crewed Mars transfer vehicle (MTV) for the "7-Launch" Mars DRA [6] included the NCPS plus an integrated saddle truss and LH_2 drop tank to carry the propellant load needed for this round trip mission. Like the cargo vehicle, the NCPS uses three 25 klb_f Pewee-class engines plus it also carries additional radiation shielding to protect the crew. The baseline engine performance parameters for the crewed MTV are the same as used on the cargo MTV except for the number of burns and the total burn duration. The engines on the crewed MTV are also used for the Mars orbit capture and trans-Earth injection maneuvers. For this round trip mission, the 4 primary burns use ~178.4 t of LH_2 propellant. With 75 klb_f of total thrust and a I_{sp} of ~906 s, the total burn time on the engines is just under 80 minutes. The longest single burn is the first perigee burn at ~44.5 minutes. Overall, the performance requirements for a human Mars mission like DRA 5.0 are well under the ~2 hours accumulated burn time and 27 restarts demonstrated on the NERVA eXperimental Engine – the NRX-XE in 1969.

References:

[1] Houts M. G. et al. (2012) NETS-2012, #3093
[2] Schnitzler B. G. (2013) INL/EXT-13-28027.
[3] Borowski S. K. et al. (2012) AIAA-2012-5144.
[4] Borowski S. K. et al. (2013) AIAA-2013-5465.
[5] Schnitzler B. G. et al. (2009) AIAA-2009-5239.
[6] Borowski S. K. et al. (2009) AIAA-2009-5308.

Table 1. NTR Engine Performance Parameters for Science, Cargo Delivery and Crewed Exploration Missions

Requirements / Missions	Engine Thrust (klb_f)	T/W_{eng}	T_{ex} (°K)	I_{sp} (s)	No. Engines	Fuel Loading (gU/cm^3)	U-235 Mass (kg)	Longest Single burn (min)	Total burn duration (min)	No. burns
Robotic Science	**7.4**	**~1.9**	**2736**	**894**	**1**	**0.6**	**27.5**	**~22**	**~29.5**	**2**
Lunar Cargo	**16.7**	**~3.1**	**2726**	**900**	**3**	**0.6**	**60**	**~21.4**	**~49.2**	**5**
Lunar Piloted	**16.7**	**~3.1**	**2726**	**900**	**3**	**0.6**	**60**	**~20.9**	**~55**	**5**
NEA - *Apophis* Piloted	**25**	**~3.5**	**2790 - 2940**	**906-940**	**3**	**0.25**	**36.8**	**~25 - 37.2**	**~43.8 - ~77.3**	**4-5**
Mars Cargo	**25**	**~3.5**	**2790 - 2940**	**906-940**	**3**	**0.25**	**36.8**	**~22**	**~38**	**2**
Mars Piloted	**25**	**~3.5**	**2790 - 2940**	**906–940**	**3**	**0.25**	**36.8**	**~44.5**	**~79.2**	**4**