How Does Nuclear Thermal Propulsion (NTP) Work?

• Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
• Low molecular weight propellant – typically Hydrogen
• Thrust directly related to thermal power of reactor: 100,000 N ≈ 450 MW$_{th}$ at 900 sec
• Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
• Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O$_2$/H$_2$ engine runs much hotter than NTP)

NERVA Nuclear Thermal Rocket Prototype
Fission is Different from Previous NASA “Nuclear”

Radioisotope

Pu-238

U-234

5.5 MeV

α (He-4)

Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)
Natural decay rate (87.7-year half-life)

Long history of use on Apollo and space science missions
44 RTGs and hundreds of RHUs launched by U.S. during past 5 decades
Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
Used for both thermal management and electricity production

Fission

Neutron

U-235

Fissile Nucleus (U-235)

Neutrons (2.5)

γ

Product Nuclei (KE 168 MeV)

190 MeV*

γ

U-235

Heat Energy = 0.851 MeV/nucleon
Controllable reaction rate (variable power levels)

Used terrestrially for over 70 years
Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal (>20 GW-hr)
One US space reactor (SNAP-10A) flown (1965)
Former U.S.S.R. flew 33 space reactors
Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
At steady-state, 1 of the 2 to 3 neutrons released in the reaction causes a subsequent fission in a “chain reaction” process
Heat converted to electricity, or used directly to heat a propellant
Typical First Generation NTP Reactor Design

NERVA Reactor Cross Section

Fuel Segment Cluster

Control Drums

Control Drum Absorber Plate

Core

Reflector
20 NTP Engines Designed, Built, and Tested During Rover/NERVA
The most powerful nuclear rocket engine ever tested (Phoebus 2a) is shown during a high-power test. The reactor operated for about 32 minutes, 12 minutes at power levels of more than 4.0 million kilowatts. NTP reference system is ~0.5 million kilowatts.
Why is NTP Attractive for Human Missions to Mars?

- NTP allows for shorter total mission time and shorter trip time (Less exposure to galactic cosmic radiation and zero-g)
- NTP allows mission robustness and potential abort scenarios
- Fewer SLS launches can save operation time, money, and reduce risk
- NTP is initial step towards advanced space nuclear power and propulsion, which could eventually help enable exploration and development of the solar system
Why is NTP Attractive for Human Missions to Mars?
Recent Studies include:

- The Evolvable Mars Campaign (EMC) @ NASA HQ
- The Mars Transportation Analysis of Alternatives (AoA) @ MSFC
- The Mars NTP system study @ MSFC executed by Aerojet-Rocketdyne
Can NTP Exhaust Be Captured During a Ground Test?

Ground Test Exhaust Capture System

- Engine Containment
- Nuclear Thermal Engine
- Shielding
- Water Cooled Diffuser
- H₂O
- H₂O/O₂
- O₂
- O₂ Afterburner
- H₂ Flare
- Water Cooled Steel Ducts
- H₂O/O₂
- Heat Exchanger
- H₂O
- H₂O/O₂
- Reactor Debris Trap
- Exhaust Water Storage
- LO₂ Injection
- GO₂
- Desiccant Filter (GO₂ de-humidifier)
- LO₂
- LOX
- LN₂
- Post Test Boil-Off Vent to Air
- Post Test Process
- Water Filter
- Retention Pond (devoid of any radiological contamination)
Facility located at SSC’s A3 Test Stand

• Most of the infrastructure required by ground test facility (including exhaust capture) is already in place:
  • Tower, test cell, propellant, HPIW & data and controls infrastructure, the Test Control Center, electric power, etc.
  • Major modifications, procurements, and construction work will be required and are captured in the ROM estimate.
SSC’s Acoustic Buffer Zone
Illustration of Comparable NRC-Designated Planning Zones

13,800 Acre
Fee Area/“Exclusion Area”
(20 mi²)

“Fee Area” Avg. Radius ~ 2.5 mi

125,000 Acre
Buffer Zone/“Low-Population Zone”
(195 mi²)

“Buffer Zone” Avg. Radius ~ 7.9 mi

• Slidell, LA
  • Population ~ 27,000
  • PCD from A3 ~ 8 miles
=> LPZ < 6 miles

PCD (Population Center Distance ~8 miles) > 1.333 x LPZ ~ 1.333 x 6 miles ~ 8.0 miles

Ref.: NRC Regulatory Guide 4.7
Can NTP systems using Low-Enriched Uranium (LEU) be Developed?

• Directly reduce cost through savings related to safeguards and security

• Indirectly (and more significantly) reduced cost through enabling use of an optimal development approach and team

• Consistent with ongoing programs to convert operational Highly Enriched Uranium (HEU) systems to LEU

• Consistent with US policy. “The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes.” (2012 White House “Fact Sheet”)

Initial LEU Conceptual Designs Very Promising
Evolving LEU Designs Have Significant Potential Advantages

- Graded Mo to Mo/W approach reduces engine mass and need for W-184.
- Multiple potential cermet fuel fabrication options. Optimize for performance and affordability.
- Potential for dual-use core design. Optimize for NTP, but close derivatives potentially applicable to high performance space fission power systems.

Courtesy BWXT
Objective:
The overall goal of this three-year GCD technology project is to determine the feasibility and affordability of a Low Enriched Uranium (LEU)-based NTP engine with solid cost and schedule confidence.

Approach:
Leverages government, industry and academic expertise to achieve project objectives.

Success Criteria:
1. Demonstrate the ability to purify tungsten to 90 percent purity and determine the cost to produce a kilogram at that level of purity.
2. Determine the technical and programmatic feasibility of an NTP engine in the thrust range of interest for a human Mars mission.
3. Determine the program cost of a LEU NTP system and the confidence level of each major cost element.

Team:
MSFC (Lead), GRC, SSC, DoE, industry partners, academia

Milestones:
Tungsten purified to 50%; 70%; and 90%
Testing of Surrogate Cermet FE in CFEET (SEP17)
Testing of the DU Cermet FE in NTREES/CFEET (SEP18)
Observations

• Space fission power and propulsion systems are game changing technologies for space exploration.

• First generation NTP systems could provide significant benefits to sustained human Mars exploration and other missions.
  – Imagine Earth-Mars transit times of 120 days; imagine 540 day total Mars mission times; imagine reduced crew health effects from cosmic radiation and exposure to microgravity; imagine robust architectures including abort capability.

• Advanced space fission power and propulsion systems could enable extremely ambitious space exploration and development.