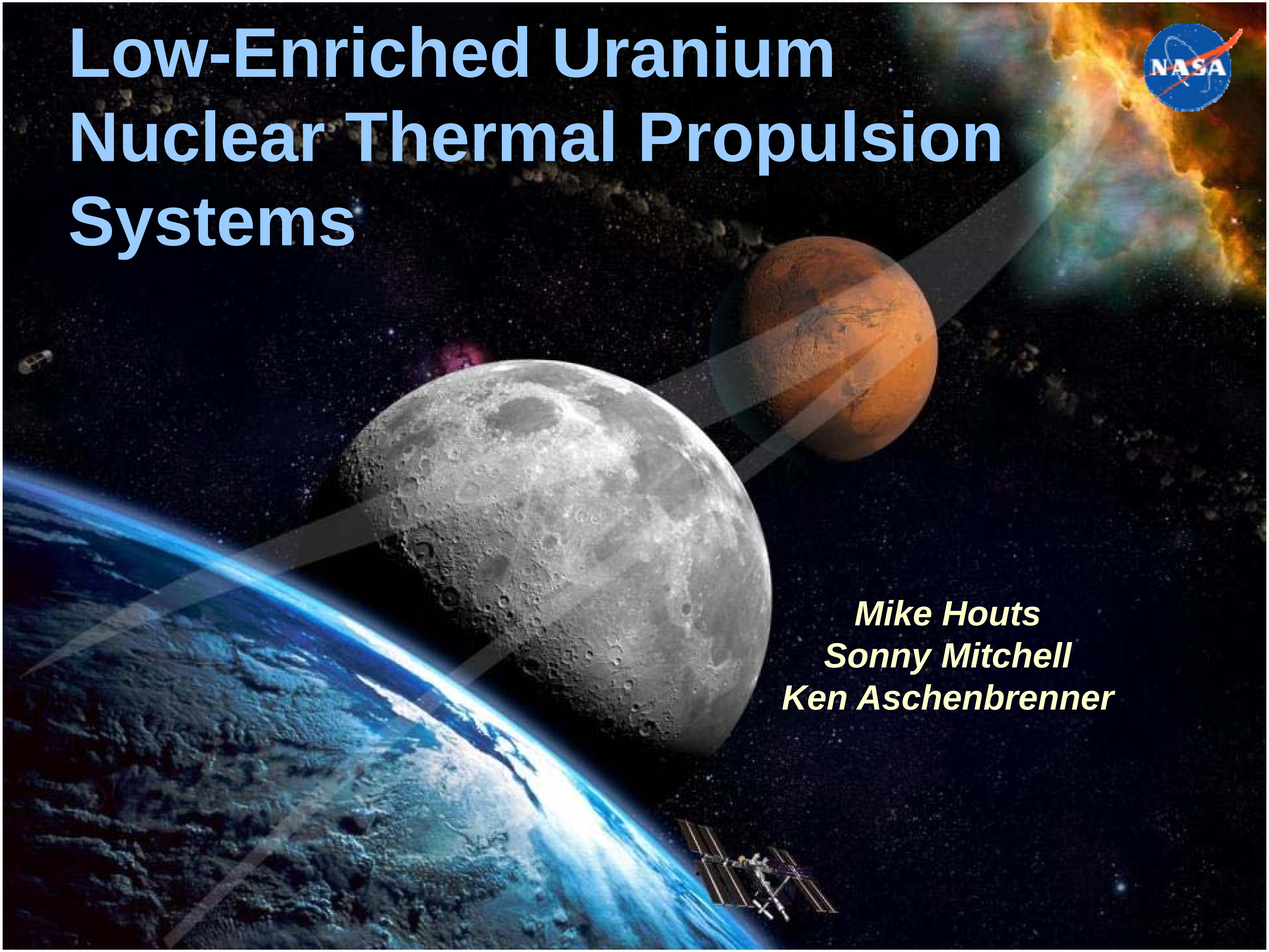
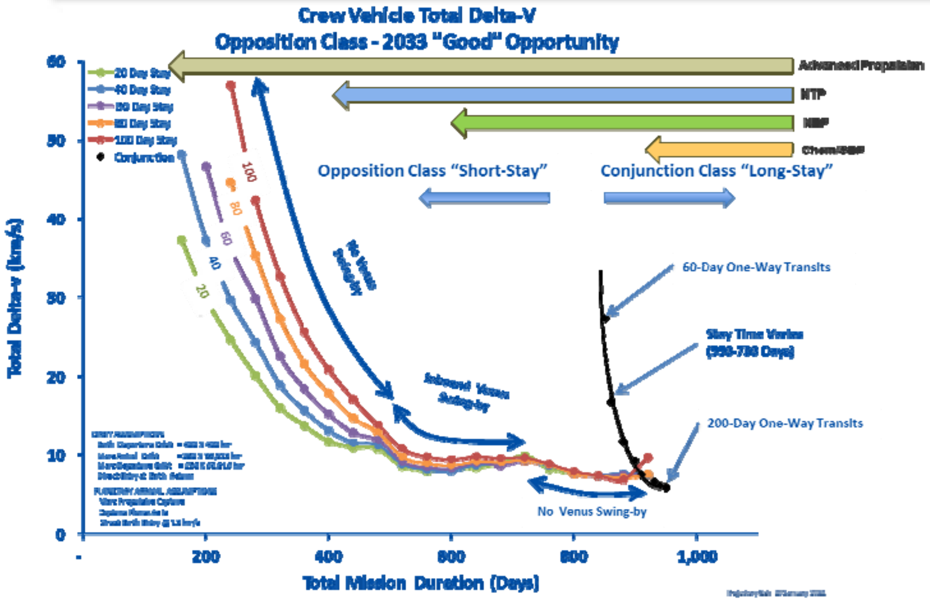
Low-Enriched Uranium Nuclear Thermal Propulsion Systems

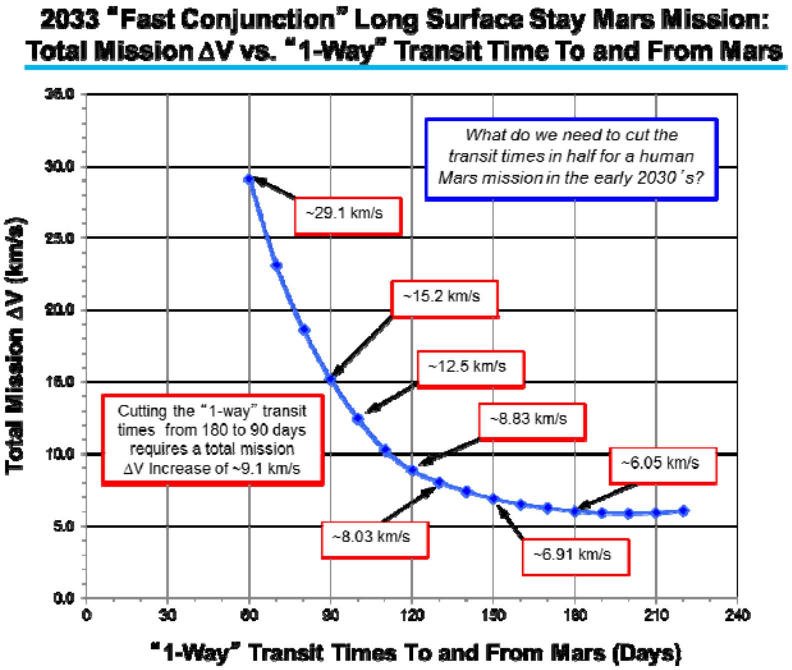


Mike Houts
Sonny Mitchell
Ken Aschenbrenner

Why is NTP Attractive for Human Missions to Mars?



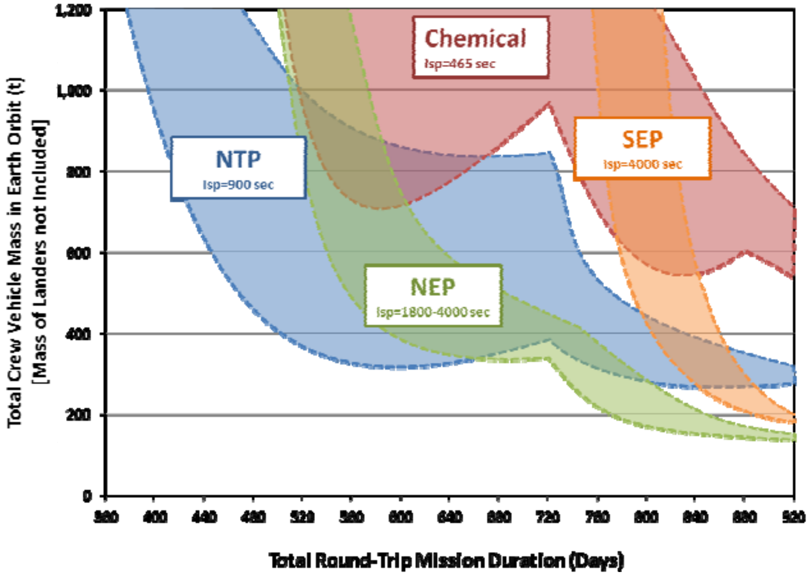
Crew Vehicle Total Delta-V
Opposition Class - 2033 "Good" Opportunity



2033 "Fast Conjunction" Long Surface Stay Mars Mission:
Total Mission ΔV vs. "1-Way" Transit Time To and From Mars

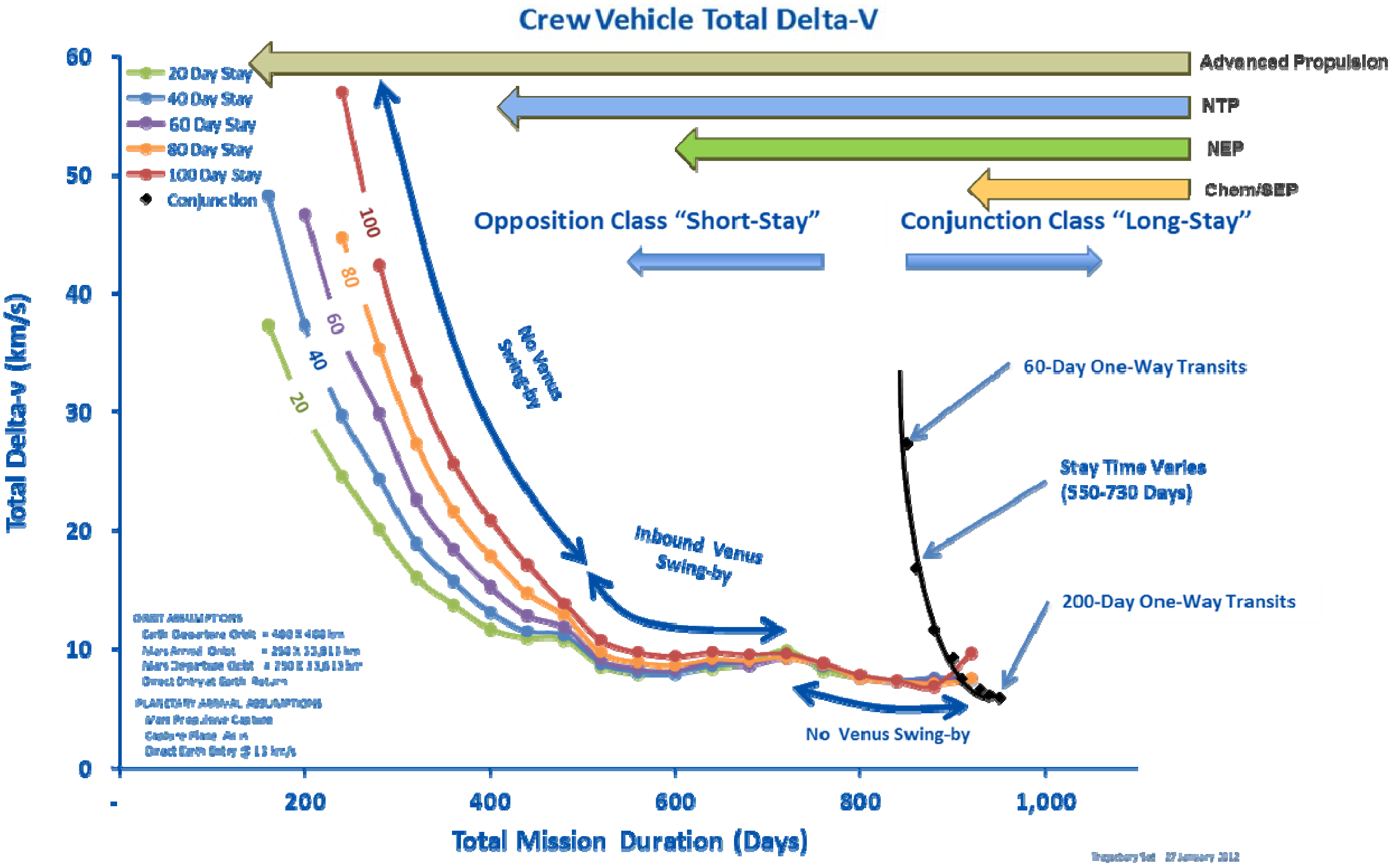
Ref: Borowski et al., Space 2013, AIAA-2013-5354

Short Stay Opposition Mission with Earth Departure Dates 2028-2045



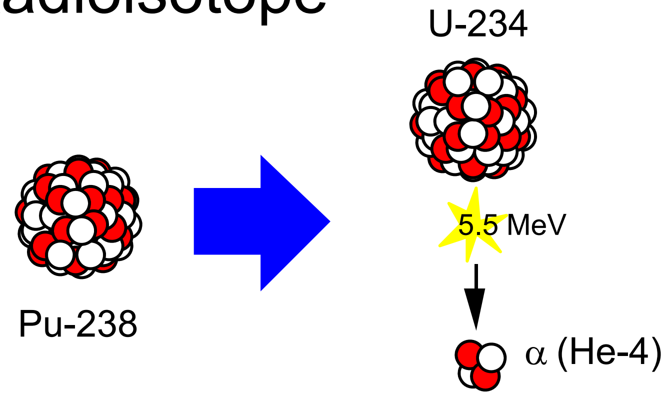
- **NTP allows for shorter total mission time and shorter trip time (Less exposure to galactic cosmic radiation and zero-g)**
- **NTP allows mission robustness and potential abort scenarios**
- **Fewer SLS launches can save operation time, money, and reduce risk**
- **NTP is initial step towards advanced 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?



Fission is Different from Previous NASA “Nuclear”

Radioisotope

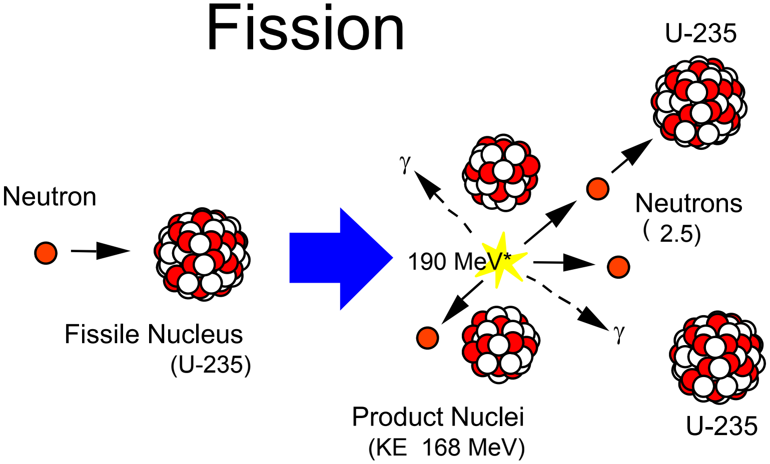


Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

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



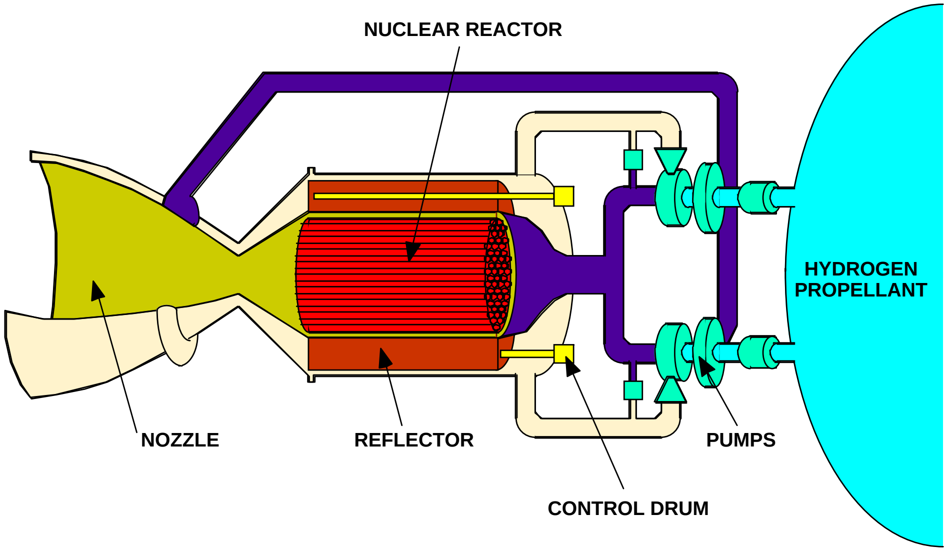
Heat Energy = 0.851 MeV/nucleon

Controllable reaction rate (variable power levels)

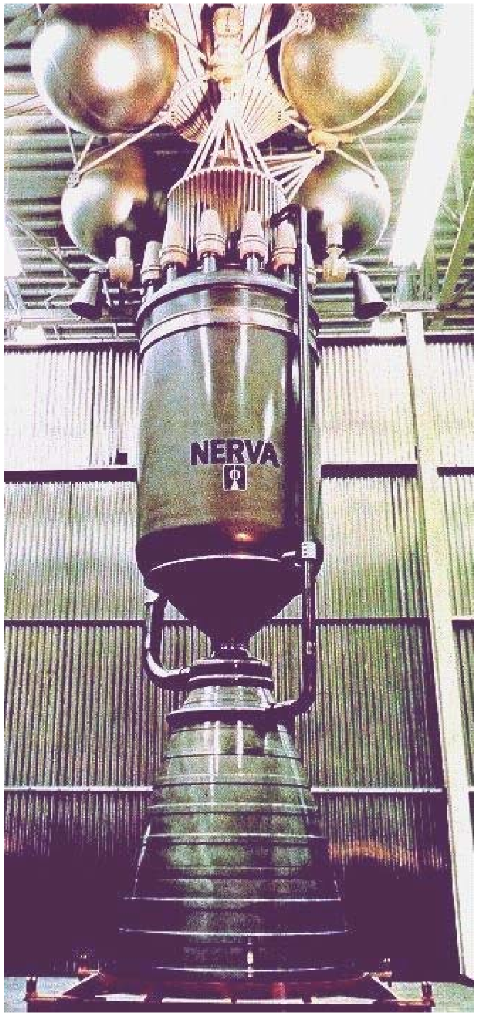
- Used terrestrially for over 70 years
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal (>20 GW-hr)
- One US space reactor (SNAP-10A) flown (1965)
  - Former U.S.S.R. flew 33 space reactors
- Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
  - 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

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)

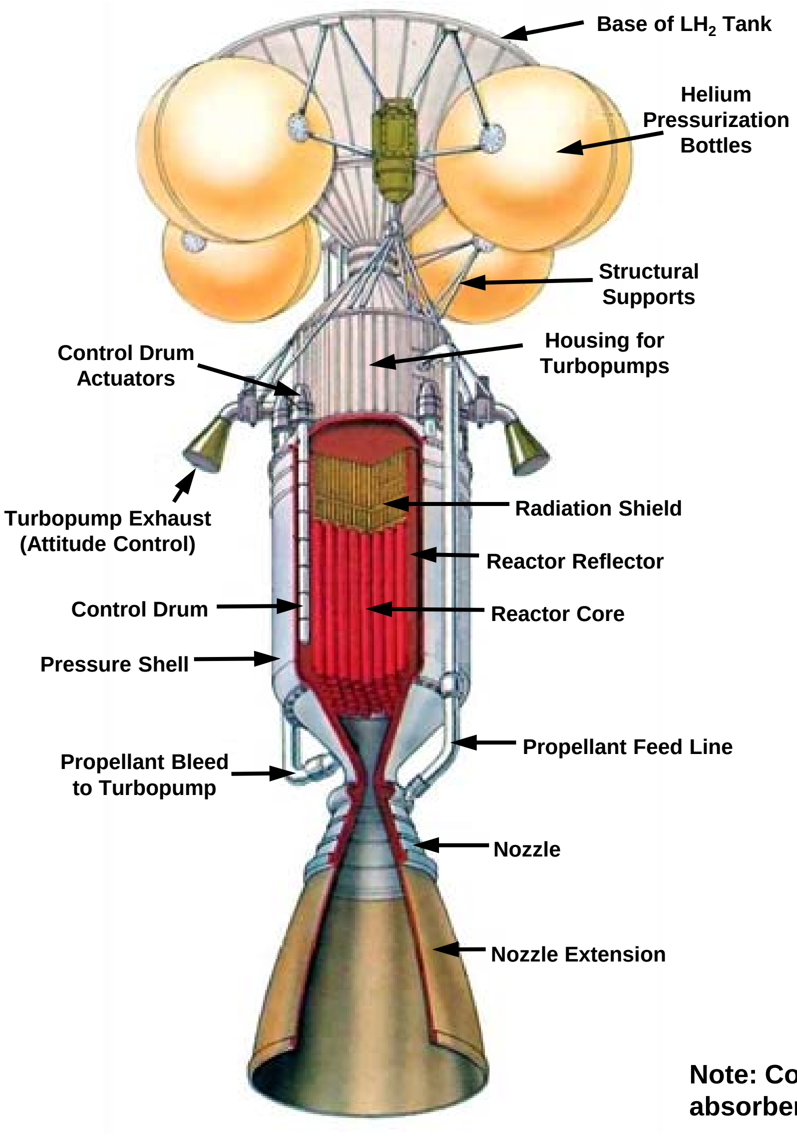


Major Elements of a Nuclear Thermal Rocket

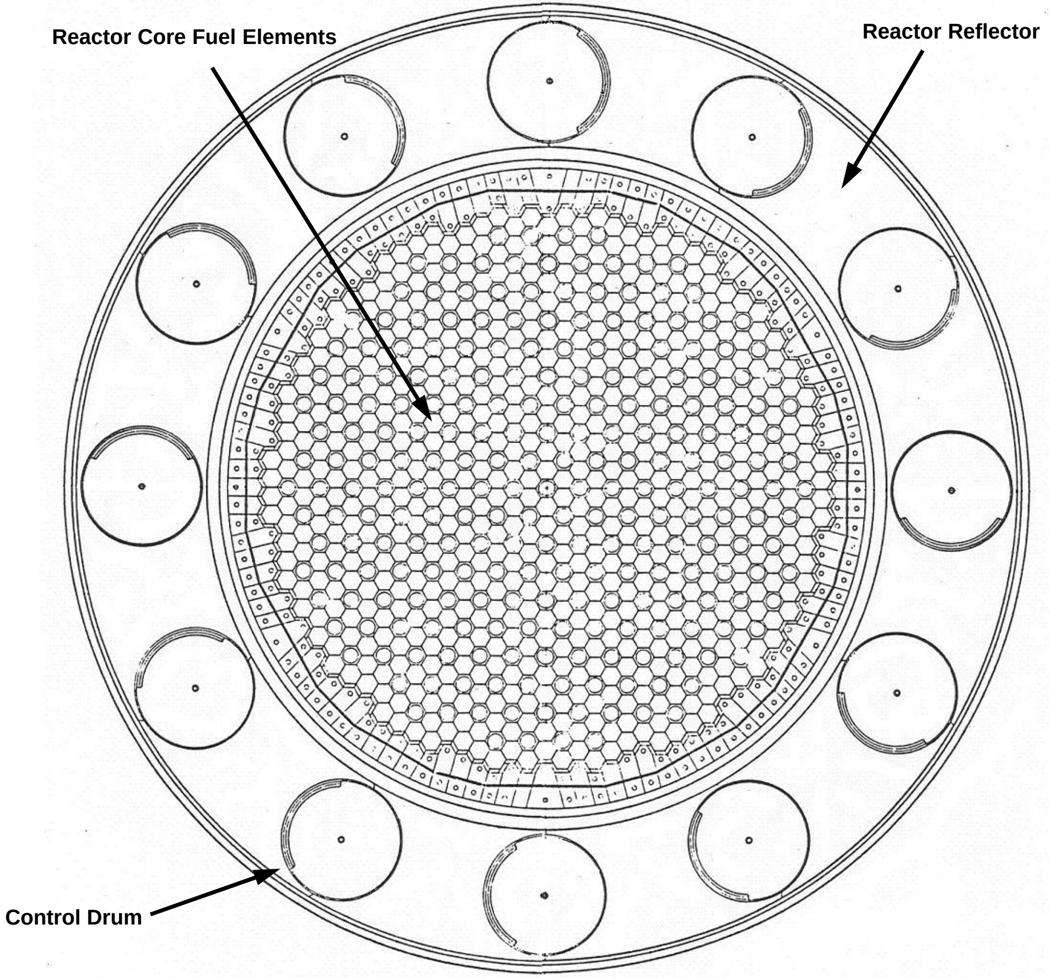


NERVA Nuclear Thermal Rocket Prototype

NTP Engines / Components

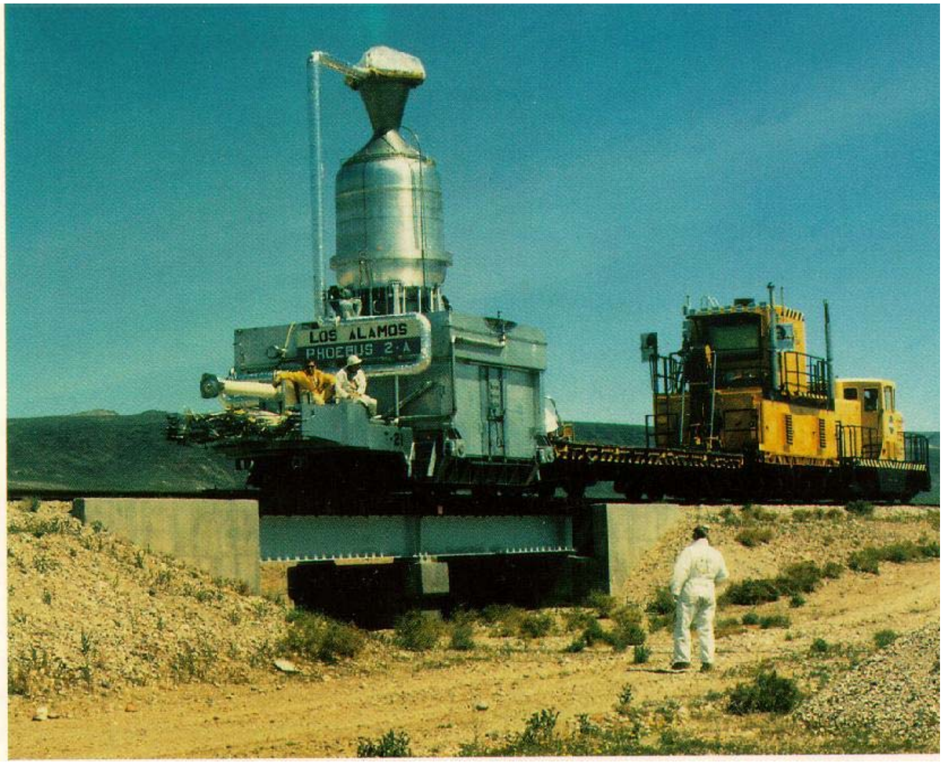


Cross Section



Note: Control drums rotate to control reactivity. Part of circumference covered with absorber and the rest is a reflector.

Previous NTP Reactors: Phoebus-2A



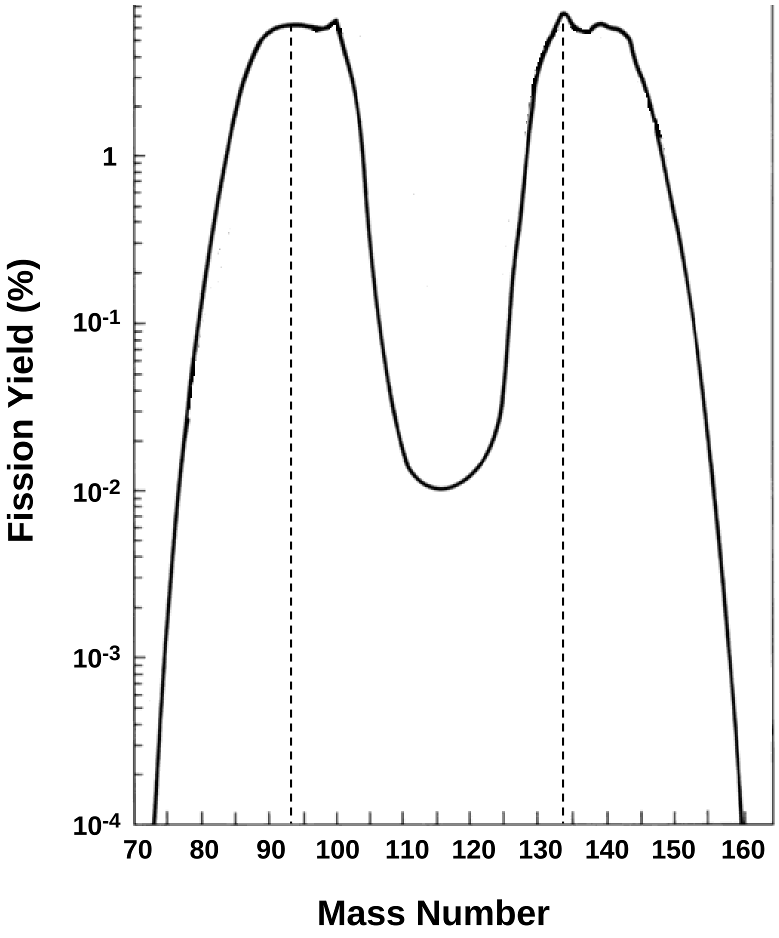
Phoebus-2A

- **Tested 1968**
- **5 GW Reactor Core (tested at 4.2 GW)**
- **805 seconds Isp space equiv., designed to provide 250,000 lbf thrust (ten times current thrust requirement)**

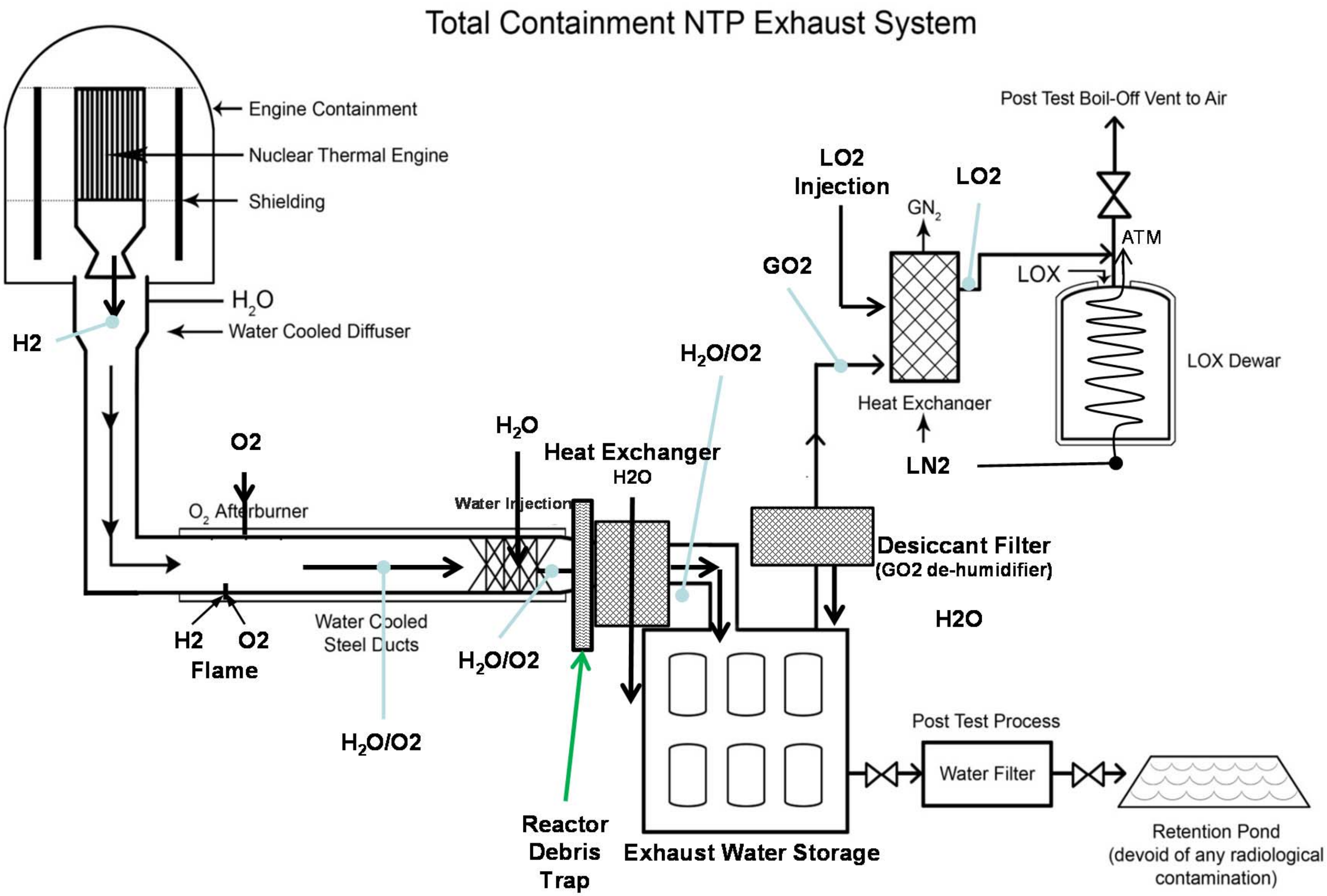
Fission Products

- Fission events yield bimodal distribution of product elements.
- These products are generally neutron-rich isotopes and emit beta and gamma particles in radioactive decay chains.
- Most products rapidly decay to stable forms – a few, however, decay at slow rates or decay to daughter products which have long decay times.
- Example fission products of concern:
  - —Strontium-90 (28.8-year half-life)
  - —Cesium-137 (30.1-year half-life)
- Isotope amounts decrease by factor of 1,000 after 10 half-lives and 1,000,000 after 20 half-lives.
- Decay power 6.2% at t=0 (plus fission from delayed neutrons), 1.3% at 1 hour, 0.1% at 2 months (following 5 years operation).

Product Yields for Thermal Neutron (0.025 eV) Fission of U-235



Could NTP Exhaust Be Captured During a Ground Test?



Could an NTP system 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 Designs / Results are Very Promising

Nuclear Thermal Propulsion

Project Manager: Sonny Mitchell

Objective:

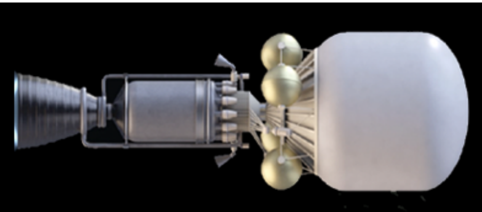
The overall goal of this three-year GCD technology project is to determine the feasibility and affordability of a Low Enriched Uranium (LEU)-based NTP engine with solid cost and schedule confidence.

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.



System Feasibility Analysis

Fuel Element Development and Testing

Exhaust Capture Analysis and Testing

Project Status

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

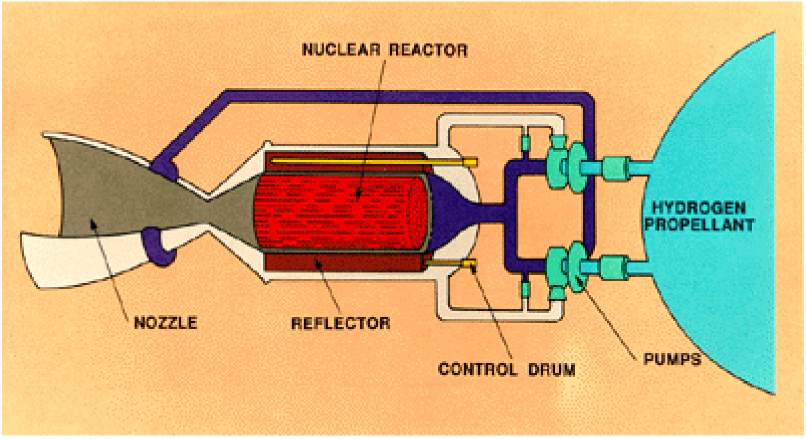
Milestones:
Tungsten purified to 50% (APR17); 70% (SEP17);
90% (SEP18)
Testing of Surrogate Cermet FE in CFEET (SEP17)
Testing of the DU Cermet FE in NTREES/CFEET (SEP18)

Green: On schedule / In budget

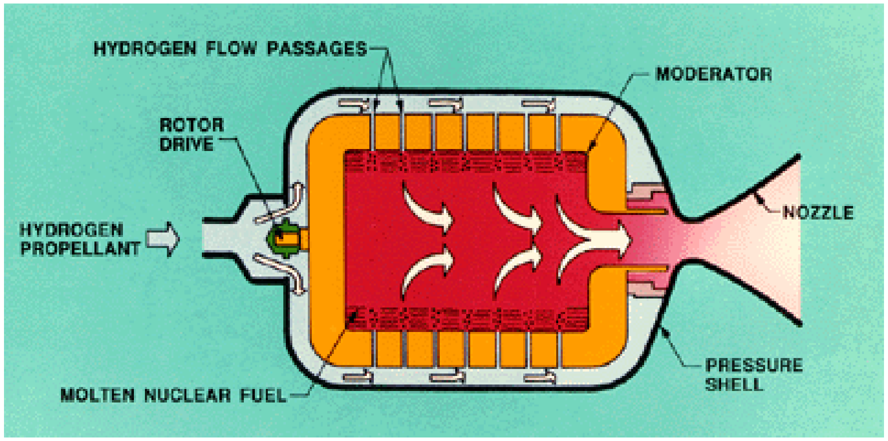
Guidance Navigation and Control: Unique Considerations

- Relatively slow engine start (up to 1 minute from zero thrust to full thrust).
- Potential for significant feedback during engine start. Introduction of hydrogen into reactor, temperature change in fuel, temperature change in neutron reflector, control drum rotation, etc.
- Deviations between predicted thrust and actual thrust during startup.
- Heat from fission products precludes instantaneous shutdown. Desire to minimize mission performance penalty associated with cool down.
- Significantly different mission profiles, even with first generation systems.
- Second generation (or beyond) NTP systems may incorporate electric propulsion at some level, using energy from the reactor to power electric thrusters. This “bimodal” operation may also have unique guidance, navigation, and control characteristics.

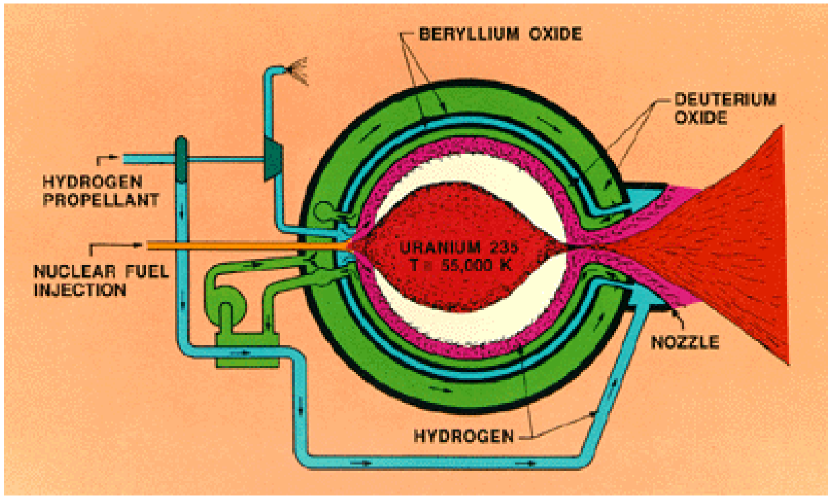
Proposed Types of Nuclear Thermal Propulsion



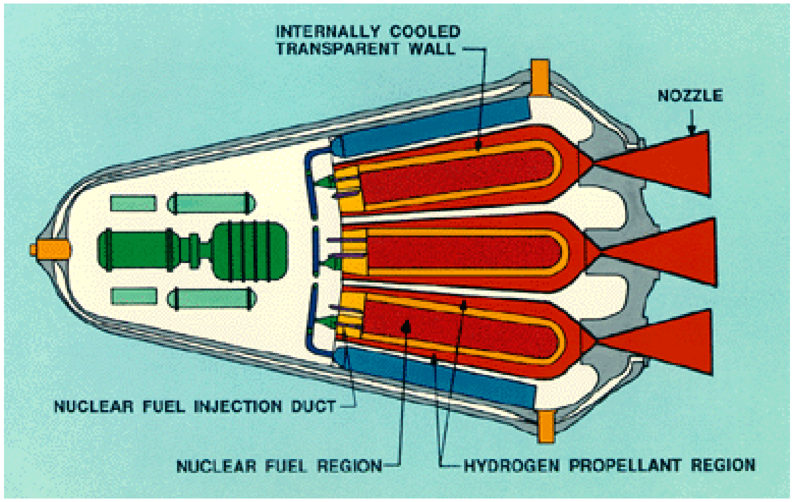
SOLID CORE NUCLEAR ROCKET



LIQUID CORE NUCLEAR ROCKET



Open-Cycle Gas Core Nuclear Rocket



Closed-Cycle Gas Core Nuclear Rocket

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.

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

- Some aspects of guidance, navigation, and control will be unique for NTP systems. However, there do not appear to be insurmountable issues or concerns.