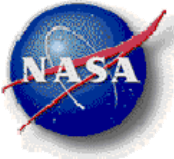




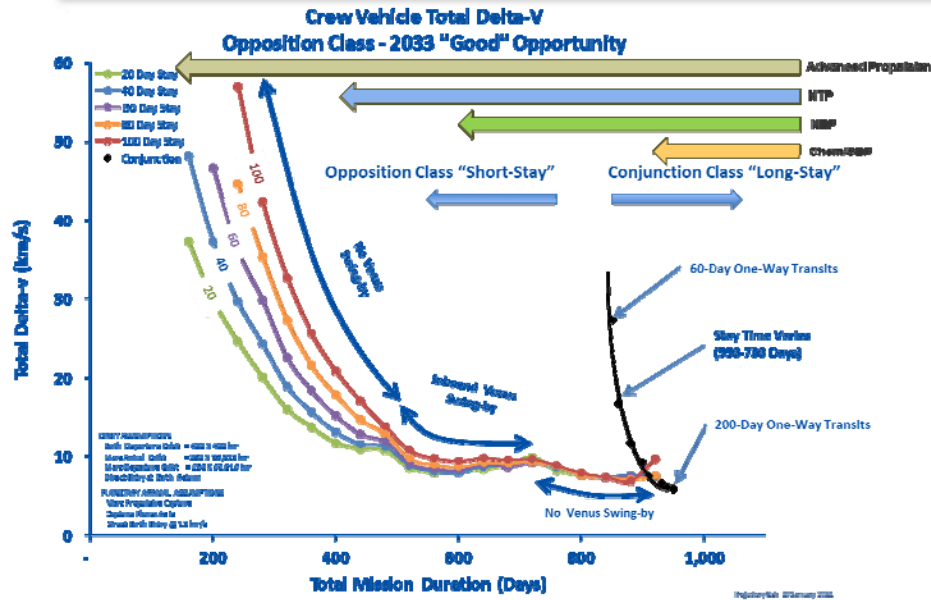
# Low-Enriched Uranium Nuclear Thermal Propulsion Systems

*Mike Houts  
Sonny Mitchell  
Ken Aschenbrenner*

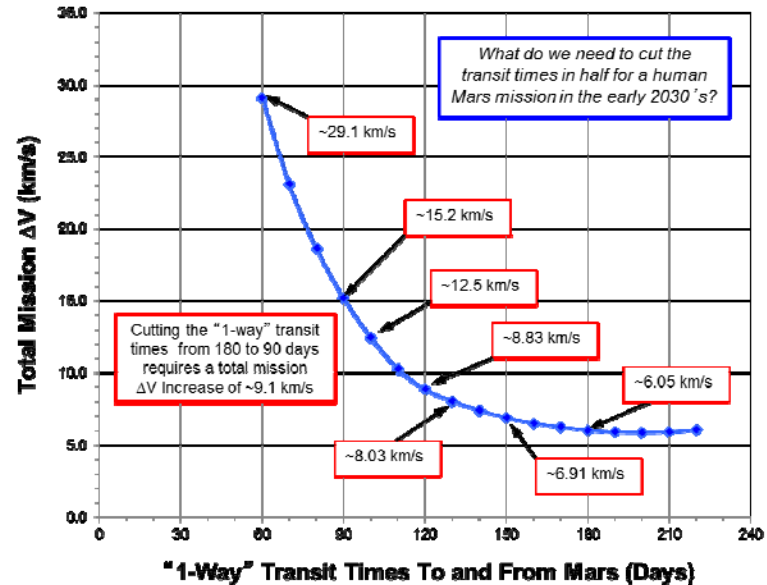




# Why is NTP Attractive for Human Missions to Mars?

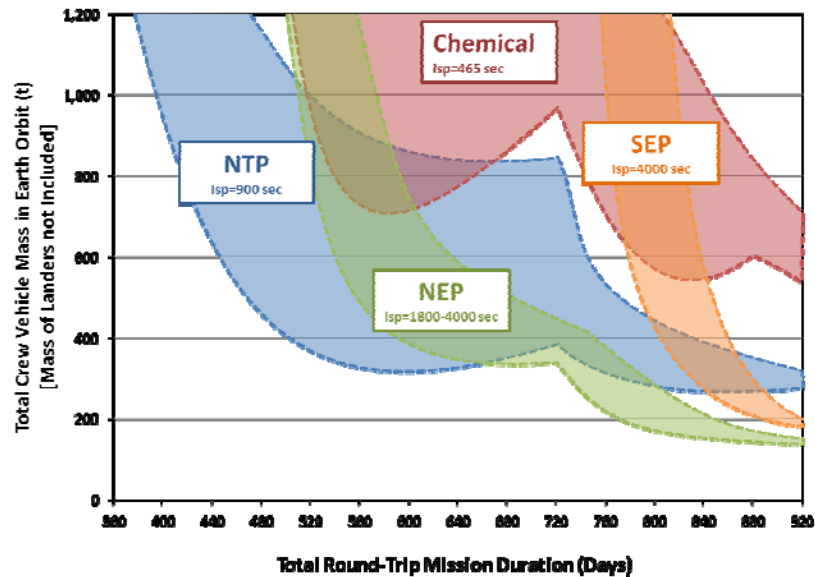


## 2033 "Fast Conjunction" Long Surface Stay Mars Mission: Total Mission $\Delta V$ vs. "1-Way" Transit Time To and From Mars

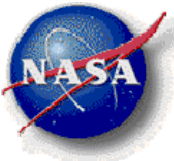


Ref: Borowski et al., Space 2013, AIAA-2013-5354

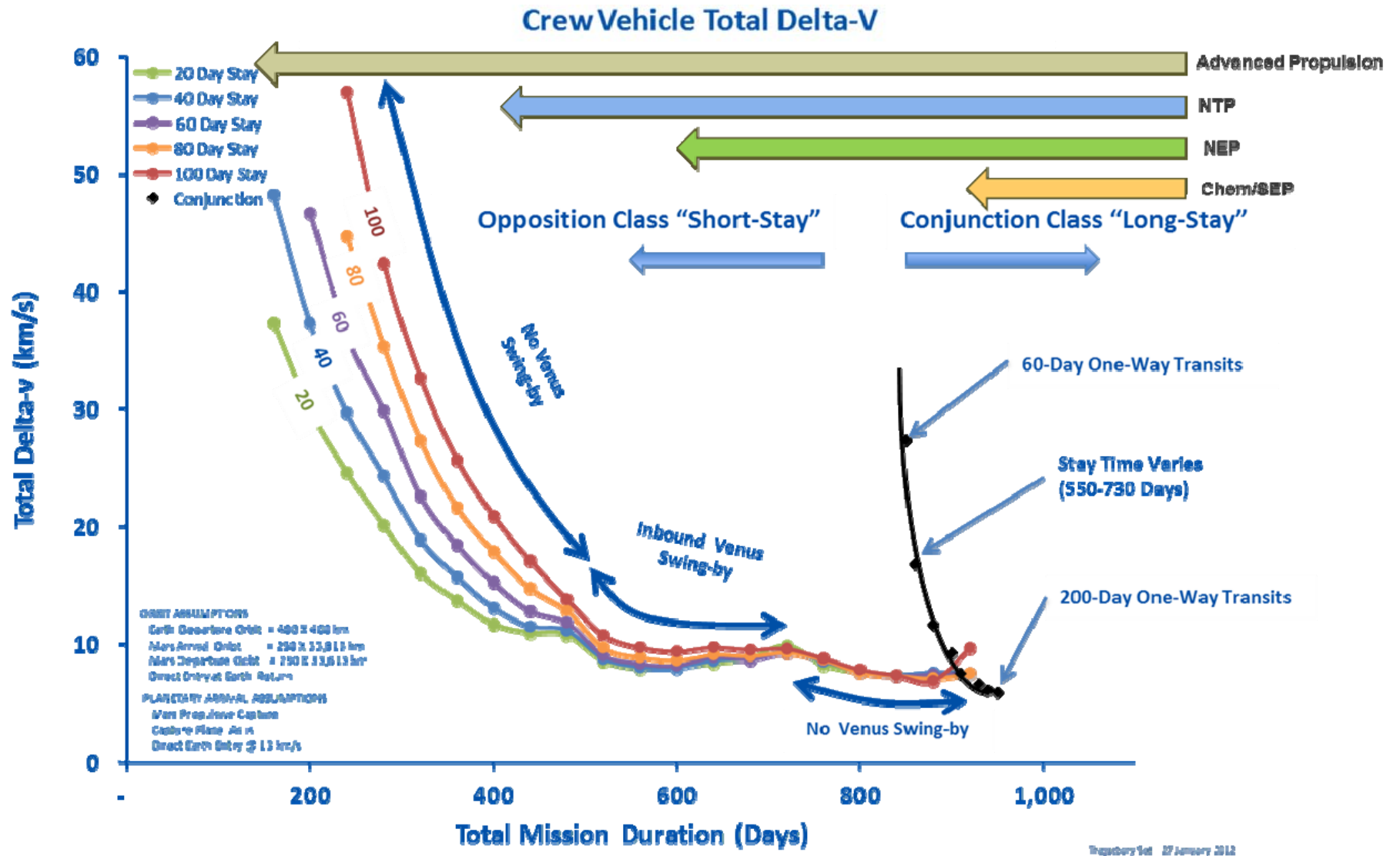
## Short Stay Opposition Mission with Earth Departure Dates 2028-2045

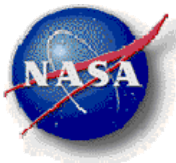


- NTP allows for shorter total mission time and shorter trip time (Less exposure to galactic cosmic radiation and zero-g)
- NTP allows mission robustness and potential abort scenarios
- Fewer SLS launches can save operation time, money, and reduce risk
- NTP is initial step towards advanced space nuclear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



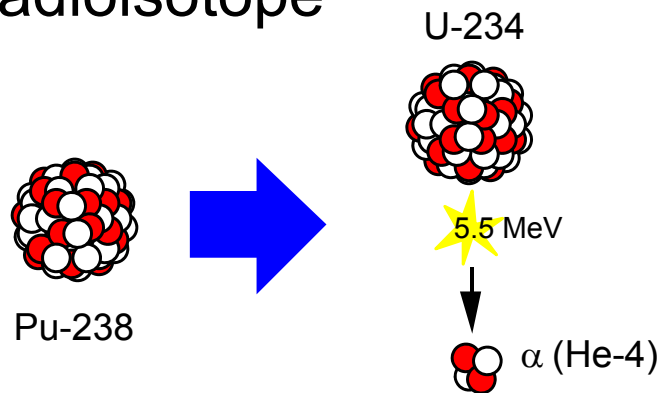
# Why is NTP Attractive for Human Missions to Mars?





# 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)*

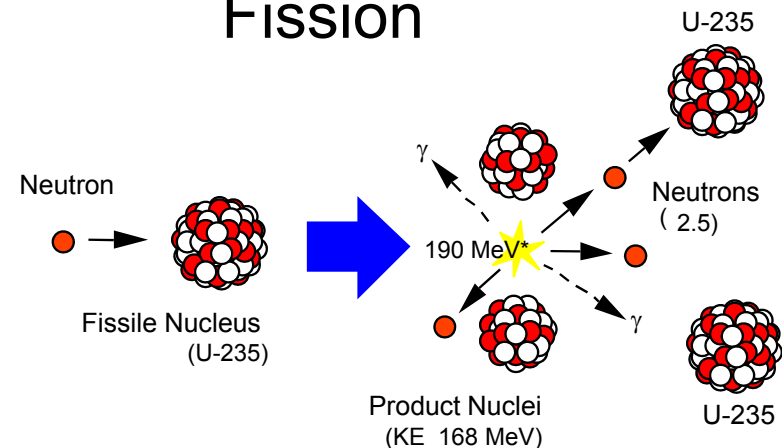
Long history of use on Apollo and space science missions

44 RTGs and hundreds of RHUs launched by U.S. during past 5 decades

Heat produced from natural alpha ( $\alpha$ ) 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)

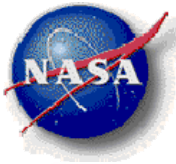
Former U.S.S.R. flew 33 space reactors

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

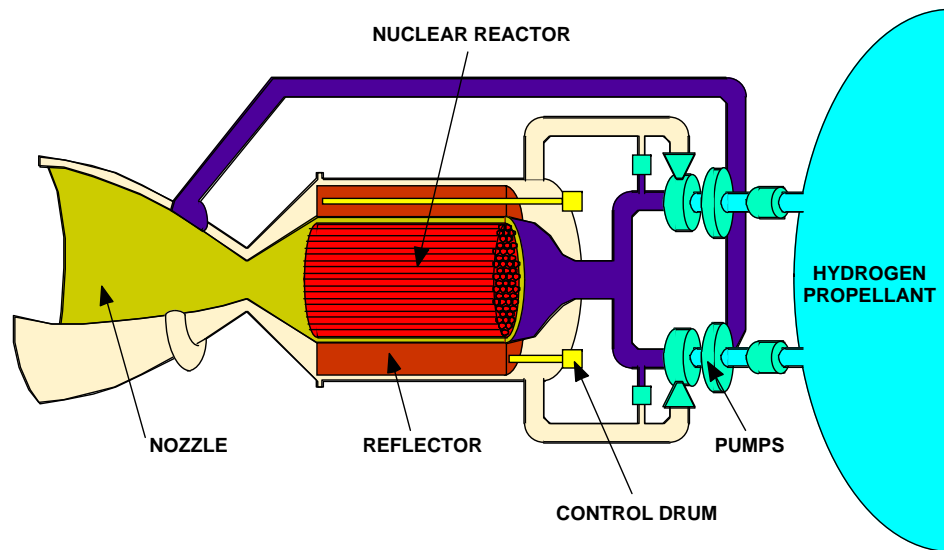
Heat converted to electricity, or used directly to heat a propellant





# How Does Nuclear Thermal Propulsion (NTP) Work?

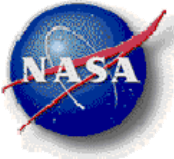
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor:  $100,000 \text{ N} \approx 450 \text{ MW}_{\text{th}}$  at 900 sec
- Specific Impulse directly 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  $\text{O}_2/\text{H}_2$  engine runs much hotter than NTP)



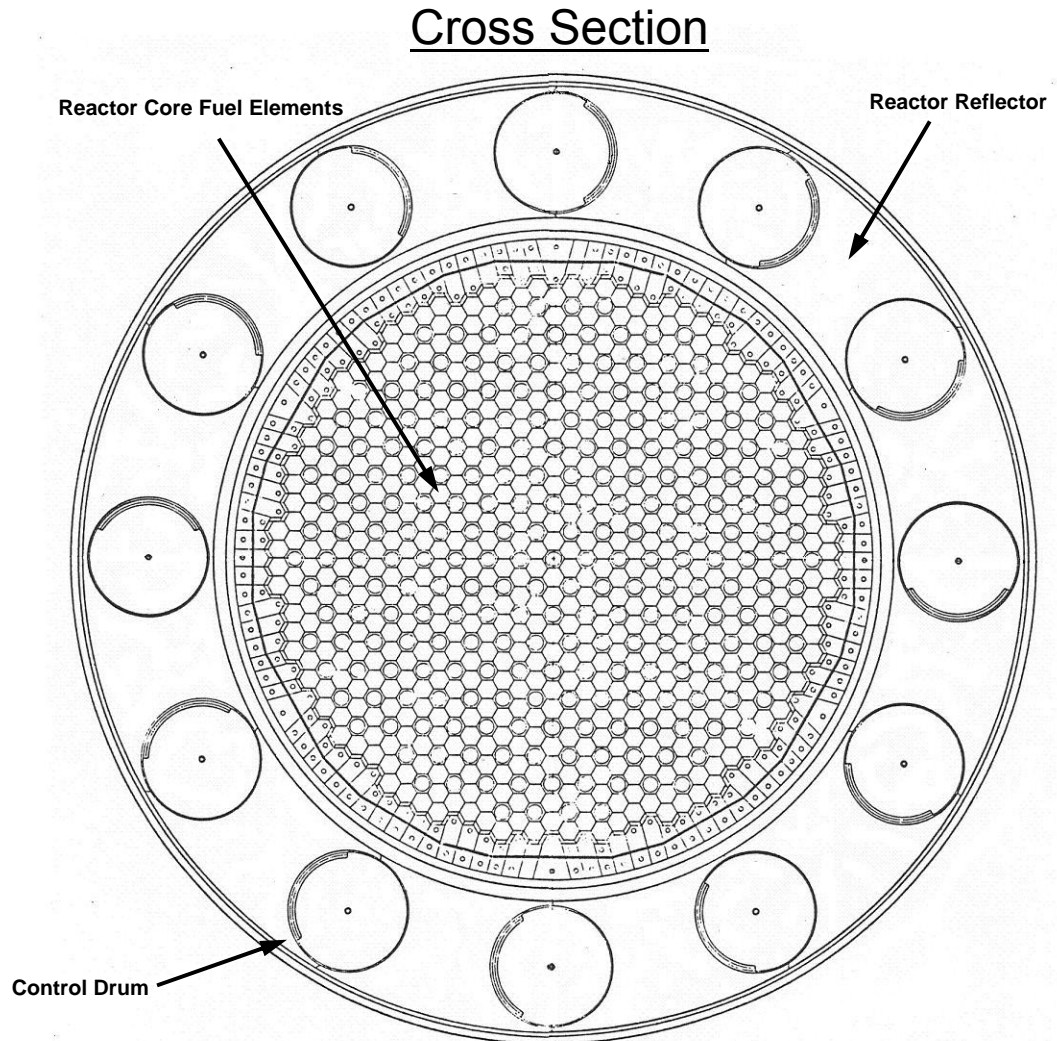
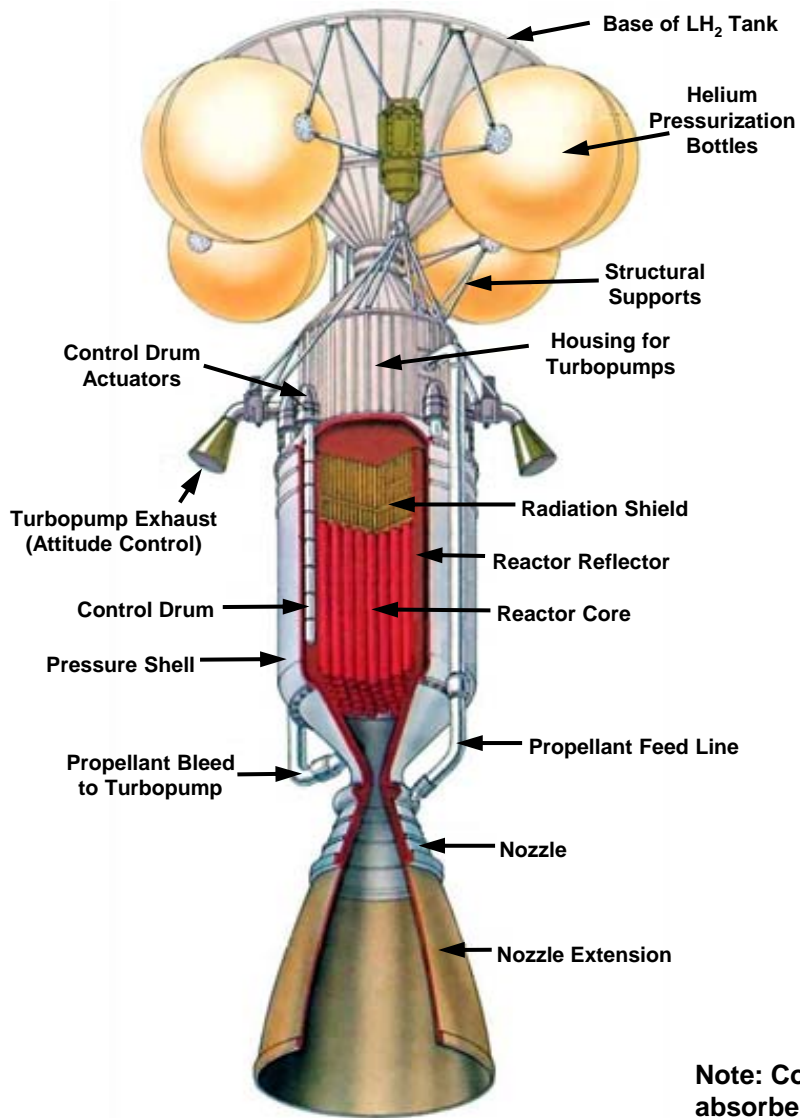
Major Elements of a Nuclear Thermal Rocket



NERVA Nuclear Thermal Rocket Prototype



# NTP Engines / Components

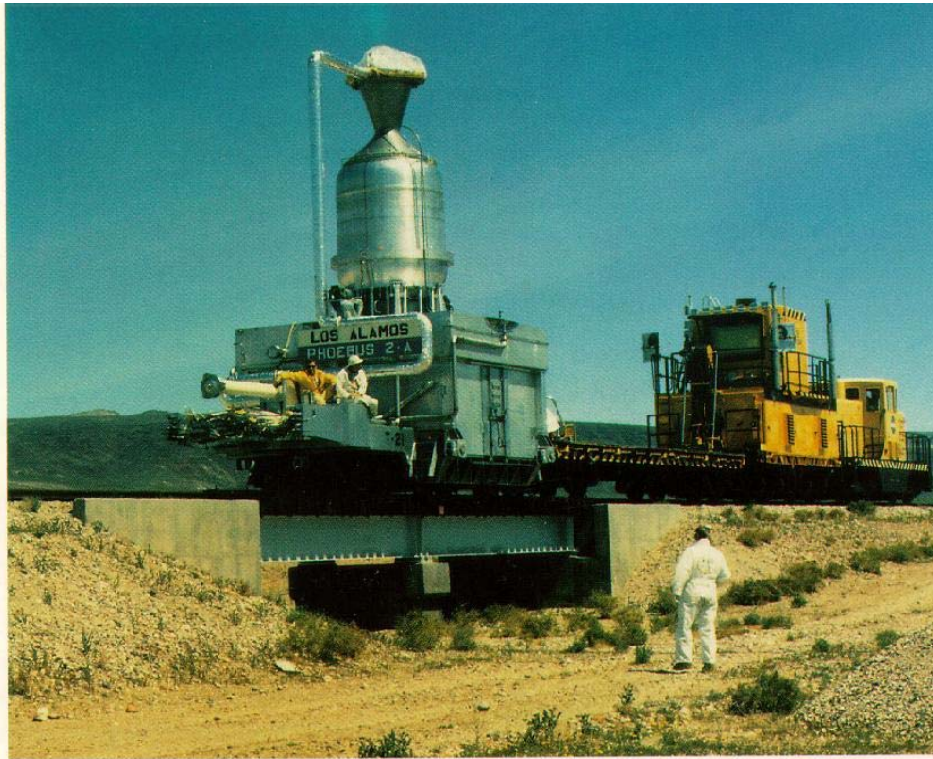


Note: Control drums rotate to control reactivity. Part of circumference covered with absorber and the rest is a reflector.





## Previous NTP Reactors: Phoebus-2A

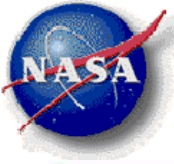


### Phoebus-2A

**Tested 1968**

**5 GW Reactor Core (tested at 4.2 GW)**

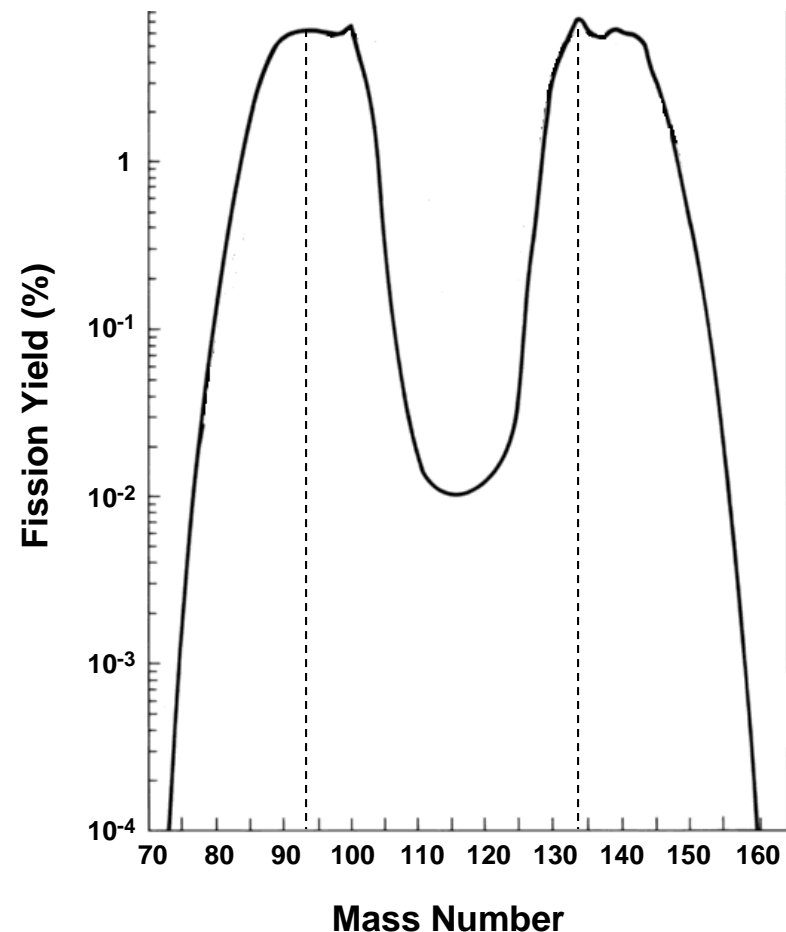
**805 seconds Isp space equiv., designed to provide  
250,000 lbf thrust (ten times current thrust requirement)**



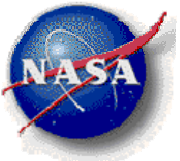
# Fission Products

- 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

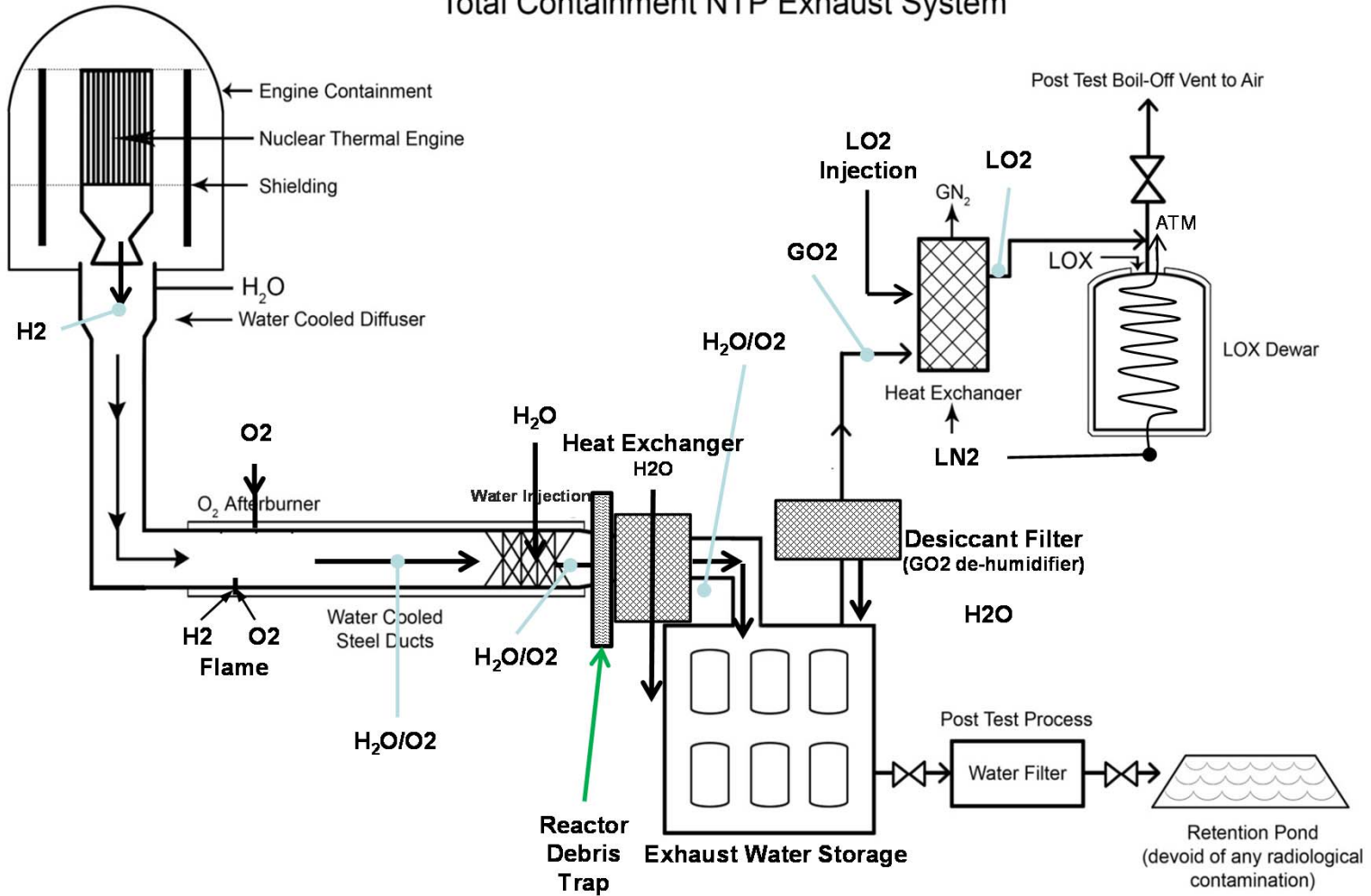






# Could NTP Exhaust Be Captured During a Ground Test?

Total Containment NTP Exhaust System





## Could an NTP system using Low-Enriched Uranium (LEU) be Developed?

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- 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:

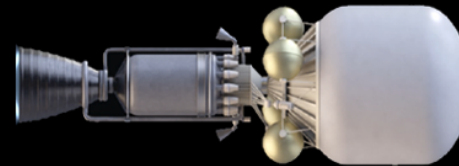
The overall goal of this three-year GCD technology project is to determine the feasibility and affordability of a Low Enriched Uranium (LEU)-based NTP engine with solid cost and schedule confidence.

## 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:

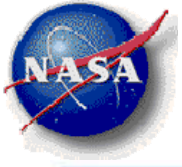
Tungsten purified to 50% (APR17); 70% (SEP17);  
90% (SEP18)

Testing of Surrogate Cermet FE in CFEET (SEP17)

Testing of the DU Cermet FE in NTREES/CFEET (SEP18)

**Green:** On schedule / In budget

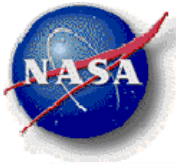




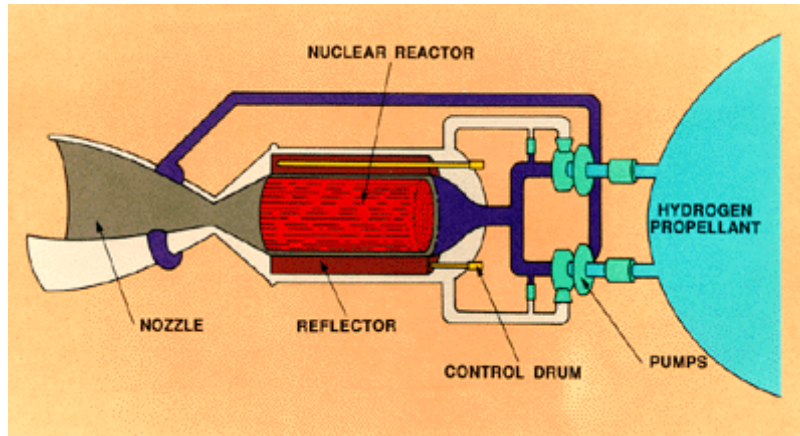
## Guidance Navigation and Control: Unique Considerations

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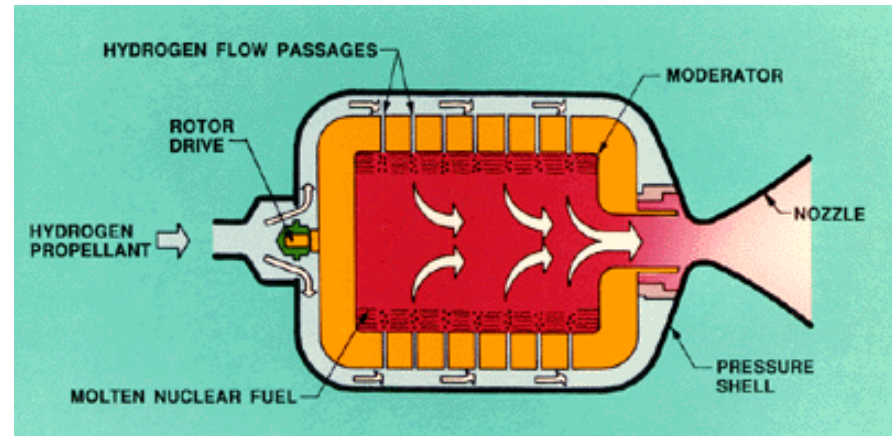
- Relatively slow engine start (up to 1 minute from zero thrust to full thrust).
- Potential for significant feedback during engine start. Introduction of hydrogen into reactor, temperature change in fuel, temperature change in neutron reflector, control drum rotation, etc.
- Deviations between predicted 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.



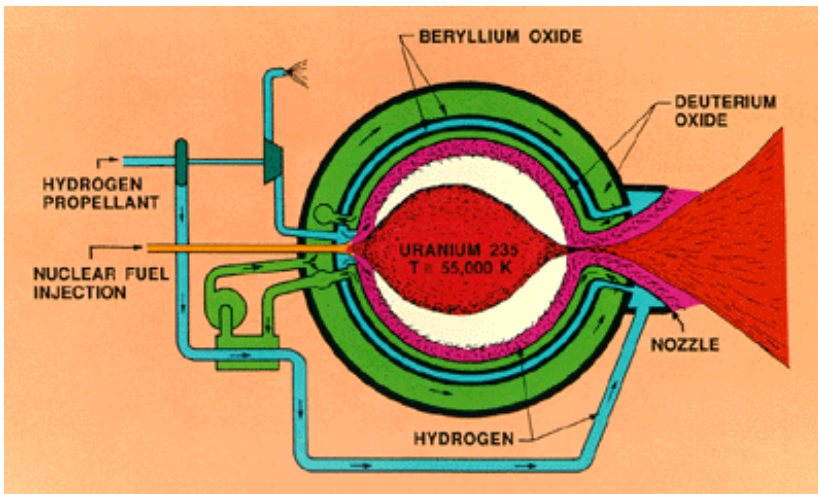
# Proposed Types of Nuclear Thermal Propulsion



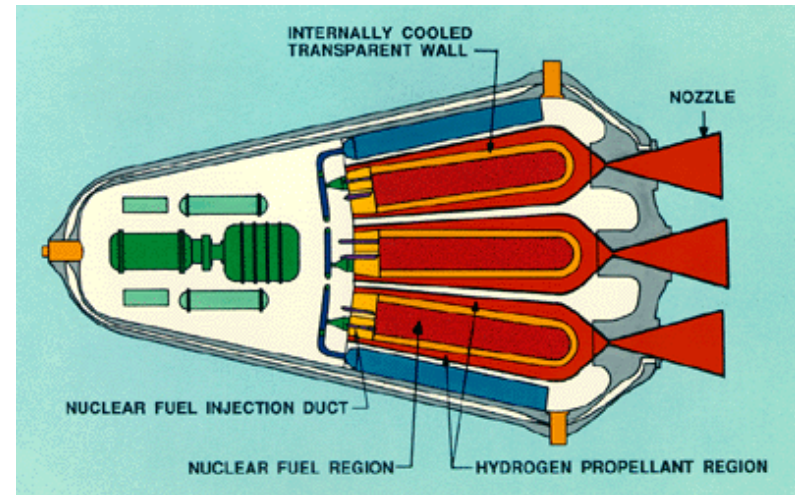
SOLID CORE NUCLEAR ROCKET



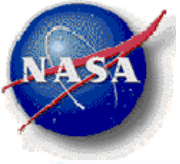
LIQUID CORE NUCLEAR ROCKET



Open-Cycle Gas Core Nuclear Rocket



Closed-Cycle Gas Core Nuclear Rocket



## Observations

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- 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.