Advanced Space Fission Propulsion Systems

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Fission has been considered for in-space propulsion since the 1940s. Nuclear Thermal Propulsion (NTP) systems underwent extensive development from 1955 – 1973, completing 20 full power ground tests and achieving specific impulses nearly twice that of the best chemical propulsion systems. Space fission power systems (which may eventually enable Nuclear Electric Propulsion) have been flown in space by both the United States and the Former Soviet Union. Fission is the most developed and understood of the nuclear propulsion options (e.g. fission, fusion, antimatter, etc.), and fission has enjoyed tremendous terrestrial success for nearly 7 decades.

Current space nuclear research and technology efforts are focused on devising and developing first generation systems that are safe, reliable and affordable. For propulsion, the focus is on nuclear thermal rockets that build on technologies and systems developed and tested under the Rover/NERVA and related programs from the Apollo era. NTP Affordability is achieved through use of previously developed fuels and materials, modern analytical techniques and test strategies, and development of a small engine for ground and flight technology demonstration. Initial NTP systems will be capable of achieving an Isp of ~900 s at a relatively high thrust-to-weight ratio.

The development and use of first generation space fission power and propulsion systems will provide new, “game changing” capabilities for NASA. In addition, development and use of these systems will provide the foundation for developing extremely advanced power and propulsion systems capable of routinely and affordably accessing any point in the solar system.

The energy density of fissile fuel (8×10^{13} Joules/kg) is more than adequate for enabling extensive exploration and utilization of the solar system. For space fission propulsion systems, the key is converting the virtually unlimited energy of fission into thrust at the desired specific impulse and thrust-to-weight ratio.

This presentation will discuss potential space fission propulsion options ranging from first generation systems to highly advanced systems. Ongoing research that shows promise for enabling second generation NTP systems with Isp > 1000 s will be discussed, as will the potential for liquid, gas, or plasma core systems. Space fission propulsion systems could also be used in conjunction with simple (water-based) propellant depots to enable routine, affordable missions to various destinations (e.g. moon, Mars, asteroids) once in-space infrastructure is sufficiently developed. As fuel and material technologies advance, very high performance Nuclear Electric Propulsion (NEP) systems may also become viable. These systems could enable sophisticated science missions, highly efficient cargo delivery, and human missions to numerous destinations. Commonalities between NTP, fission power systems, and NEP will be discussed.

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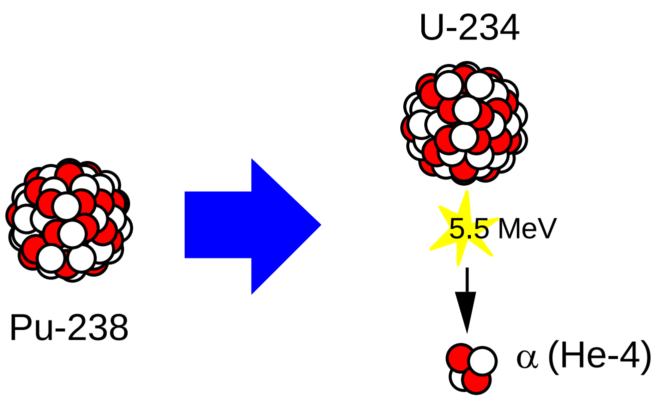
Two Types of Space Nuclear Systems Flown to Date

Radioisotope Decay (Pu-238)

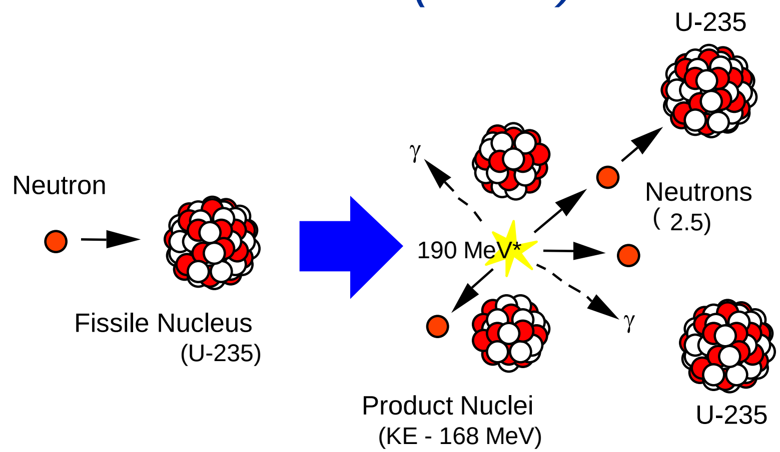


Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

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 4 decades
- **Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
- **Used for both thermal management and electricity production**

Fission (U-235)



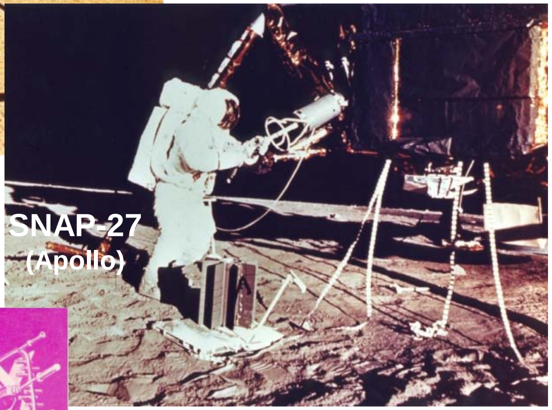
Heat Energy = 0.851 MeV/nucleon

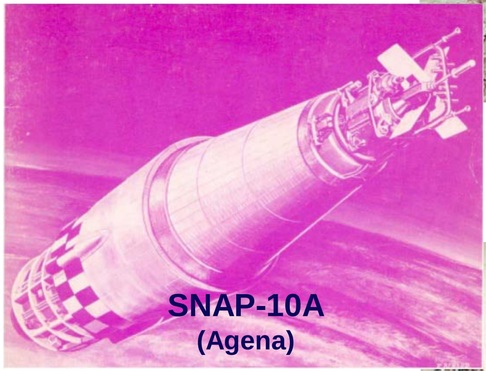
Controllable reaction rate (variable power levels)

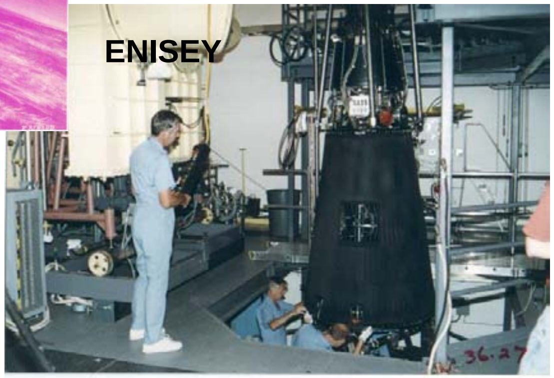
- **Used terrestrially for over 65 years**
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal
- **Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)**
  - At steady-state, 1 of the 2 to 3 neutrons released causes a subsequent fission in a “chain reaction”
- **Heat converted to electricity, or used directly to heat a propellant**

Two Types of Space Nuclear Systems

- Radioisotope Power Systems
  - 44 Successful U.S. Radioisotope Thermoelectric Generators (RTGs) Flown Since 1961
  - Some Examples:
    - Apollo SNAP-27 (1969-72)
    - Viking SNAP-19 (1975)
    - Voyager MHW-RTG (1977)
    - Galileo GPHS-RTG (1989)
    - New Horizons GPHS-RTG (2005)
- Fission Reactor Systems
  - SNAP-10A (1 launched 1965)
  - BUK (31 launched 1970-1988)
  - TOPAZ (2 launched 1987)
  - Significant space fission technology developed via non-flight programs.





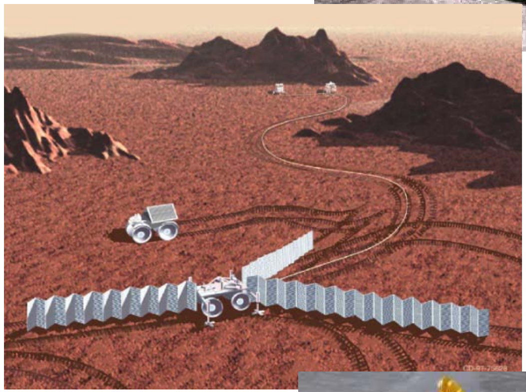


Fission Straightforward, Highly Developed for Certain Applications

- Creating a fission chain reaction is conceptually simple
  - Requires right materials in right geometry
- Good engineering needed to create safe, useful, long-life fission systems
  - *1938 Fission Discovered*
  - *1939 Einstein letter to Roosevelt*
  - *1942 Manhattan project initiated*
  - *1942 First sustained fission chain reaction (CP-1)*
  - *1943 X-10 Reactor (ORNL), 3500 kWt*
  - *1944 B-Reactor (Hanford), 250,000 kWt*
  - *1944-now Thousands of reactors at various power levels*

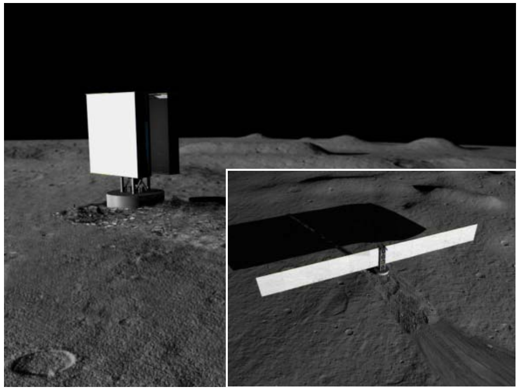
Recent Interest in Fission Surface Power (FSP) to Support Moon / Mars Exploration

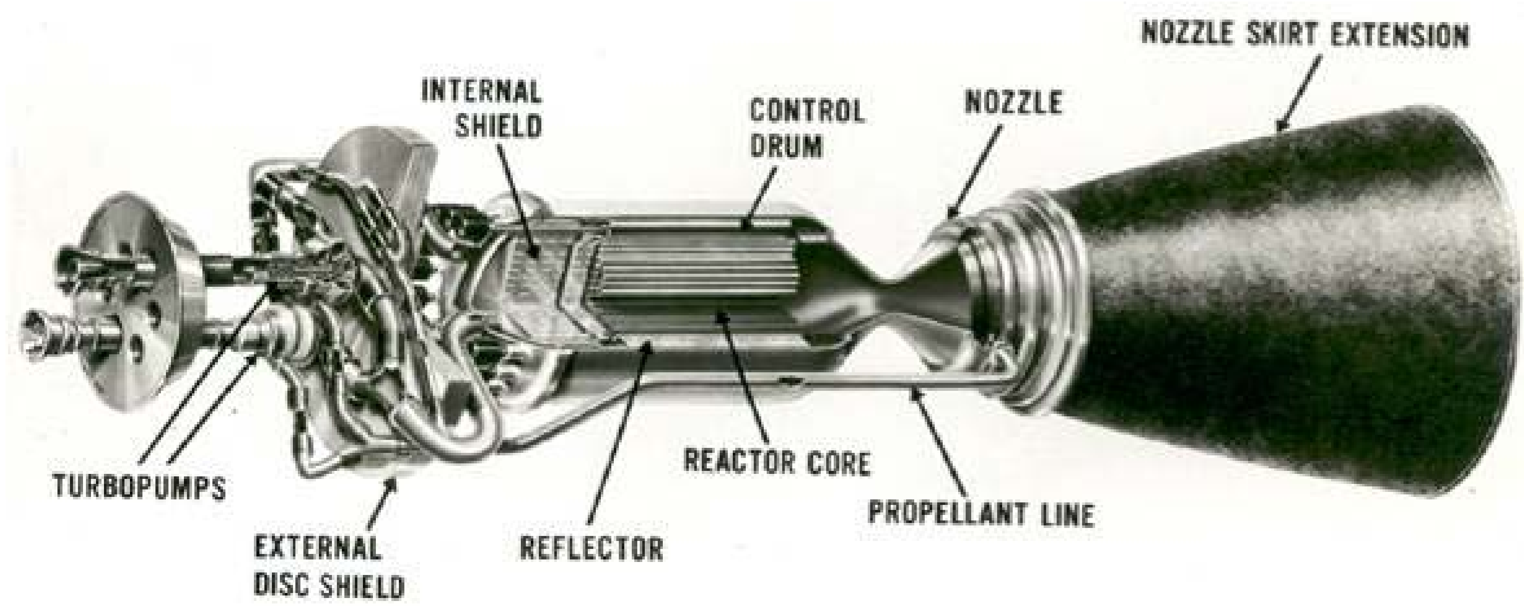
- Continuous Day/Night Power for Robust Surface Ops
- Same Technology for Moon and Mars
- Suitable for any Surface Location
  - Lunar Equatorial or Polar Sites
  - Permanently Shaded Craters
  - Mars Equatorial or High Latitudes
- Environmentally Robust
  - Lunar Day/Night Thermal Transients
  - Mars Dust Storms
- Operationally Robust
  - Multiple-Failure Tolerant
  - Long Life without Maintenance
- Highly Flexible Configurations
  - Excavation Shield Permits Near-Habitat Siting
  - Option for Above-Grade System or Mobile System (with shield mass penalty)
  - Option for Remote Siting (with high voltage transmission)
  - Option for Process Heat Source (for ISRU or habitat)



Recent Interest in Fission Surface Power (FSP) to Support Moon / Mars Exploration

- Safe During All Mission Phases
  - Launched Cold, No Radiation Until Startup
  - Safe during Operation with Excavation or Landed Shield
  - Safe after Shutdown with Negligible Residual Radiation
- Scalable to Higher Power Levels (kWs to MWs)
- Performance Advantages Compared to PV/RFC
  - Significant Mass & Volume Savings for Moon
  - Significant Mass & Deployed Area Savings for Mars
- Competitive Cost with PV/RFC
  - Detailed, 12-month "Affordable" Fission Surface Power System Cost Study Performed by NASA & DOE
  - LAT2 FSP and PV/RFC Options had Similar Overall Cost
  - Modest Unit Cost Enables Multiple Units and/or Multiple Sites
- Technology Primed for Development
  - Terrestrial Reactor Design Basis
  - No Material Breakthroughs Required
  - Lineage to RPS Systems (e.g. Stirling) and ISS (e.g. Radiators, Electrical Power Distribution)





- Hydrogen from propellant tank (not shown) directly heated by reactor and expanded through nozzle to provide thrust.
- ~850 second Isp demonstrated in ground tests at high thrust/weight.
- Potential for > 900 s Isp with advanced fuel forms and cycles.
- Potential Applications
  - Rapid robotic exploration missions throughout solar system
  - Piloted missions to moon or Mars

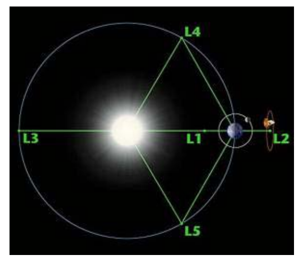
Near-term NTP enhances or enables missions throughout the inner solar system.

NTP could enhance or enable the ability to reach new destinations

NTP could enable a robust, flexible, and affordable exploration program

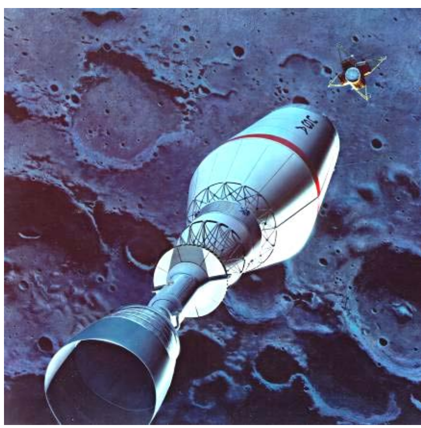
Mars Cargo and Human Missions

Phobos Mission



Sun-Earth Lagrange Point

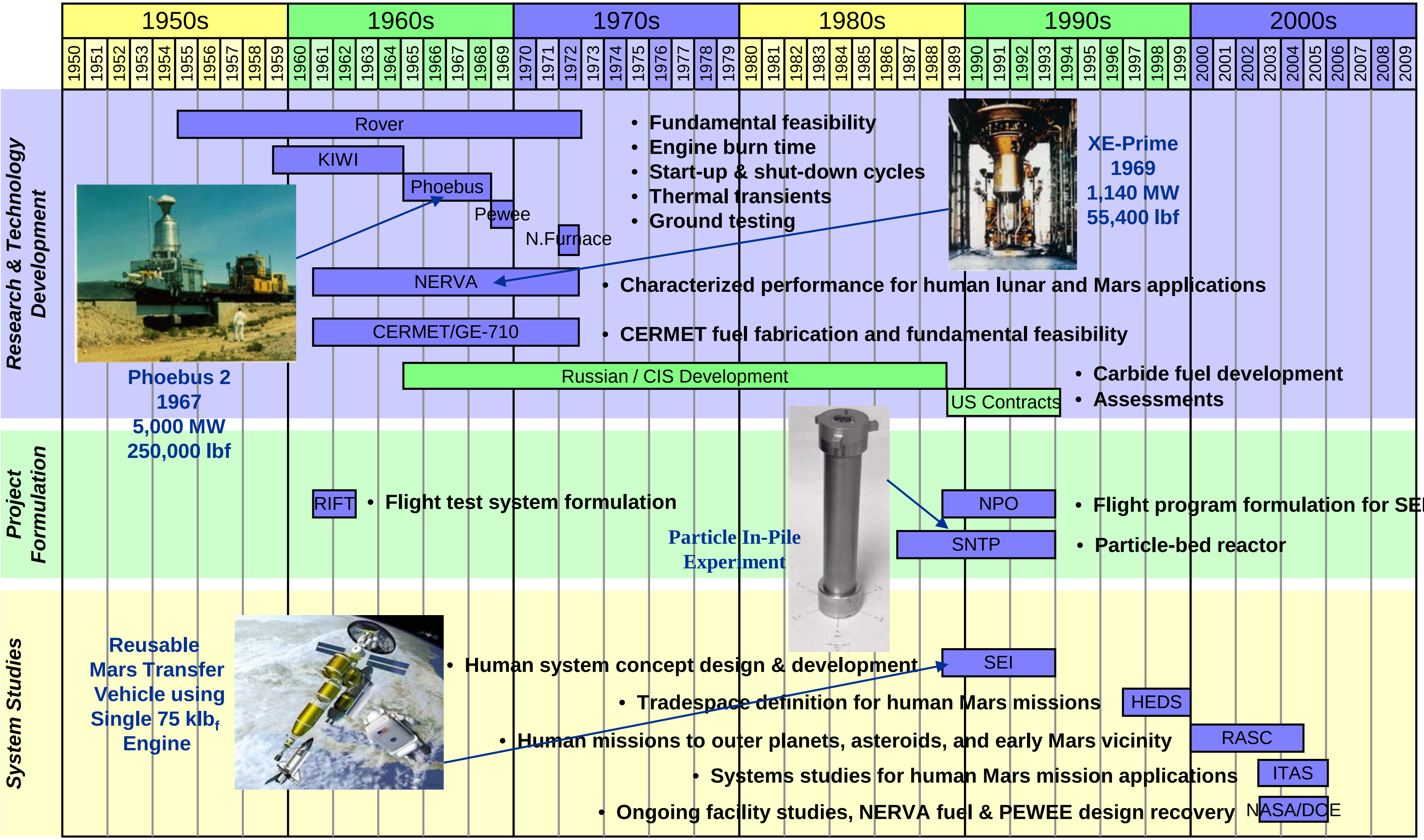
NEO Mission



Lunar Cargo Missions

As envisioned, NTP reduces required launch mass, reduces trip time, and increases mission opportunity. Over time, NTP could reduce exploration costs

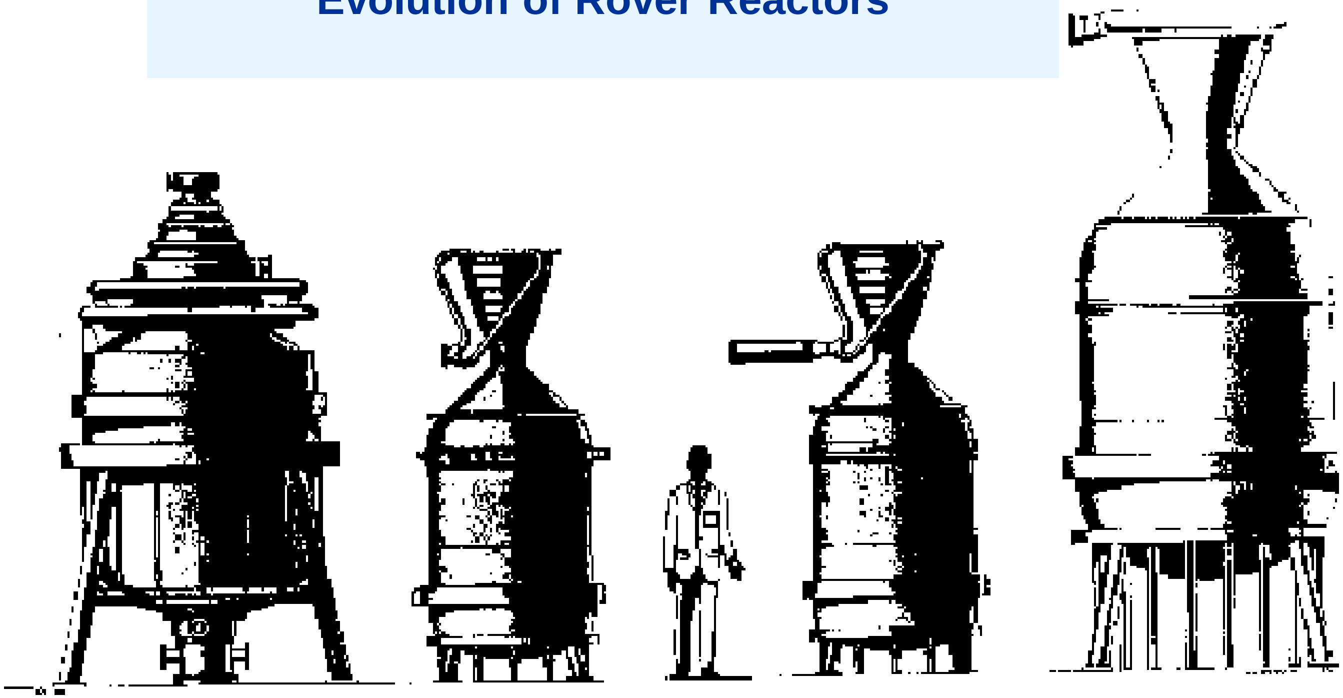
NTP History

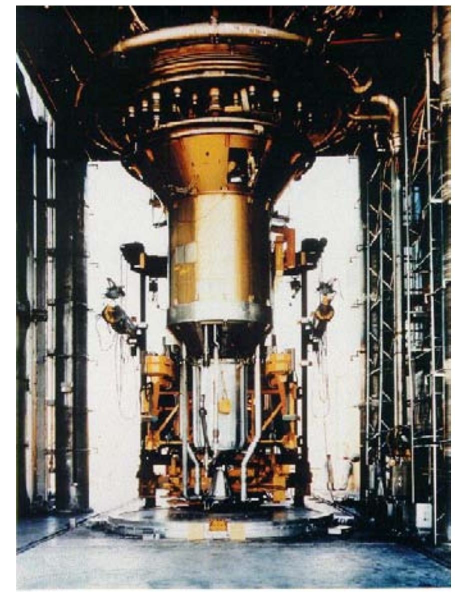

1950s
1960s
1970s
1980s
1990s
2000s
1950 1951 1952 1953 1954 1955 1956 1957 1958 1959
1960 1961 1962 1963 1964 1965 1966 1967 1968 1969
1970 1971 1972 1973 1974 1975 1976 1977 1978 1979
1980 1981 1982 1983 1984 1985 1986 1987 1988 1989
1990 1991 1992 1993 1994 1995 1996 1997 1998 1999
2000 2001 2002 2003 2004 2005 2006 2007 2008 2009
Research & Technology Development
Rover
KIWI
Phoebus
Pewee
N.Furnace
NERVA
CERMET/GE-710
Russian / CIS Development
US Contracts
• Fundamental feasibility
• Engine burn time
• Start-up & shut-down cycles
• Thermal transients
• Ground testing
XE-Prime
1969
1,140 MW
55,400 lbf
Phoebus 2
1967
5,000 MW
250,000 lbf
• Characterized performance for human lunar and Mars applications
• CERMET fuel fabrication and fundamental feasibility
• Carbide fuel development
• Assessments
Project Formulation
RIFT
• Flight test system formulation
Particle In-Pile Experiment
NPO
SNTP
• Flight program formulation for SEI
• Particle-bed reactor
System Studies
Reusable Mars Transfer Vehicle using Single 75 klb$_f$ Engine
• Human system concept design & development
SEI
• Tradespace definition for human Mars missions
HEDS
• Human missions to outer planets, asteroids, and early Mars vicinity
RASC
• Systems studies for human Mars mission applications
ITAS
• Ongoing facility studies, NERVA fuel & PEWEE design recovery
NASA/DOE

Rover/NERVA Engine Comparison

Evolution of Rover Reactors

Culmination of NERVA Program

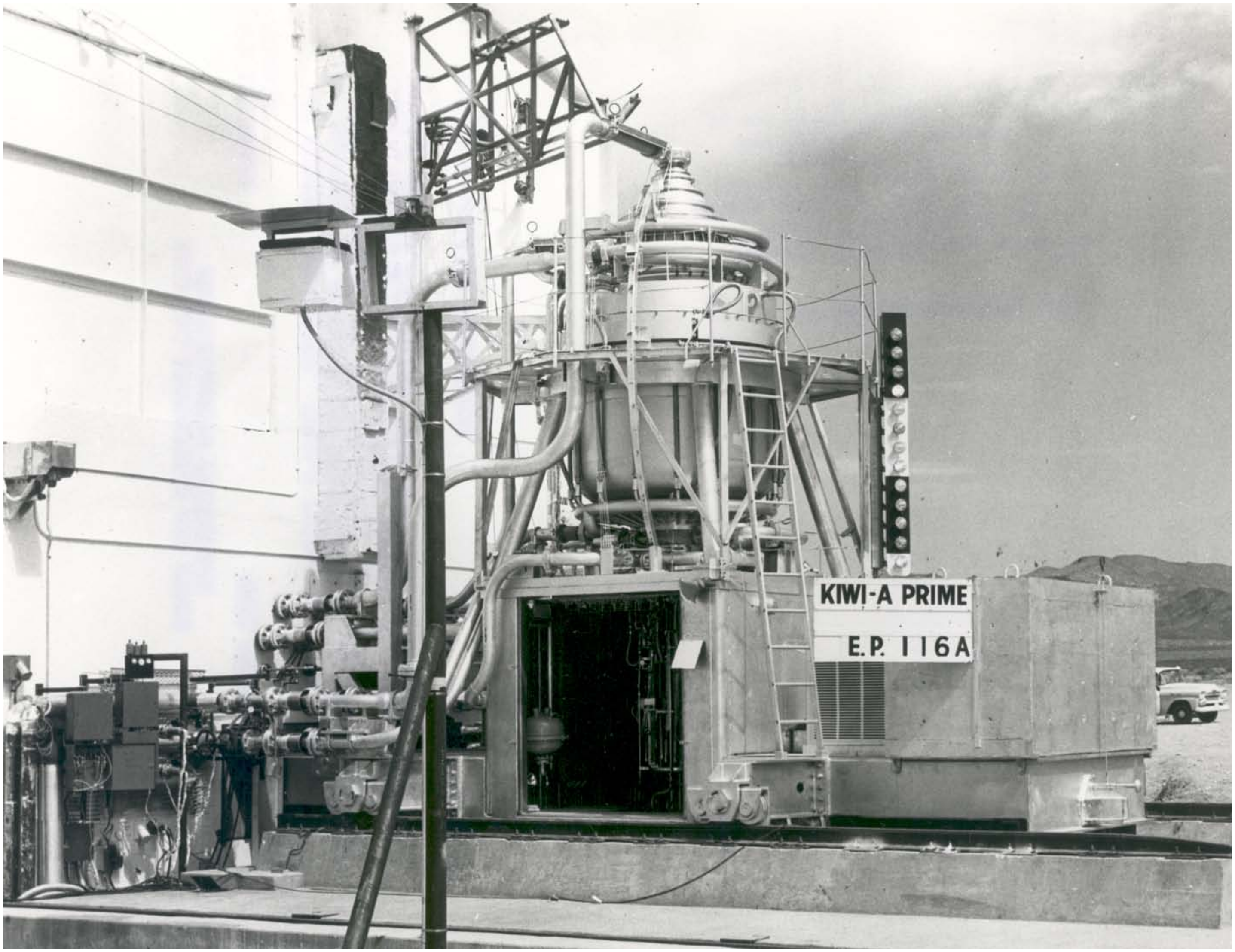




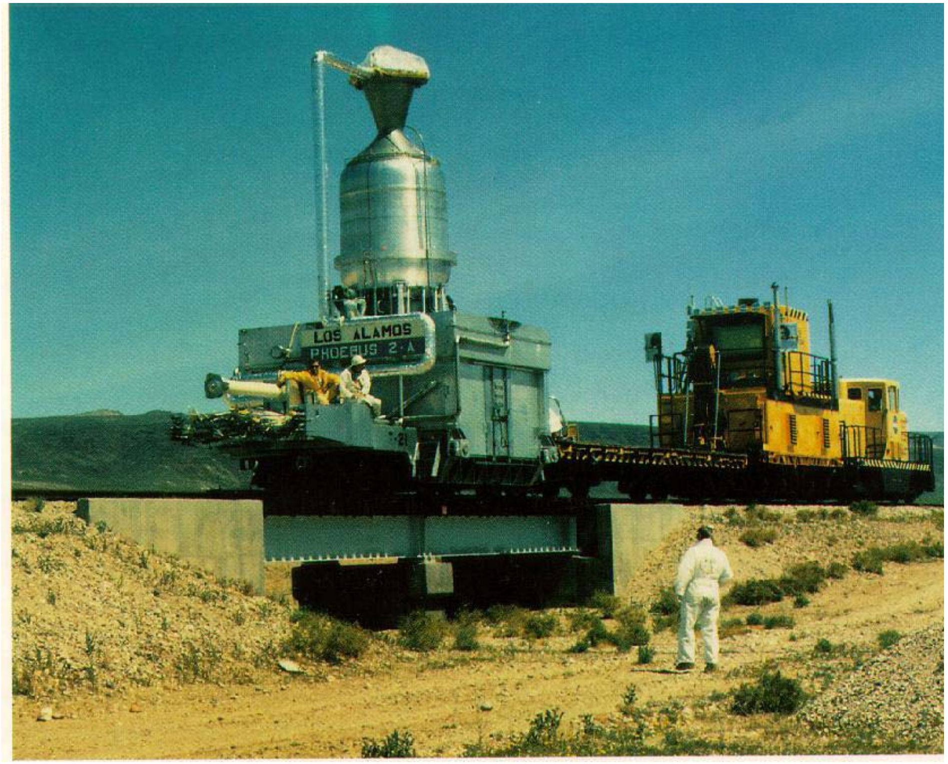
KIWI A	KIWI B	Phoebus 1	Phoebus 2	XE-Prime
1958-1960	1961-1964	1965-1966	1967	1969
100 MW	1,000 MW	1,000 & 1,500 MW	5,000 MW	1,140 MW
0 lbf Thrust	50,000 lbf Thrust	50,000 lbf Thrust	250,000 lbf Thrust	55,400 lbf Thrust

NERVA engines based largely on the KIWI B reactor design.

KIWI A'



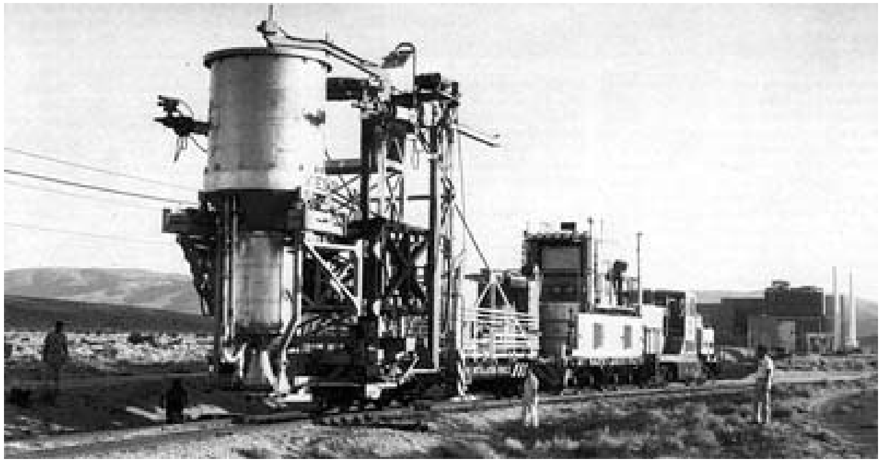
Phoebus-2A

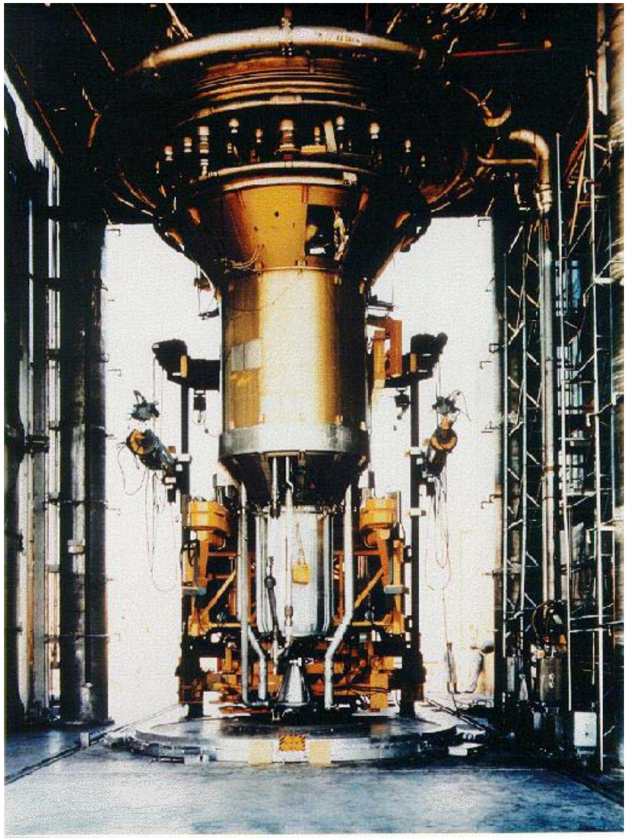


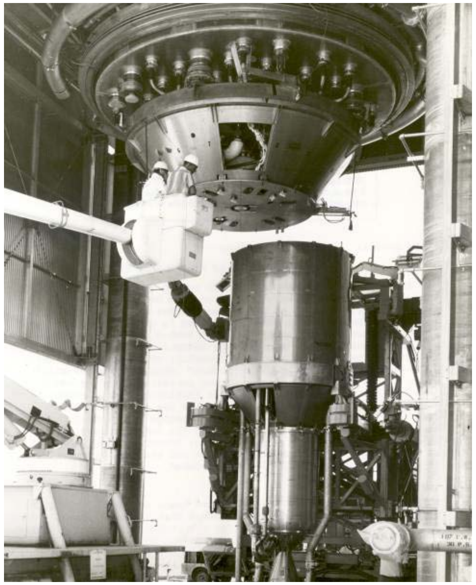
Phoebus-2A

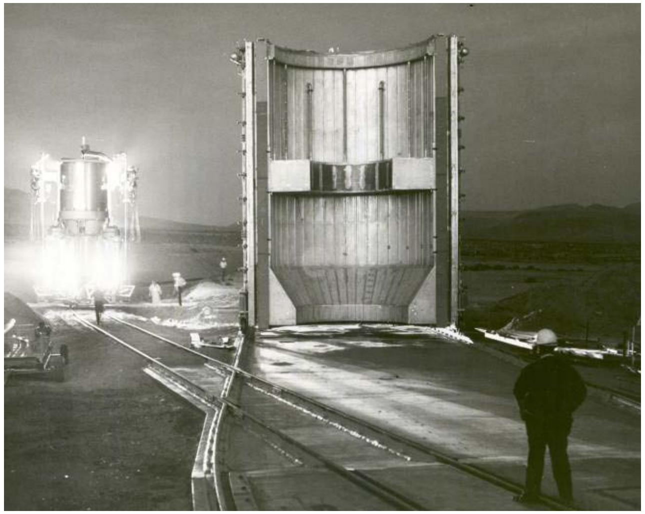
- Tested 1968
- 5 GW Reactor Core (tested at 4.2 GW)
- 805 seconds Isp space Equiv.
- 250,000 lbf Thrust

XE’







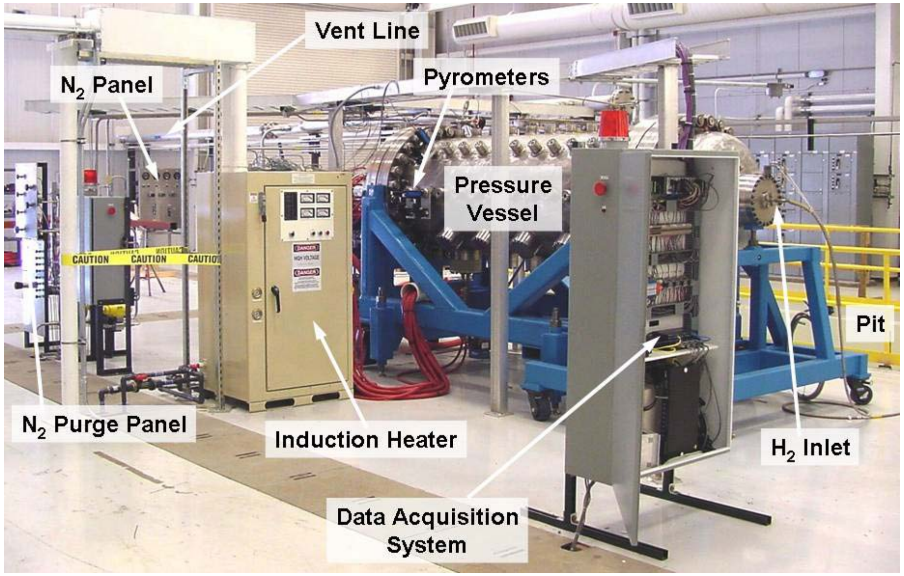


XE’ Engine

- Tested 1969
- 1.1 GW Reactor Core
- 820 seconds Isp space Equiv.
- 55,000 lbf Thrust

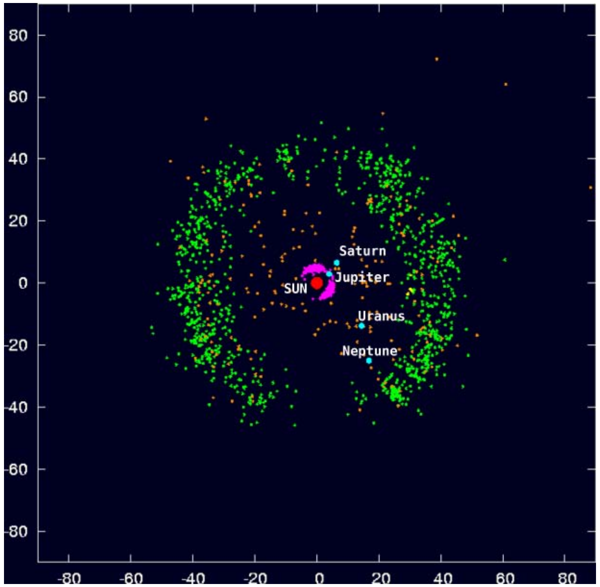
Facilities / Development Strategies Exist for 21st Century Program

- NTR Element Environmental Simulator (NTREES)
  - Non-nuclear testing of potential nuclear thermal propulsion fuel elements.
  - Up to 3000 K fuel temperature.
  - Near-prototypic hydrogen flow for single channels (potential upgrade to full-element).



What has changed in the past 20 years?

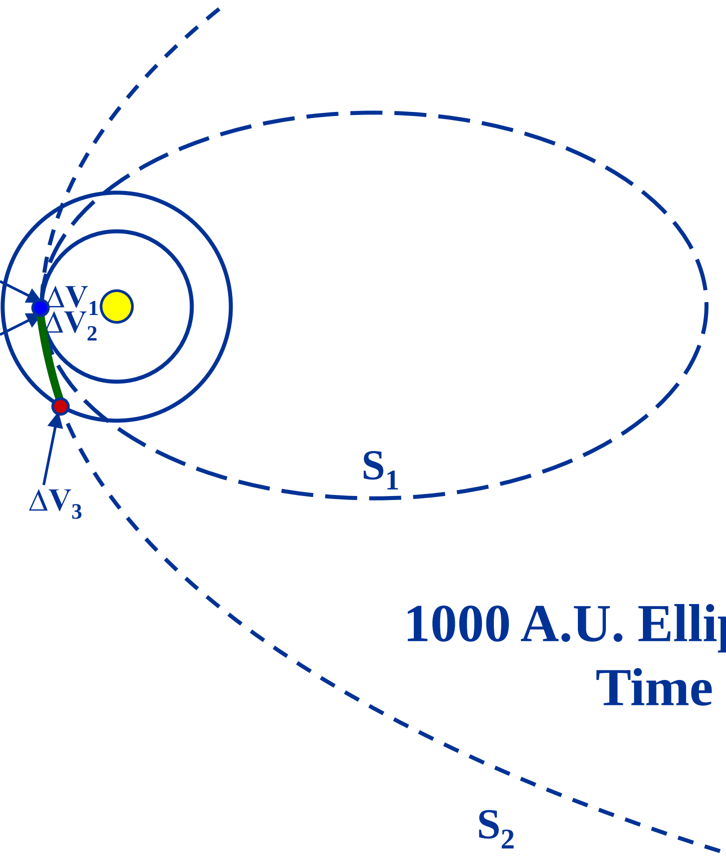
- Over a thousand Kuiper Belt objects identified since 1992.
  - Composed primarily of methane, ammonia, water.
- Small icy moons, asteroids, and comets also identified.
- Could nuclear thermal "steam" rockets change orbits of icy bodies?
  - In theory, any vapor can be used for NTP propellant
  - No chemical reactions required
  - Improved NTP materials will improve performance
  - Gravity assists to reduce required ΔV
- Could icy bodies be propellant depots?
  - Volatiles used directly as propellant in NTP-based transportation system
- Could icy bodies enable terraforming?



Could Ice Depots Enable Rapid Transits and Sustainable Exploration?

Three-Burn Quick Mars Trip
Quickest Mission w/o Becoming Hyperbolic

- Earth's Path
- Mars' Path
- Post ΔV_1 Ellipse
- Post ΔV_2 Ellipse
- Mars "Fast" Trajectory



$r_{aphelion\ 1} \approx 2.92$ A.U.
ΔV_1 (from LEO) = 5.01 km/s
ΔV_2 (from S_1 to S_2) = 5.75 km/s
ΔV_3 (from S_2 to Mars) = 20.3 km/s
~~Payload: 100 mt~~
~~IMLEO: 1763.6 mt~~

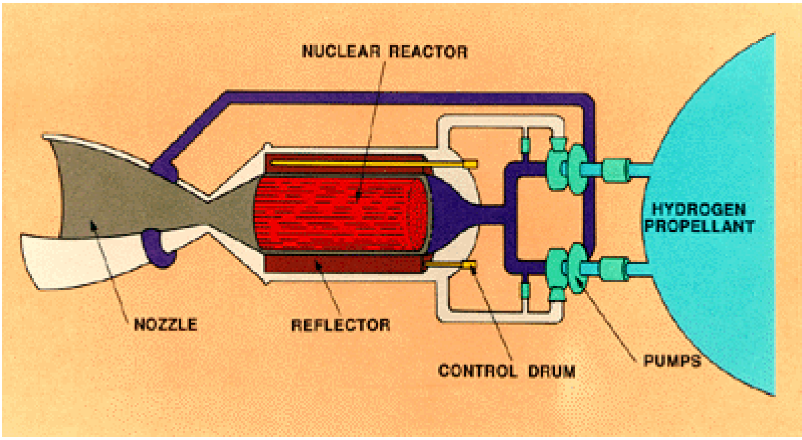
$r_{aphelion\ 1} \approx 4.42$ A.U.
ΔV_1 (from LEO) = 5.96 km/s
ΔV_2 (from S_1 to S_2) = 4.06 km/s
ΔV_3 (from S_2 to Mars) = 20.3 km/s
~~Payload: 100 mt~~
~~IMLEO: 1774.6~~

1000 A.U. Ellipse is Near to a Solar System Escape Trajectory
Time to Mars approx. 2.3 months

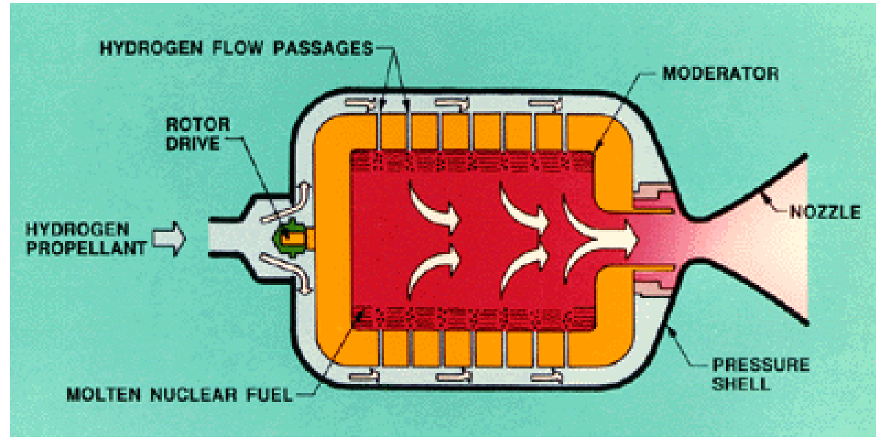
$r_{aphelion\ 2} \approx 1000$ A.U.

Larry Kos
MSFC/TD31
8/4/99

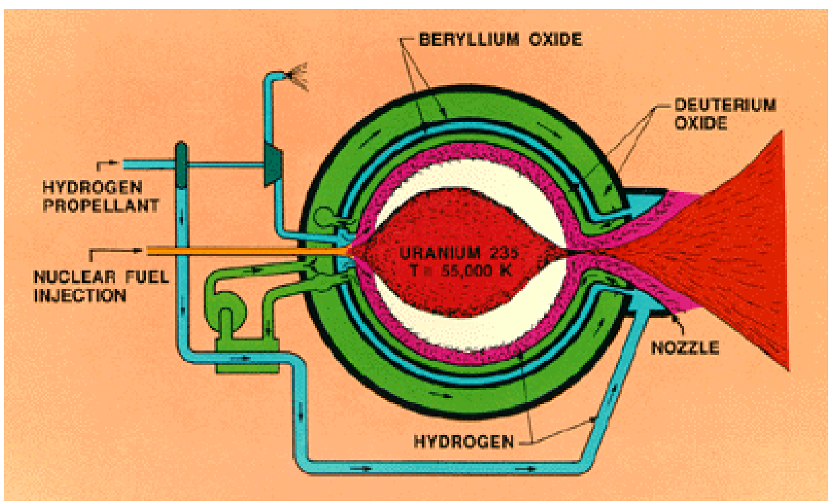
Could Modern Design, Technology, and Thermal Hydraulics Enable Extremely High Temperature / High Isp Systems?



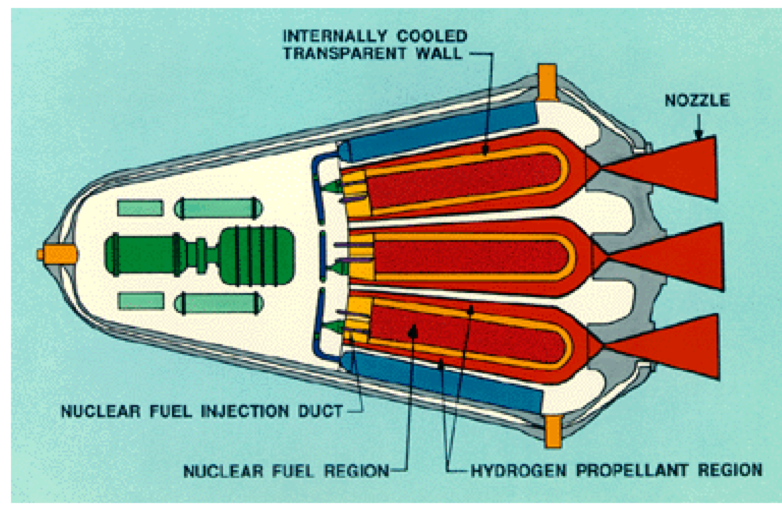
SOLID CORE NUCLEAR ROCKET



LIQUID CORE NUCLEAR ROCKET

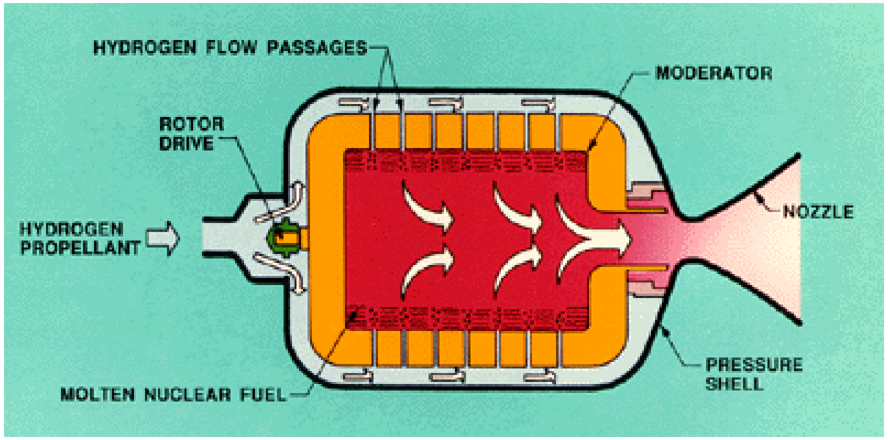


Open-Cycle Gas Core Nuclear Rocket



Closed-Cycle Gas Core Nuclear Rocket

Could an Affordable Experiment be Devised to Demonstrate the Fundamental Feasibility of a High Thrust (T/W >1) Very High Isp (> 1500 s) NTP System?



Uranium Metal Temperature (K)	Vapor Pressure (kPa)
2235	0.001
2564	0.01
2859	0.1
3234	1.0
3727	10.0
4402	100.0

Need method for ensuring adequate thermal contact between hydrogen and liquid uranium.

Need method for containing or recapturing high temperature uranium vapor.

Could a low-temperature analog be devised?

Summary

- Fission power and propulsion systems can enable exciting space exploration missions. These include bases on the moon and Mars; and the exploration, development, and utilization of the solar system.

- In the near-term, fission surface power systems could provide abundant, constant, cost-effective power anywhere on the surface of the Moon or Mars, independent of available sunlight. Affordable access to Mars, the asteroid belt, or other destinations could be provided by nuclear thermal rockets.

- In the further term, high performance fission power supplies could enable both extremely high power levels on planetary surfaces and fission electric propulsion vehicles for rapid, efficient cargo and crew transfer. Advanced fission propulsion systems could eventually allow routine access to the entire solar system. Fission systems could also enable the utilization of resources within the solar system.