Nuclear Energy for Space Exploration

Presented

June 5-6, 2010

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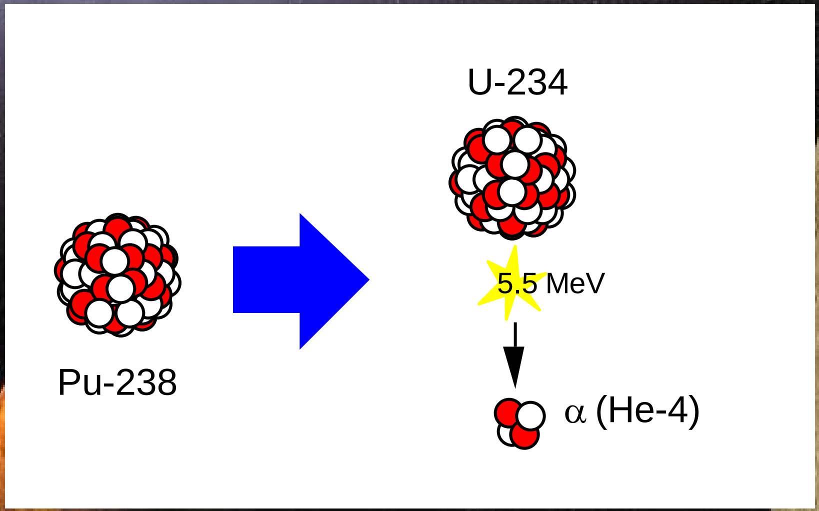
Basics of Space Nuclear Systems

Space Nuclear Power and Propulsion

Radioisotope Decay (Pu-238)

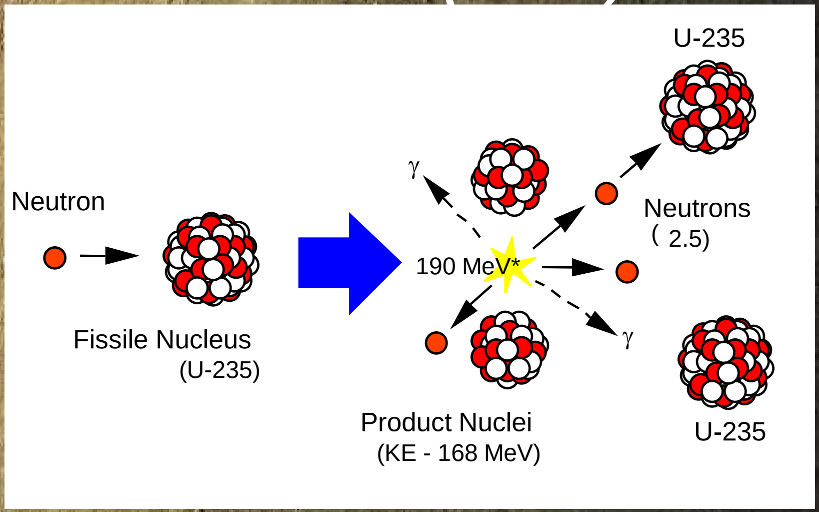


Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

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 (a) 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
- **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**

Fission Introduction

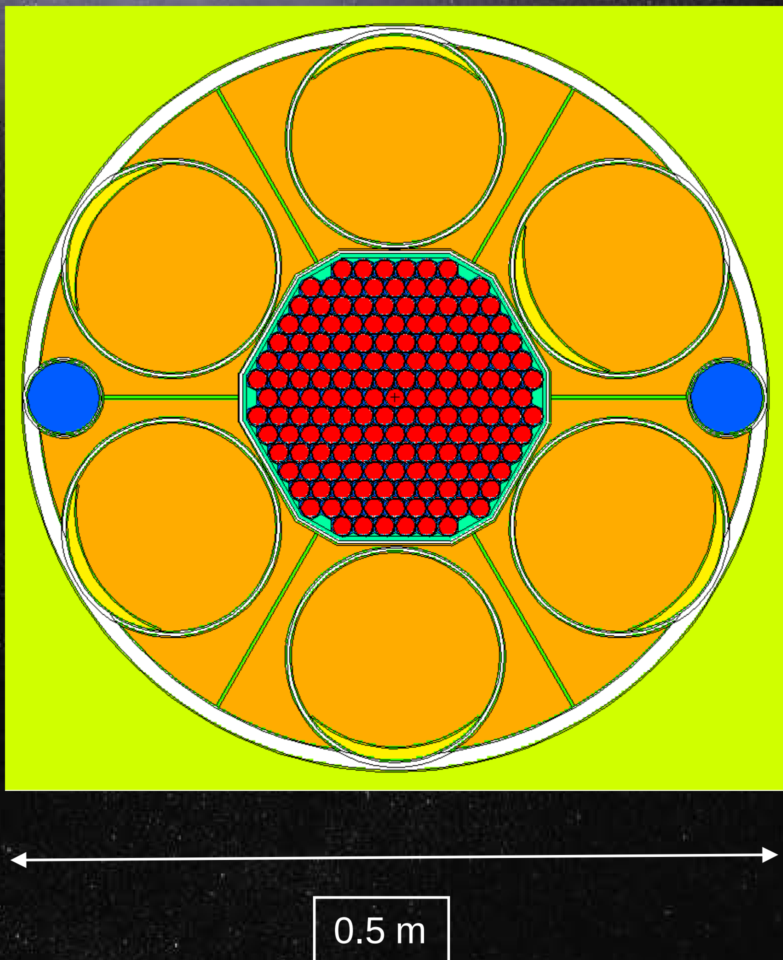
Space Nuclear Power and Propulsion

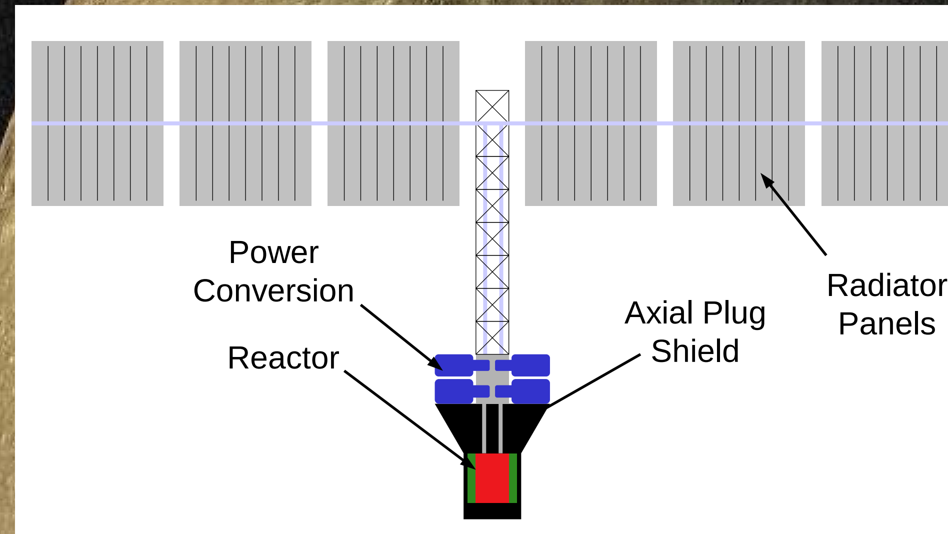
- **Creating a fission chain reaction is conceptually simple**
  - **Requires right materials in right geometry**
- **Good engineering needed to create safe, useful, long-life fission systems**

- ***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***

Fission Reactor Operation

Space Nuclear Power and Propulsion



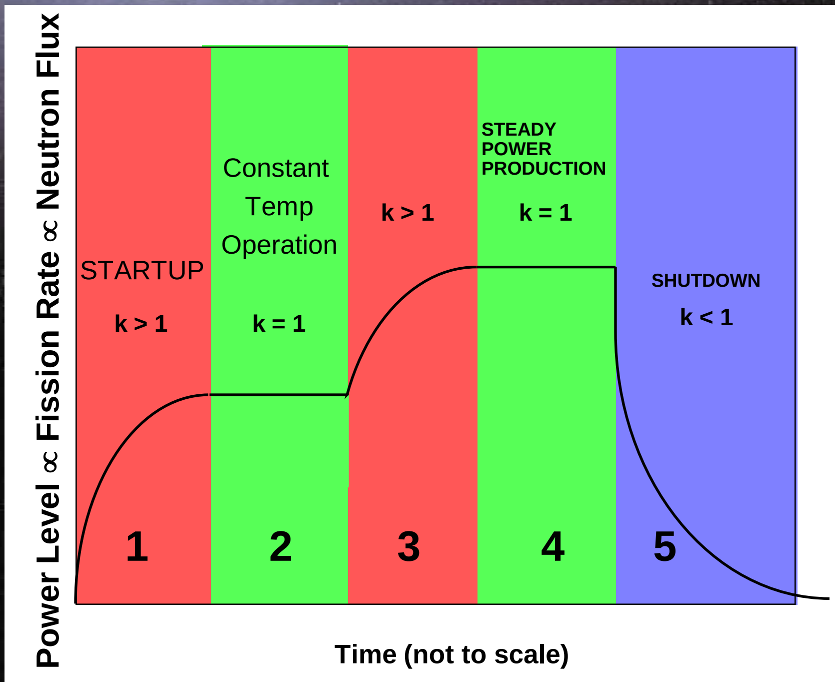


- System power controlled by neutron balance
- Average 2.5 neutrons produced per fission
  - Including delayed
- Constant power if 1.0 of those neutrons goes on to cause another fission
- Decreasing power if < 1.0 neutron causes another fission, increasing if > 1.0
- System controlled by passively and actively controlling fraction of neutrons that escape or are captured
- Natural feedback enables straightforward control, constant temperature operation
- 200 kWt system burns 1 kg uranium every 13 yrs

ARES 1

Reactor Operation (Notional)

Space Nuclear Power and Propulsion



$$k \equiv \text{Multiplication Factor}$$

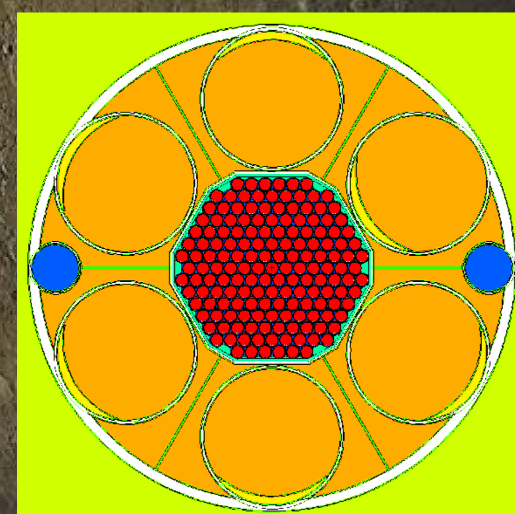
$$= \frac{\text{Production Rate}}{\text{Loss Rate}} = \frac{N(t+l_n)}{N(t)}$$

$$\begin{array}{ll} <1 & (\text{subcritical},\ \ dN/dt < 0) \\ =1 & (\text{critical},\ \ dN/dt = 0) \\ >1 & (\text{supercritical},\ \ dN/dt > 0) \end{array}$$

$$\text{Thermal Power}\,(t) \propto N(t)$$

$$\text{Reactivity} \equiv \rho \equiv \frac{k-1}{k}$$

1. Control drums rotate to provide positive reactivity (supercritical). Power increases, reactor heats up.
2. As reactor temperature increases, natural feedback reduces reactivity to zero. System maintains temperature.
3. Control drums rotate to provide additional reactivity, until desired operating temperature is achieved.
4. Reactor follows load, maintaining desired temperature. Control drums rotate ~monthly to compensate for fuel that is consumed.
5. Control drums rotate to shut system down.



Uranium Fuel

- **Natural uranium consists of**
  - U-234 0.0055%
  - U-235 0.720%
  - U-238 99.274%
- **Most reactor designs use uranium fuel enriched in U-235**
- **Prior to operation at power, uranium fuel is essentially non-radioactive and non-heat producing**
- **Following long-term operation, fission product decay power is 6.2% at t=0 (plus fission power from delayed neutrons)**
  - 1.3% at 1 hour
  - 0.1% at 2 months
- **Space reactor radiation exposure risk is primarily from inadvertent system start while personnel are near reactor**
  - Prevent inadvertent start via procedures, hardware, and design techniques developed over the past 6 decades

Radiation Shielding

- **Reactor needs to be shielded during operation and for a period of time following operation at significant power**

- **Hydrogen bearing compounds (e.g. LiH, H_2O) are most mass effective neutron shields**
  - Neutron shielding only needed while operating

- **High density, high atomic number materials (e.g. tungsten, uranium) best for gamma shielding, although areal density (mass/area) is primary requirement.**

- **NTP missions typically propose using propellant, consumables, and other “available” materials for shielding.**

- **Reactor can be shielded to any level desired**
  - Dose rate drops rapidly following shutdown

Fission is Highly Versatile with Many Applications

- **Small research reactors**
  - Examples include 2000 kWt TRIGA reactor recently installed in Morocco (< $50M)
- **Advanced, high-power research reactors and associated facilities**
  - Examples include the US Fast Flux Test Facility (400,000 kWt, ~$3.0B FY08)
- **Commercial Light Water Reactors 1,371,000 kWe (3,800,000 kWt)**
  - Recent TVA cost estimate ~$2.2B
- **Space reactors**
  - SNAP-10A 42 kWt / 0.6 kWe
  - Soviet reactors typically 100 kWt / 3 kWe (some systems >150 kWt)
  - Cost is design-dependent

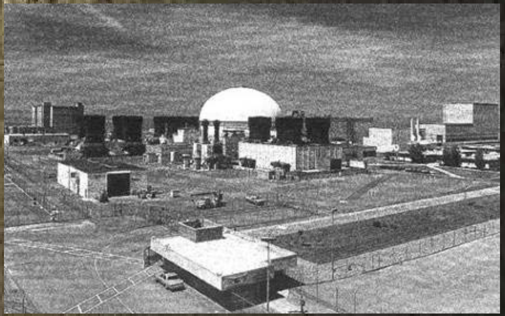
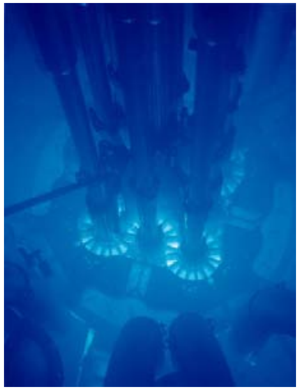


Figure II-92. SNAP 10A Flight System

Fission is Highly Versatile with Many Applications (continued)

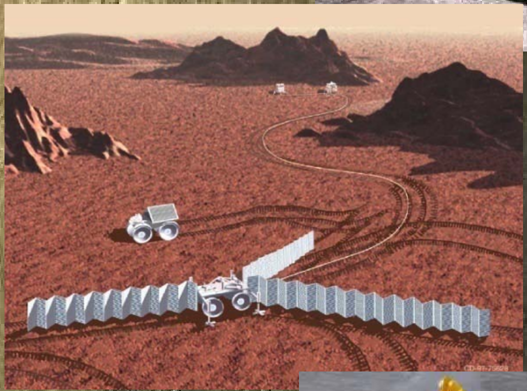
- **Naval Reactors**
  - Hundreds of submarines and surface ships worldwide
- **Production of medical and other isotopes**
- **Fission Surface Power**
  - Safe, abundant, cost effective power on the moon or Mars
- **Nuclear Thermal Propulsion**
  - Potential for fast, efficient transportation throughout inner solar system
- **Nuclear Electric Propulsion**
  - Potential for efficient transportation throughout solar system
- **Highly advanced fission systems for solar system exploration**



Recent interest in Fission Surface Power (FSP) to support moon / Mars exploration

Space Nuclear Power and Propulsion

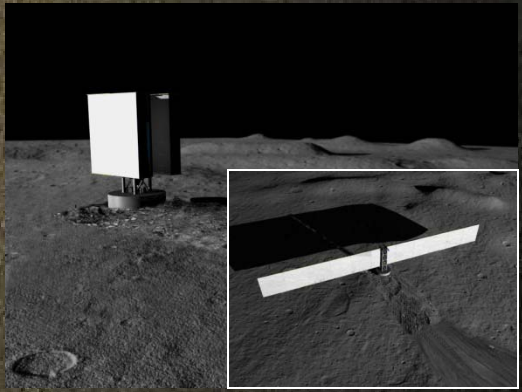
- **Continuous Day/Night Power for Robust Surface Operations**
- **Same Technology for Moon and Mars**
- **Suitable for any Surface Location**
  - Lunar Equatorial or Polar Sites
  - Permanently Shaded Craters
  - Mars Equatorial or High Latitudes
- **Environmentally Robust**
  - Lunar Day/Night Thermal 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

Space Nuclear Power and Propulsion

- **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)



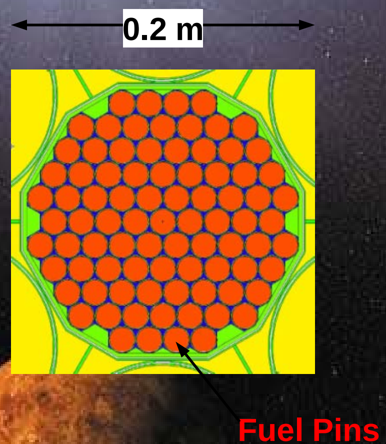
"Affordable" Design Philosophy

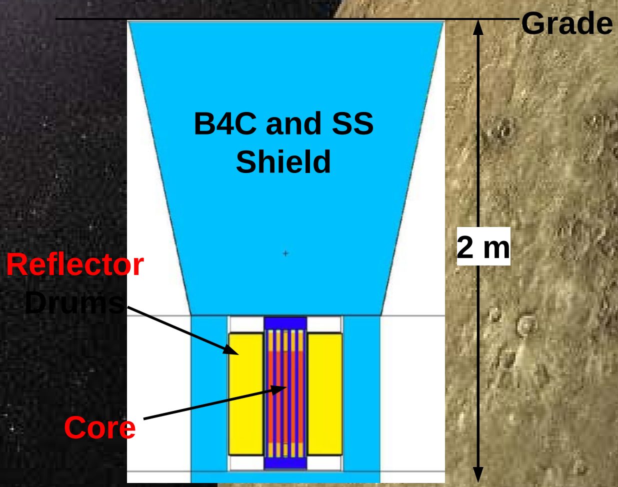
- **Conservative**
  - Low Temperature
  - Known Materials and Fluids
  - Generous Margins
  - Large Safety Factors
  - Terrestrial Design Basis
- **Simple**
  - Modest Power & Life Requirements
  - Simple Controls
    - Negative Temperature Reactivity Feedback: assures safe response to reactor temperature excursions
    - Parasitic Load Control: maintains constant power draw regardless of electrical loads and allows thermal system to remain near steady-state
  - Slow Thermal Response
  - Conventional Design Practices
  - Established Manufacturing Methods
  - Modular and Testable Configurations
- **Robust**
  - High Redundancy
  - Fault Tolerance… including ability to recover from severe conditions such as:
    - Loss of Reactor Cooling
    - Stuck Reflector Drums
    - Power Conversion Unit Failure
    - Radiator Pump Failure
    - Loss of Radiator Coolant
    - Loss of Electrical Load
  - High TRL Components
  - Hardware-Rich Test Program
  - Multiple Design Cycles

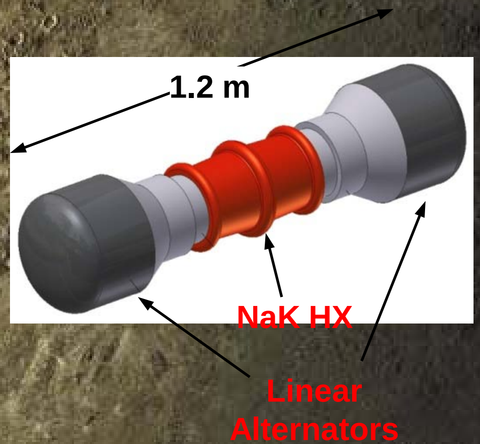
Minimize Cost by Reducing Risk -- Accept Mass Penalties if Needed

Key Design Features

Space Nuclear Power and Propulsion







Reactor Core:

- Well-known UO_2 fuel and SS-316 cladding at moderate temperature (<900K)
- Low power (<200 kWt), low fuel burn-up (~1%)
- Fluence levels well below material thresholds
- NaK coolant: low freeze temp (262K), extensive space & terrestrial technology base
- Simple and safe, negative temperature feedback control

Reactor Module:

- Fault-tolerant, radial Be reflector control drums
- Low-risk B4C and SS shielding with regolith augmentation
- <2 Mrad and $1x10^{14}$ n/cm^2 at power conversion; <5 rem/yr at outpost (100 m)
- SS-316 primary & intermediate coolant loops with redundant EM pumps
- Cavity cooling with surface-mounted radiators

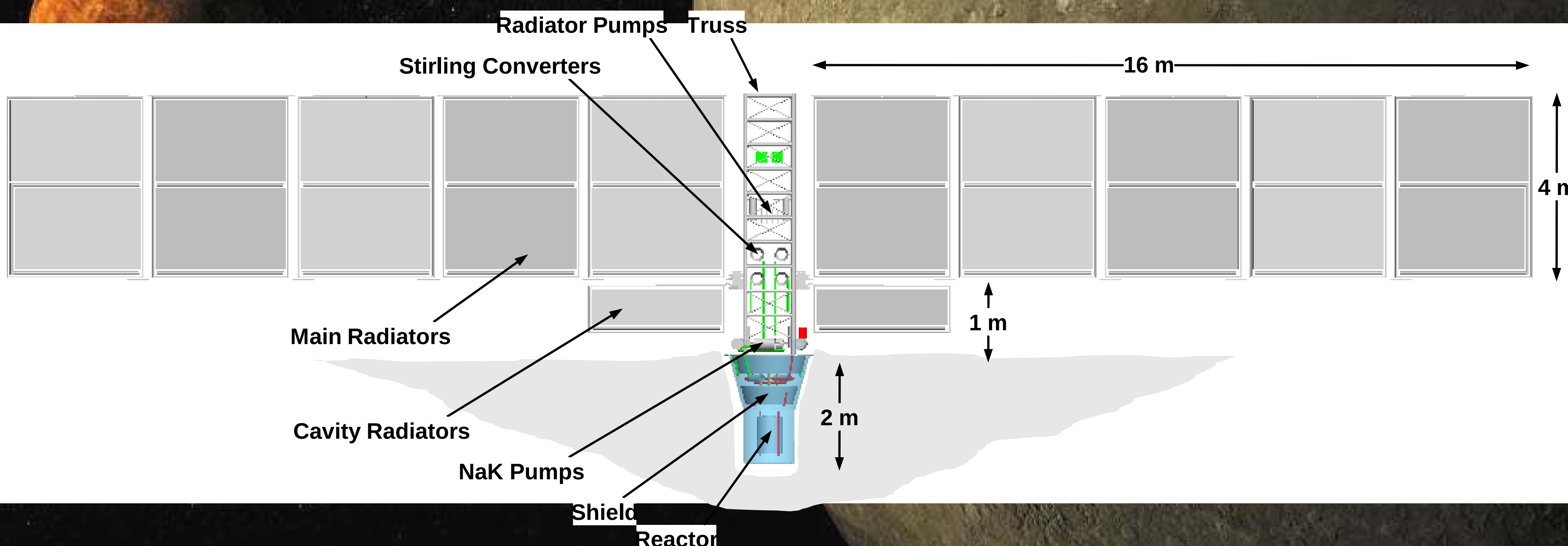
Stirling Power Conversion:

- High efficiency (>25%) at low hot-end temperature (830K)
- Pumped-water cooling (400K)
- Smallest radiator size among PC options
- 4 dual opposed engines, 8 linear alternators
- 400 Vac power distribution
- Demonstrated technology at 25 kW size in 1980's
- Potential to leverage current RPS program

FSP Reference Concept

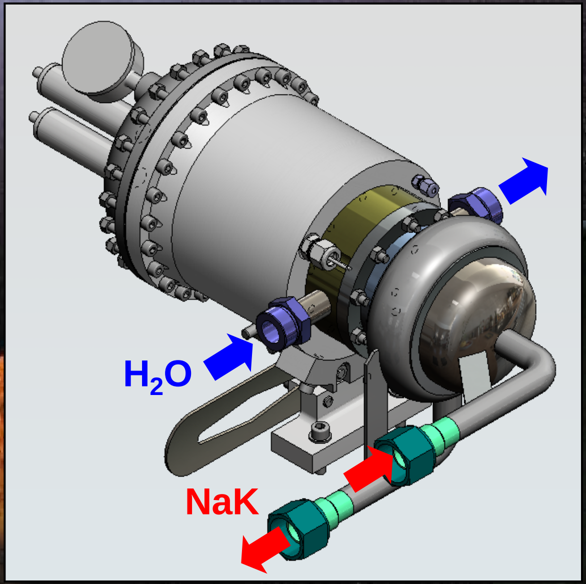
Space Nuclear Power and Propulsion

- Modular 40 kWe System with 8-Year Design Life suitable for (Global) Lunar and Mars Surface Applications
- Emplaced Configuration with Regolith Shielding Augmentation Permits Near-Outpost Siting (<5 rem/yr at 100 m Separation)
- Low Temperature, Low Development Risk, Liquid-Metal (NaK) Cooled Reactor with UO_2 Fuel and Stainless Steel Construction

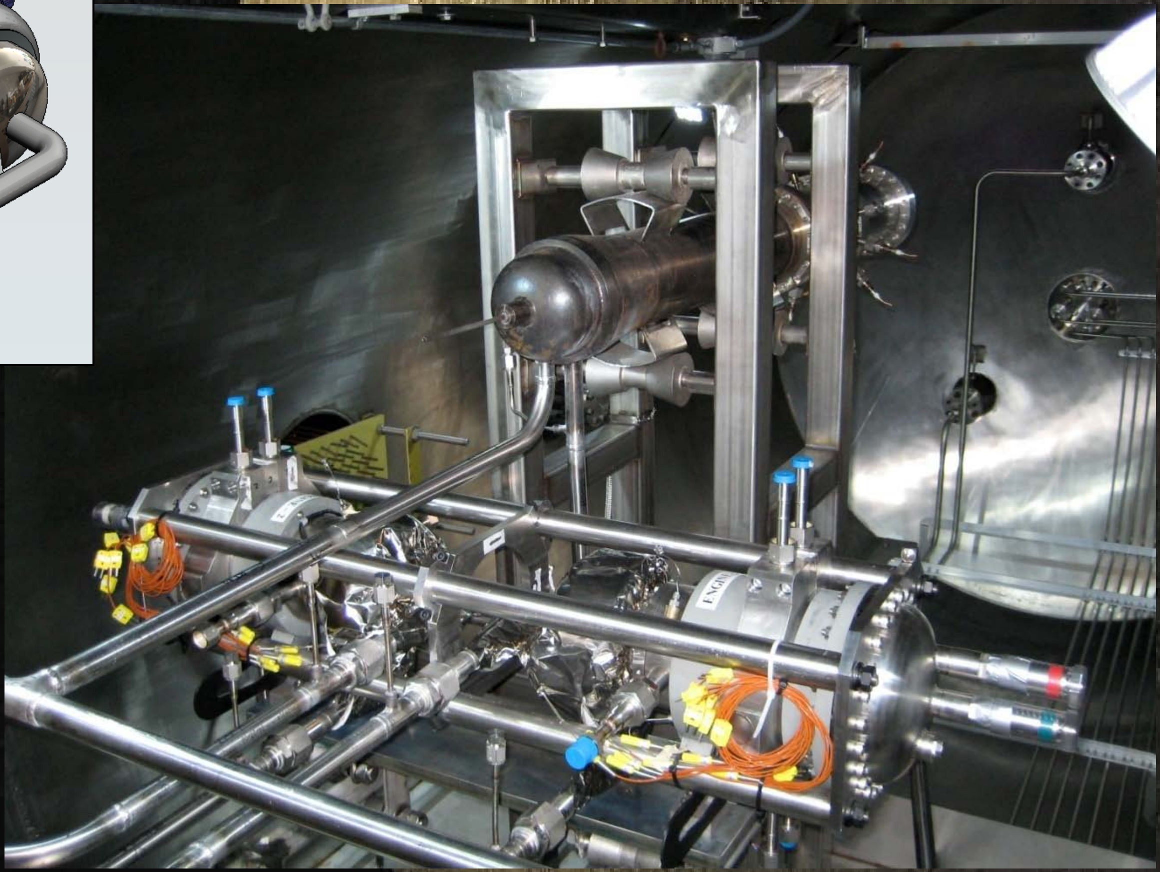


2 kWe NaK Stirling Demonstration Test

Space Nuclear Power and Propulsion



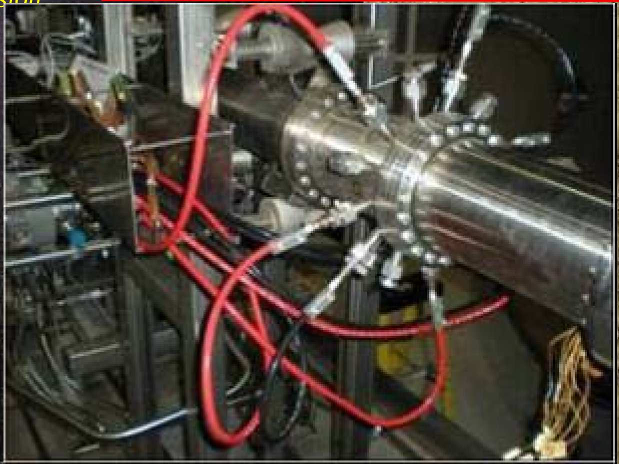
Test Validated Reactor-Stirling Heat Transfer Approach for FSP (Stirling provided by NASA–GRC)



- 2.4 kWe at Thot=550ºC, Tcold=50ºC
- 32% Thermal Efficiency
- <5ºC Circum. Gradient on Heater Head
- 41 Steady-State Test Points; 9 Transients
- 6 Reactivity Control Simulations

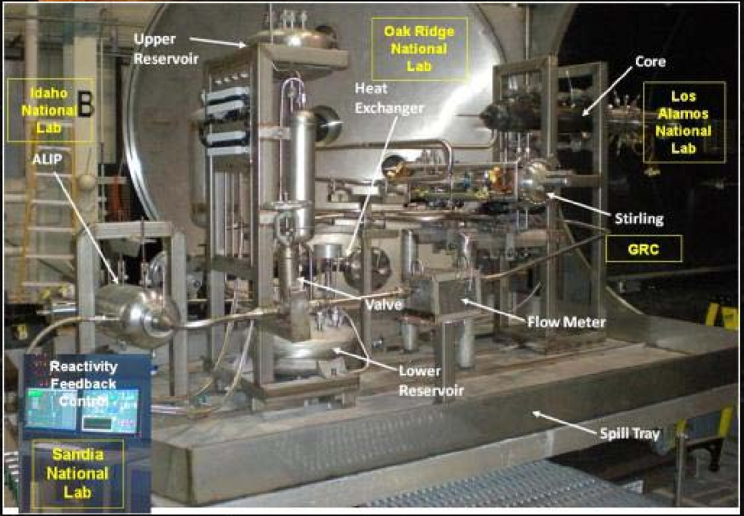
Coupled NaK Loop / Stirling Test

Cable tray providing protection from heat/NaK



Core Simulator Design by Los Alamos National Laboratory

Power Cable path to core



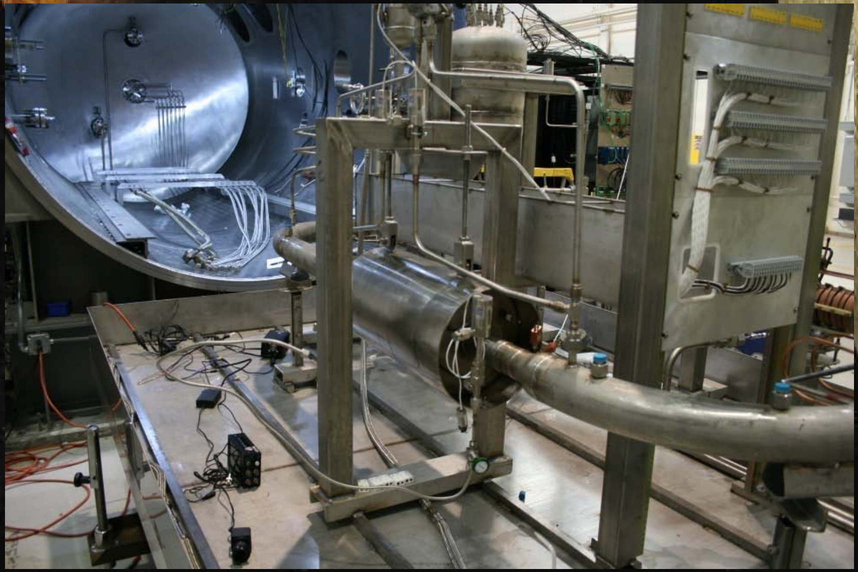
Integrated Stirling Test Assembly

ALIP Provided By Idaho National Laboratory

EFF-TF ALIP Test Circuit

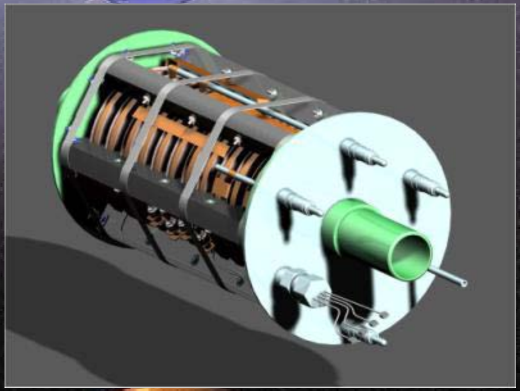
Space Nuclear Power and Propulsion

Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory



NaK Pump Testing

Space Nuclear Power and Propulsion



ALIP Drawing

ALIP unpacked at MSFC EFF-TF by INL and MSFC team members

Performance Mapping of Annular Linear Induction Pump (ALIP) provided by Idaho National Laboratory

Space Nuclear Power and Propulsion

ALIP Test Circuit (ATC)

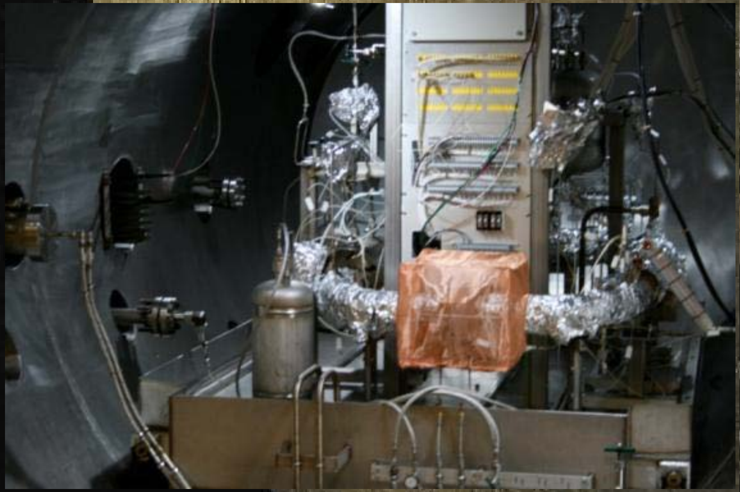
ALIP

ATC ready for chamber prior to NaK fill

NaK fill

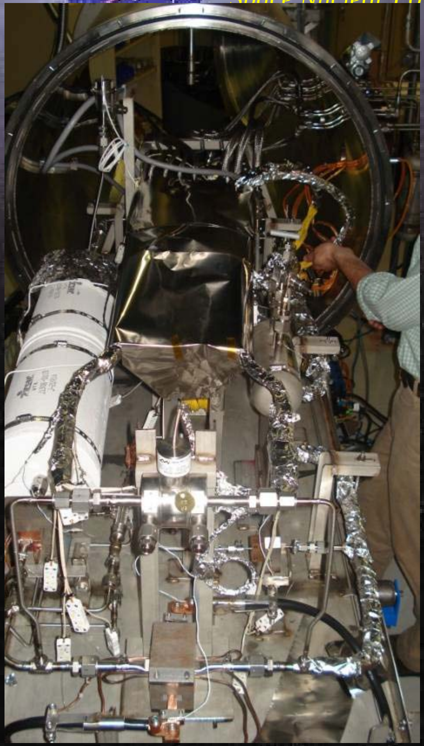
Enhanced heating assembly

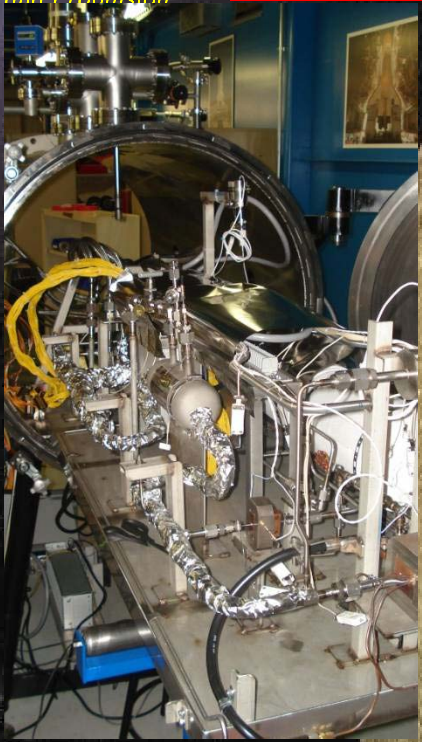
Enhanced heating assembly ready for application of insulation

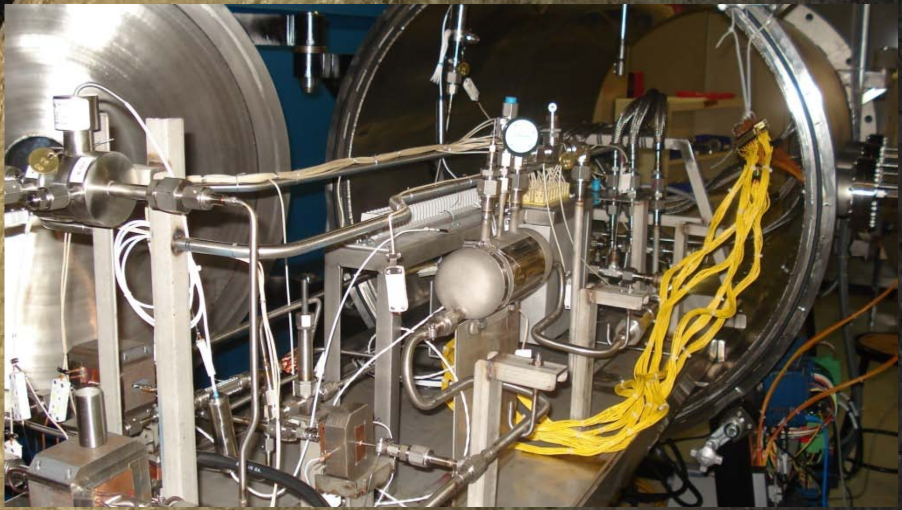


ATC Testing

EFF-TF Feasibility Test Loop







Feasibility Test Loop:

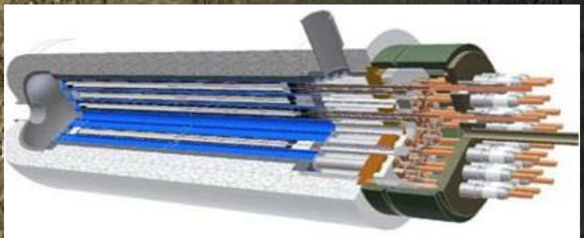
Investigate potential issues and optimizations related to pumped alkali metal systems

Fission Surface Power – Primary Test Circuit (FSP-PTC)
7 – Pin Reactor (Rx) Core Simulator Testing

Space Nuclear Power and Propulsion

MSFC Designed Advanced Simulators

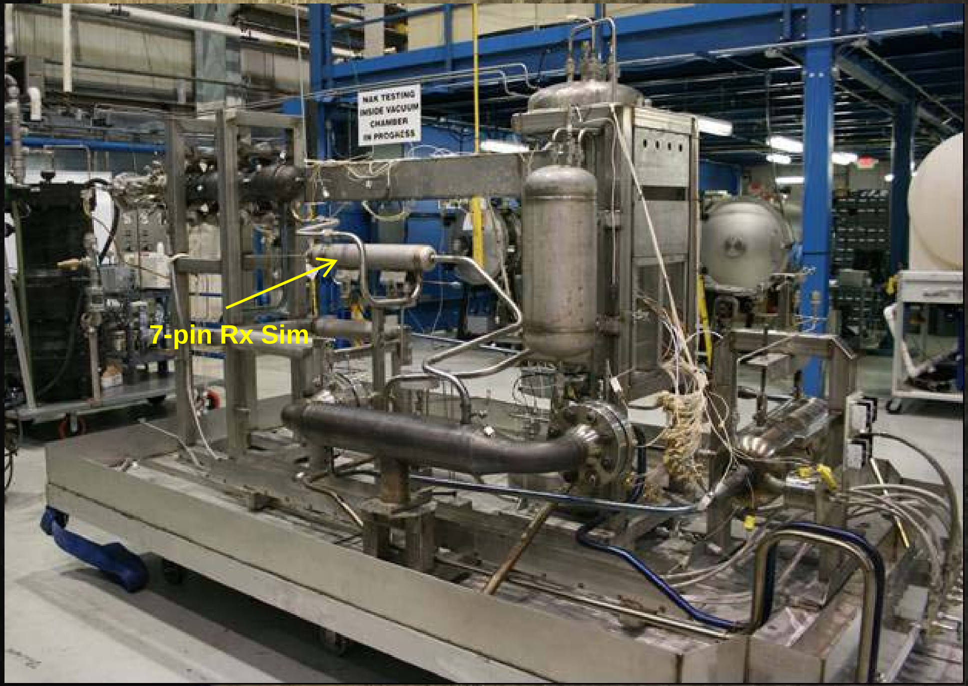
7-Pin Rx Core Sim



37 – Pin TDU Rx Core Sim

7 – Pin Rx Core Sim Rendering

Revised FSP-PTC layout for 7 – Pin Rx Core Sim



7 Pin Rx Core Sim installed in FSP-PTC

FSPS Accomplishments

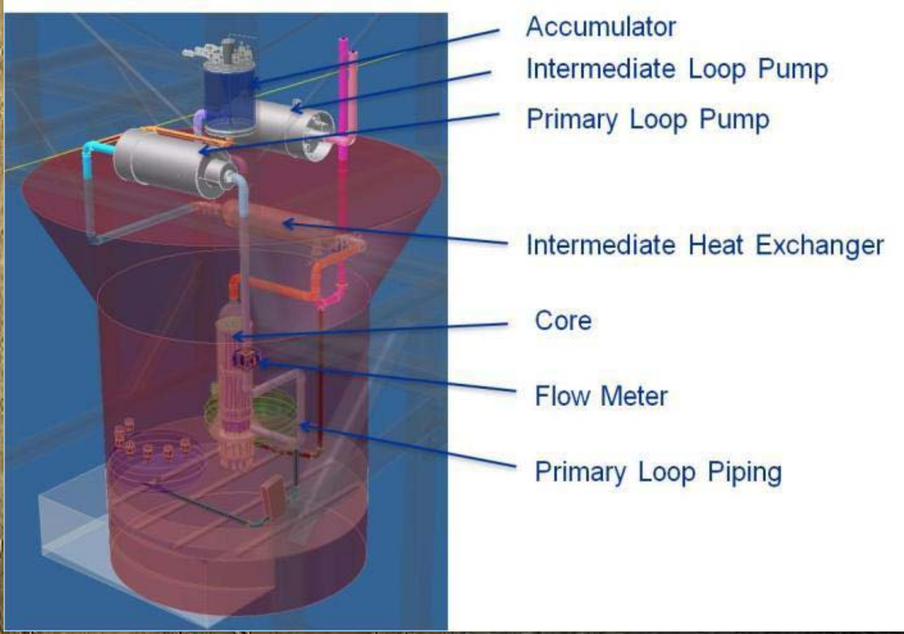
Space Nuclear Power and Propulsion

FSP-PTC Stirling & 7 Pin Rx Core Sim Testing

ATC Testing

FTL Testing

Recent Activities Focused Towards TDU Reactor Simulator



MSFC Designed Reactor Simulator in TDU
(top view close up)

MILESTONES
Fabricate & Test : 2010-2011
Ship to GRC 2012

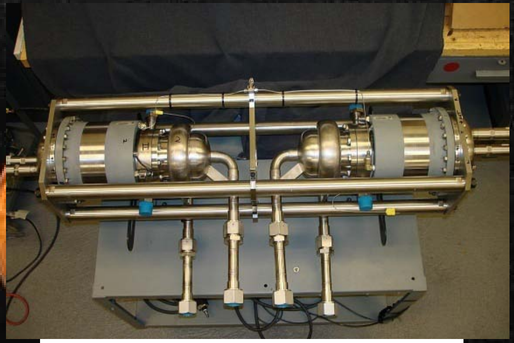
FSP Technology Project: Risk Reduction

Space Nuclear Power and Propulsion

20 kWt NaK Reactor Simulator

NaK Annular Linear Induction Pump

25 kWe Dual Brayton System



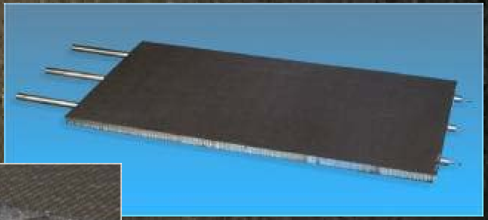
2 kWe NaK Stirling System

10 kWe Stirling Alternator Test Rig

Ti-H2O Heat Pipe Life Test

2 kWe Direct Drive Gas Brayton

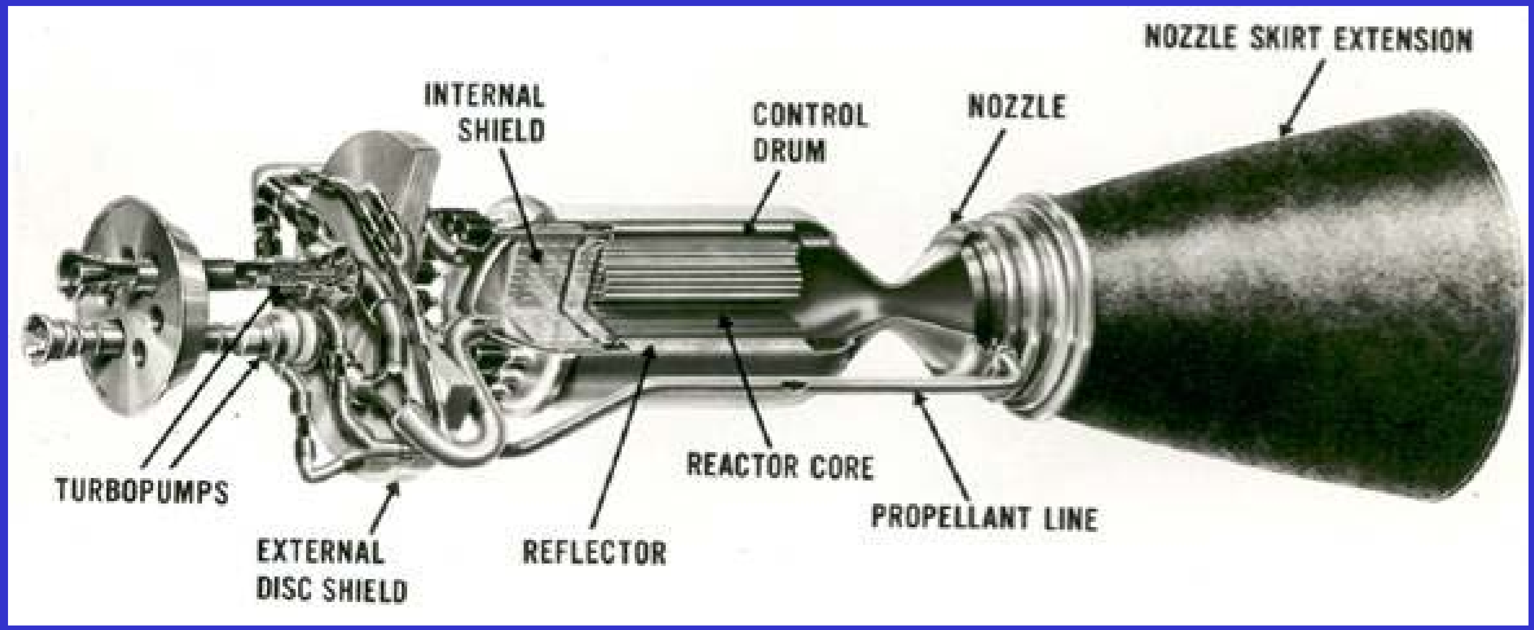
5 kWe Stirling Demonstrator



1 kWt Radiator Demo Unit

Nuclear Thermal Propulsion (NTP)

Space Nuclear Power and Propulsion



- Typical system: 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 Mars and other potential destinations
  - Potential to significantly reduce propellant needs and/or trip time

Nuclear Thermal Propulsion (NTP)

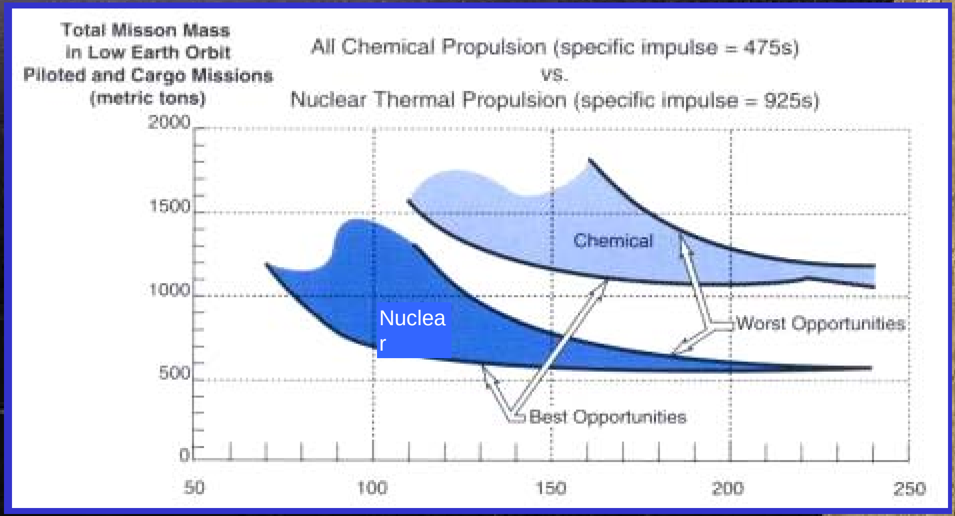
Space Nuclear Power and Propulsion

- **NTP Concerns**
  - Cost/schedule – new engine system, nuclear testing, launch processing, potential opposition, INSRP process, etc.
  - Potential operational constraints.
- **NTP Benefits**
  - Significant new capability. Reduce mission mass and/or time.
  - Flexible choice of propellant, effectively unlimited energy.
  - Significant cost savings /sustainable exploration program.

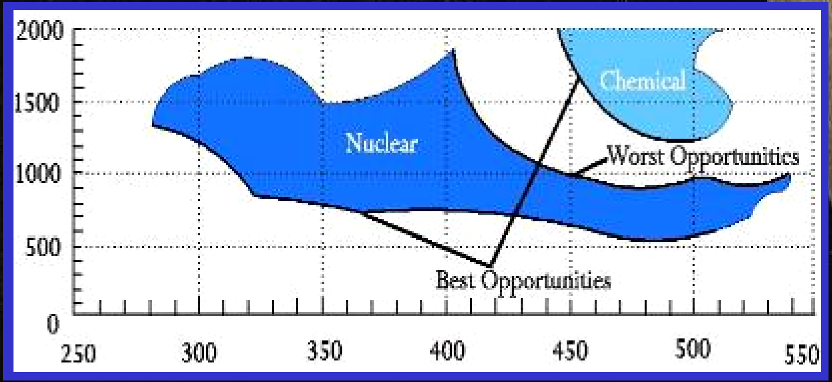
Nuclear Thermal Propulsion (NTP) Has The Potential to be Mission Enabling

Space Nuclear Power and Propulsion

Comparison of IMLEO vs. Trip Time for All-up Opposition and Conjunction Mars Missions*



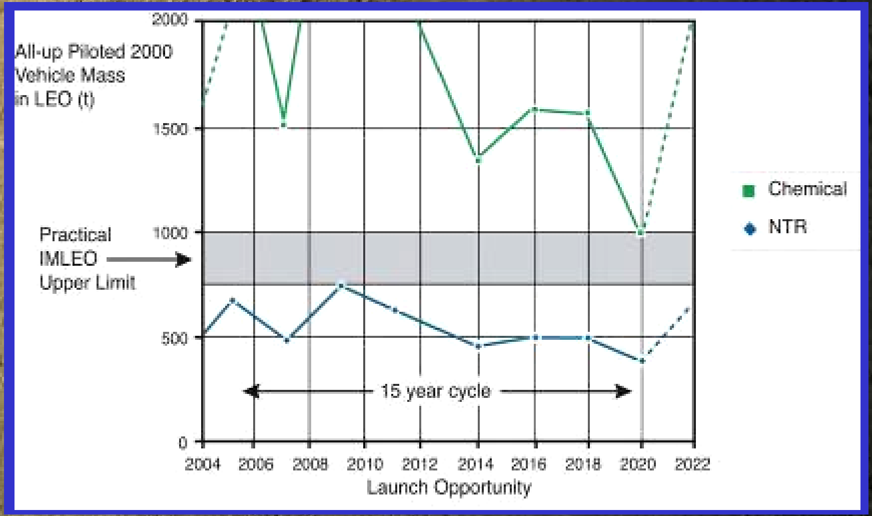
Conjunction Class (Long Stay) Mission



Opposition Class (Short Stay) Mission

Short Stay-Time Missions:

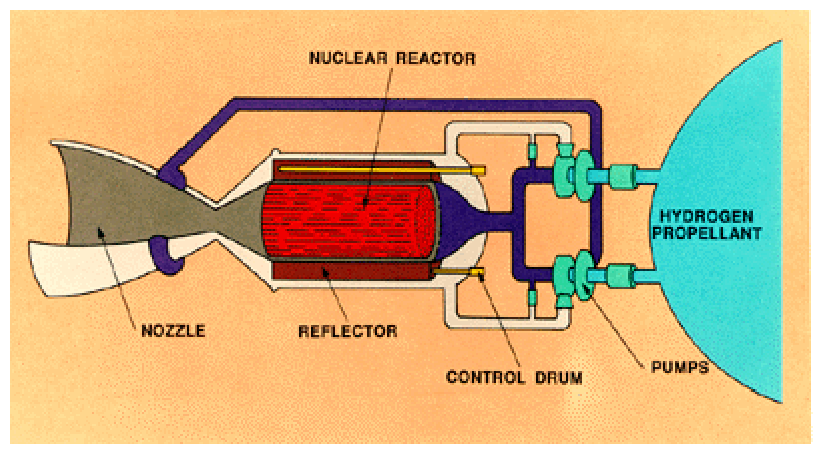
NTP captures most opportunities, and chemical systems capture only one opportunity



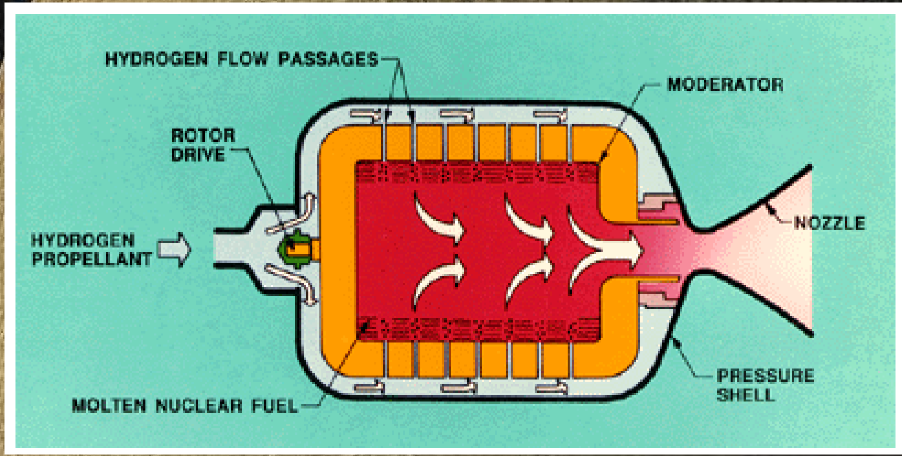
***Source:** NASA's Office of Aeronautics, Exploration and Technology, presented to Stafford Synthesis Team in 1991

Proposed Types of Nuclear Thermal Propulsion

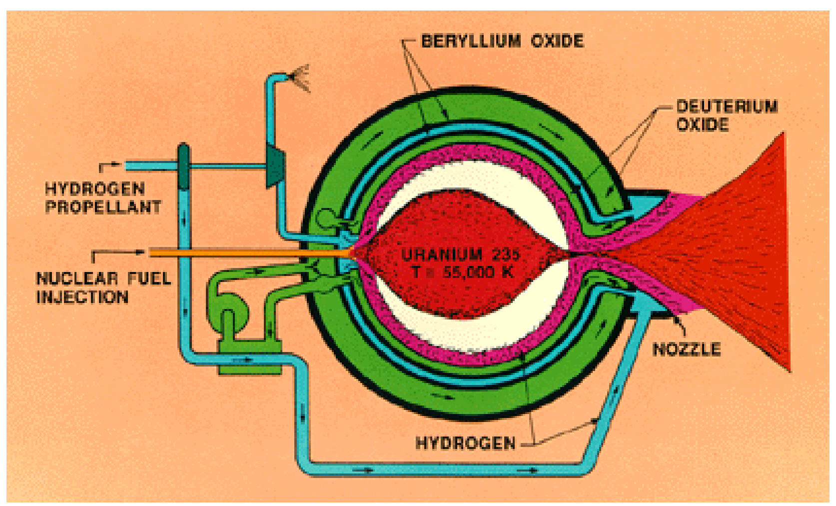
Space Nuclear Power and Propulsion



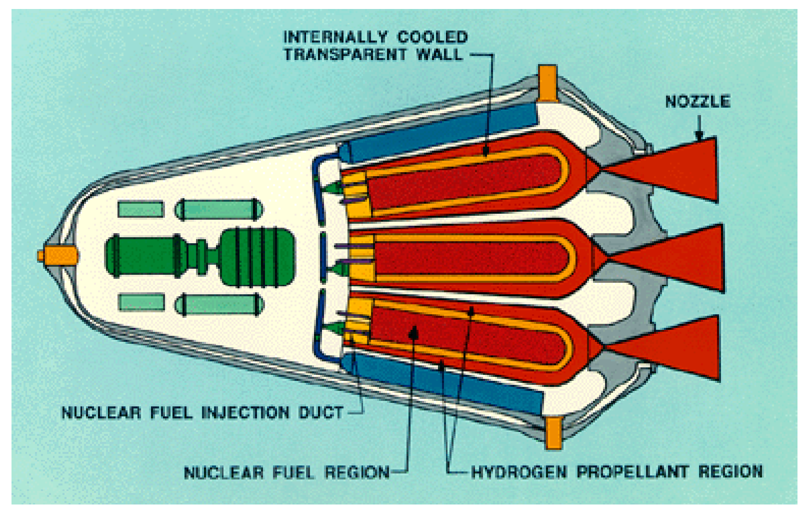
SOLID CORE NUCLEAR ROCKET



LIQUID CORE NUCLEAR ROCKET



Open-Cycle Gas Core Nuclear Rocket



Closed-Cycle Gas Core Nuclear Rocket

NTP History

Space Nuclear Power and Propulsion

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

- Fundamental feasibility
- Engine burn time
- Start-up & shut-down cycles
- Thermal transients
- Ground testing

Phoebus 2
1967
5,000 MW
250,000 lbf

XE-Prime
1969
1,140 MW
55,400 lbf

NERVA
- Characterized performance for human lunar and Mars applications

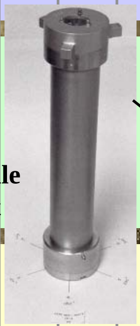
CERMET/GE-710
- CERMET fuel fabrication and fundamental feasibility

Russian / CIS Development

US Contracts
- Carbide fuel development
- Assessments

Project Formulation

RIFT
- Flight test system formulation



Particle In-Pile Experiment

NPO
- SEI

SNTP
- 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
- NTP facility and design studies — NASA/DOE

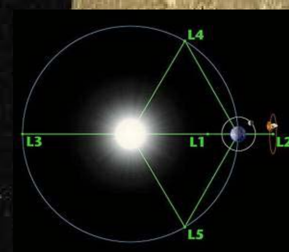
NTP could be mission-enhancing

NTP could enhance the ability to reach new destinations

NTP could enable a steady, progressive, regular and affordable exploration program

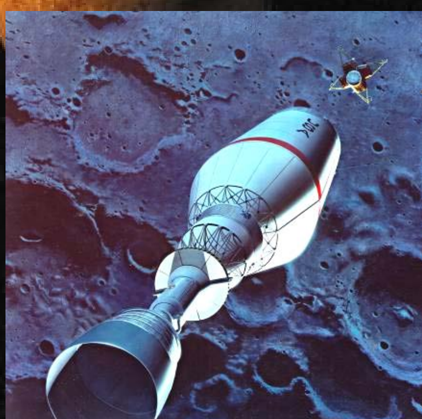
Mars Cargo and Human Missions

Phobos Mission



Sun-Earth Lagrange Point

NEO Mission



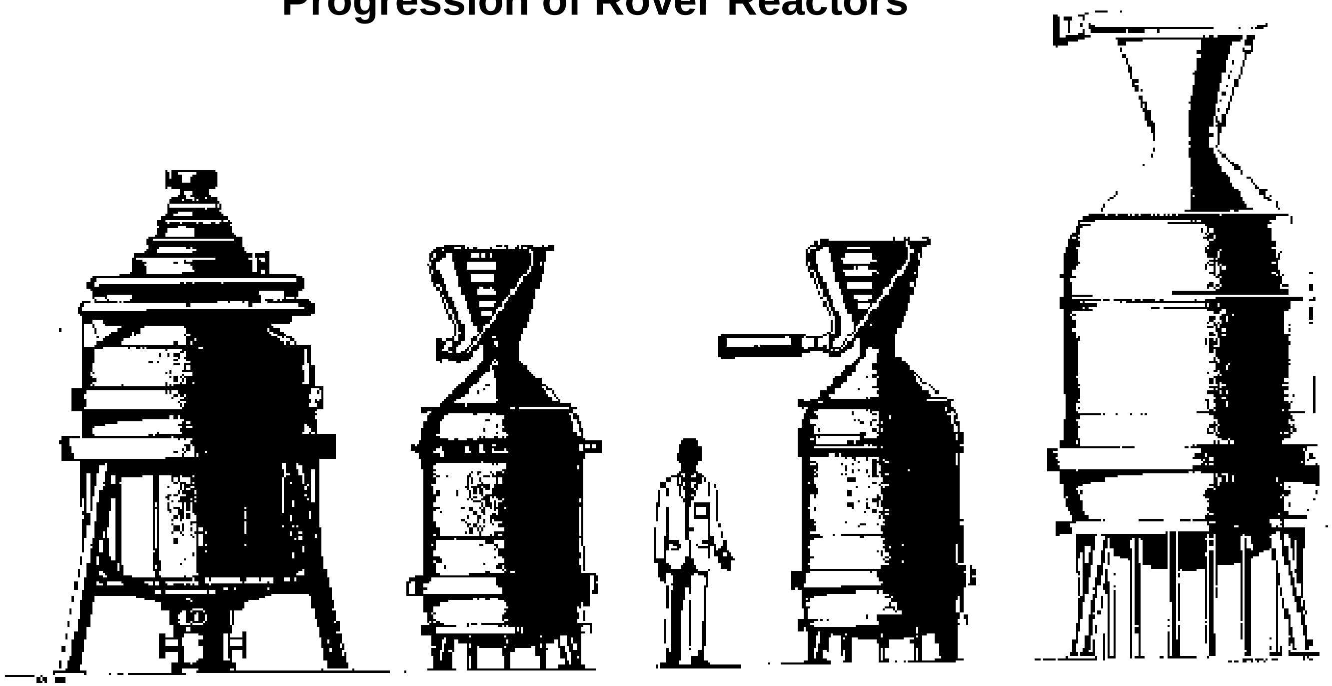
Lunar Cargo Missions

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

Rover/NERVA Engine Comparison

Space Nuclear Power and Propulsion

Progression of Rover Reactors



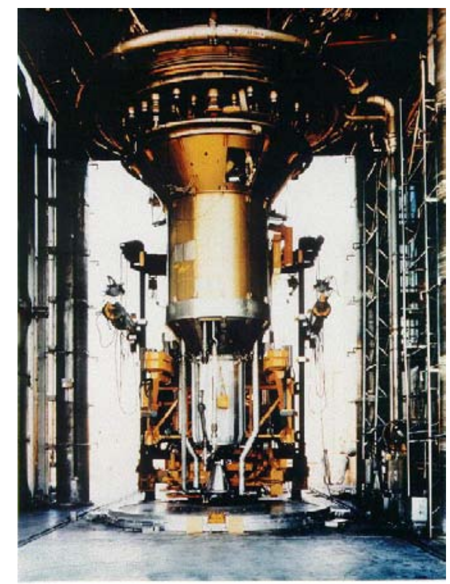
KIWI A
1958-1960
100 MW
0 lbf Thrust

KIWI B
1961-1964
1,000 MW
50,000 lbf Thrust

Phoebus 1
1965-1966
1,000 & 1,500 MW
50,000 lbf Thrust

Phoebus 2
1967
5,000 MW
250,000 lbf Thrust

Culmination of NERVA Program

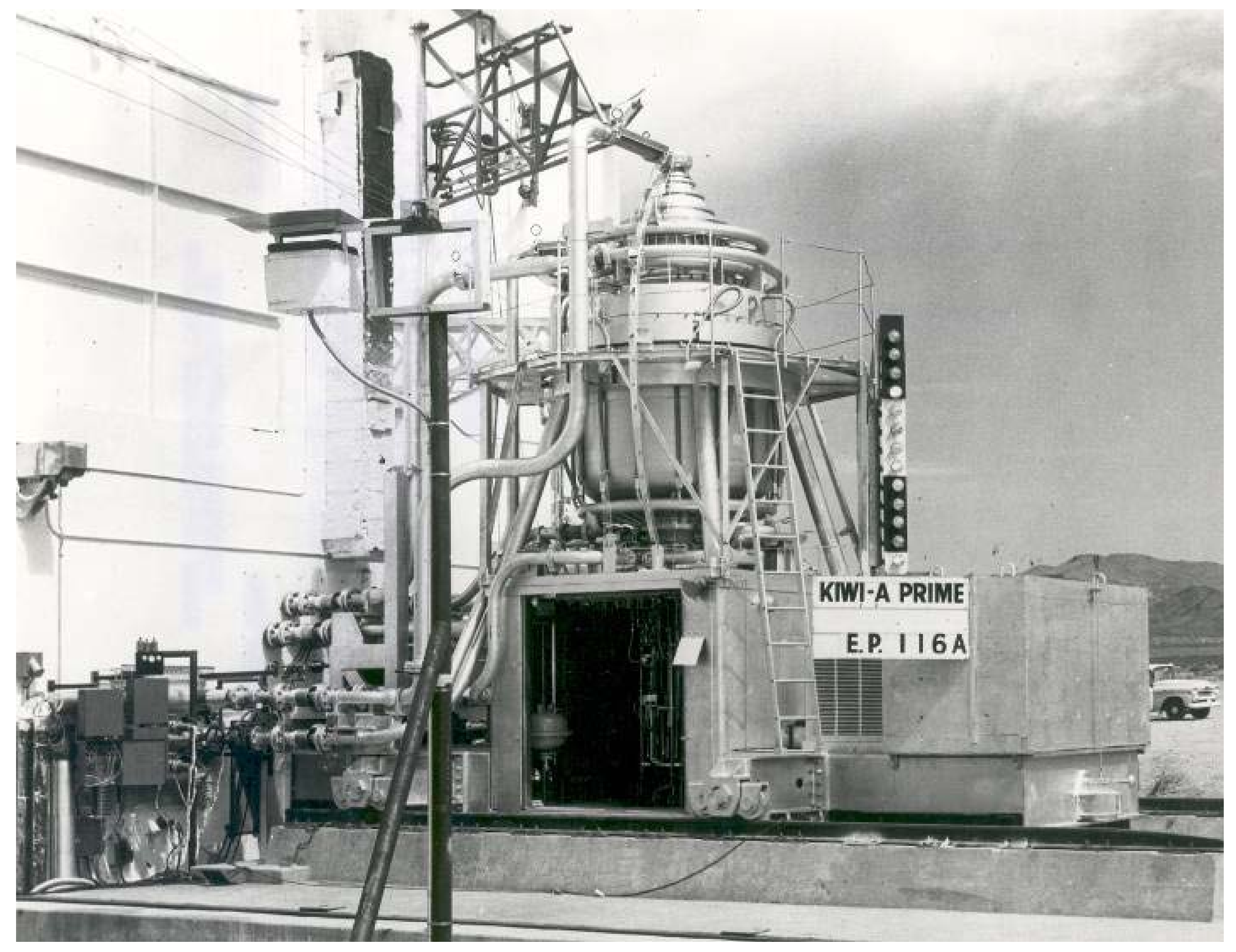


XE-Prime
1969
1,140 MW
55,400 lbf Thrust

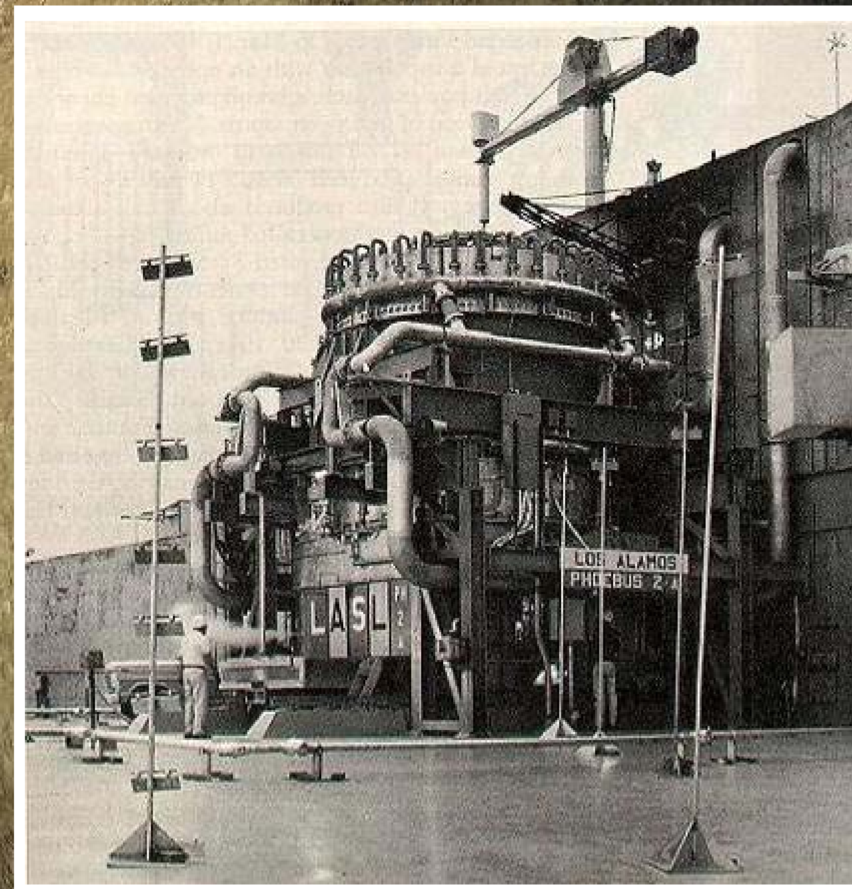
NERVA engines based largely on the KIWI B reactor design.

KIWI A’

Space Nuclear Power and Propulsion

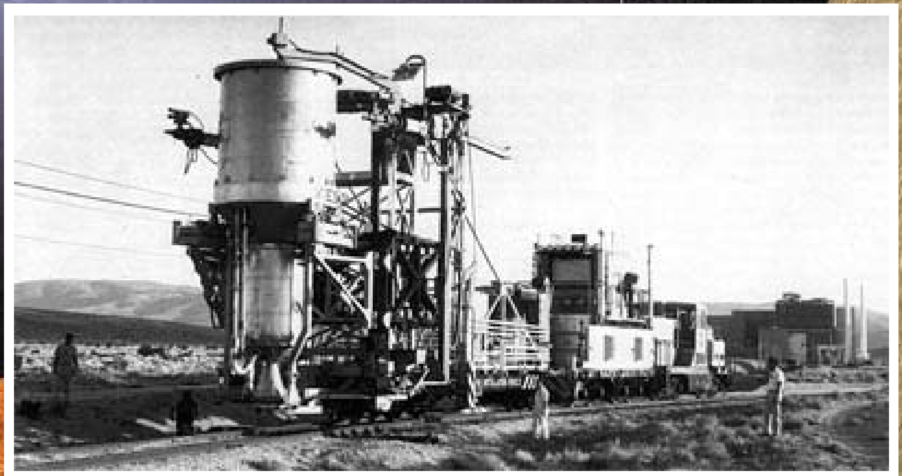


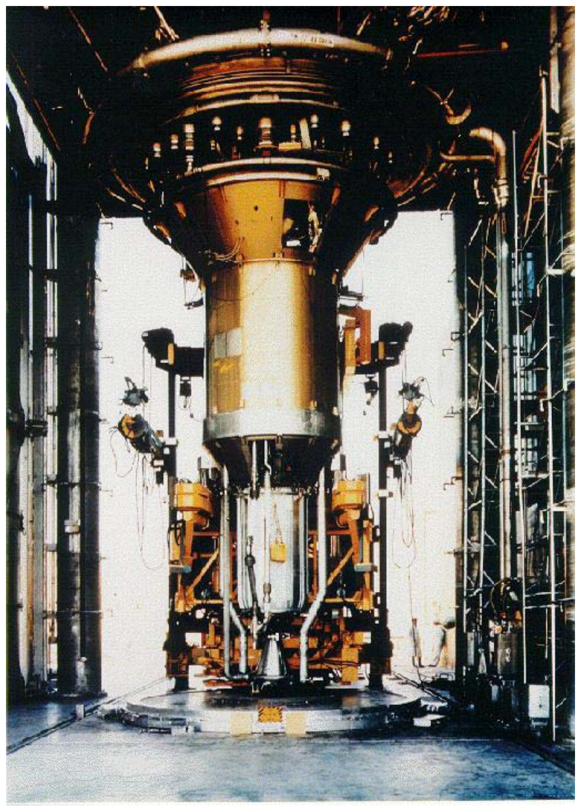
Phoebus-2A



- Phoebus-2A
  - •Tested 1968
  - •5 GW Reactor Core (tested at 4.2 GW)
  - •805 seconds Isp space Equiv.
  - •250,000 lbf Thrust

XE’



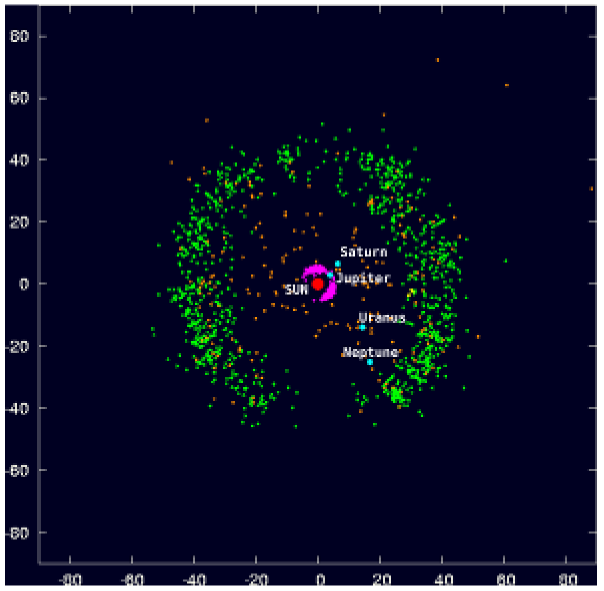


- XE’ Engine
  - Tested 1969
  - 1.1 GW Reactor Core
  - 820 seconds Isp space Equiv.
  - 55,000 lbf Thrust

Potential Advanced Topics - Example

Space Nuclear Power and Propulsion

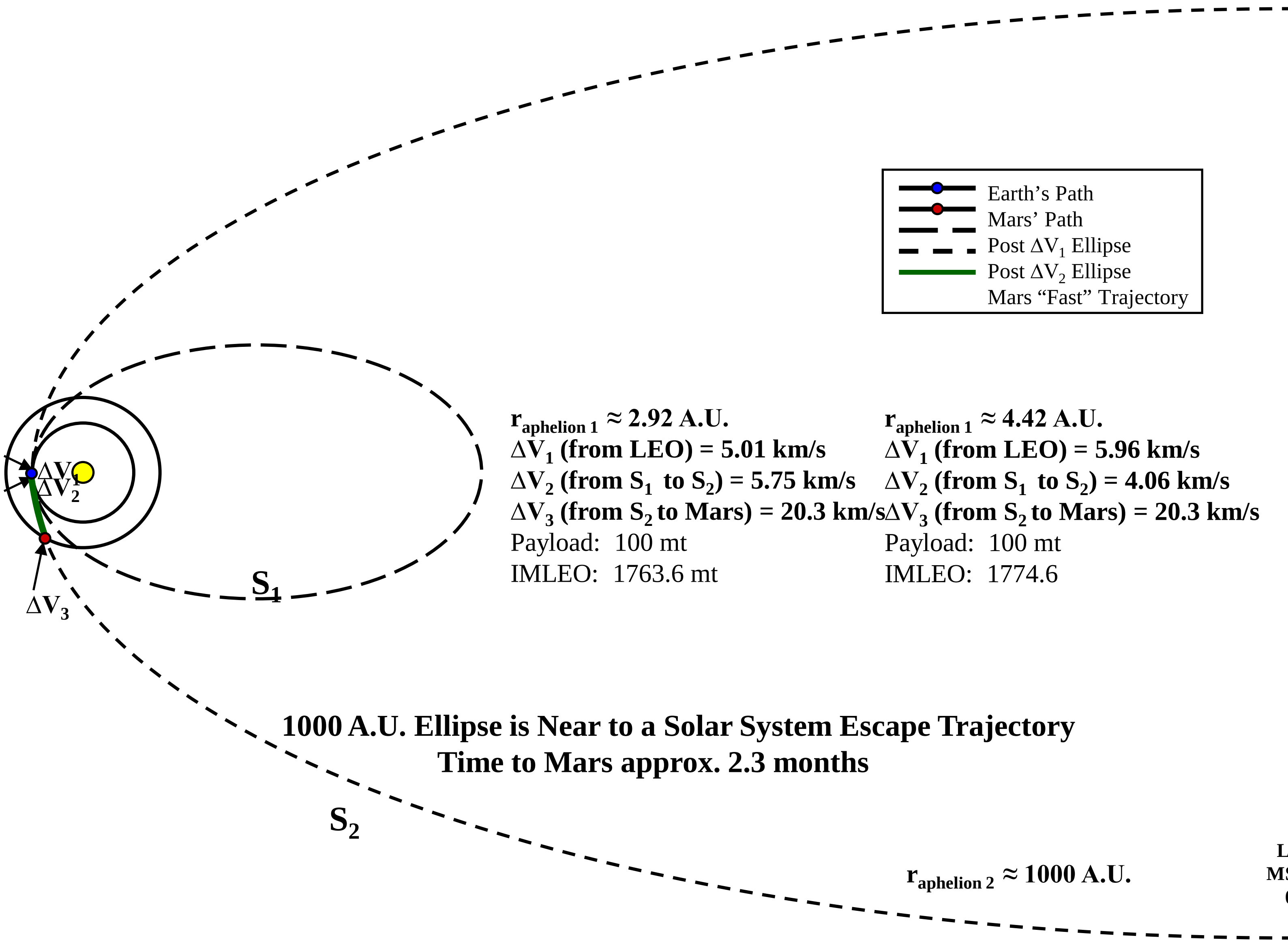
- Over a thousand Kuiper Belt objects identified since 1992
  - Composed primarily of methane, ammonia, water
- Small icy moons, asteroids, and comets also identified
- Use nuclear thermal "steam" rockets to change orbits of icy bodies?
  - In theory, any vapor can be used for NTP propellant
  - No chemical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



Three-Burn Quick Mars Trip

Quickest Mission w/o Becoming Hyperbolic

Space Nuclear Power and Propulsion



$r_{aphelion\ 1} \approx 2.92$ 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

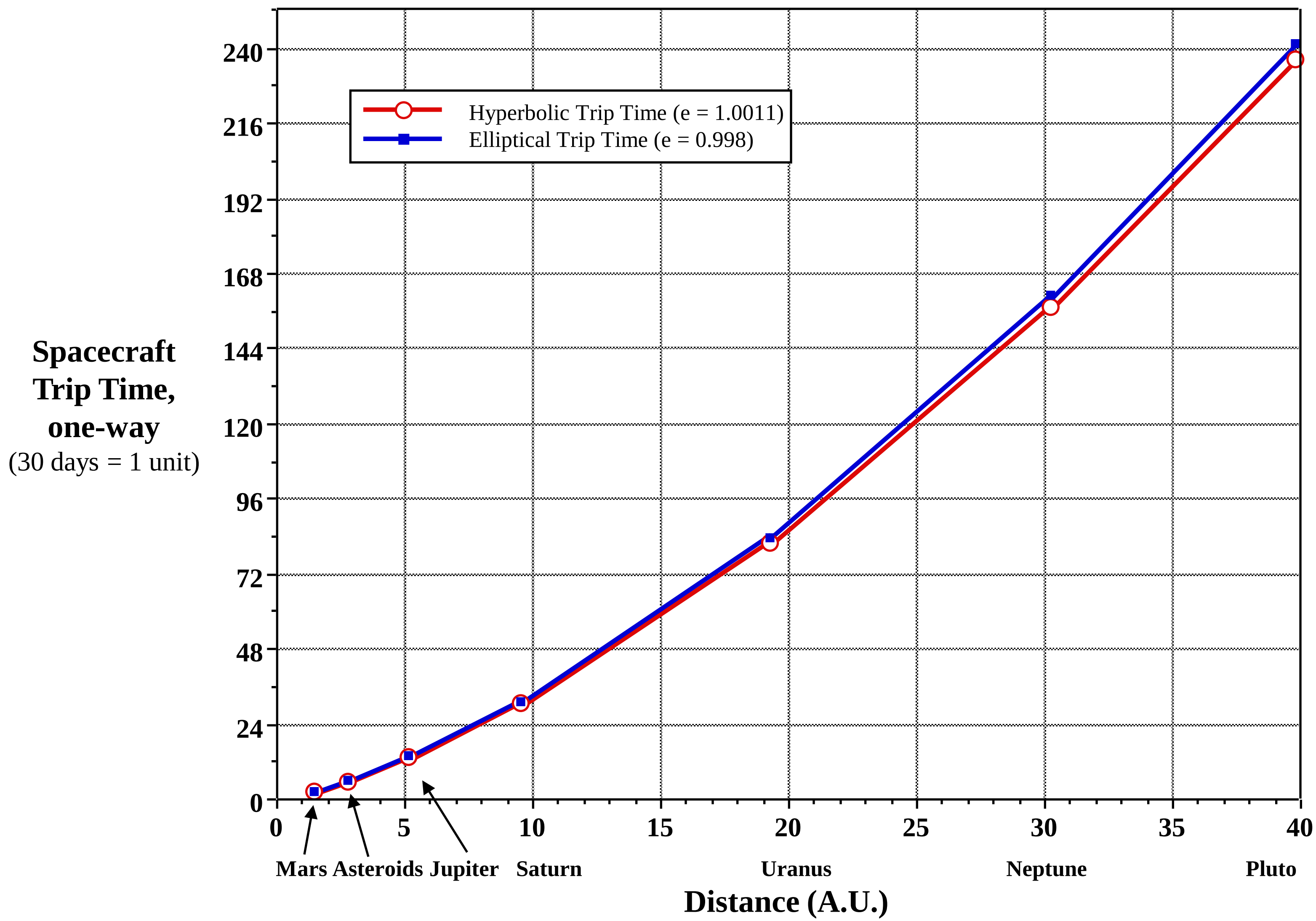
$r_{aphelion\ 1} \approx 4.42$ A.U.
ΔV_1 (from LEO) = 5.96 km/s
ΔV_2 (from S_1 to S_2) = 4.06 km/s
ΔV_3 (from S_2 to Mars) = 20.3 km/s
Payload: 100 mt
IMLEO: 1774.6

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
08/04/99

Planetary Trip Times
Quickest Missions w/o Becoming Hyperbolic



Larry Kos
MSFC/TD31
6/4/99

Beyond Fission: Potential Futuristic Nuclear Energy Sources

Space Nuclear Power and Propulsion

Fusion Reactions

Sun

^{1}H + ^{1}H --> ^{2}H + antielectron + neutrino
^{1}H + ^{1}H --> ^{2}H + antielectron + neutrino
electron + antielectron --> photon + photon
electron + antielectron --> photon + photon
^{2}H + ^{1}H --> ^{3}He + photon
^{2}H + ^{1}H --> ^{3}He + photon
^{3}He + ^{3}He --> ^{4}He + ^{1}H+ ^{1}H

Net Result:

4 ^{1}H+ 2e=>^{4}He+2 neutrinos+6 gamma (26 MeV)

Potential Small, Controlled Systems

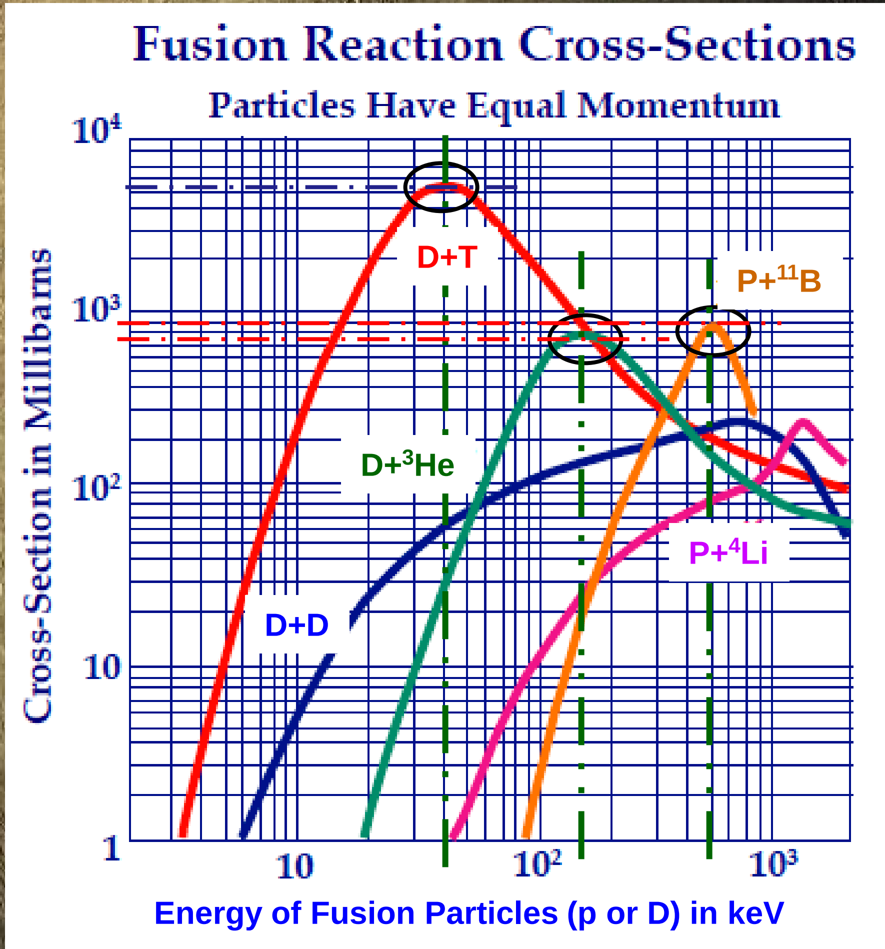
D + T => n^{0} (14.07 MeV) + ^{4}He (3.52 MeV)

D + D => n^{0} (2.45 MeV) + ^{3}He (0.82 MeV) (50%)
D + D => p (3.02 MeV) + T (1.01 MeV) (50%)

D + ^{3}He => p (14.68 MeV) + ^{4}He (3.67 MeV)

^{3}He + ^{3}He => ^{4}He + 2 p (12.9 MeV)

p + ^{11}B => 3 ^{4}He (8.7 MeV)



Typical Fusion Reaction Cross Sections

Beyond Fission: Potential Futuristic Nuclear Energy Sources

Space Nuclear Power and Propulsion

Fusion: The performance potential of lightweight, high gain fusion propulsion systems operating with aneutronic fuels (e.g. p-^{11}B) theoretically exceeds that of fission by an order of magnitude.

Fundamental Issues to Resolve:

1. Aneutronic Fuels. The performance potential of fusion propulsion systems operating with deuterium or tritium bearing fuels (e.g. D-T, D-D, or D-^{3}He) is severely limited because of waste heat production from neutron kinetic energy, and the additional waste energy released when a neutron of any energy is captured. The use of aneutronic fuels (e.g. p-^{11}B) will be required for high performance.

2. High Gain. Recent studies (Chakrabarti et al., 2001) have shown that high engineering gain (Q>50) is needed to minimize the mass of the fusion reaction driver and enable high performance.

3. Compact Systems. Significant funds and five decades have been spent on research related to controlled fusion. While the two leading approaches for achieving engineering breakeven are extremely massive, knowledge and experience from the ongoing terrestrial fusion effort may be useful in devising compact systems suitable for space propulsion applications.

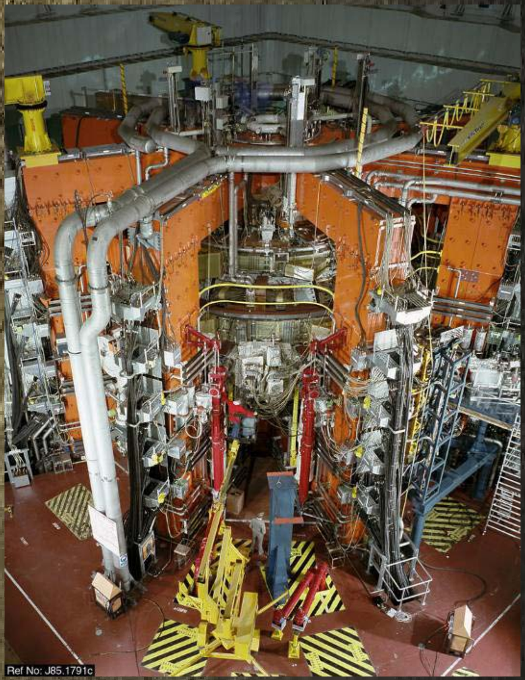
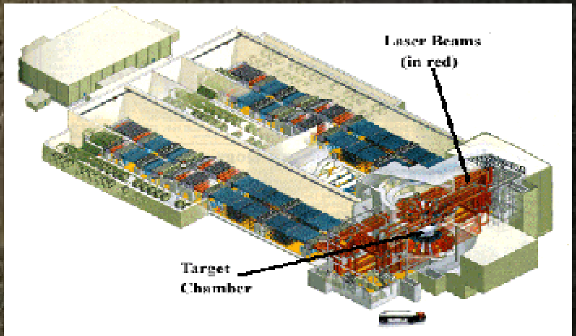


Photo Courtesy of EFDA-JET



National Ignition Facility

Beyond Fission: Potential Futuristic Nuclear Energy Sources

Space Nuclear Power and Propulsion

Antimatter: Energy stored as antimatter has a specific energy of 1.8×10^{17} J/kg, over 500 times that of fission or fusion.

Fundamental Issues to Resolve:

1. Production. Antiproton production rates must increase by several orders of magnitude, and the cost per antiproton must decrease correspondingly.

2. Storage. Effective methods for long-term antiproton storage and transportation must be developed.

3. Thrust Production. Effective methods for converting energy stored as antimatter into high specific impulse thrust must be devised.

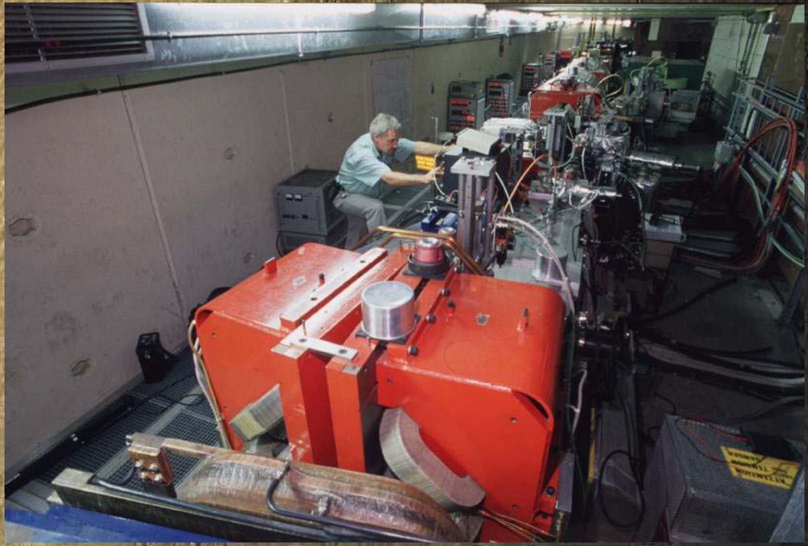


Photo Courtesy of Cern

Antiproton Decelerator at CERN

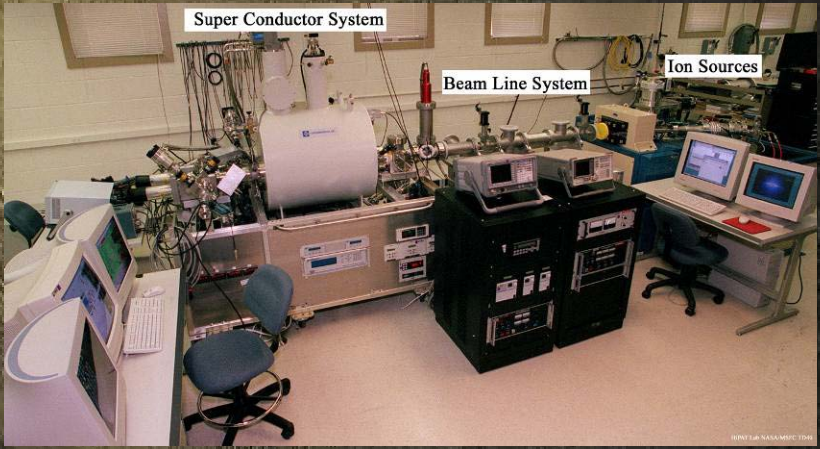


Photo: Marshall Space Flight Center

High Performance Antiproton Trap (HiPAT) at NASA MSFC

Summary

- Nuclear 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. Fusion and antimatter systems may also be viable in the future.