The current focus of NASA's space fission effort is Fission Surface Power (FSP). FSP systems could be used to provide power anytime, anywhere on the surface of the Moon or Mars. FSP systems could be used at locations away from the lunar poles or in permanently shaded regions, with no performance penalty. A potential reference 40 kWe option has been devised that is cost-competitive with alternatives while providing more power for less mass. The potential reference system is readily extensible for use on Mars. At Mars the system could be capable of operating through global dust storms and providing year-round power at any Martian latitude.

To ensure affordability, the potential near-term, 40 kWe reference concept is designed to use only well established materials and fuels. However, if various materials challenges could be overcome, extremely high performance fission systems could be devised. These include high power, low mass fission surface power systems; in-space systems with high specific power; and high performance nuclear thermal propulsion systems.

This tutorial will provide a brief overview of space fission systems and will focus on materials challenges that, if overcome, could help enable advanced exploration and utilization of the solar system.

Space Nuclear Power and Propulsion: Materials Challenges for the 21st Century

Presented at the
2008 National Space & Missile Materials Symposium
June 24, 2008

by
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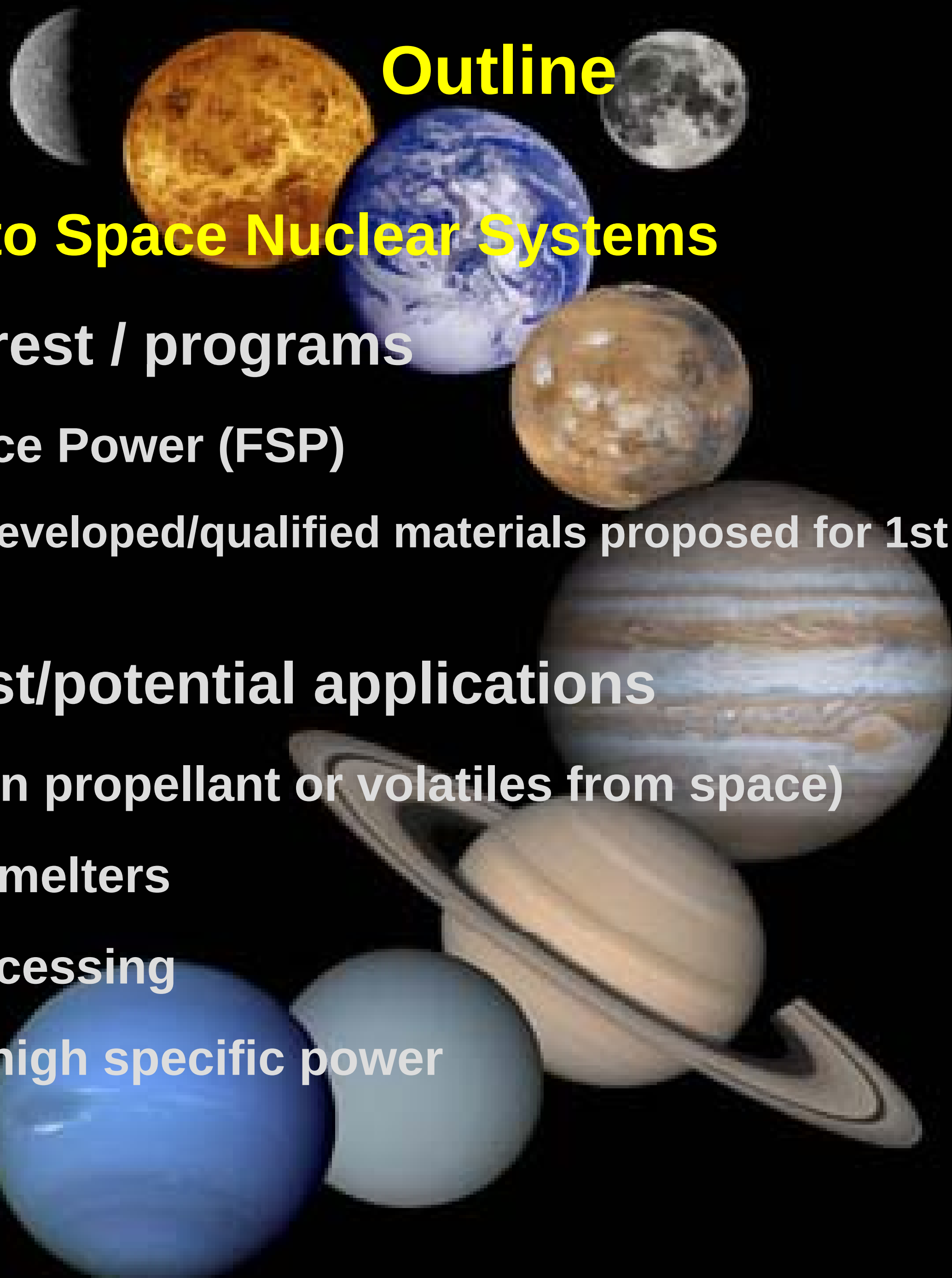
Outline

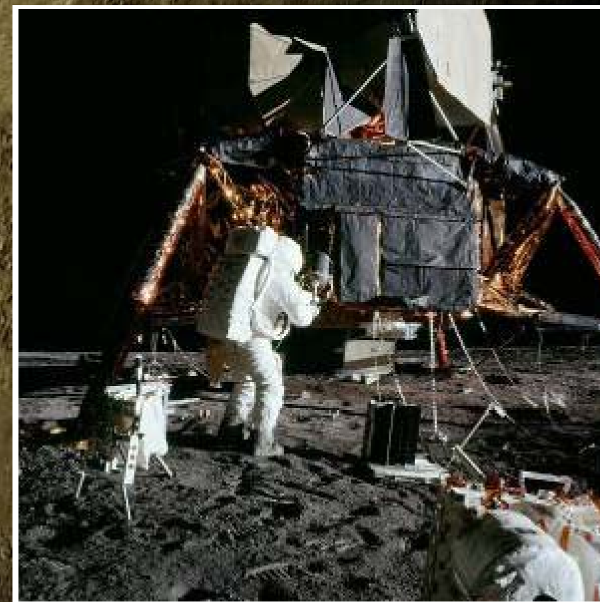


- ♦ **Introduction to Space Nuclear Systems**
- ♦ **Ongoing interest / programs**
  - **Fission Surface Power (FSP)**
    - **Previously developed/qualified materials proposed for 1st generation systems**
- ♦ **Future interest/potential applications**
  - **NTP (hydrogen propellant or volatiles from space)**
  - **Regolith / ice melters**
  - **Resource processing**
  - **High power / high specific power**
  - **Water shield**

Nuclear Surface Power Systems

Fission Surface Power

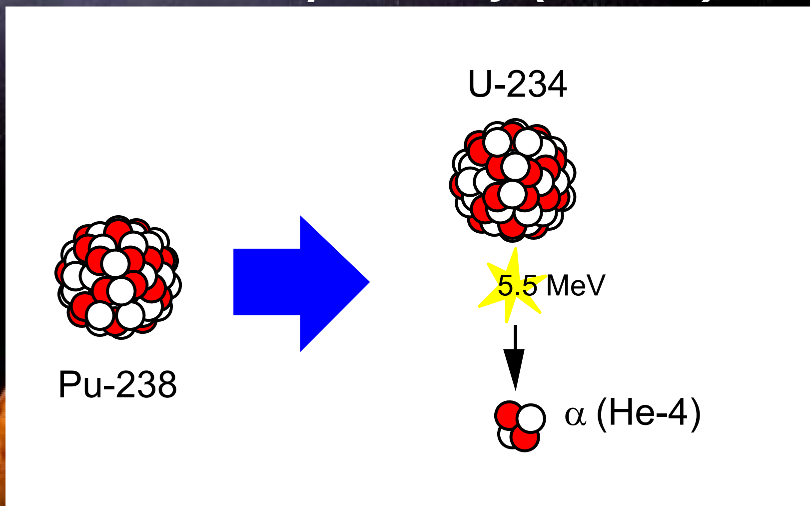
- Power anytime, anywhere on Moon or Mars
  - Operate through lunar night
  - Operate in permanently shaded regions
  - Operate through Mars global dust storms
  - Operate at high Martian latitudes
- **Enable power-rich architecture**
  - Site Preparation, In-Situ Resource Utilization, Propellant Production, Fabrication, Life support, Communication, Mobility, Deep Drilling
- **Nuclear technology useful anywhere in space**
  - Not dependent on available sunlight



Fission Surface Power

Basics of Nuclear Systems

Radioisotope Decay (Pu-238)

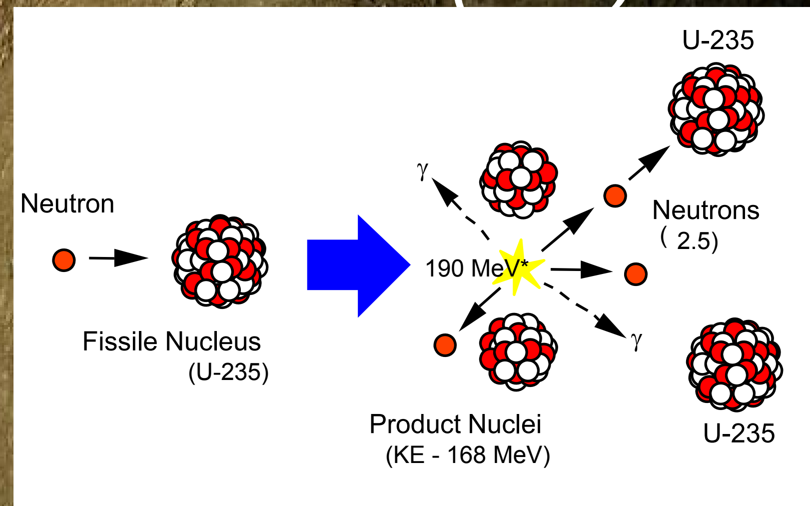


Heat Energy = 0.023 MeV/nucleon (0.558 W/g Pu-238)

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)



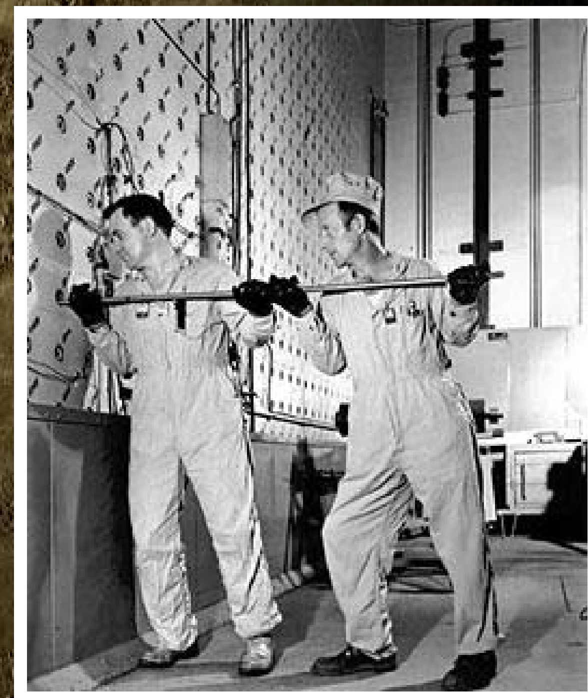
Heat Energy = 0.851 MeV/nucleon

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

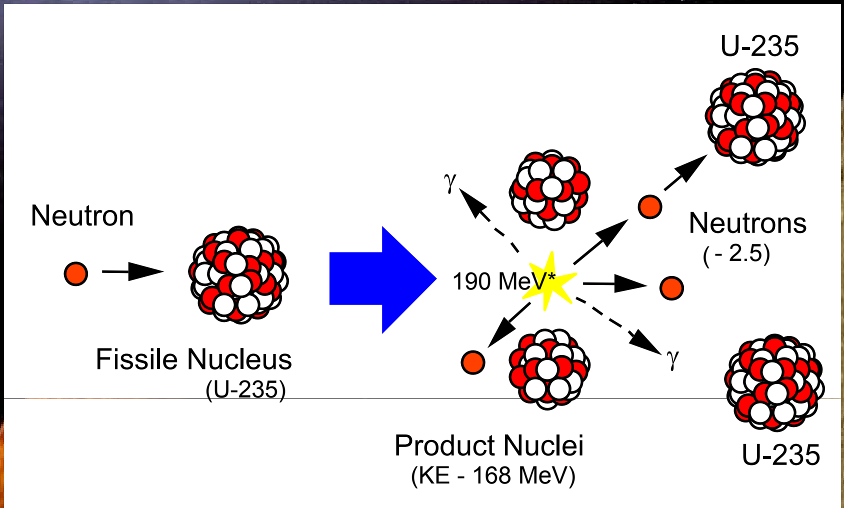
Fission Introduction

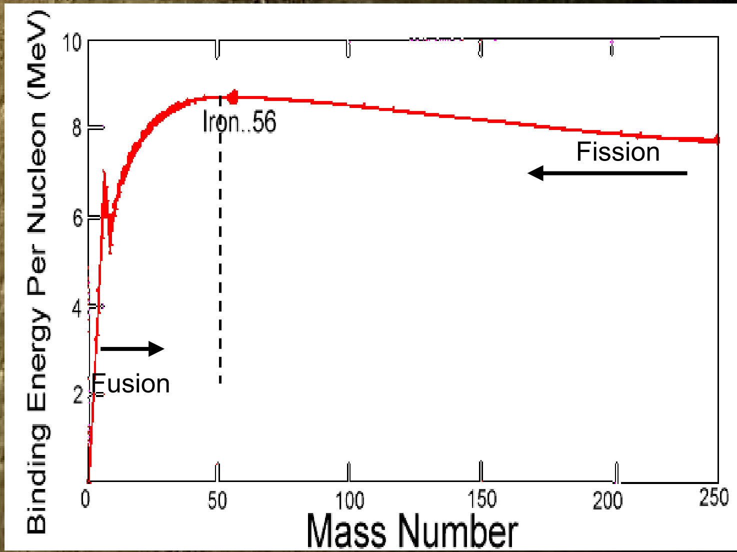
- Creating a fission chain reaction is conceptually simple
  - Requires right materials in right geometry
- Good engineering needed to create safe, useful, long-life fission systems
  - *1938 — Fission Discovered*
  - *1939 — Einstein letter to Roosevelt*
  - *1942 — Manhattan project initiated*
  - *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*



Nuclear Fission Process

Fission Surface Power



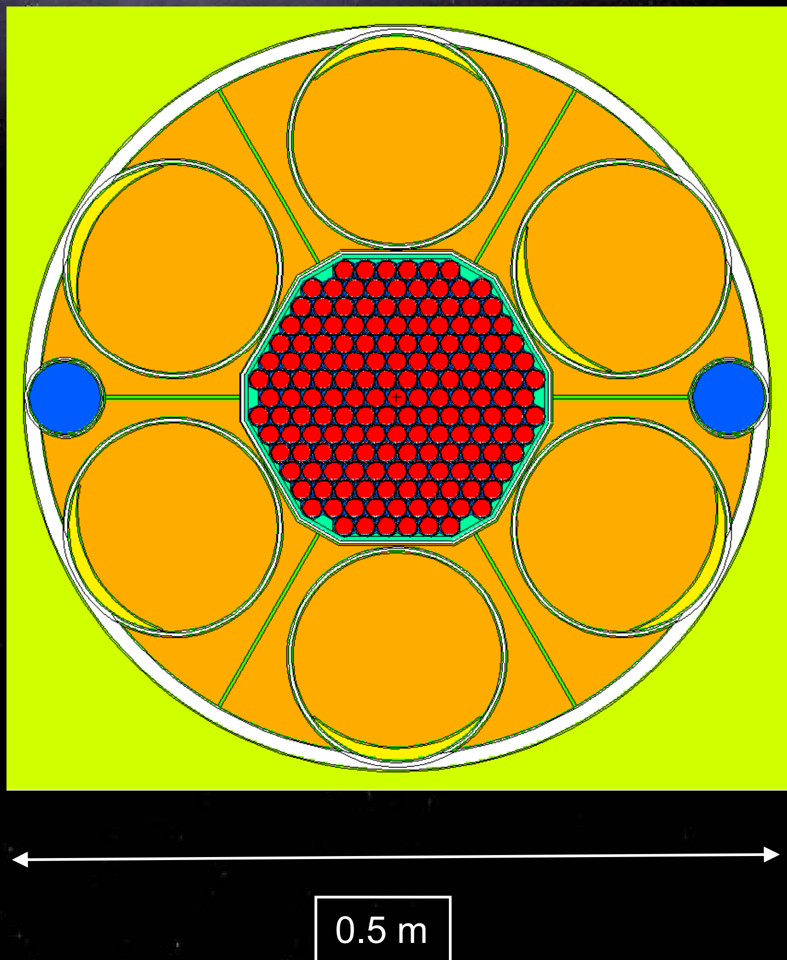


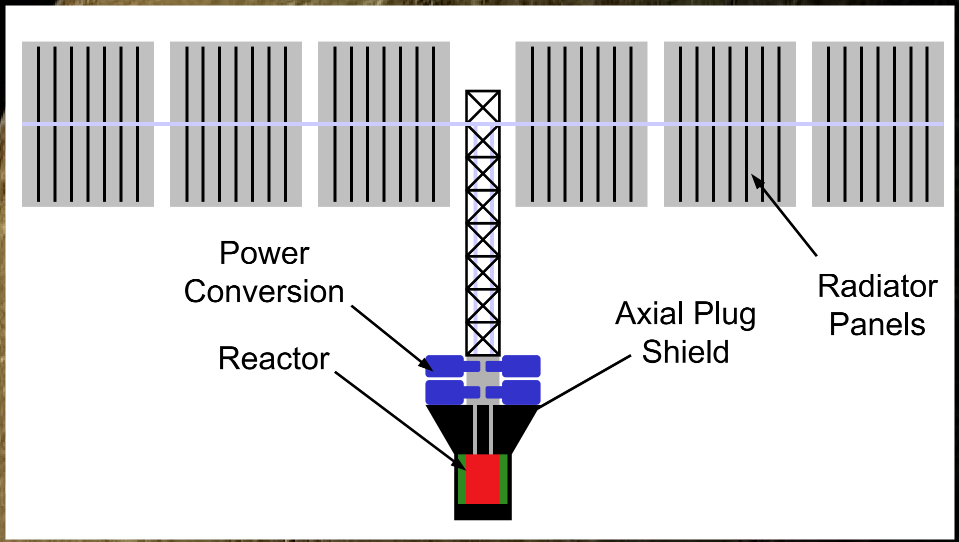
180 MeV prompt useful energy (plus 10 MeV neutrinos) - additional energy released in form of fission product beta particles, gamma rays, neutron capture gammas (~200 MeV total useful)

- Neutron absorbed by heavy nucleus, which splits to form products with higher binding energy per nucleon. Difference between initial and final masses = prompt energy released (190 MeV)
  - Fissile isotopes (U-233, U-235 and Pu-239) fission at any neutron energy
  - Other actinides (U-238) fission at only high neutron energies
- Fission fragment kinetic energy (168 MeV), instantaneous gamma energy (7 MeV), fission neutron kinetic energy (5 MeV), Beta particles from fission products (7 MeV), Gamma rays from fission products (6 MeV), Gamma rays from neutron capture (~7 MeV)
- For steady power production, 1 of the 2 to 3 neutrons released in each fission reaction must cause a subsequent fission in a chain reaction process
- Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal

Fission Reactor Operation

Fission Surface Power

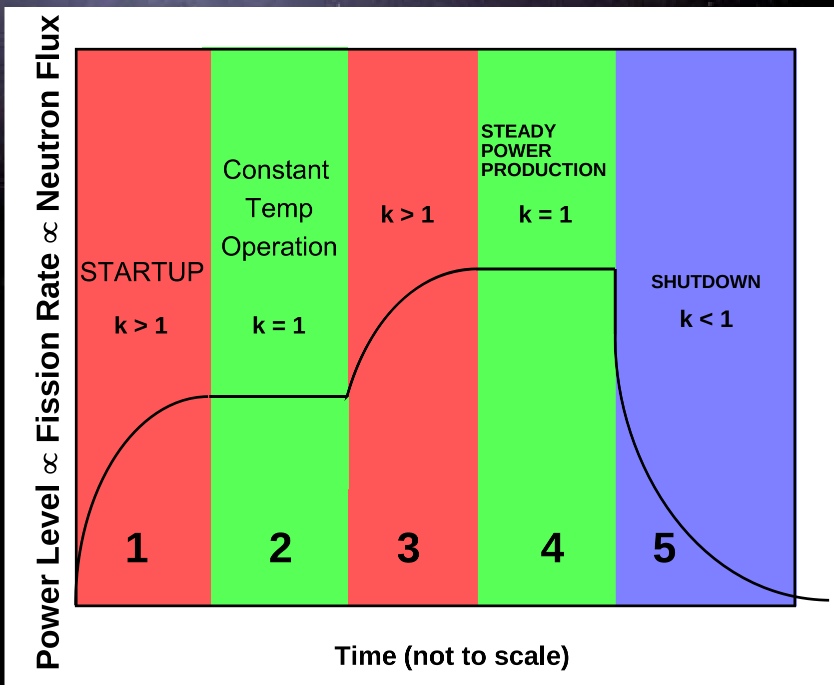




- System power controlled by neutron balance
- Average 2.5 neutrons produced per fission
  - Including delayed
- Constant power if 1.0 of those neutrons goes on to cause another fission
- Decreasing power if < 1.0 neutron causes another fission, increasing if > 1.0
- System controlled by passively and 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

Reactor Operation (Notional)

Fission Surface Power



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

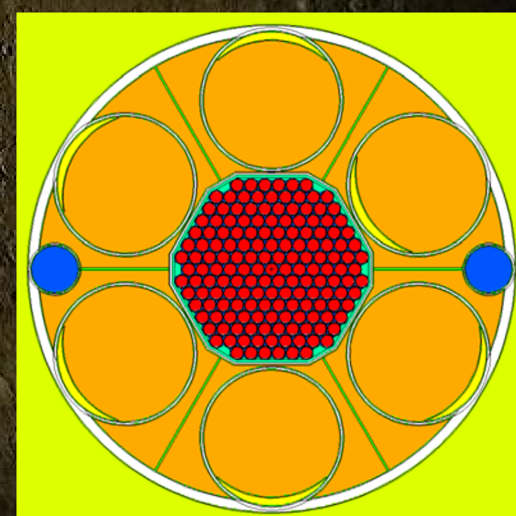
$$= \frac{\text{Production Rate}}{\text{Loss Rate}} = \frac{N(t+l_n)}{N(t)}$$

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

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

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

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



Space Fission Systems Cannot Explode

Fission Surface Power

- Nuclear weapons require different materials and highly sophisticated methods for rapidly assembling and triggering a supercritical mass
- Space reactor fuel form, in core materials, and fundamental physics do not allow for an explosion
- Potential radiation risk is from inadvertent system start while personnel are near reactor
  - Prevent inadvertent start via procedures, hardware, and design techniques developed over the past 6 decades

Uranium Fuel

Fission Surface Power

- 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
  - Space reactors typically use uranium fuel with >90% 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

Radiation Shielding

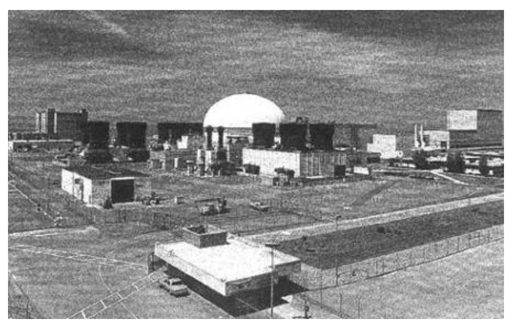
Fission Surface Power

- 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) are the most mass effective gamma shields
- Regolith is a good gamma shield, adequate neutron shield
- Reactor can be shielded to any level desired
  - "Trade" is against mass or burial depth
  - Reference configuration reduces operating dose to < 1/10 natural lunar background at 100 m.
  - Dose rate drops rapidly following shutdown

Fission is Highly Versatile with Many Applications

Fission Surface Power

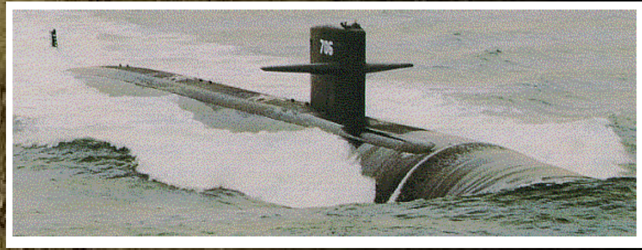
- Small research reactors
  - Examples include 2000 kWt TRIGA reactor recently installed in Morocco (< $50M)
- Advanced, high-power research reactors and associated facilities
  - Examples include the US Fast Flux Test Facility (400,000 kWt, ~$3.0B FY08)
- Commercial Light Water Reactors 1,371,000 kWe (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

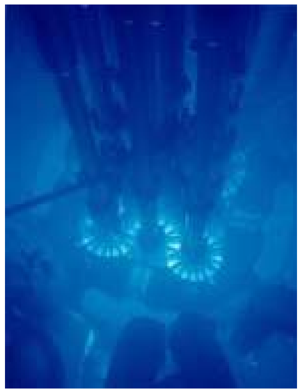


Fission is Highly Versatile with Many Applications (continued)

Fission Surface Power

- 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



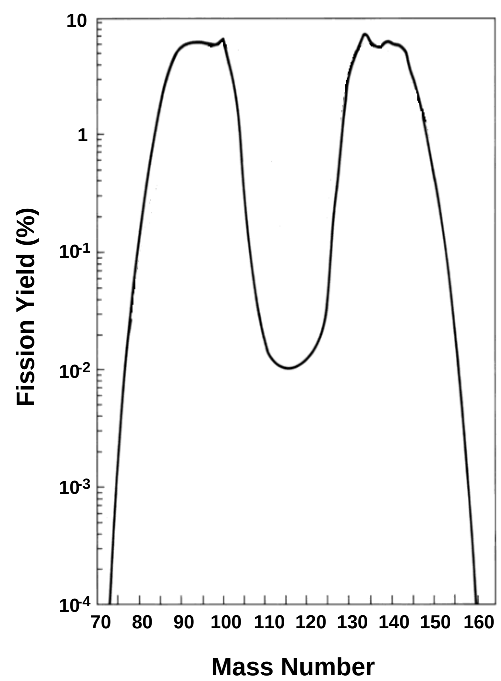


Fission Products

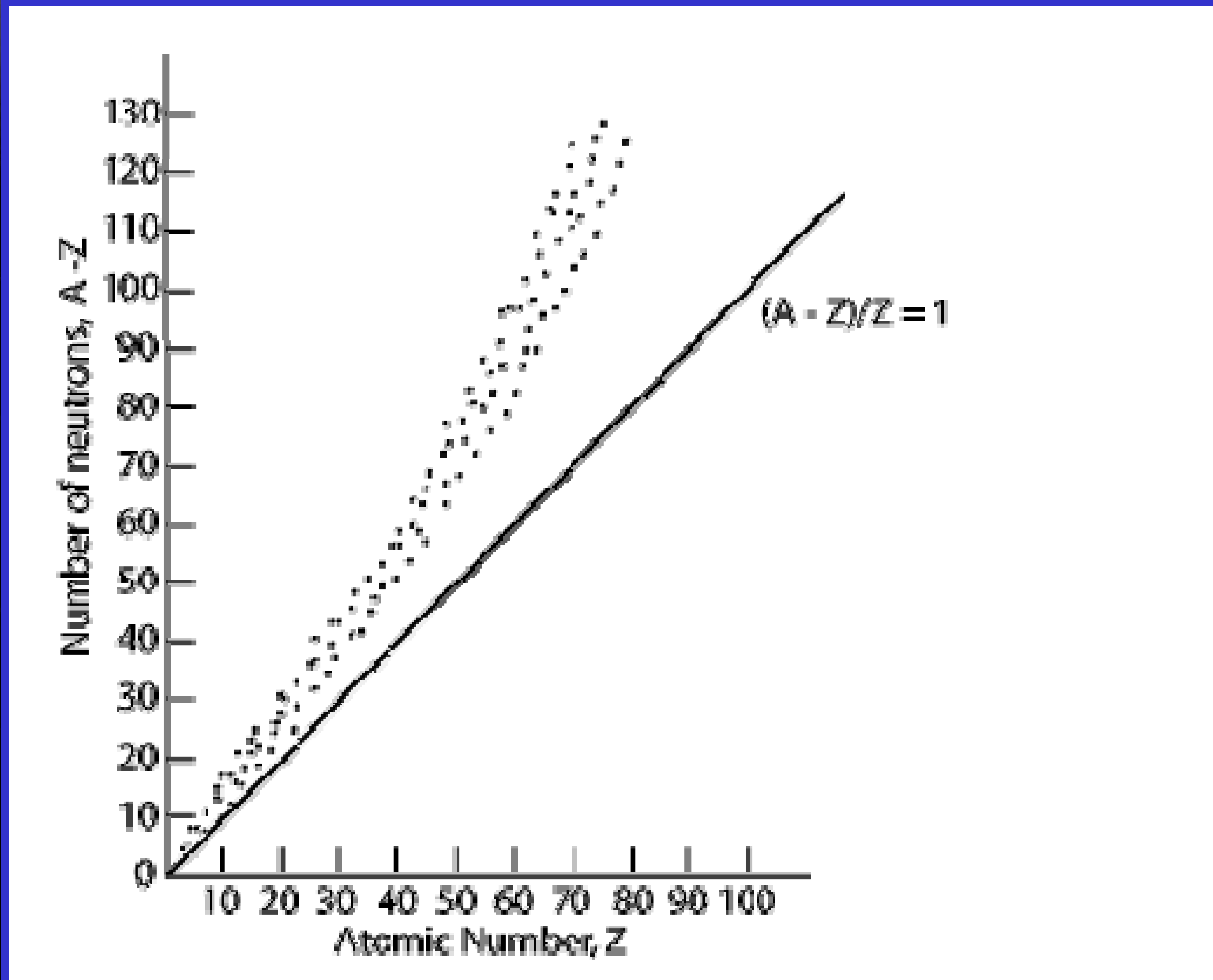
Fission Surface Power

- Prior to operation at power, uranium fuel is essentially non-radioactive and non-heat producing
- Fission events yield bimodal distribution of product elements
- These products are generally neutron-rich isotopes that emit beta particles and gamma rays 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)

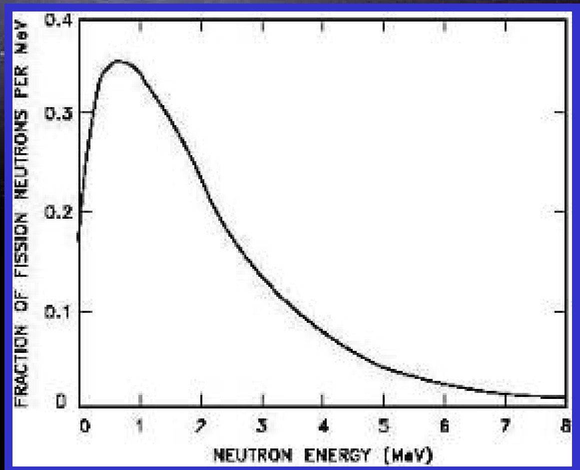
Product Yields for Thermal Neutron (0.025 eV) Fission of U-235



Band of Stability



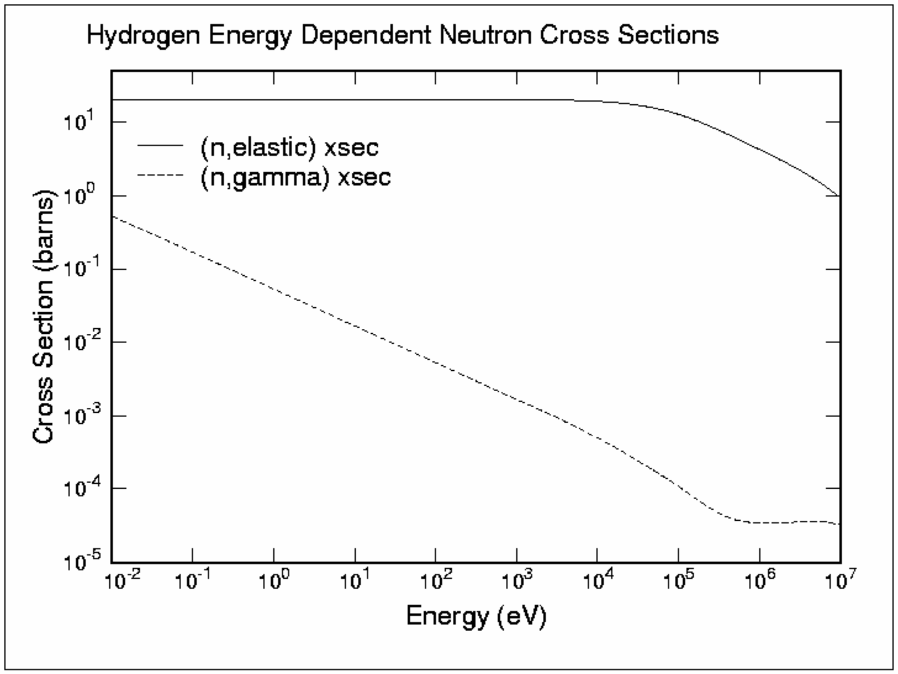
Neutron Spectrum

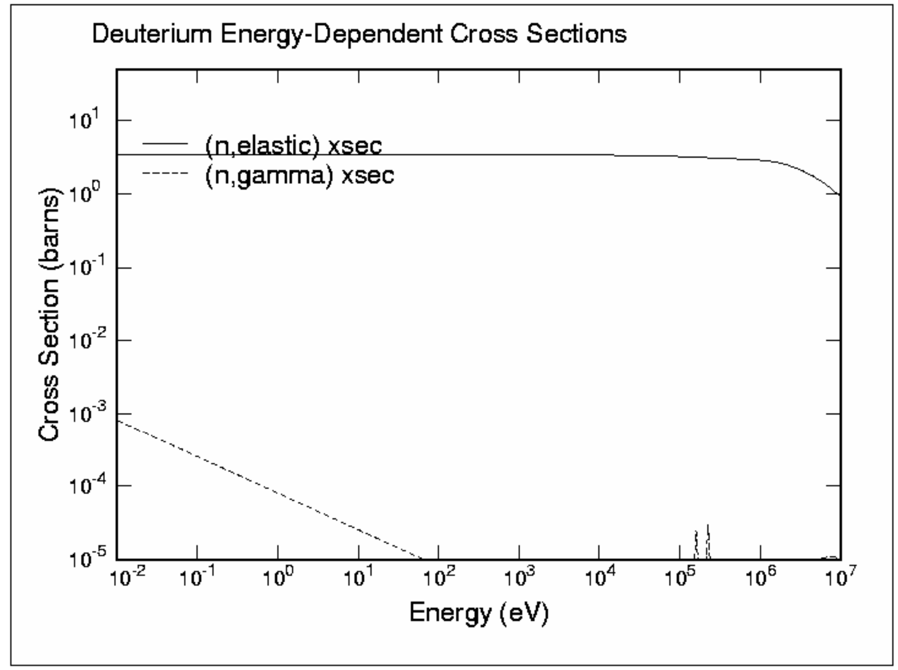


- Most “prompt” neutrons born with energy between 0.8 and 2 MeV
- Fast spectrum systems use these neutrons with minimal moderation
- Thermal spectrum systems “moderate neutrons”
- Hydrogen is the best moderator for compact systems
- Deuterium, Beryllium, graphite also good for larger systems
- Fast spectrum systems use fission neutrons with minimal moderation
- Thermal spectrum systems “moderate neutrons”
- Define $\alpha \equiv ((A-1)/(A+1))2$, where A = atomic mass
- $Emin = \alpha E1$
- $In(E1/E2) = 1 + (\alpha / (1 - \alpha)) In \alpha$ = 1 for hydrogen
- For hydrogen, 15 neutron scatters 2 MeV to 1 eV. Carbon 92, Uranium 1700

Comparison of Hydrogen and Deuterium Cross Sections

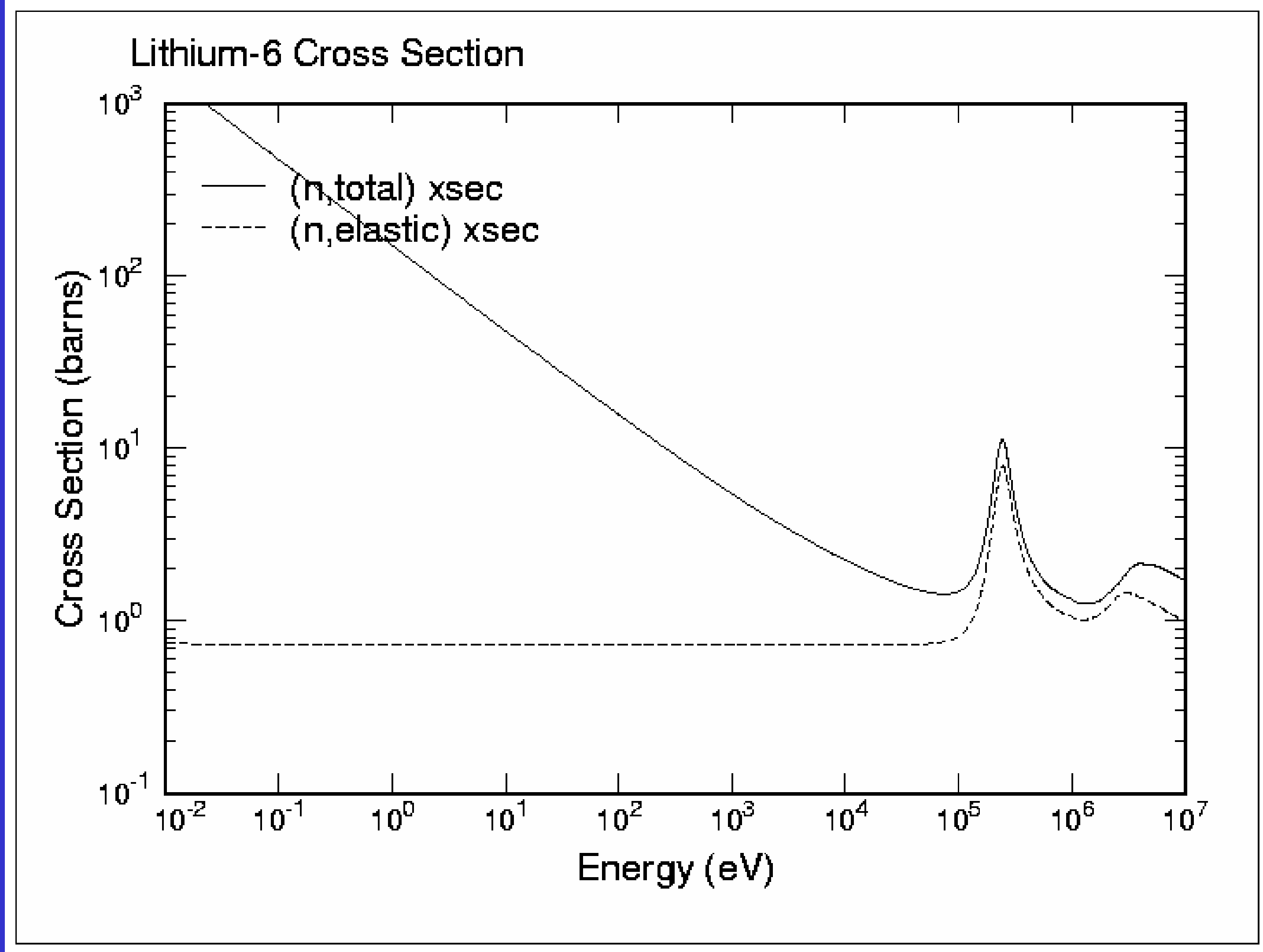
Fission Surface Power



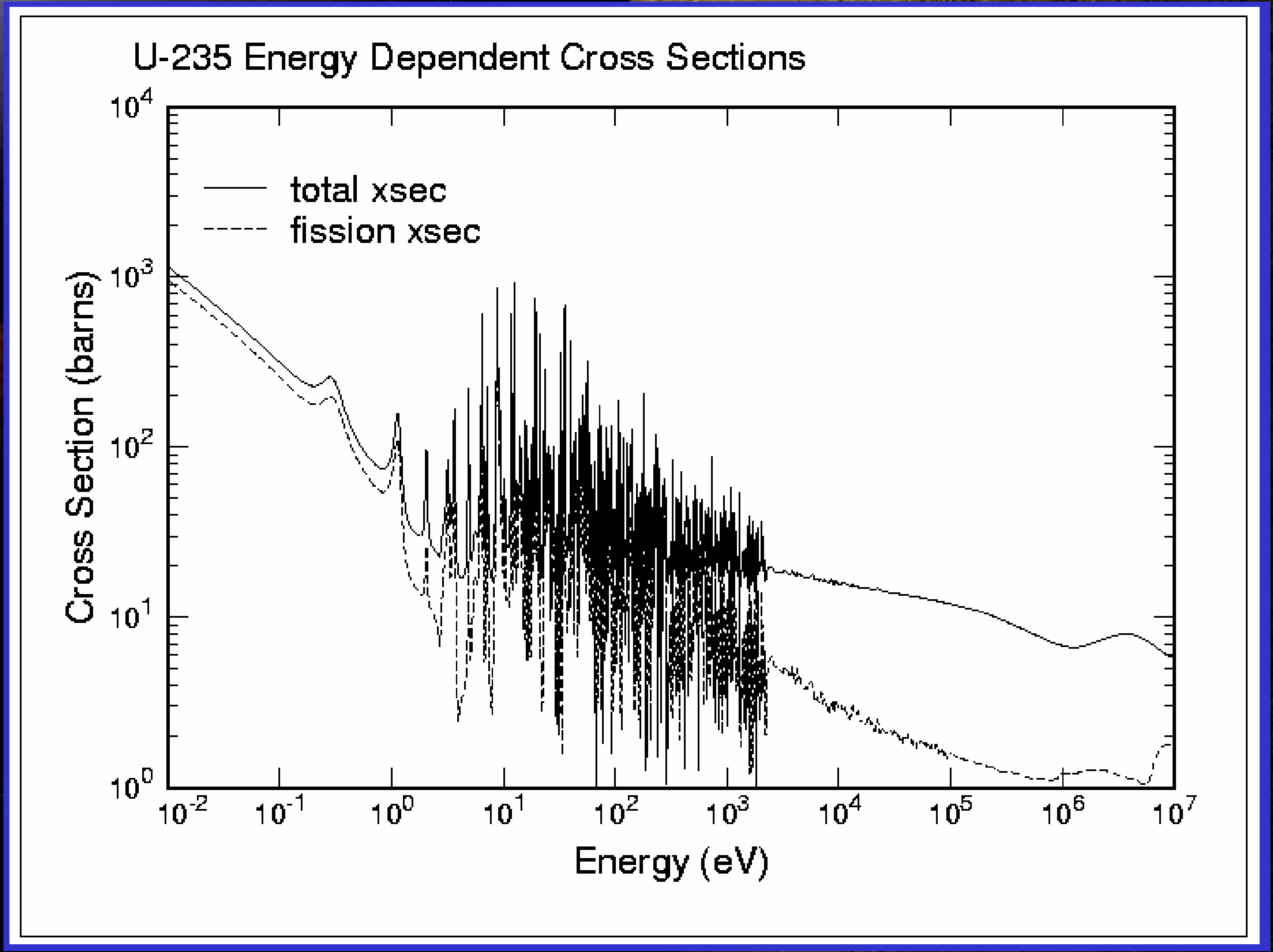


Lithium-6 Cross Section

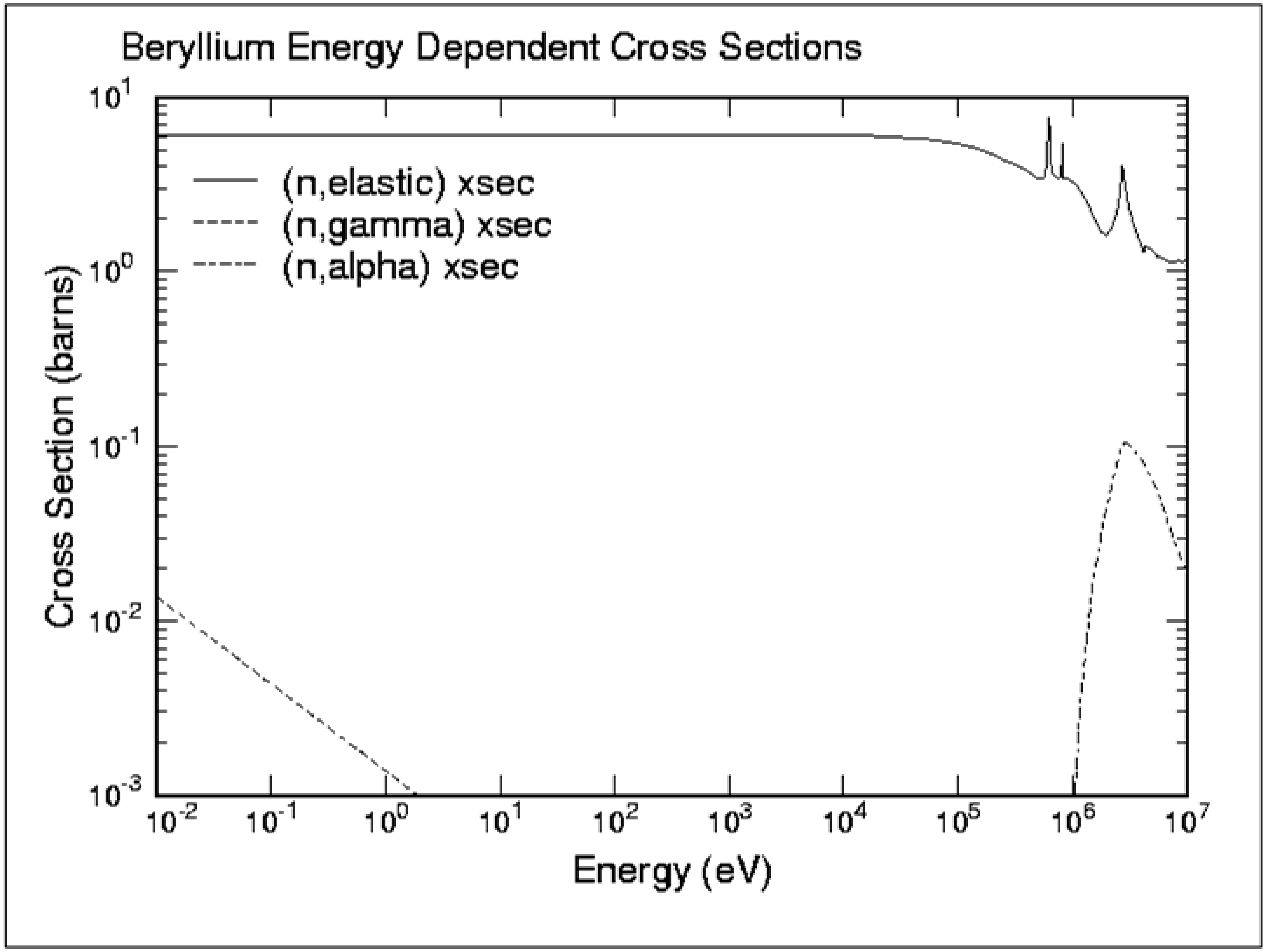
Fission Surface Power



U-235 Cross Sections

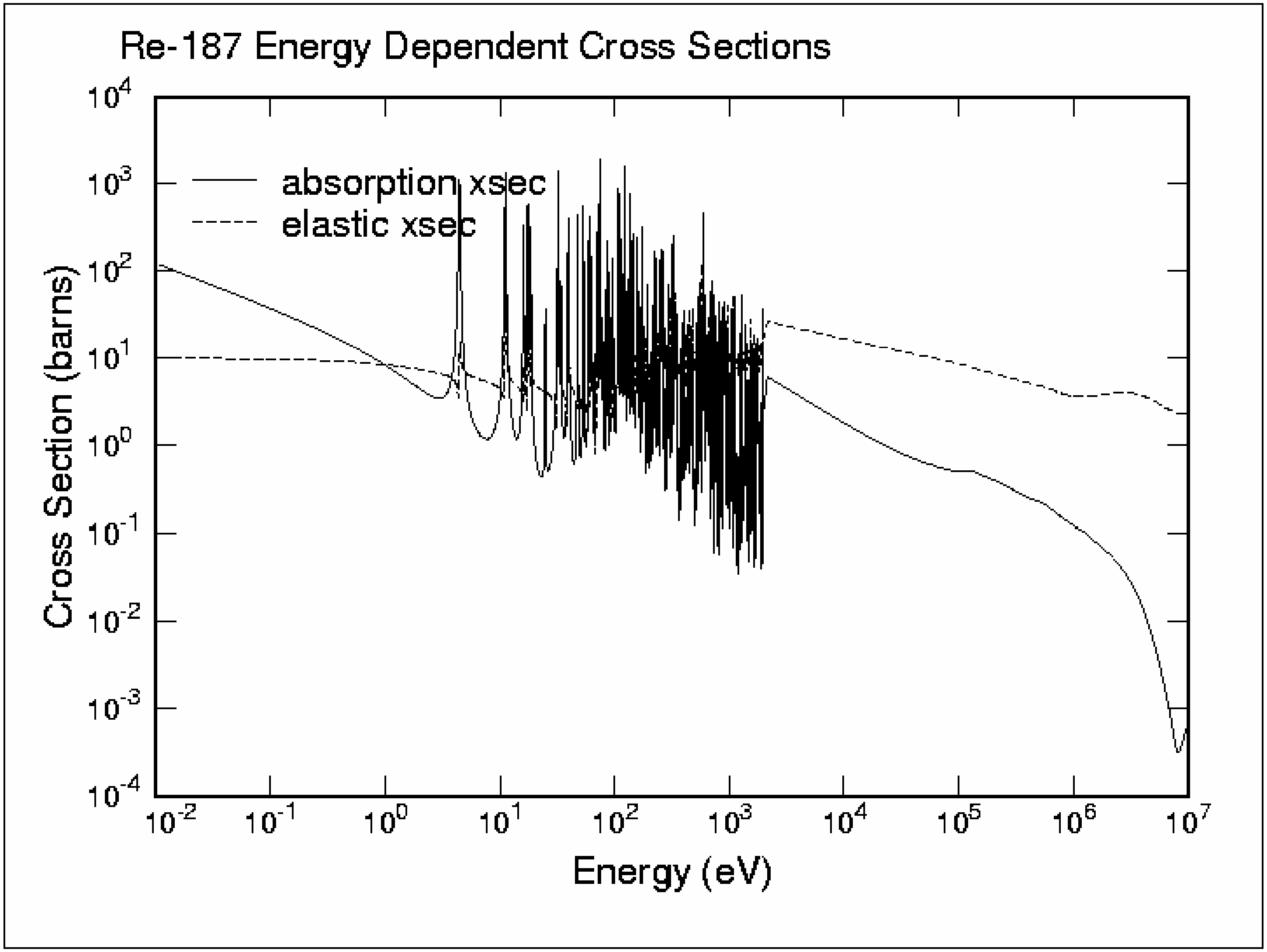


Beryllium Cross Sections



Re-187 Cross Sections

Fission Surface Power

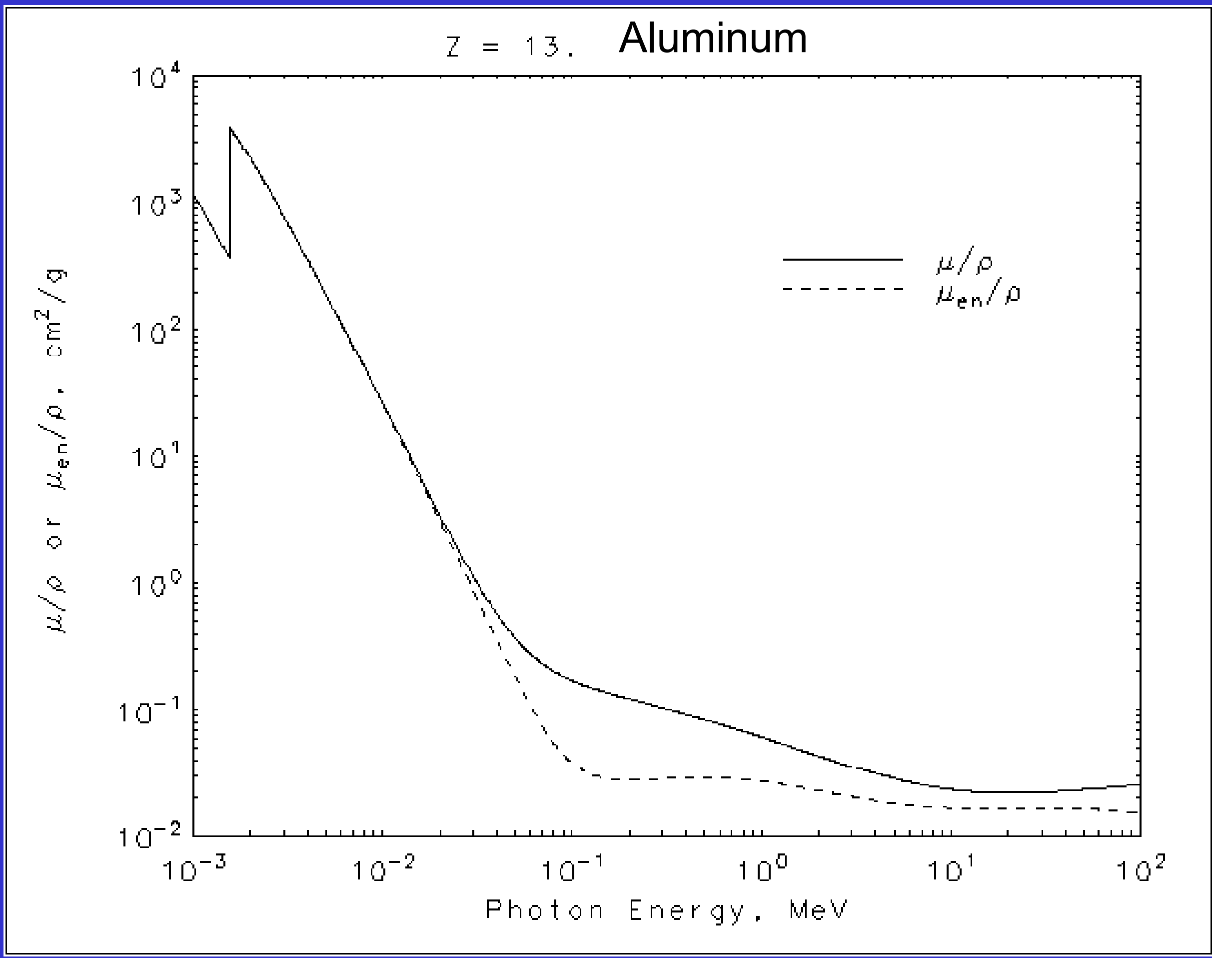


Potential Uses for Advanced Materials (Moderators and Shields)

- High temperature hydrides with high hydrogen content
  - e.g. YHx; ZrHx
- High temperature uranium-bearing hydrides
  - e.g. UZrHx
- High temperature hydrogen diffusion barriers
  - SNAP reactors
- Passive water shields for high radiation environments
  - Withstand chemistry, radiolysis
- High temperature, radiation-resistant beryllium alloys for structural applications, vessels, and pipes

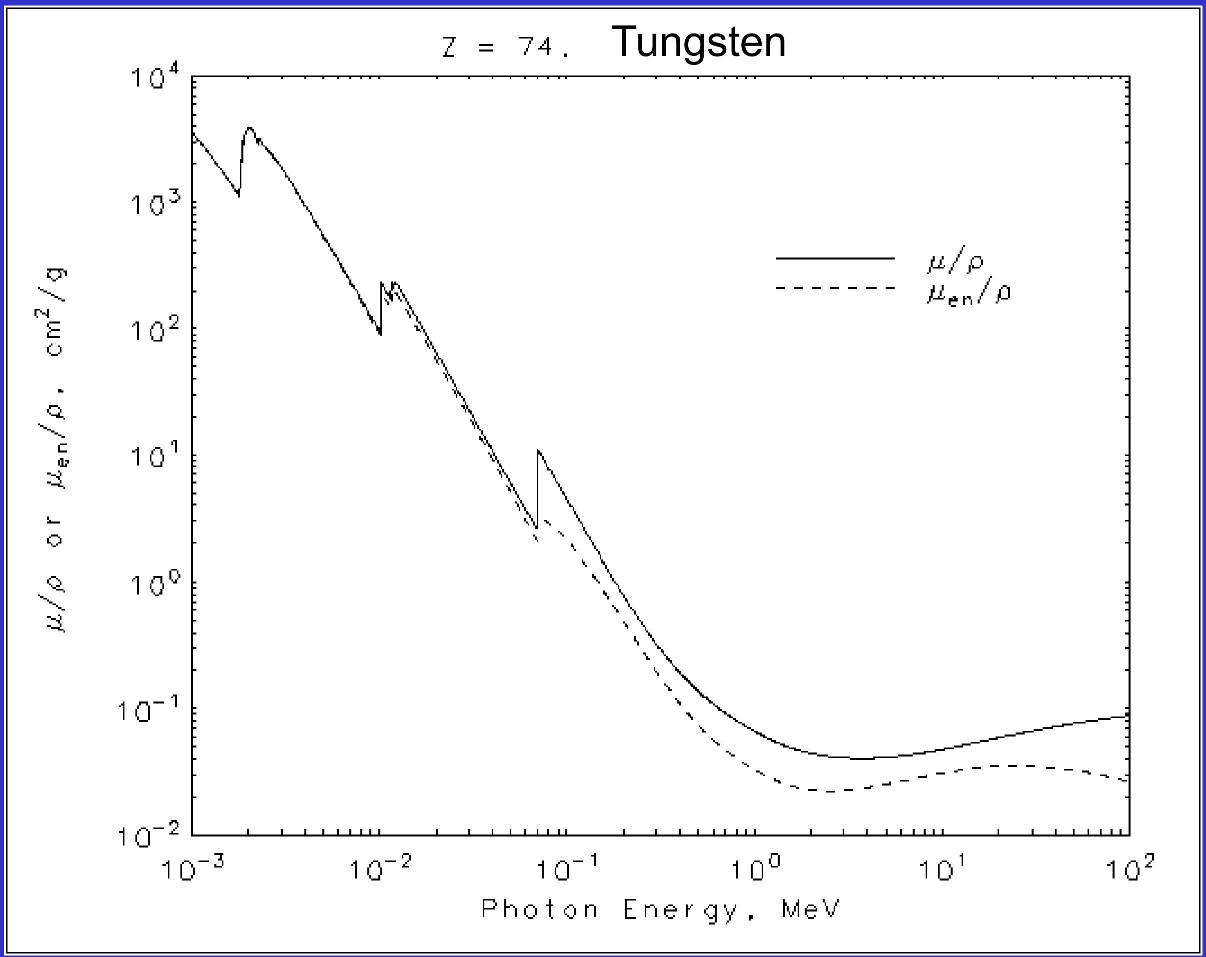
Gamma Ray Absorption is Energy and "Z" Dependent

Fission Surface Power



Values of the mass attenuation coefficient, μ/ρ and the mass energy-absorption coefficient, μ_{en}/ρ as a function of photon energy

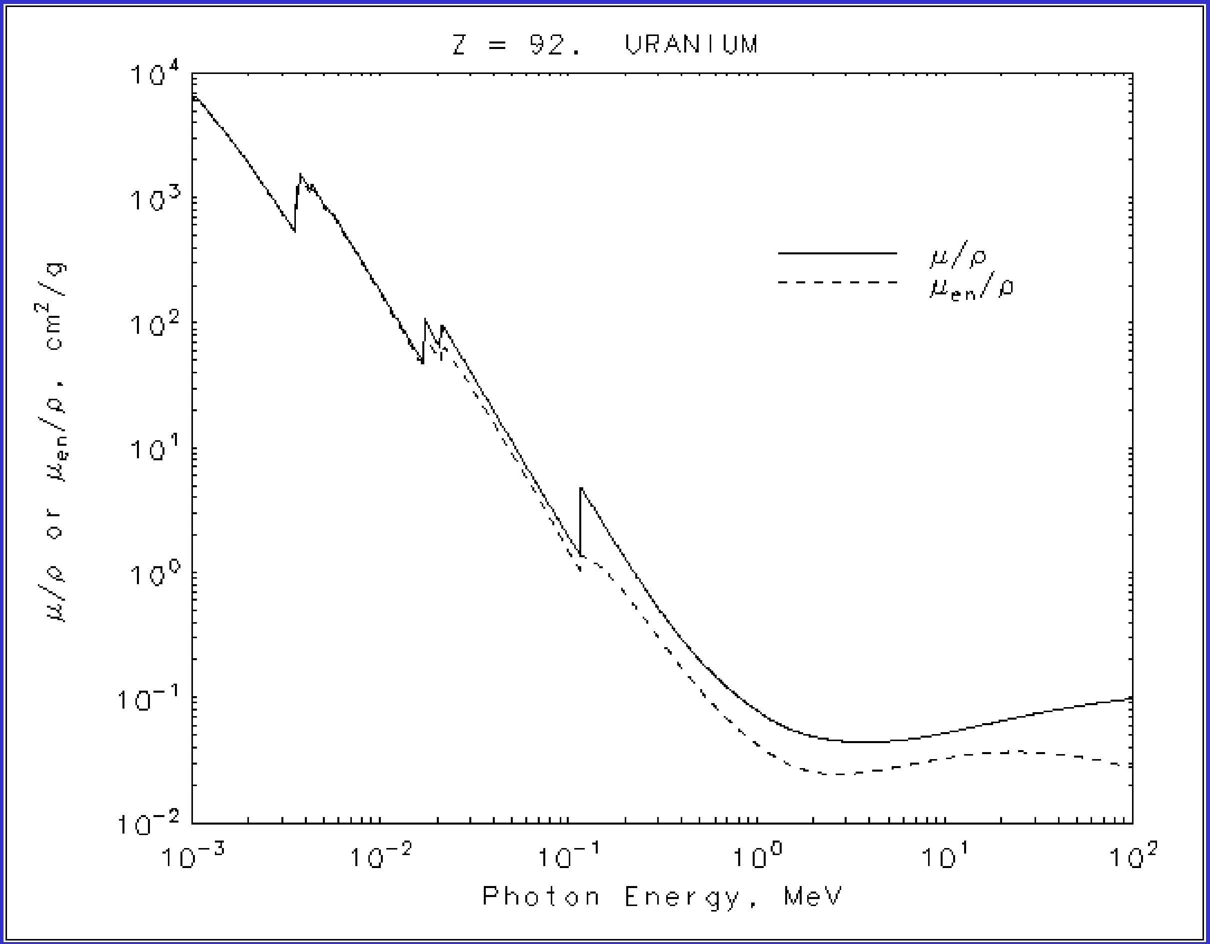
Gamma Ray Absorption is Energy and "Z" Dependent



Values of the mass attenuation coefficient, μ/ρ and the mass energy-absorption coefficient, μ_{en}/ρ as a function of photon energy

Gamma Ray Absorption is Energy and "Z" Dependent

Fission Surface Power



Values of the mass attenuation coefficient, μ/ρ and the mass energy-absorption coefficient, μ_{en}/ρ as a function of photon energy

Fission Surface Power

High Atomic Number Best for Gamma Shielding

Mass Attenuation Coefficient (μ/ρ cm^2/g)
of Al, Fe, W, and U at 1.0, 3.0, and 8.0 MeV

	Al	Fe	W	U
1.0 MeV	0.0615	0.0600	0.0618	0.0790
3.0 MeV	0.0354	0.0362	0.0408	0.0445
8.0 MeV	0.0244	0.0299	0.0447	0.0488

Shield design must also take into account “buildup”, inelastic neutron scatter, gammas from neutron capture, geometry, thermal management, radiation damage, and other factors.

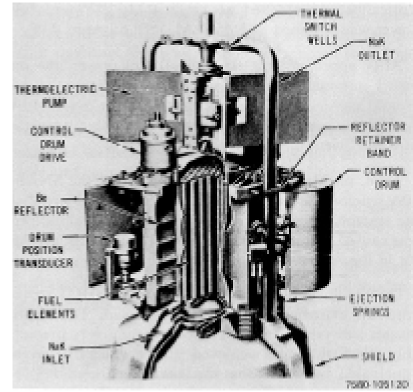
Outline

- Introduction to Space Nuclear Systems
- Ongoing interest / programs
  - Fission Surface Power (FSP)
    - Previously developed/qualified materials proposed for 1st generation systems
- Future interest/applications
  - NTP (hydrogen propellant or volatiles from space)
  - Regolith / ice melters
  - Resource processing
  - High power / high specific power
  - Water shield

Fission Surface Power

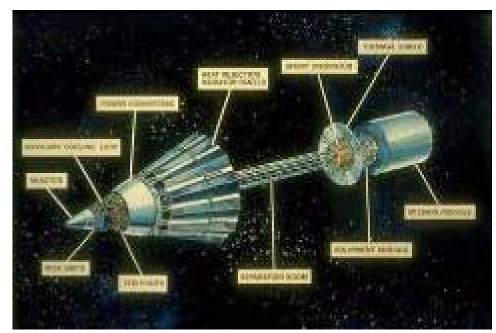
Space Power Reactors – Historical Observations

- SNAP reactors (1960s to early 1970s)
  - UZrH fueled, liquid metal (NaK) cooled w/thermoelectrics or Rankine
  - 500 We to 60 kWe (1 year life)
  - Several ground tests
  - One (SNAP-10A) flown in Earth orbit
- Russian reactors
  - U-Mo Alloy or UO2 fueled, liquid metal (NaK) cooled w/thermoelectrics (>30) or thermionics (2)
  - Low power (3-5 kWe / 100-150 kWt), short life (≤ 1 year)
  - Over 30 reactors flown in Earth orbit
- Numerous other programs developed technology but failed to lead to flight



0.5 kWe SNAP-10A Thermoelectric

5 kWe TOPAZ Thermionic



Artist Conception of SP100

Previous Human Lunar/Mars Power Studies

Fission Surface Power

Total Power Requirements 10 – 100 kWe
Option for Multiple Power Units.

LUNAR						
Studies	**Crew Size**	**Power Need**	**Power Type**	**Mass (mt)**	**Volume (m^3)**	**Comments**
1989 Office of Exploration Technical Report	4 to 12	30 kWe-avg; 50 kWe-peak;	Nuclear reactor with power conv. Unit	4	27	
1989 90-Day Study	4	75 kWe- day, 37.5 kWe - night	Nuclear reactor with power conv. Unit			Lunar surface stay-time: 6 months
1990 Economical Space Exploration Systems Architectures	4	10 kWe	PV/RFC assemblies			Requirement for Lunar STV with habitat. Lunar surface base: 2-3 kWe per person for habitation.
1991 Synthesis Group Study	6	100 kWe	Nuclear reactor with power conv. Unit	12.5		
1992 First Lunar Outpost	4	12.5 kWe - day, 9.5 kWe night	PV/RFC assemblies	9.5		Integrated Lander/Habitat

MARS						
Studies	**Crew Size**	**Power Need**	**Power Type**	**Mass (mt)**	**Volume (m^3)**	**Comments**
1989 Office of Exploration Technical Report	4 to 7	30 kWe-avg; 50 kWe-peak;(Hab/W workshop -100 kWe)	Nuclear reactor with power conv. Unit	4	27	Long stay case studies chosen (lunar and Mars evolution)
1989 90-Day Study	4	25 kWe cont.	PV/RFC assemblies			
1990 Economical Space Exploration Systems Architectures	4	25 kWe	PV/RFC assemblies			Requirement for Mars STV with habitat. Mars surface base: 2-3 kWe per person for habitation.
1991 Synthesis Group Study	6	50 kWe	Nuclear reactor with power conv. Unit	12.5		
1997 DRM 1.0	6	30 kWe	PV/RFC assemblies	~77		Mass given is for Hab/Lab.
1999 Solar Electric Power System Analyses for Mars Surface Missions	4 to 6	40 kWe	PV/RFC system	~10		Area of array: 5000 m^2
1999 Surface Nuclear Power for Human Mars Missions	6	25 kWe	PV/RFC assemblies	14	390	Data similar to DRM 1.0

* “Nuclear” DRM 3.0 (1998) assumed highly capable Mars outpost, fission based, 160 kWe

Fission Surface Power

Planetary Surface Missions: Increasing Energy Needs

- Now:
  - 290 We Deep Space / 110 We MMRTG
  - General Purpose Heat Source - Radioisotope Thermoelectric Generator (GPHS-RTG) uses 18 Pu-238 fueled GPHS modules
  - GPHS modules will be used by the 110 We Multi-Mission RTG (MMRTG, 8 modules) and the 110 We Stirling Radioisotope Generator (SRG, 2 modules)

MMRTG selected for Mars Science Laboratory

- Option for ~2020
  - 10 - 50 kWe Fission Surface Power
  - Not affected by Pu-238 availability concerns
  - Robust, power-rich environment anytime / anywhere
  - Well established reactor technology – minimize new technology development

Focus on “Workhorse” System Concept

Fission Surface Power

- Workhorse Definition
  - Workhorse system is available/desirable once power requirements cannot be met by radioisotopes and/or stored energy
  - Desired module power level (based on previous studies) 10 – 40 kWe
- Power level
  - Fit on lander(s) to be developed for lunar exploration
  - Trade cost, technology risk, programmatic risk, and power level
- Deployment
  - ~2020
  - *Anywhere* on Moon, readily extensible to Mars
- Mass
  - Deploy using vehicles and equipment that will be developed for lunar exploration.
- Operation
  - Initial system provides operational data to qualify for very long life
    - RTG, SIRTF analog
  - Extensible to Mars operation
  - Shield to robotic requirements, regolith used to provide additional shielding

Minimize program risk

Minimize cost and difficulty of getting from current state to a flight qualified system

System must be safe, reliable, and affordable in a cost-constrained environment

Workhorse System Must Be Affordable

Fission Surface Power

- A surface power system must be safe
- A surface power system must also have adequate performance, reliability, and lifetime, and meet mass and stowed volume constraints
- Once basic criteria are met, cost becomes the primary driver
- JIMO / Prometheus-1
  - 20 year life; 208 kWe; Refractory metal fuel clad; Potential for refractory metal vessel; high temperature fuel/clad operation; overseas irradiation testing (JOYO), two ground tests, two flight units, power conversion
  - $3.6B
- Fast Flux Test Facility
  - 400 MWt, fast spectrum, sodium, research)
  - $3.0B in FY08 $$
- 1371 MWe Commercial Light Water Reactor
  - $2.2B
- 2-3 MWt TRIGA reactor (fully installed/operational, research capability, no power conversion)
  - < $50M
- Search for innovative approaches to reducing FSP development and utilization cost
  - Devise cost-competitive system options

~ $3B (JIMO, FFTF, LWR)

"Modest" Space Reactor?

< $50M (TRIGA)

Development and Qualification Testing for Fission Surface Power (FSP)

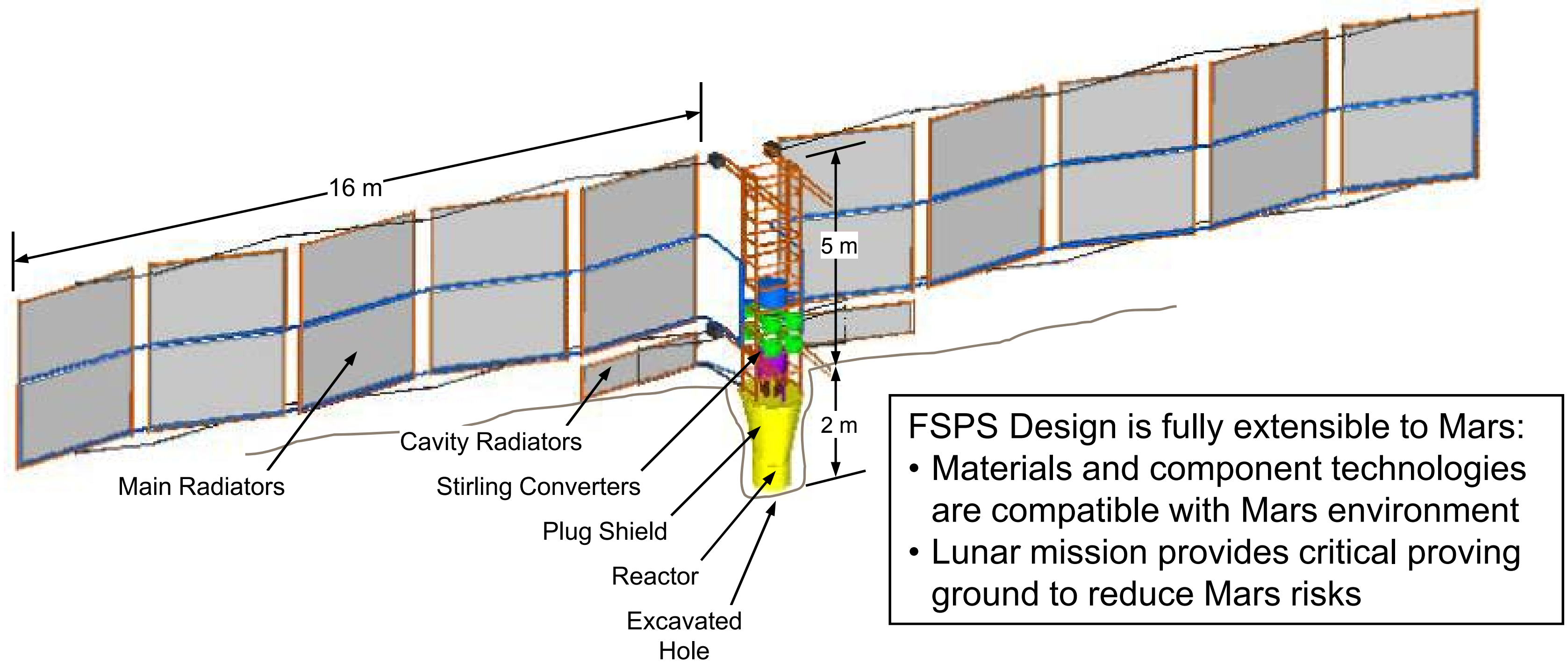
Fission Surface Power

- Use demonstrated technologies and well qualified fuels and materials to facilitate FSP system qualification
- Qualification testing strategy should be optimized
- Robust, affordable test program needed to provide high confidence in mission success
- Information for qualifying, launching, and operating an FSP system obtained from several sources
  - Component / subsystem tests
    - Both in-pile and non-nuclear
  - Cold and hot nuclear criticality tests
  - System modeling/simulations
  - “Simple” non-nuclear system tests
  - High fidelity non-nuclear system tests
- The fidelity of non-nuclear tests can be extremely high, if desired
  - The maximum achievable fidelity likely exceeds that required for development and qualification

Affordable Fission Surface Power System (FSPS)

Fission Surface Power

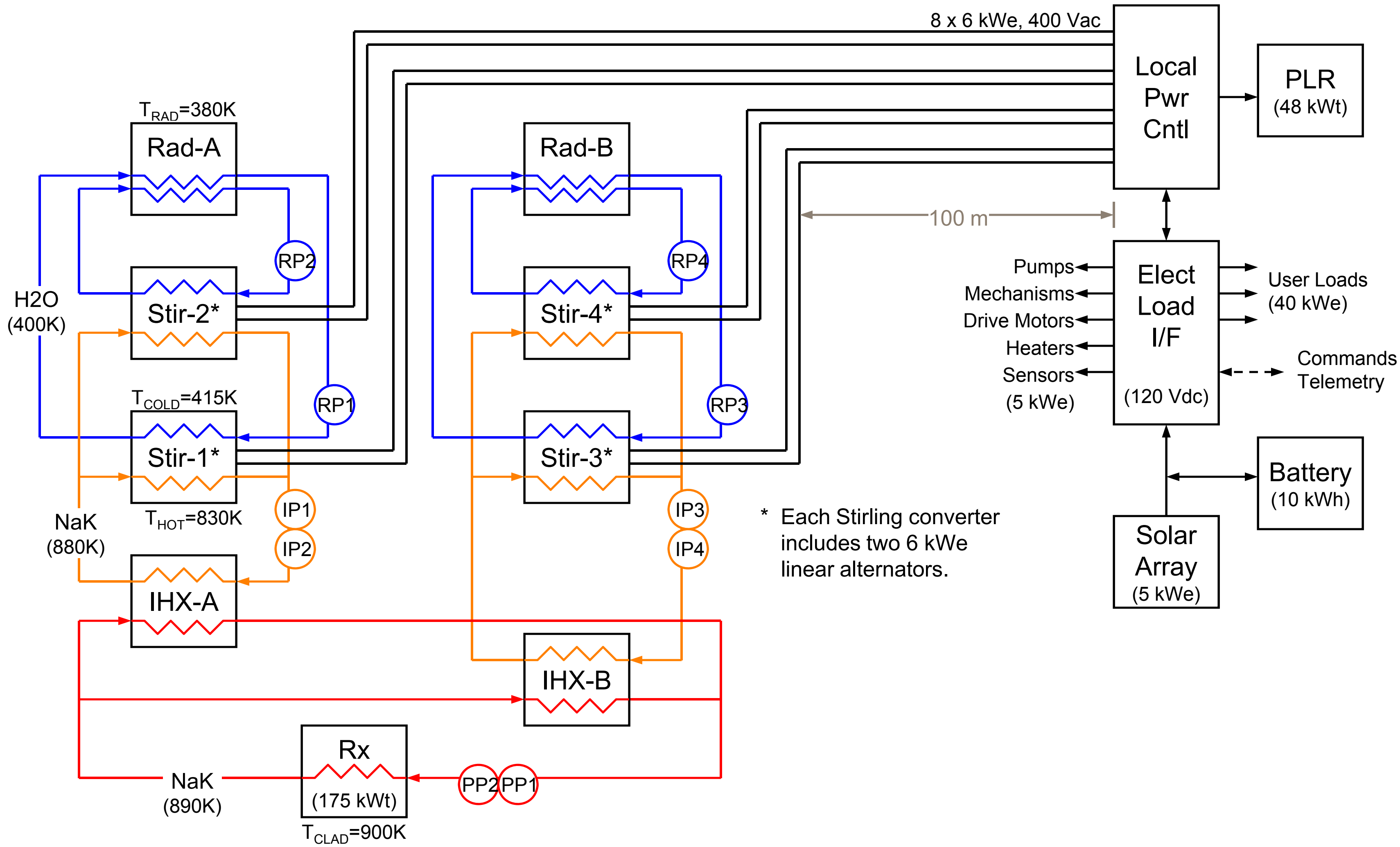
- Modular 40 kWe System with 8-Year Design Life suitable for (Global) Lunar and Mars Surface Applications
- Emplaced Configuration with Regolith Shielding Augmentation Permits Near-Outpost Siting
  - <5 rem/yr at 100 m Separation
- Low Temperature, Low Development Risk, Liquid-Metal (NaK) Cooled Reactor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



FSPS Design is fully extensible to Mars:
- Materials and component technologies are compatible with Mars environment
- Lunar mission provides critical proving ground to reduce Mars risks

FSPS Schematic

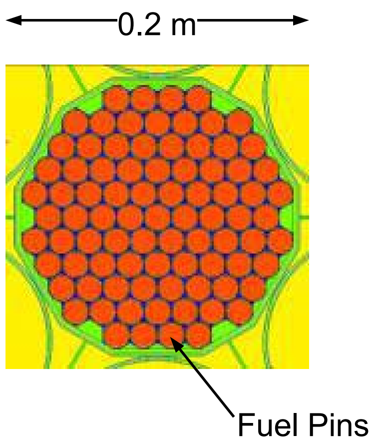
Fission Surface Power

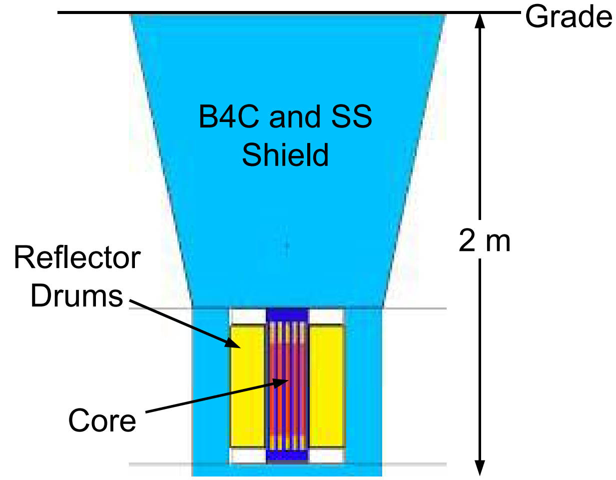


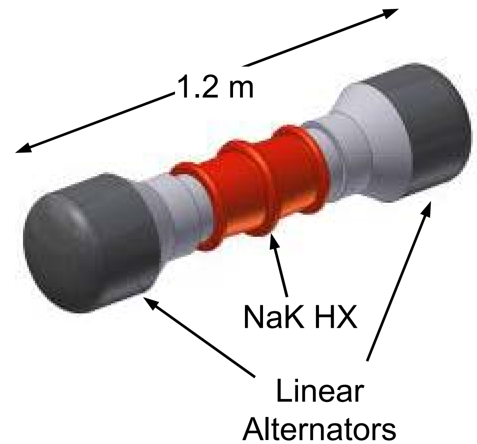
* Each Stirling converter includes two 6 kWe linear alternators.

Fission Surface Power

FSPS Design Features







♦ 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
- Close-packed, open lattice flow geometry

♦ Reactor Module:

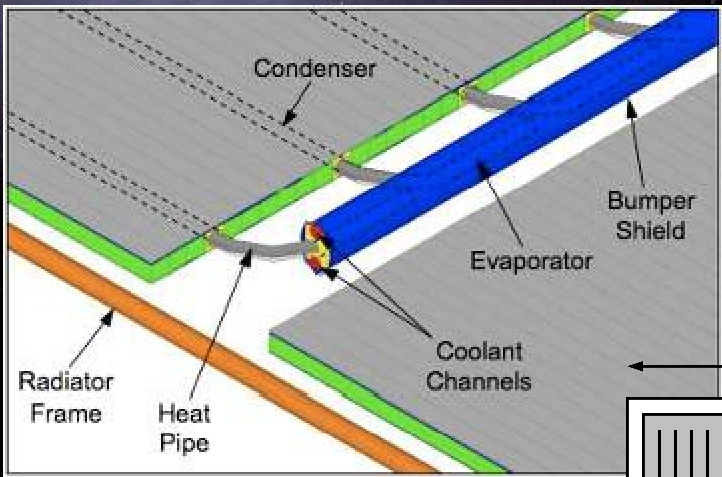
- Fault-tolerant, radial Be reflector control drums
- Low-risk B4C and SS shielding with regolith augmentation
- <2 Mrad and 1x1014 n/cm2 at power conversion; <5 rem/yr at outpost (100 m)
- SS-316 primary & intermediate coolant loops with redundant EM pumps
- Cavity cooling with surface-mounted radiators

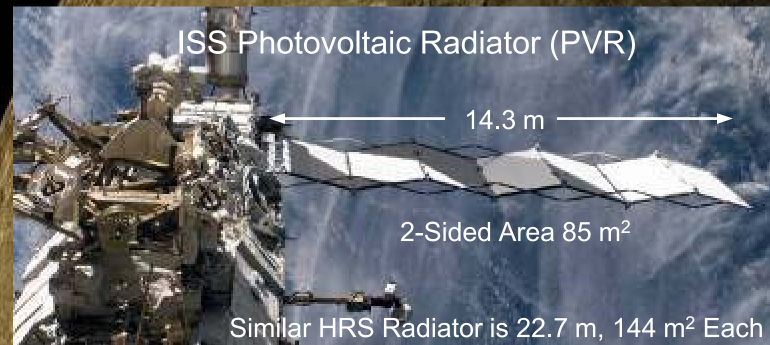
♦ Stirling Power Conversion:

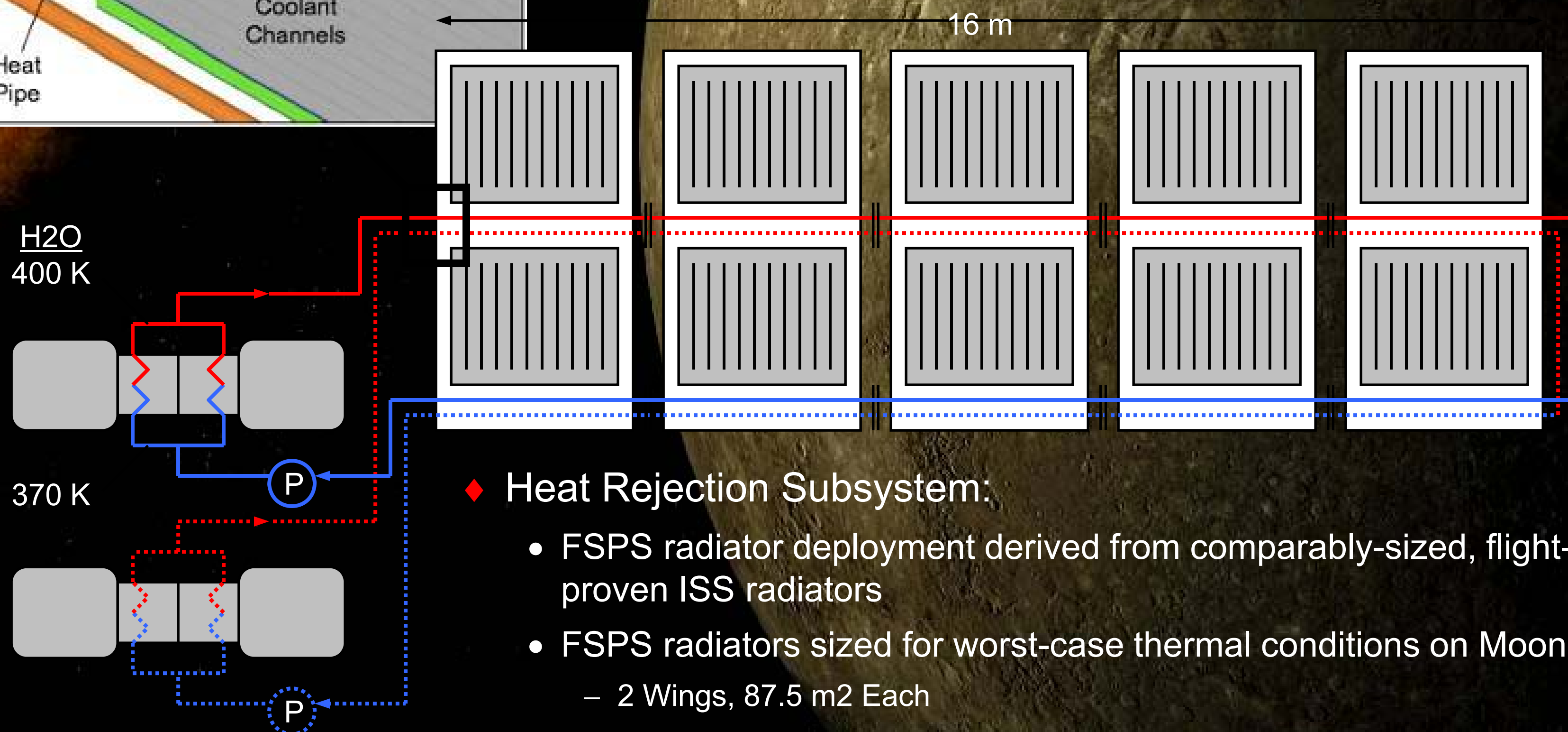
- High efficiency (>25%) at low hot-end temperature (830K)
- Pumped-water cooling (400K)
- Smallest radiator size among PC options
- 4 dual opposed engines, 8 linear alternators
- 400 Vac power distribution
- Demonstrated technology at 25 kW size in 1980’s
- Potential to leverage current RPS program

Heat Rejection Concept

Fission Surface Power



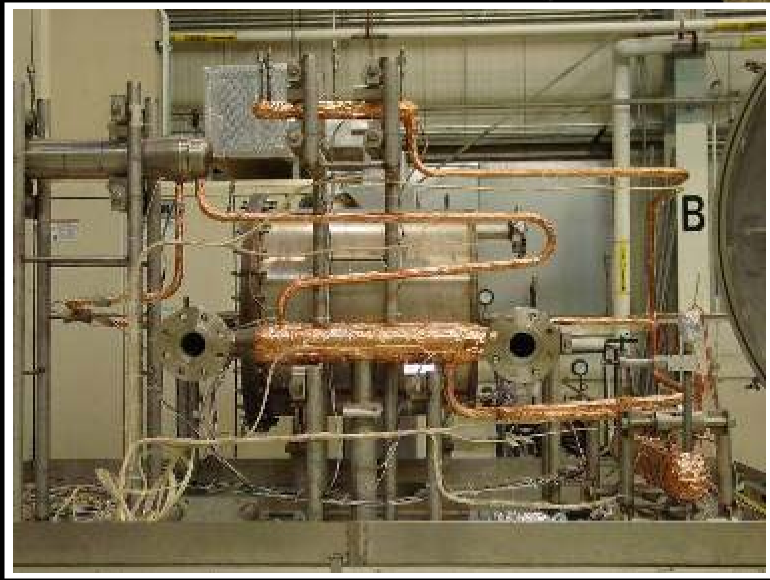


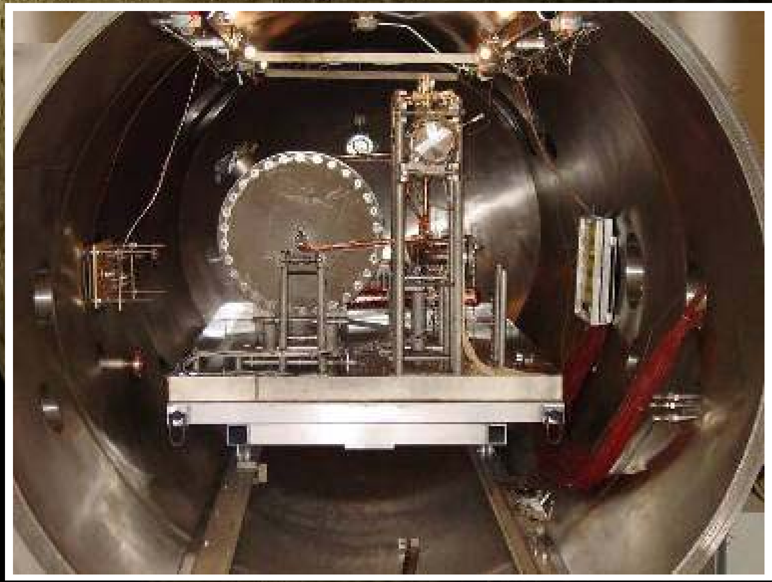


- Heat Rejection Subsystem:
  - FSPS radiator deployment derived from comparably-sized, flight-proven ISS radiators
  - FSPS radiators sized for worst-case thermal conditions on Moon
    - 2 Wings, 87.5 m2 Each
  - As much as 10% power increase possible during lunar night

Fission Surface Power Primary Test Circuit
(FSP-PTC)

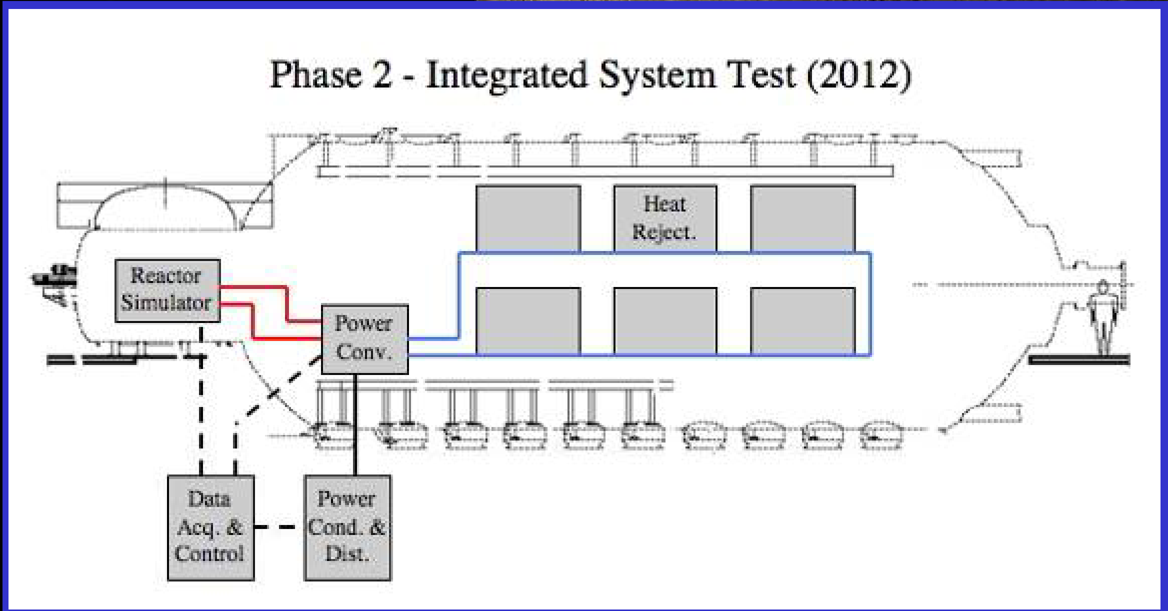
Fission Surface Power





Power Conversion, Radiator, PCAD, Integrated System Testing

Fission Surface Power



Potential Uses for Advanced Materials (Space Fission Power Systems)

Fission Surface Power

- First generation FSP systems use established materials
- Second generation systems could benefit in numerous areas:
  - Bi-metallic gas cooled systems
  - High radiation tolerance for near-core components
    - Magnets, insulators, bearings, lubricants
  - High temperature, high uranium density fuel/clad systems
    - Nb-1Zr or Mo-clad UN
  - High temperature structural materials
    - Vacuum
  - High temperature structural materials
    - moon or Mars surface
  - High temperature neutron reflector and control materials
    - Be, BeO, B_4C
  - High temperature materials compatible with alkali metals and Mars atmosphere
  - Bi-metallic alkali metal loops

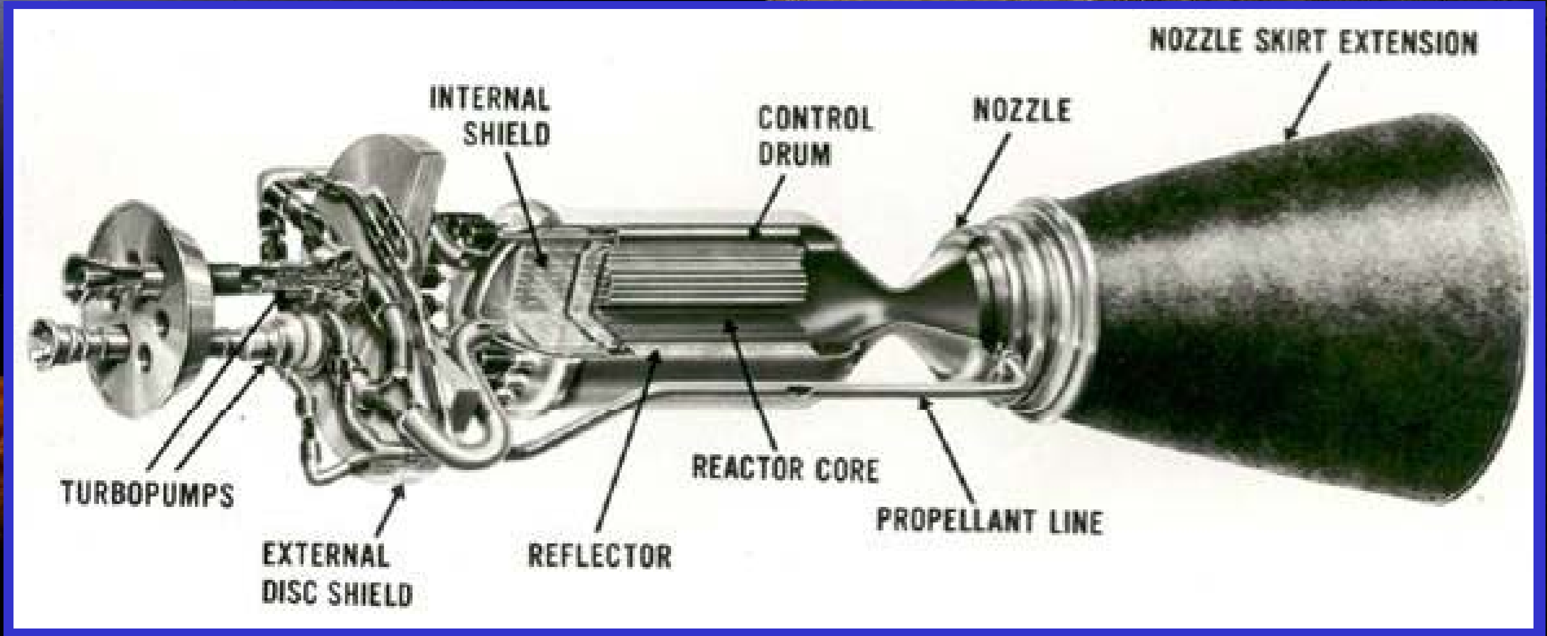
Outline

Fission Surface Power

- Introduction to Space Nuclear Systems
- Ongoing interest / programs
  - Fission Surface Power (FSP)
    - Previously developed/qualified materials proposed for 1st generation systems
- Future interest/applications
  - NTP (hydrogen propellant or volatiles from space)
  - Regolith / ice melters
  - Resource processing
  - High power / high specific power
  - Water shield

Nuclear Thermal Propulsion (NTP)

Fission Surface Power

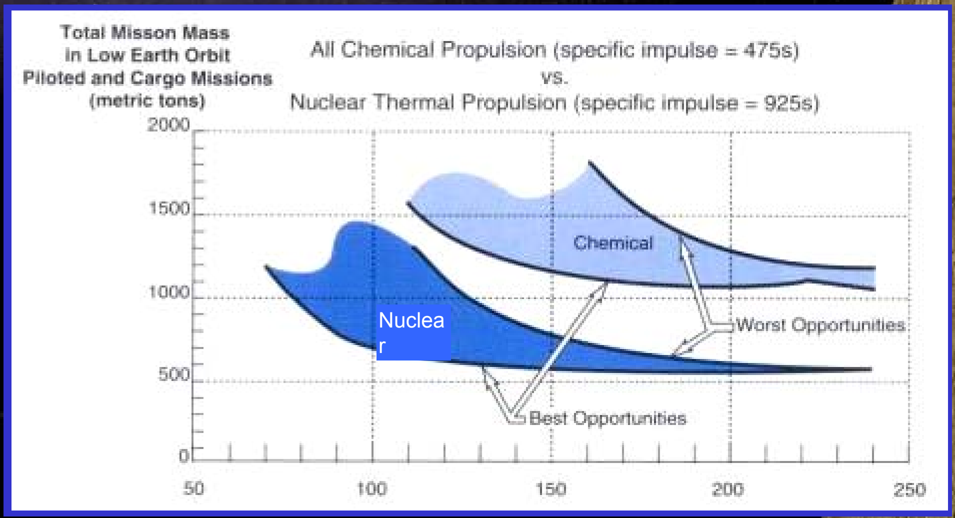


- Hydrogen from propellant tank (not shown) directly heated by reactor and expanded through nozzle to provide thrust
- ~850 second Isp demonstrated in ground tests at high thrust/weight
- Potential for > 900 s Isp with advanced fuel forms and cycles
- Potential Applications
  - Rapid robotic exploration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

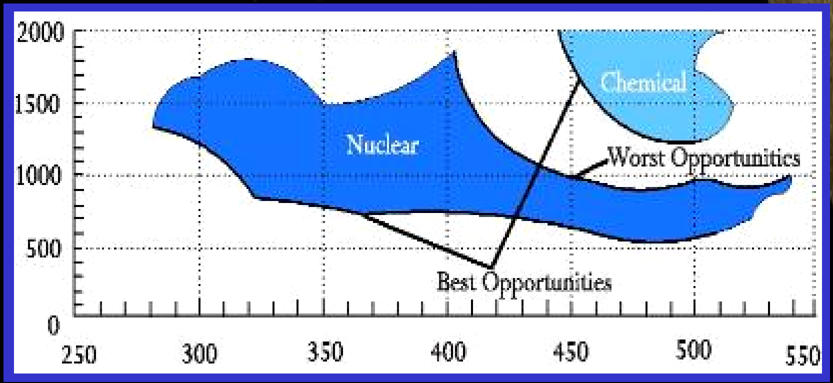
Nuclear Thermal Propulsion (NTP) Has The Potential to be Mission Enabling

Fission Surface Power

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



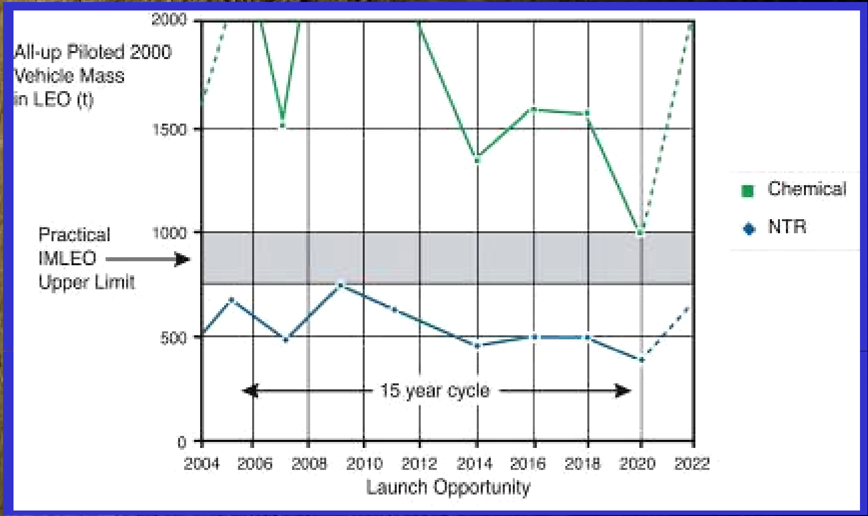
Conjunction Class (Long Stay) Mission



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

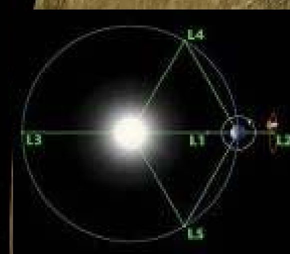
NTP Could Be Mission-Enhancing

Fission Surface Power

- NTP could enhance the ability to reach new destinations
- NTP could enable a steady, progressive, regular and affordable exploration program

Lunar Cargo Missions

NEO Mission



Sun-Earth Lagrange Point

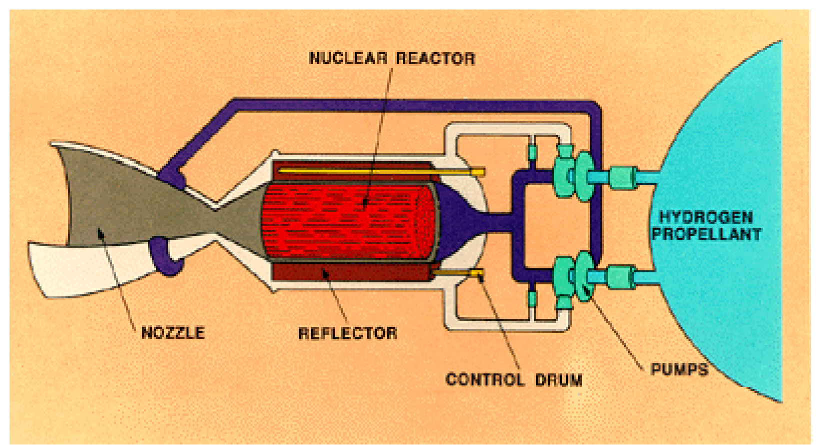
Phobos Mission

Mars Cargo and Human Missions

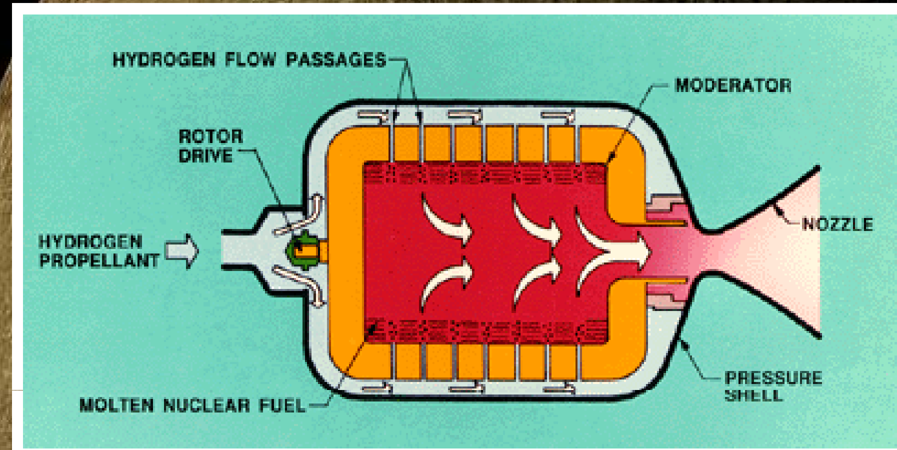
As envisioned, NTP reduces required launch mass, reduces trip time, and increases mission opportunity. Over time, NTP could reduce exploration costs

Proposed Types of Nuclear Thermal Propulsion

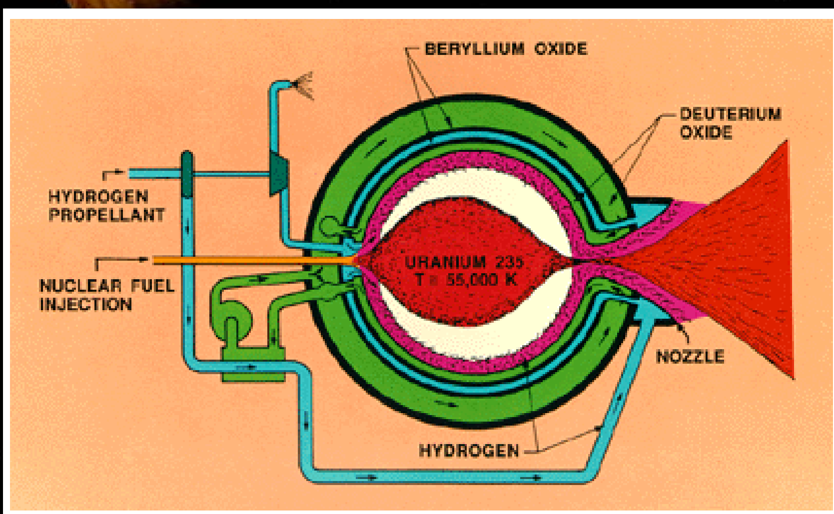
Fission Surface Power



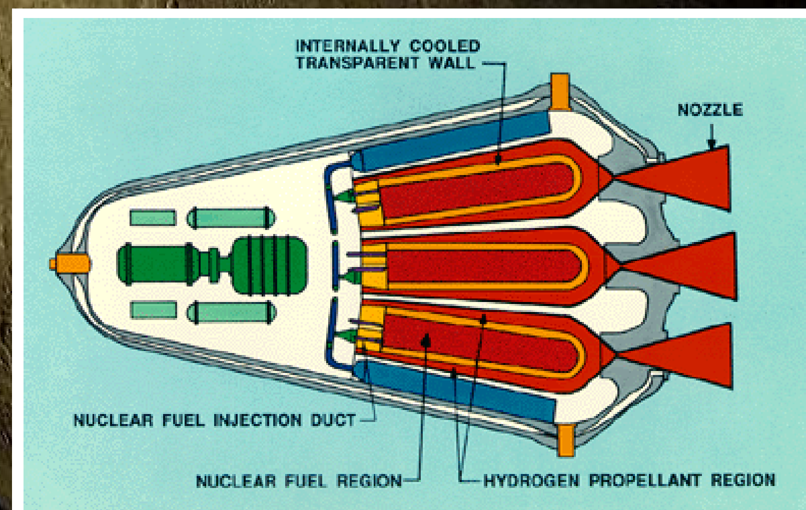
SOLID CORE NUCLEAR ROCKET



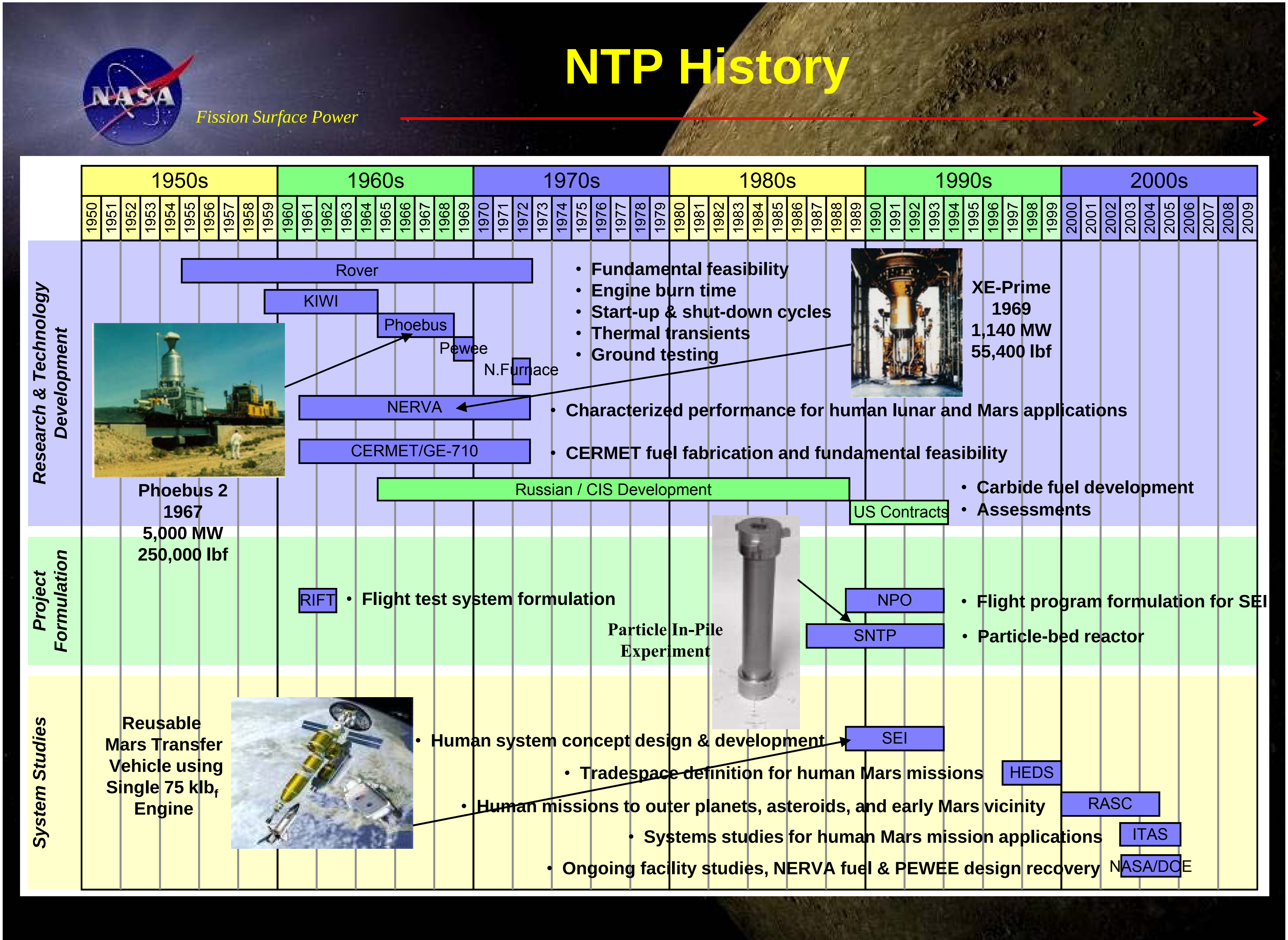
LIQUID CORE NUCLEAR ROCKET



Open-Cycle Gas Core Nuclear Rocket

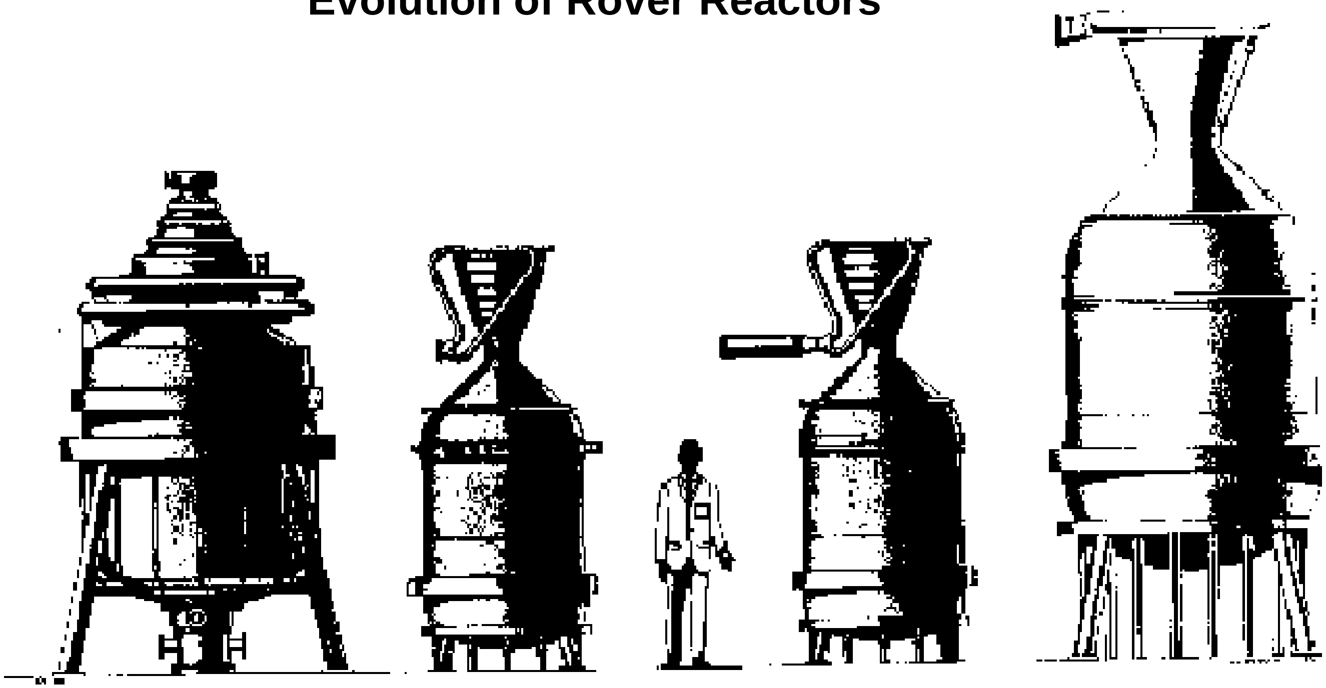


Closed-Cycle Gas Core Nuclear Rocket


NTP History
NASA
Fission Surface Power
1950s
1960s
1970s
1980s
1990s
2000s
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
• Characterized performance for human lunar and Mars applications
• CERMET fuel fabrication and fundamental feasibility
• Carbide fuel development
• Assessments
Phoebus 2
1967
5,000 MW
250,000 lbf
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 klbf
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

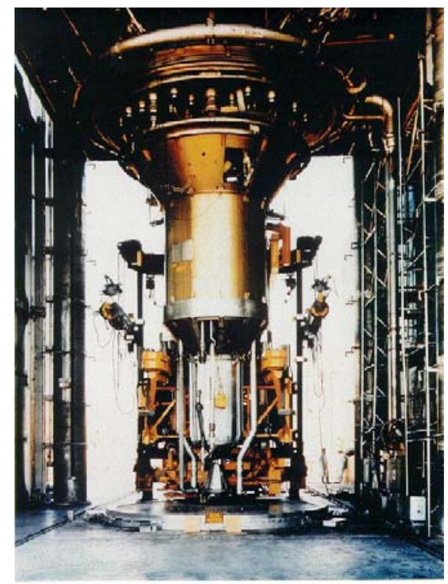
Rover/NERVA Engine Comparison

Evolution of Rover Reactors



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

Culmination of NERVA Program

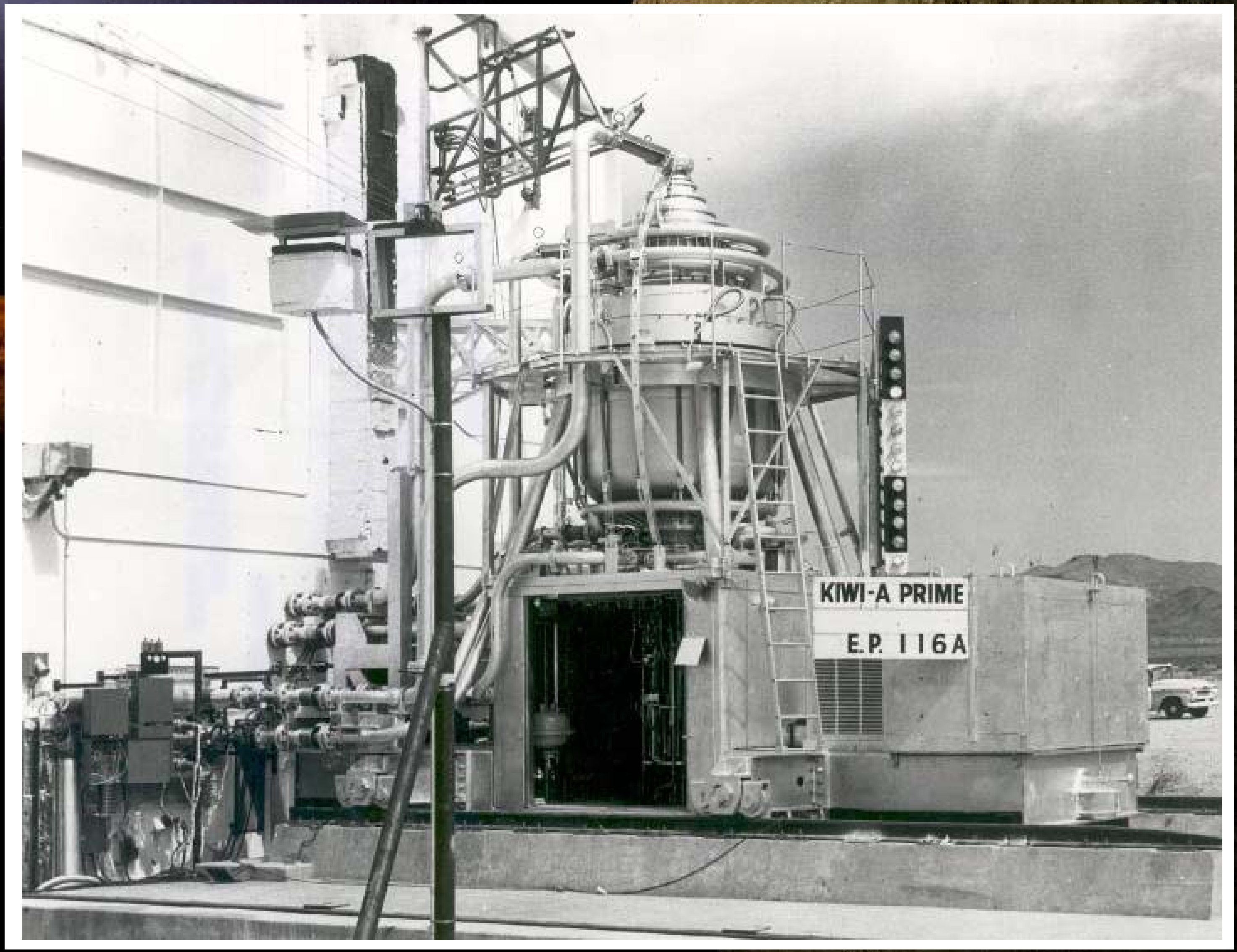


XE-Prime
1969
1,140 MW
55,400 lbf Thrust

NERVA engines based largely on the KIWI B reactor design.

Fission Surface Power

KIWI A'

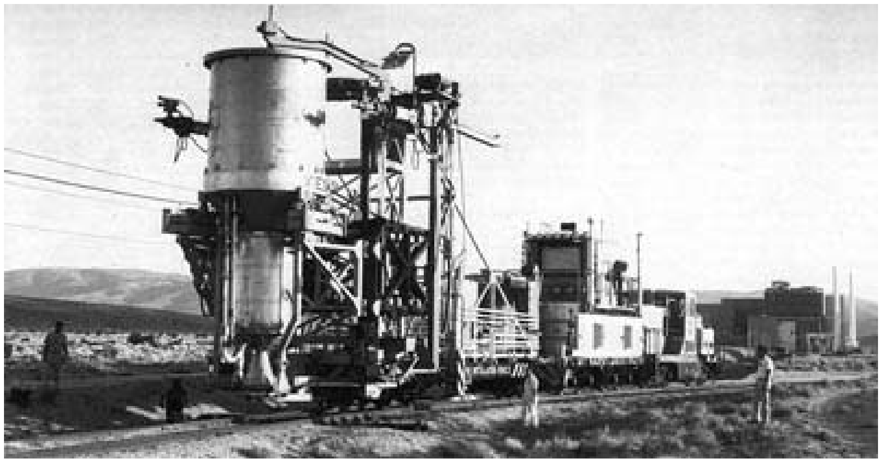


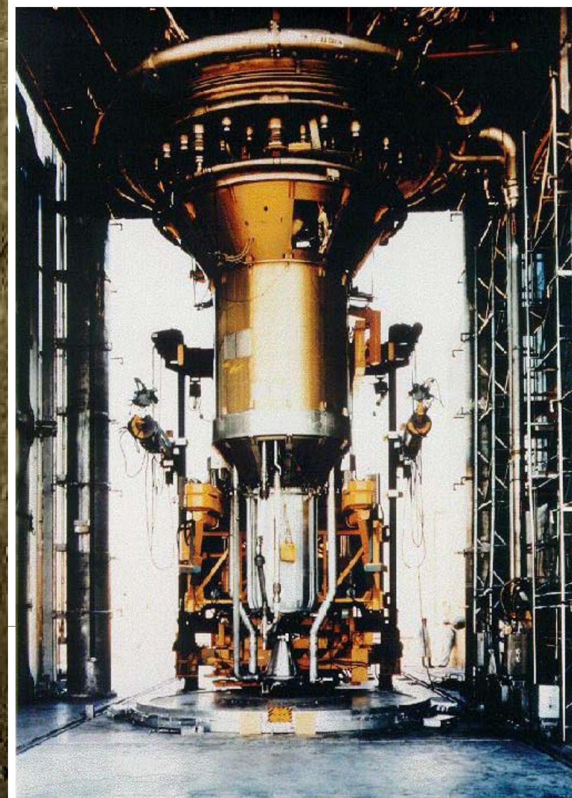
Phoebus-2A

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

Fission Surface Power

XE’



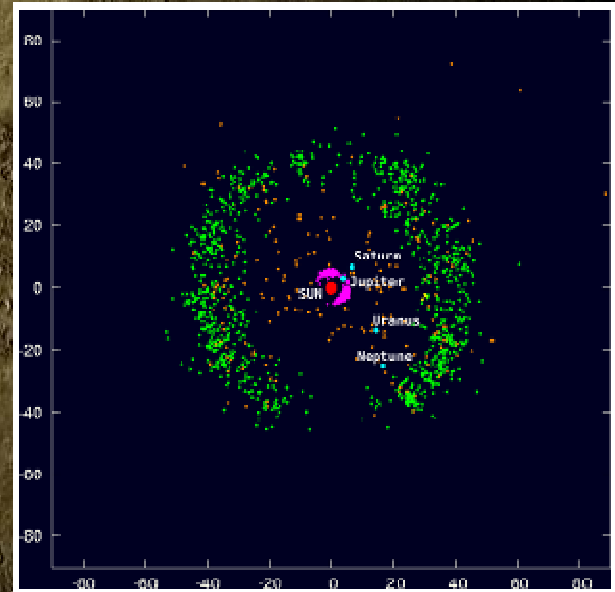


- XE’ Engine
  - Tested 1969
  - 1.1 GW Reactor Core
  - 820seconds Isp space Equiv.
  - 55,000 lbf Thrust

Potential Advanced Topics - Example

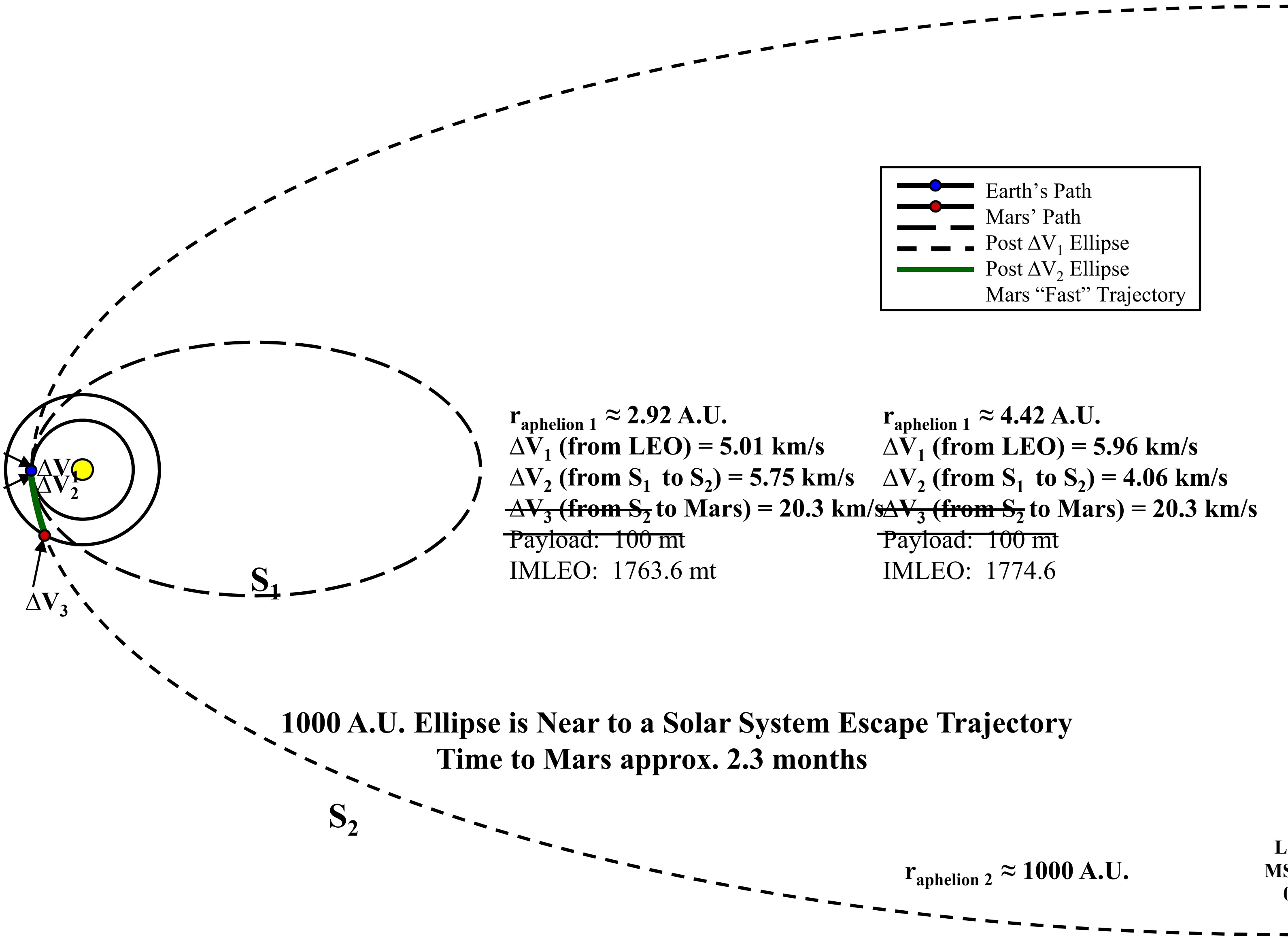
Fission Surface Power

- 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

Fission Surface Power



$r_{aphelion\ 1} \approx 2.92$ 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

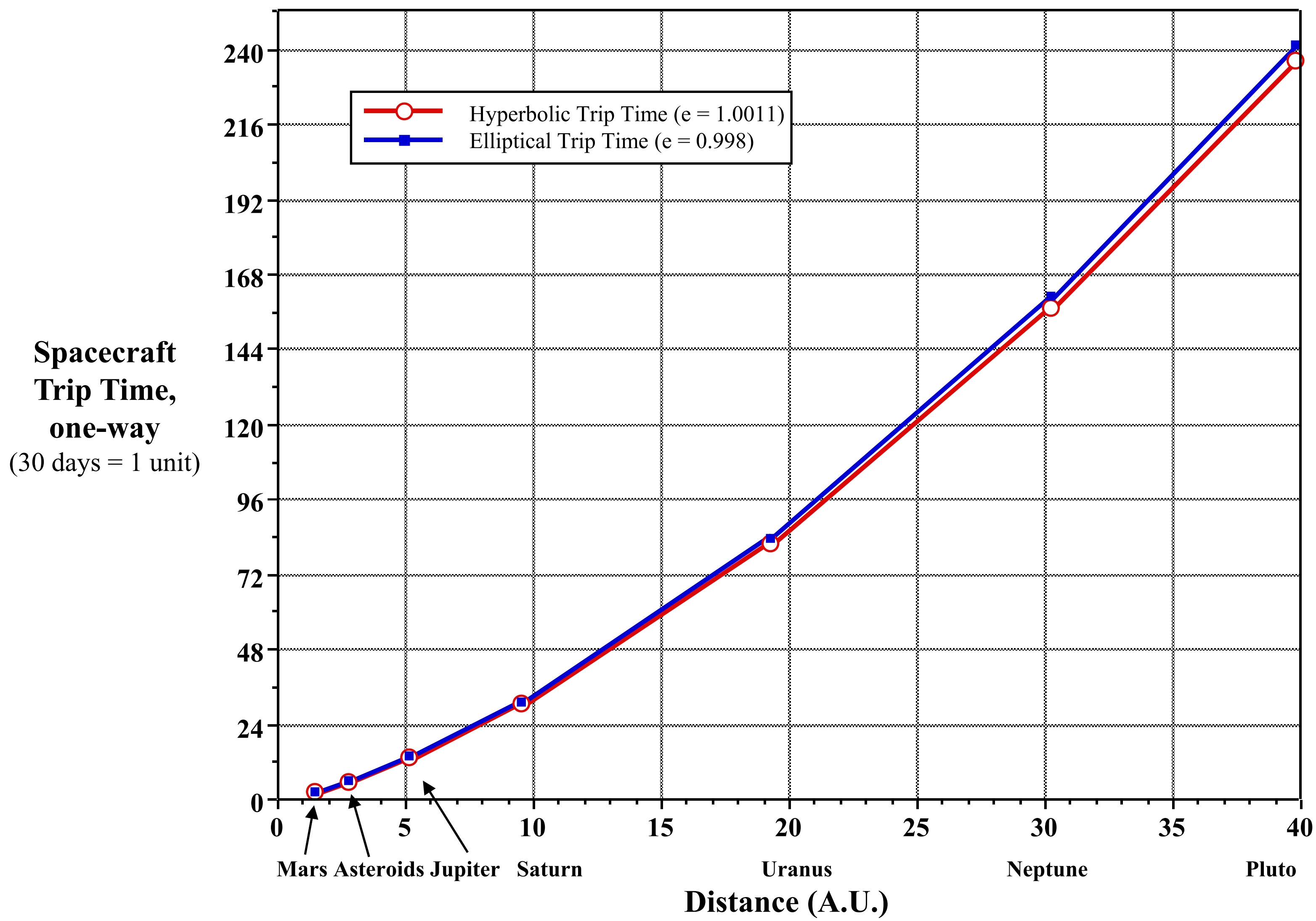
1000 A.U. Ellipse is Near to a Solar System Escape Trajectory
Time to Mars approx. 2.3 months

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

Larry Kos
MSFC/TD31
08/04/99

Planetary Trip Times
Quickest Missions w/o Becoming Hyperbolic

Fission Surface Power



Larry Kos
MSFC/TD31
6/4/99

Potential Uses for Advanced Materials NTP Systems

Fission Surface Power

- Primary need is high-temperature, hydrogen-compatible fuels with good neutronic properties
  - Recapture Rover/Nerva fuel systems
  - Cermet fuels
  - Tri-carbides
- Advanced materials for pumps, vessels, nozzles, control systems also useful for early NTP systems
- Futuristic systems have more extreme needs
  - Liquid core
  - Gas core
  - Indigenous propellants
  - Direct Fission Fragment heating

Observations

- First generation Fission Surface Power systems use established materials
  - Focus on affordability
- Second generation FSP and in-space power systems could benefit from advanced materials
- Extremely high performance space fission power systems may become practical with advanced materials
- First generation NTP systems will require recapture of fuels technology, and could benefit from the development of advanced fuels and other materials
- Highly advanced NTP systems may become feasible with advanced materials