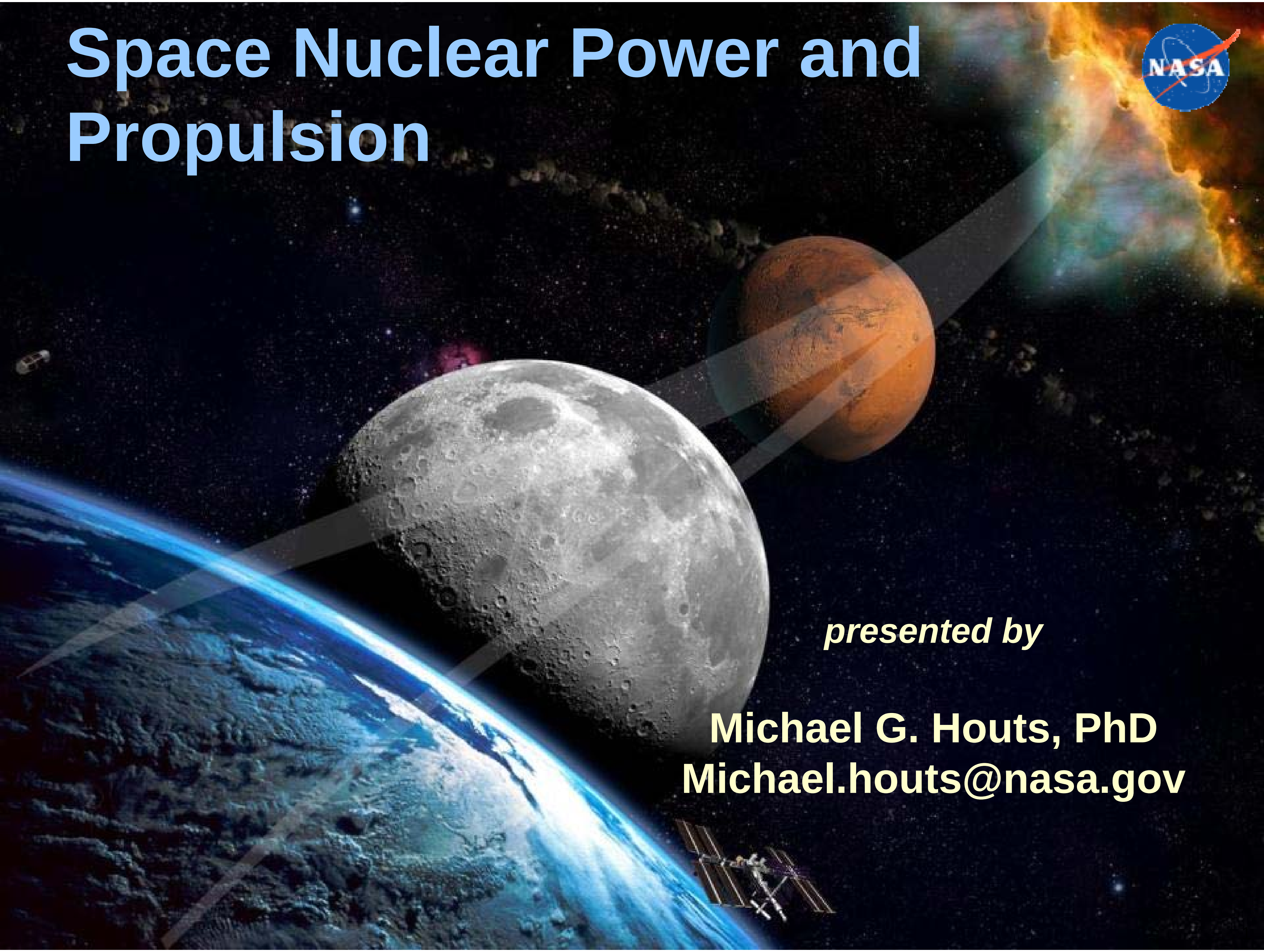
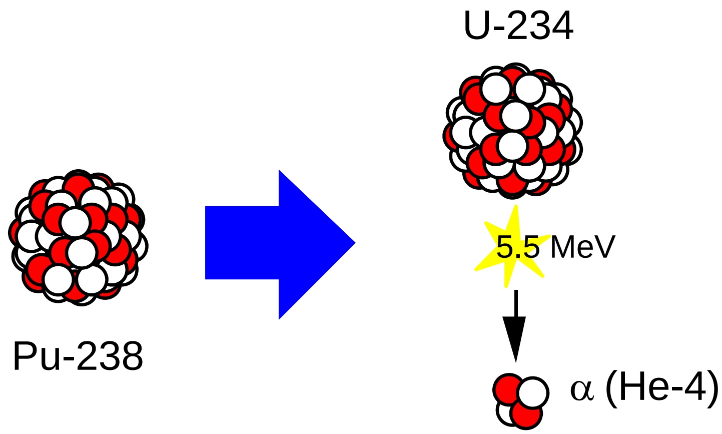
Space Nuclear Power and Propulsion

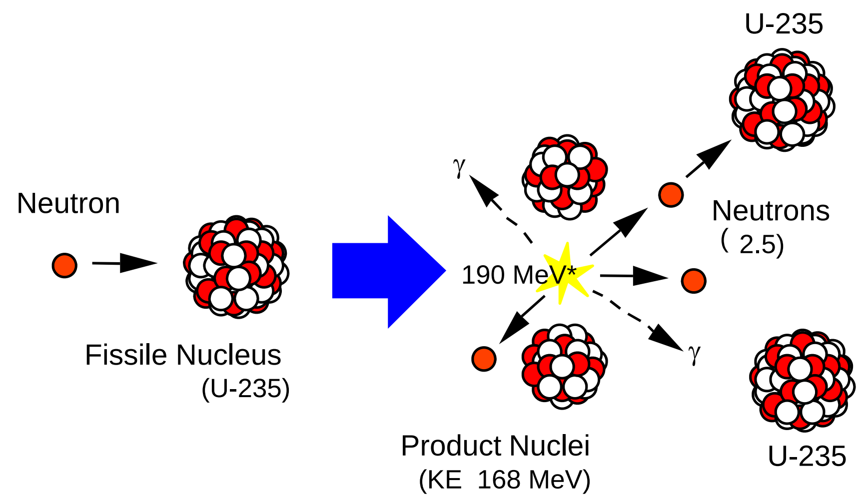


presented by

Michael G. Houts, PhD
Michael.houts@nasa.gov

Basics of Nuclear Systems





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

Heat Energy = 0.851 MeV/nucleon

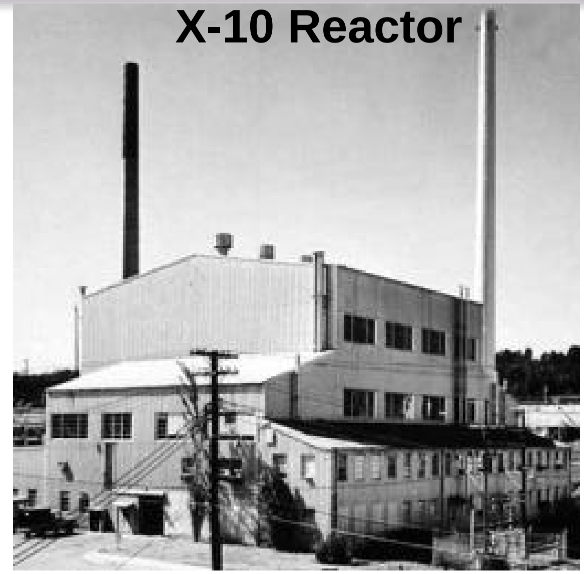
Controllable reaction rate (variable power levels)

- 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, affordable, useful fission systems**

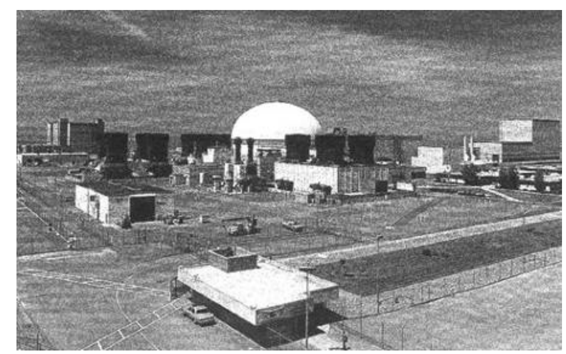
- ***1938 Fission Discovered***
- ***1939 Einstein letter to Roosevelt***
- ***1942 Manhattan project initiated***
- ***1942 First sustained fission chain reaction (CP-1)***
- ***1943 X-10 Reactor (ORNL), 3500 kWt***
- ***1944 B-Reactor (Hanford), 250,000 kWt***
- ***1944-now Thousands of reactors at various power levels***



Fission 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, EBR-II, ATR, HFIR

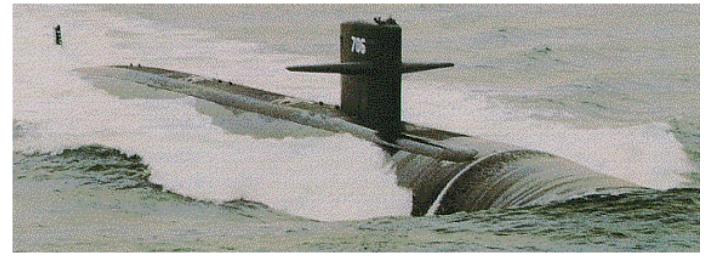


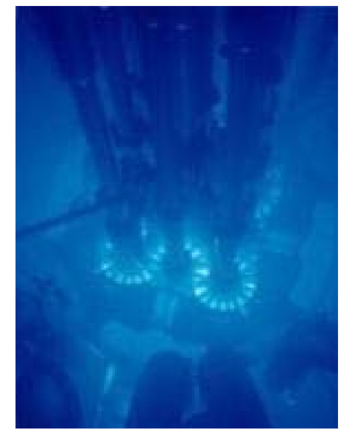
- Commercial Light Water Reactors 1,371,000 kWe (3,800,000 kWt)
- Space reactors
  - SNAP-10A 42 kWt / 0.6 kWe
  - Soviet reactors typically 100 kWt / 3 kWe (some systems >150 kWt)
  - Cost is design-dependent

Figure II-92. SNAP 10A Flight System

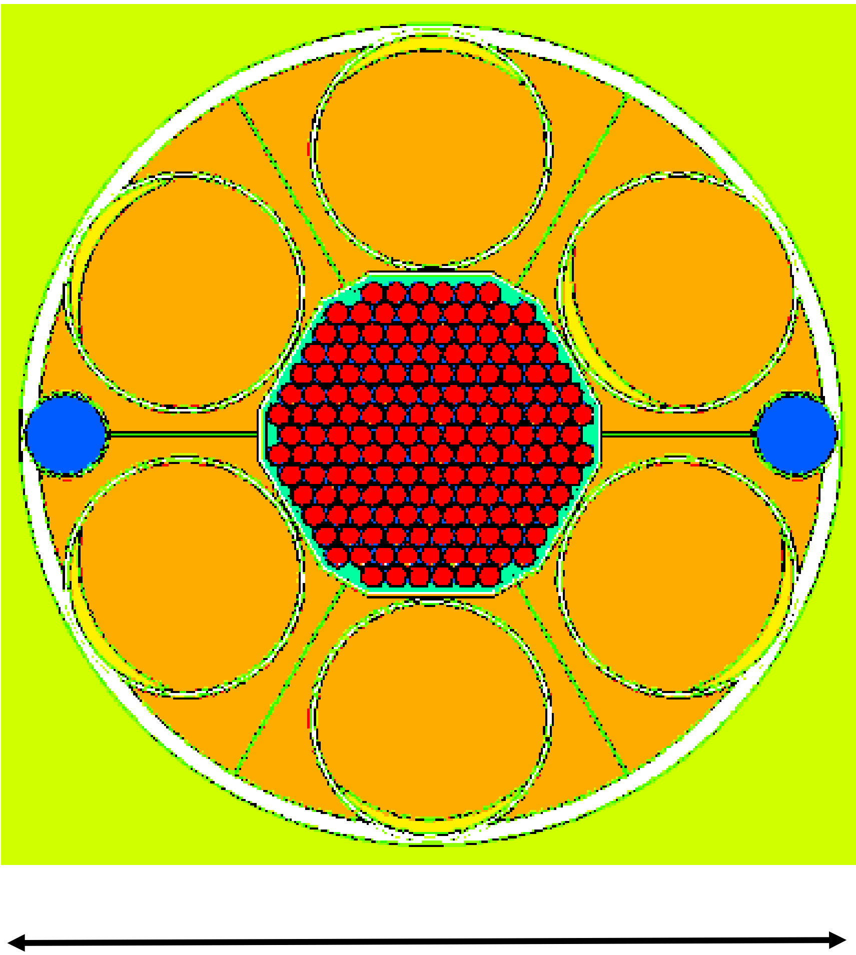
Fission is Highly Versatile with Many Applications (continued)

- 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





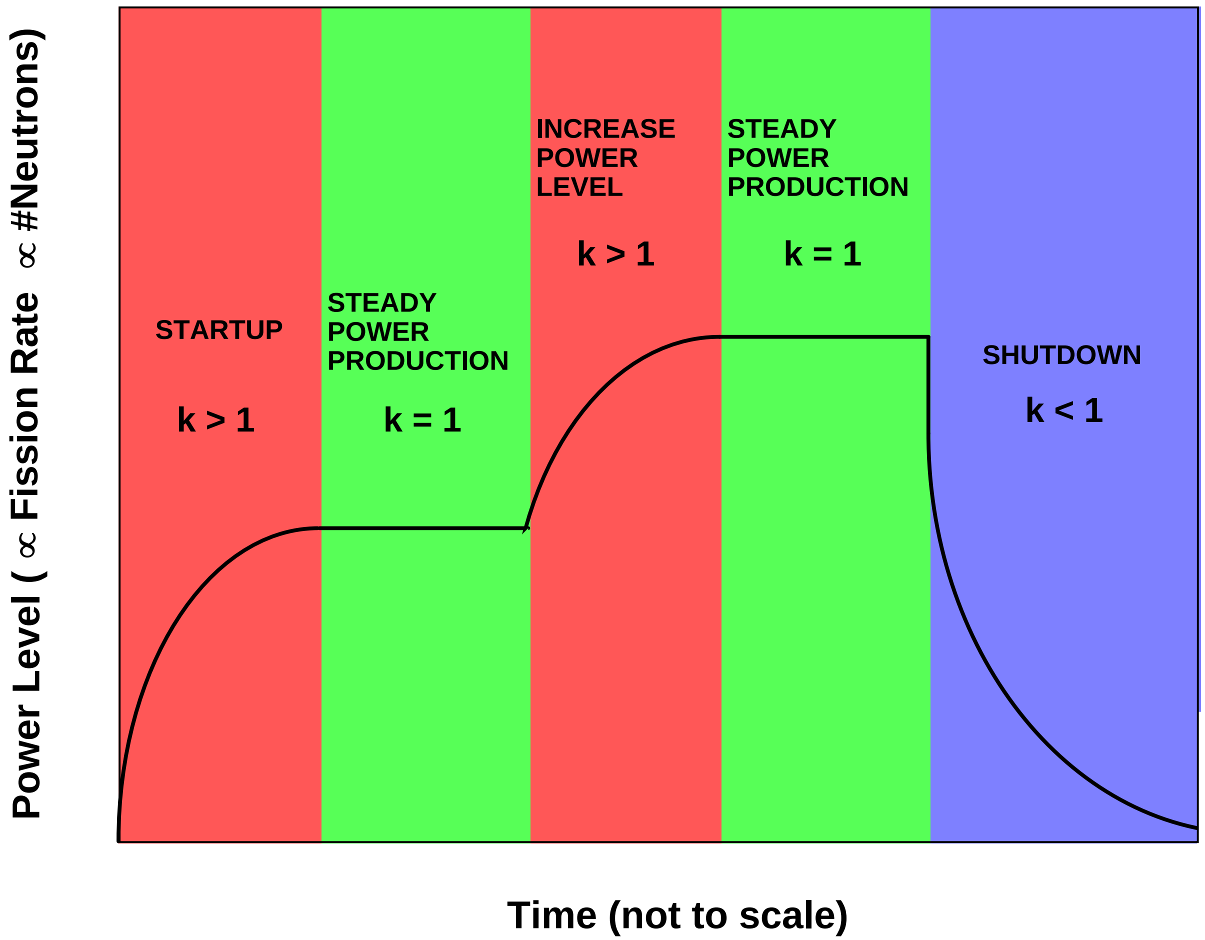
Typical Space Fission System Operation



0.5 m

- 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

Control of Reactor Conditions

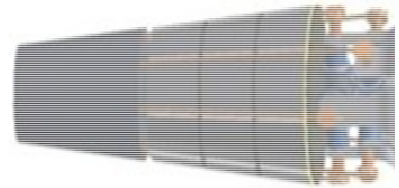


$$k \equiv \text{Multiplication Factor}$$

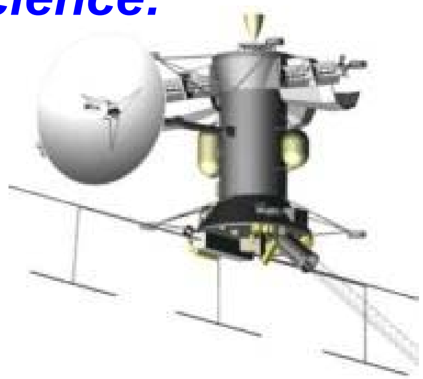
$$= \frac{\text{Production Rate}}{\text{Loss Rate}} = \frac{N(t+l_n)}{N(t)}$$

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

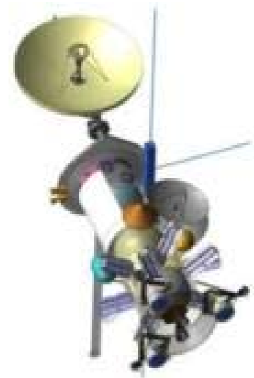
Safe, Compact, Near-Term Fission Power Systems Could Help Enable Higher Power Fission Propulsion Systems



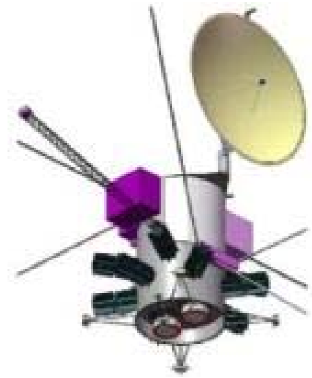
Science:



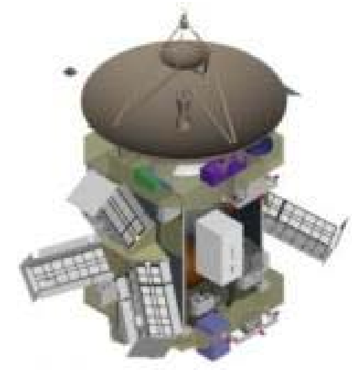
Jupiter Europa Orbiter
~600 We (5 to 6 RPS)



Neptune Systems Explorer
~3 kWe (9 Large RPS)



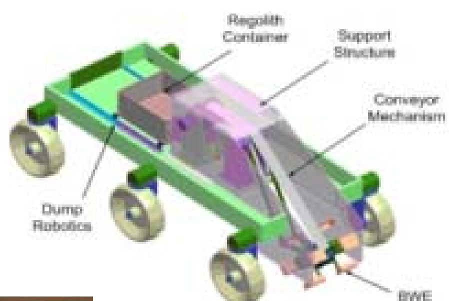
Kuiper Belt Object Orbiter
~4 kWe (9 Large RPS)



Trojan Tour
~800 We (6 RPS)

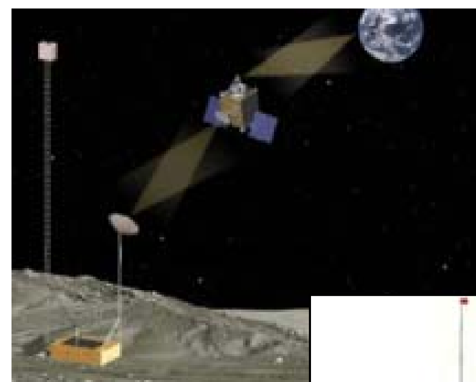
Exploration:

Teleoperated Rovers



Site Survey Landers

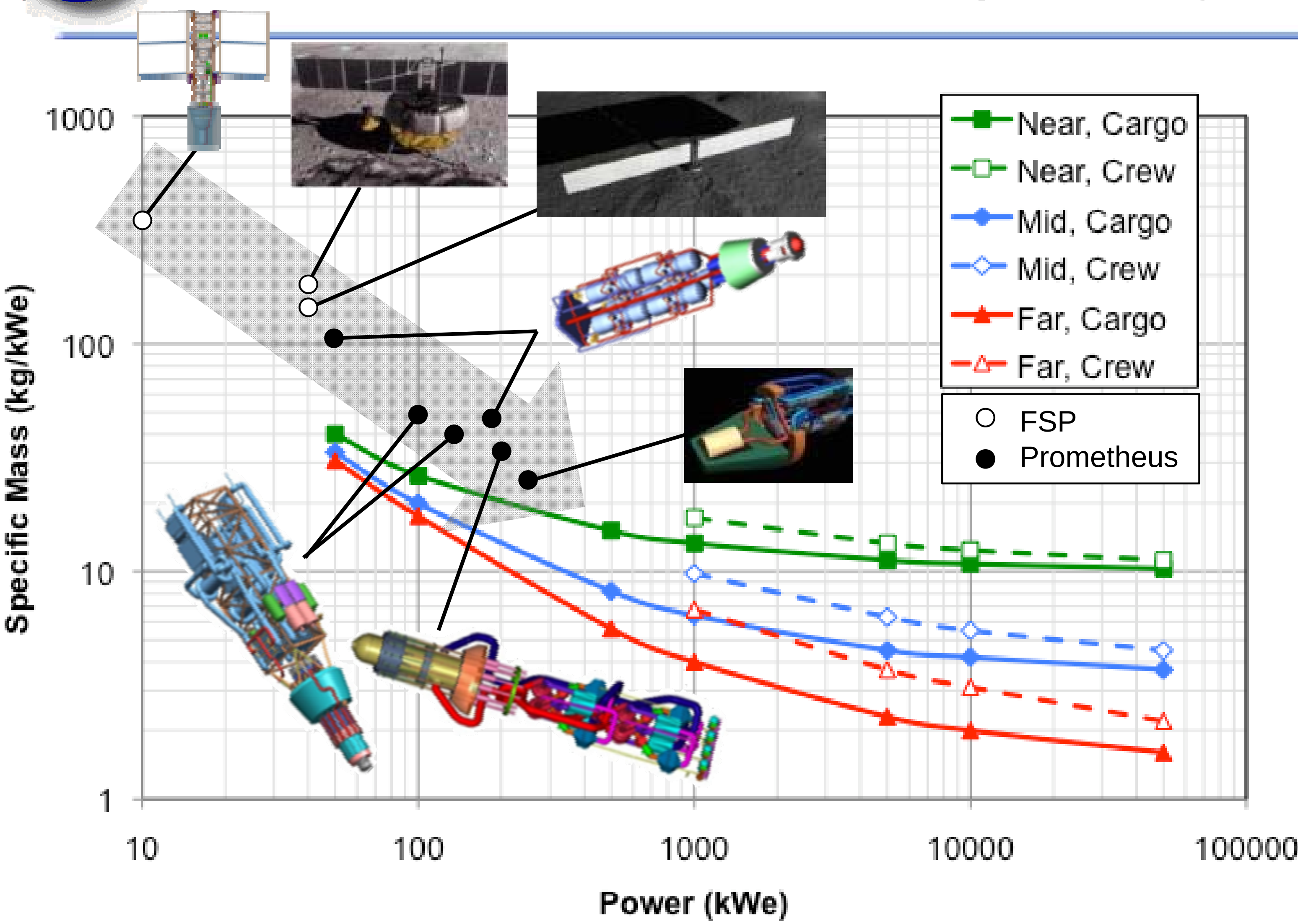
ISRU Demo Plants



Comm Relay Stations

Remote Science Packages

Fission Can Provide the Energy for Either Nuclear Thermal or Nuclear Electric Propulsion Systems

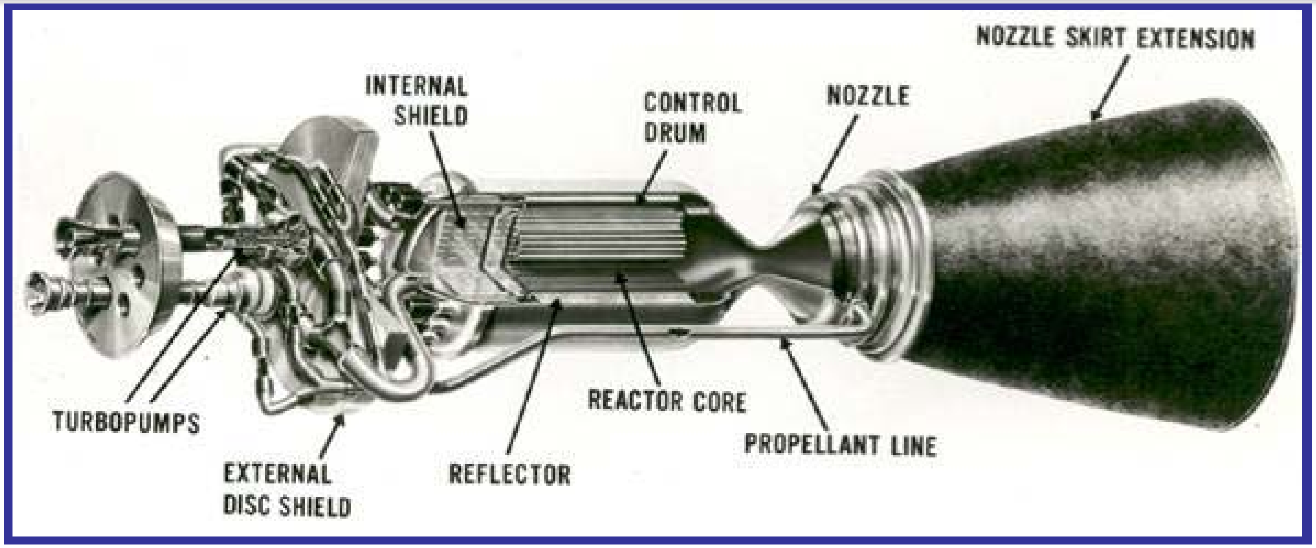


- NEP Power System Performance Projections from 2001 STAIF Conference
- Fission Surface Power and Prometheus Concepts Superimposed

Near=Liq Metal Rx, Brayton, 1300K, 6 kg/m2, 200 Vac (Available ~10 yrs)
Mid=Liq Metal Rx, Brayton, 1500K, 3 kg/m2, 1000 Vac (Available ~ 15-20 yrs)
Far=Liq Metal Rx, Brayton, 2000K, 1.5 kg/m2, 5000 Vac (Available ~ 25-30 yrs)
Cargo=Instrument rated shielding, 1.6x10^15 nvt, 1.2x10^8 rad @ 2 m
Crew=Human rated shielding, 5 rem/yr @ 100 m, 7.5° half angle

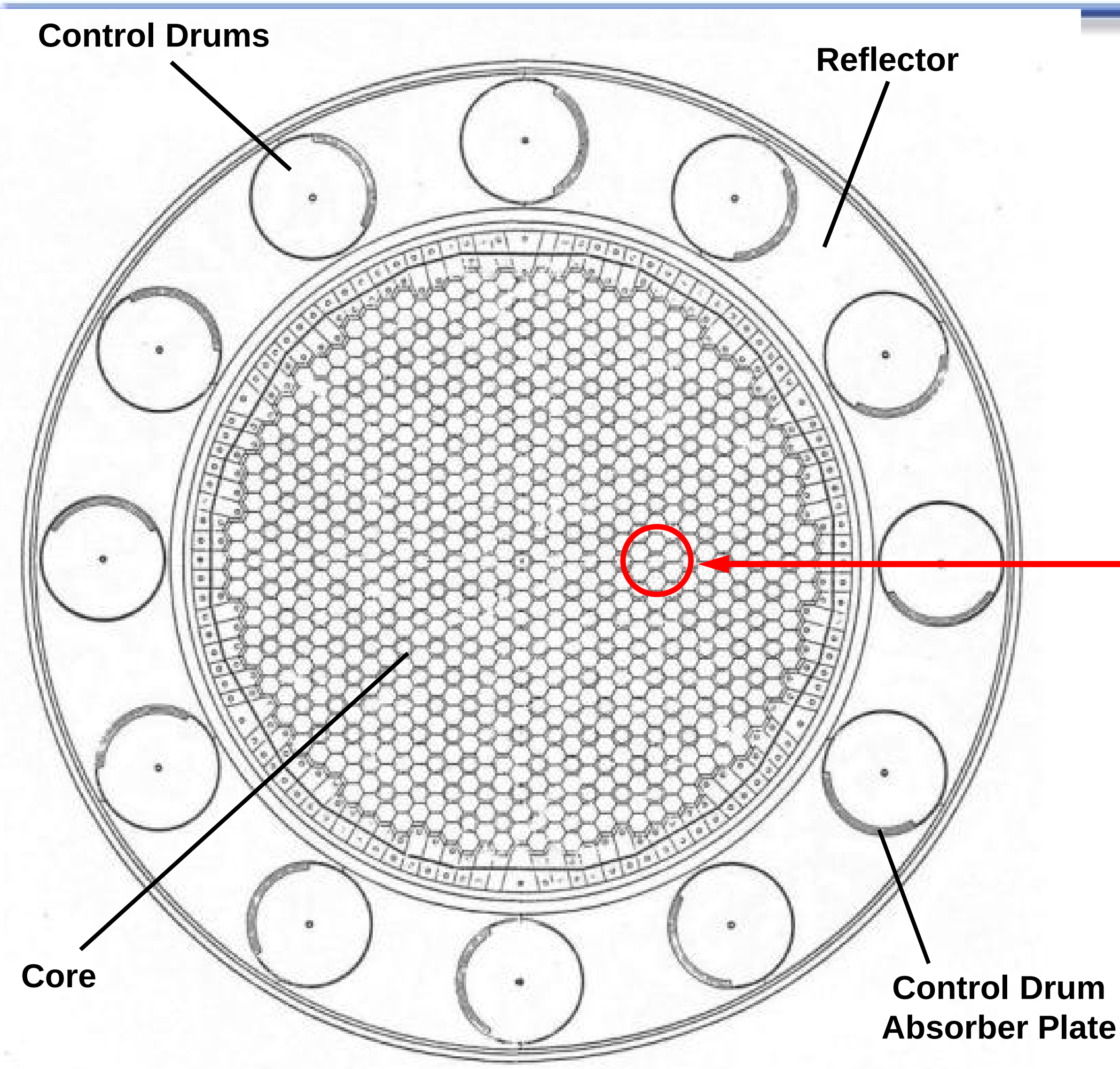
Chart courtesy Lee Mason, NASA GRC

NASA is Currently Funding an "Advanced Exploration Systems" Project Investigating Nuclear Thermal Propulsion (NTP)

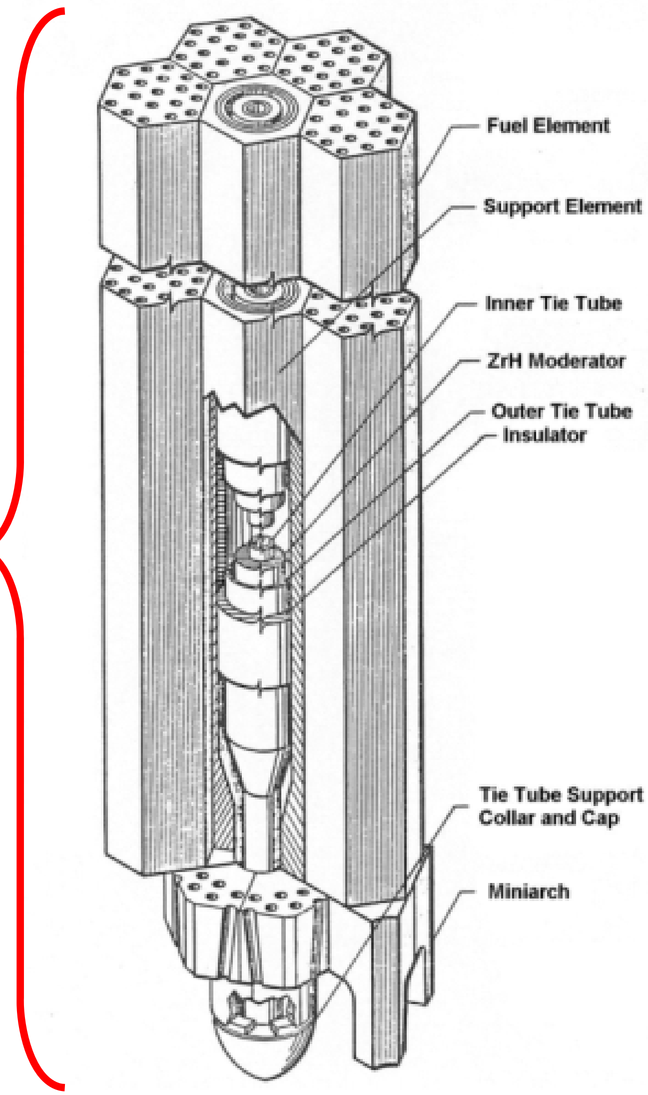


- Nuclear thermal propulsion (NTP) is a fundamentally new capability
  - Energy comes from fission, not chemical reactions
  - Virtually unlimited energy density
- Initial systems will have specific impulses roughly twice that of the best chemical systems
  - Reduced propellant (launch) requirements, reduced trip time
  - Beneficial to near-term/far-term missions currently under consideration
- Advanced nuclear propulsion systems could have extremely high performance and unique capabilities
- A first generation NTP system could serve as the "DC-3" of space nuclear power and propulsion

Current Designs Build on Previous NTP Engine Designs / Tests

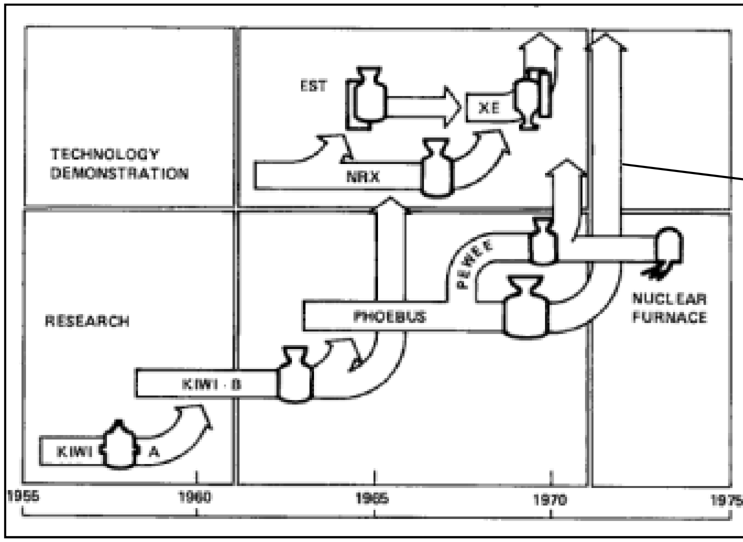


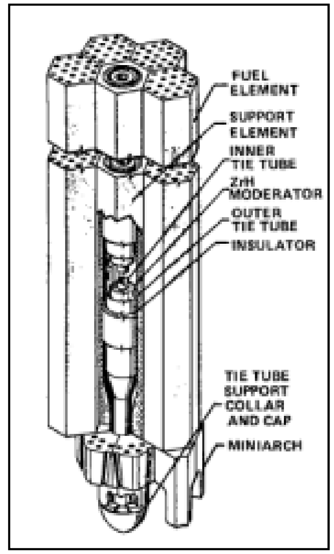
NERVA Reactor Cross Section

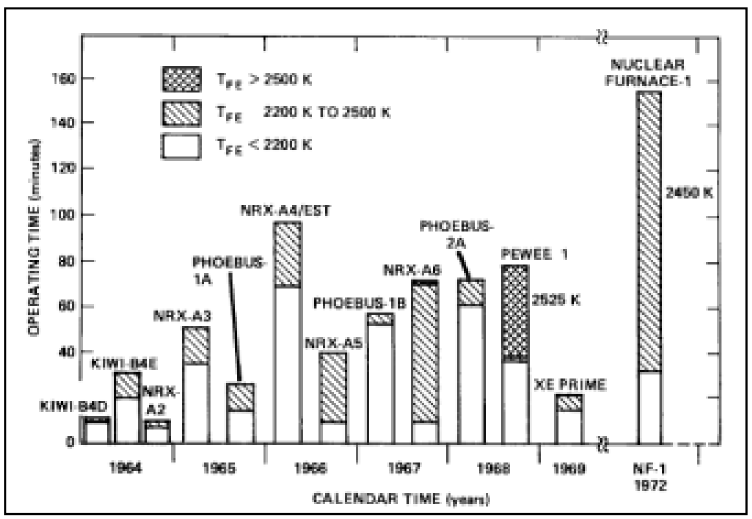


Fuel Segment Cluster

Leverage the highly successful Rover/NERVA program (1955-1973) and more recent programs



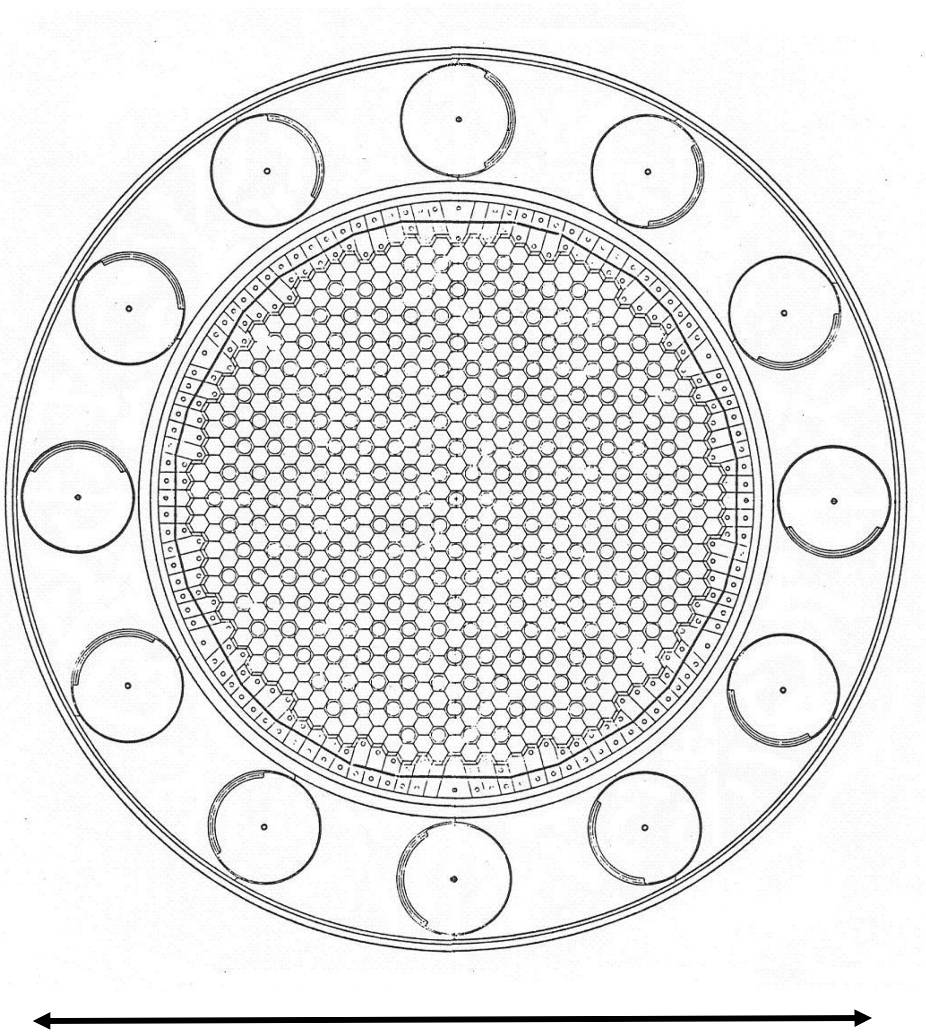




PHOEBUS NUCLEAR ROCKET ENGINE

The most powerful nuclear rocket engine ever tested (Phoebus 2a) is shown during a high-power test. The reactor operated for about 32 minutes, 12 minutes at power levels of more than 4.0 million kilowatts.

Typical Space Fission System Operation



~1.0 m

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

- 45 grams per 1000 MW-hr

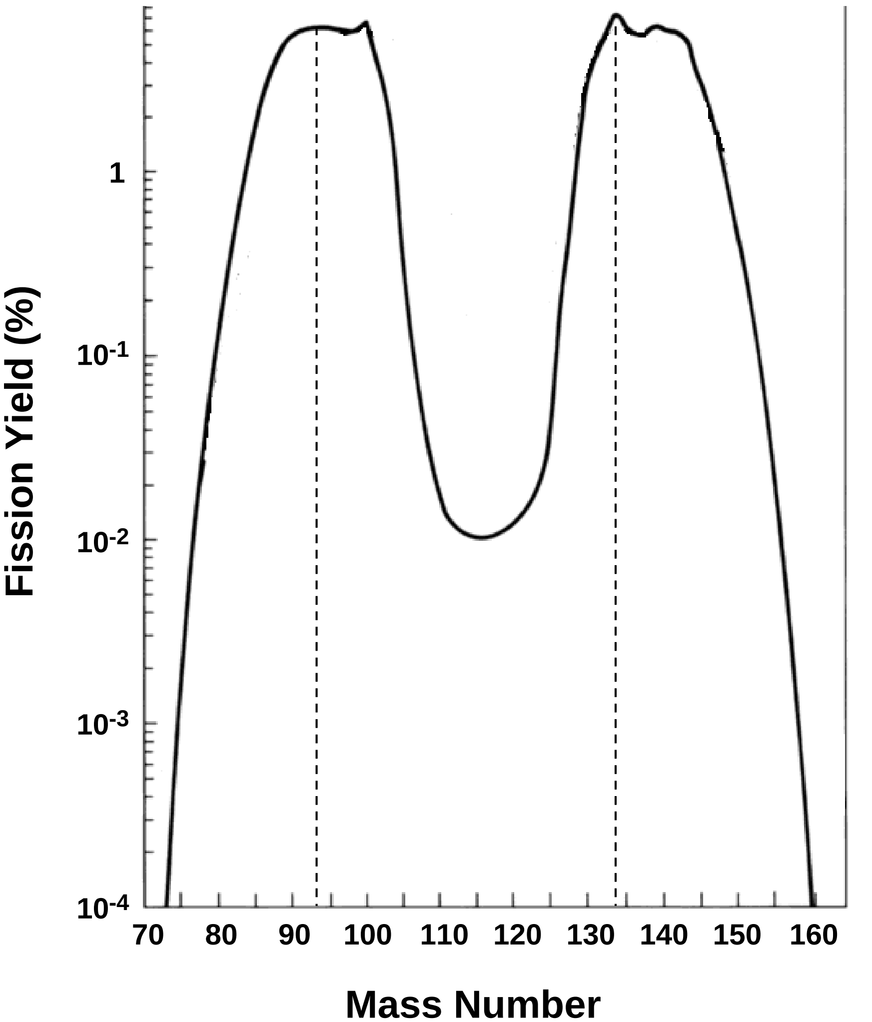
Fission Products

- 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:

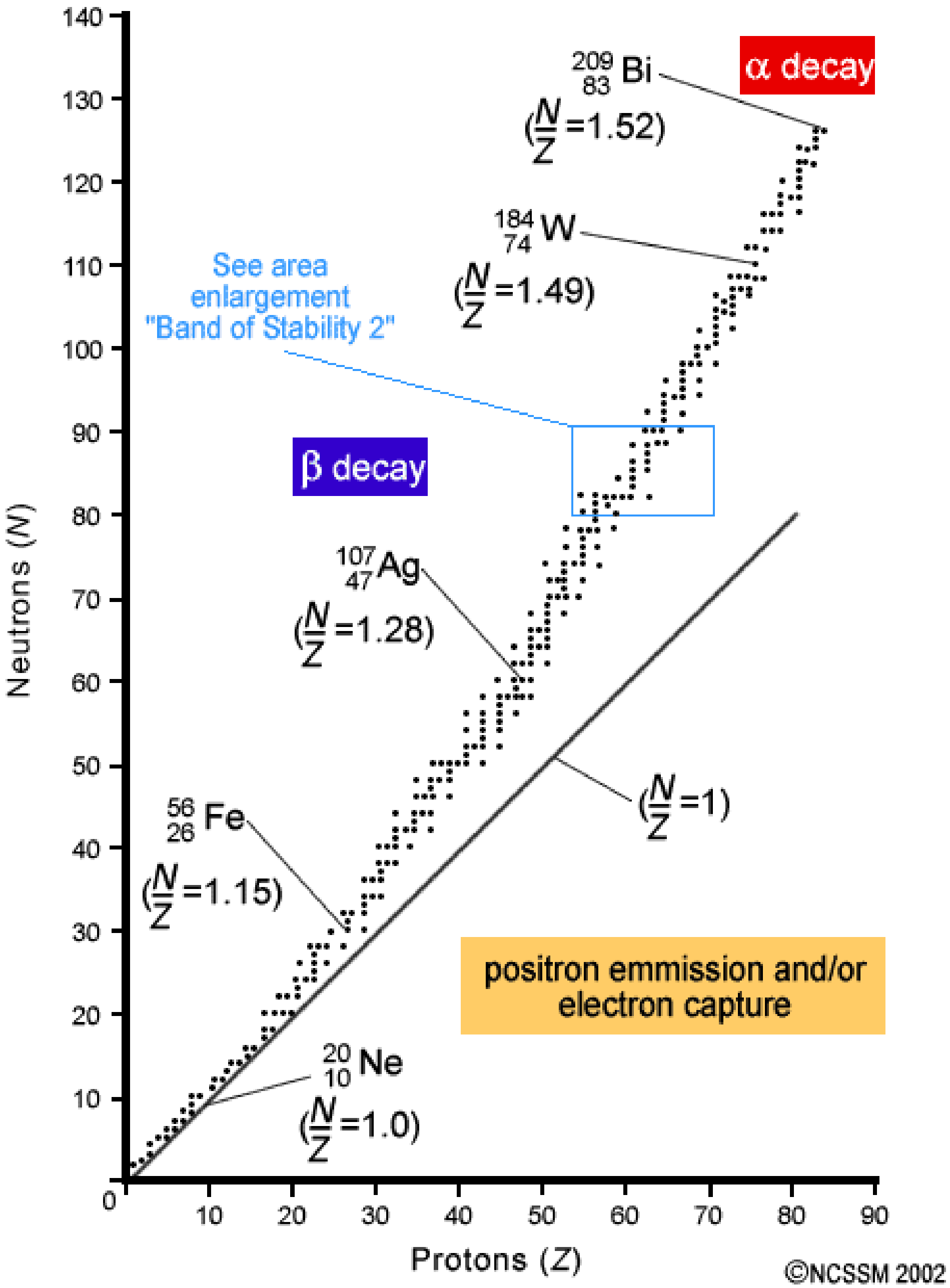
  —Strontium-90 (28.8-year half-life)

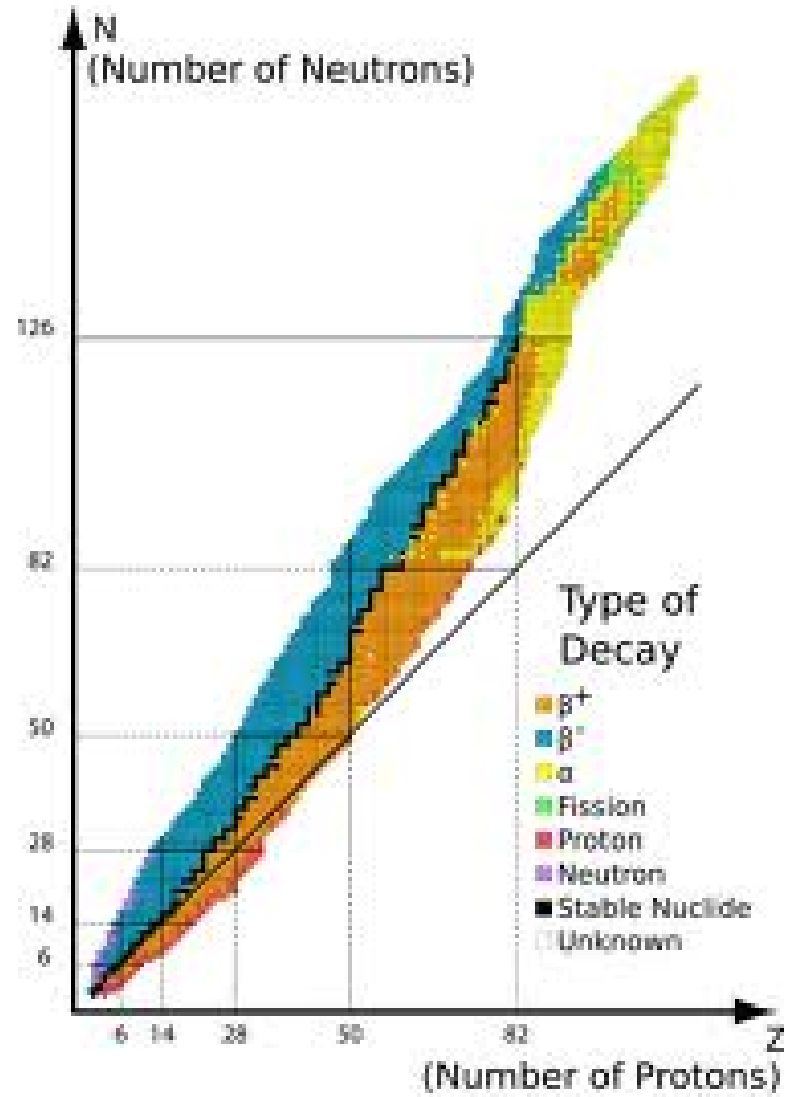
  —Cesium-137 (30.1-year half-life)
- Isotope amounts decrease by factor of 1,000 after 10 half-lives and 1,000,000 after 20 half-lives.
- Decay power 6.2% at t=0 (plus fission from delayed neutrons), 1.3% at 1 hour, 0.1% at 2 months (following 5 years operation).

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



Fission Products





Gamma Radiation Shielding

$I/I_o = (B)e^{-\mu/\rho(x\rho)}$

I = intensity

I_o = initial intensity

B = Buildup Factor

e = 2.71828

μ = linear attenuation coefficient

ρ = density

μ/ρ = mass attenuation coefficient

X = shield thickness

http://physics.nist.gov/PhysRefData/XrayMassCoef/tab3.html

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.

Neutron Radiation Shielding

Use hydrogenous material to slow neutrons.

Optimal Design – Avoid Capture Gammas, Gammas From Inelastic Scatter

^{6}Li and ^{10}B capture neutrons with no significant gamma radiation released.

Water is a great neutron shield, borated water a little better still!

Neutron Cross Sections

Measure of the probability of a particular neutron-nucleus interaction.

Property of the nucleus and the energy of the incident neutron.

Symbolized "σ", common unit is "barn" = 1.0×10^{-28} m^2

Neutron Flux = nv = Φ

n = neutrons / m3

v = neutron speed (m/s)

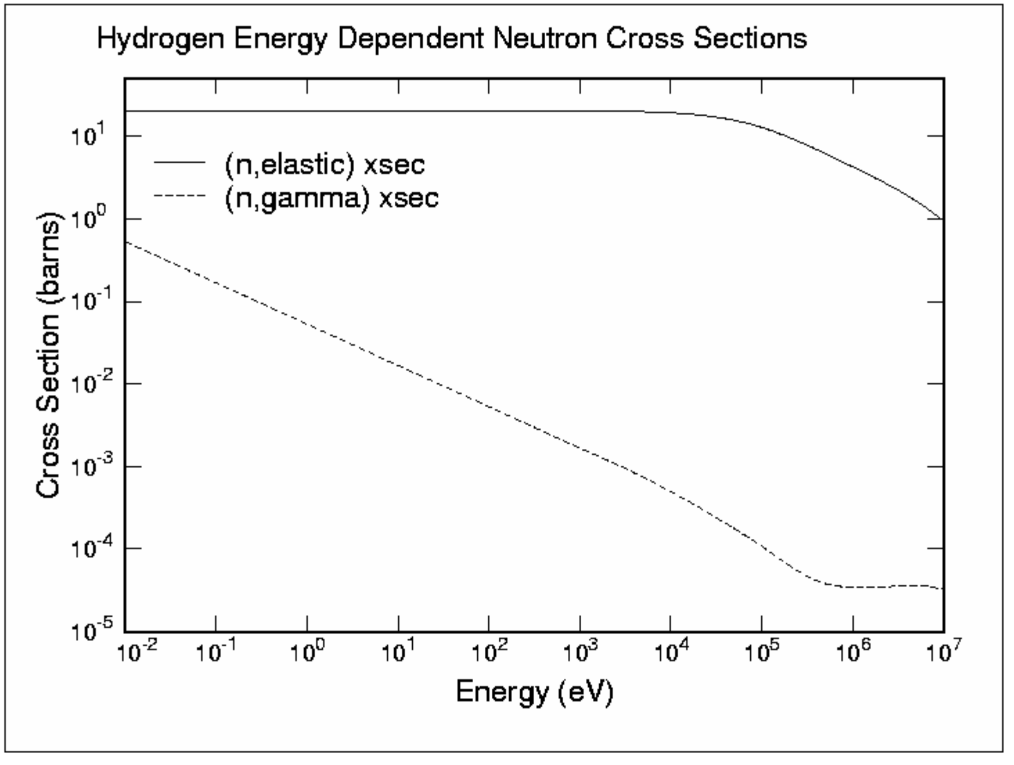
Reaction rate = Φ N σ

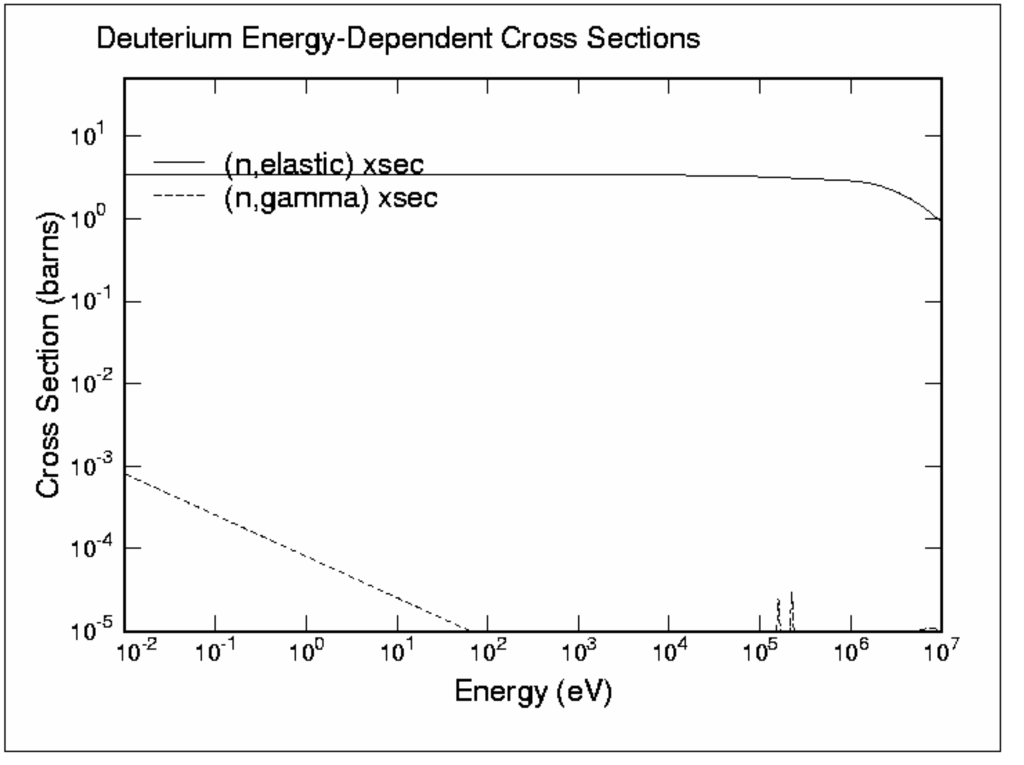
N = nuclei / m^3

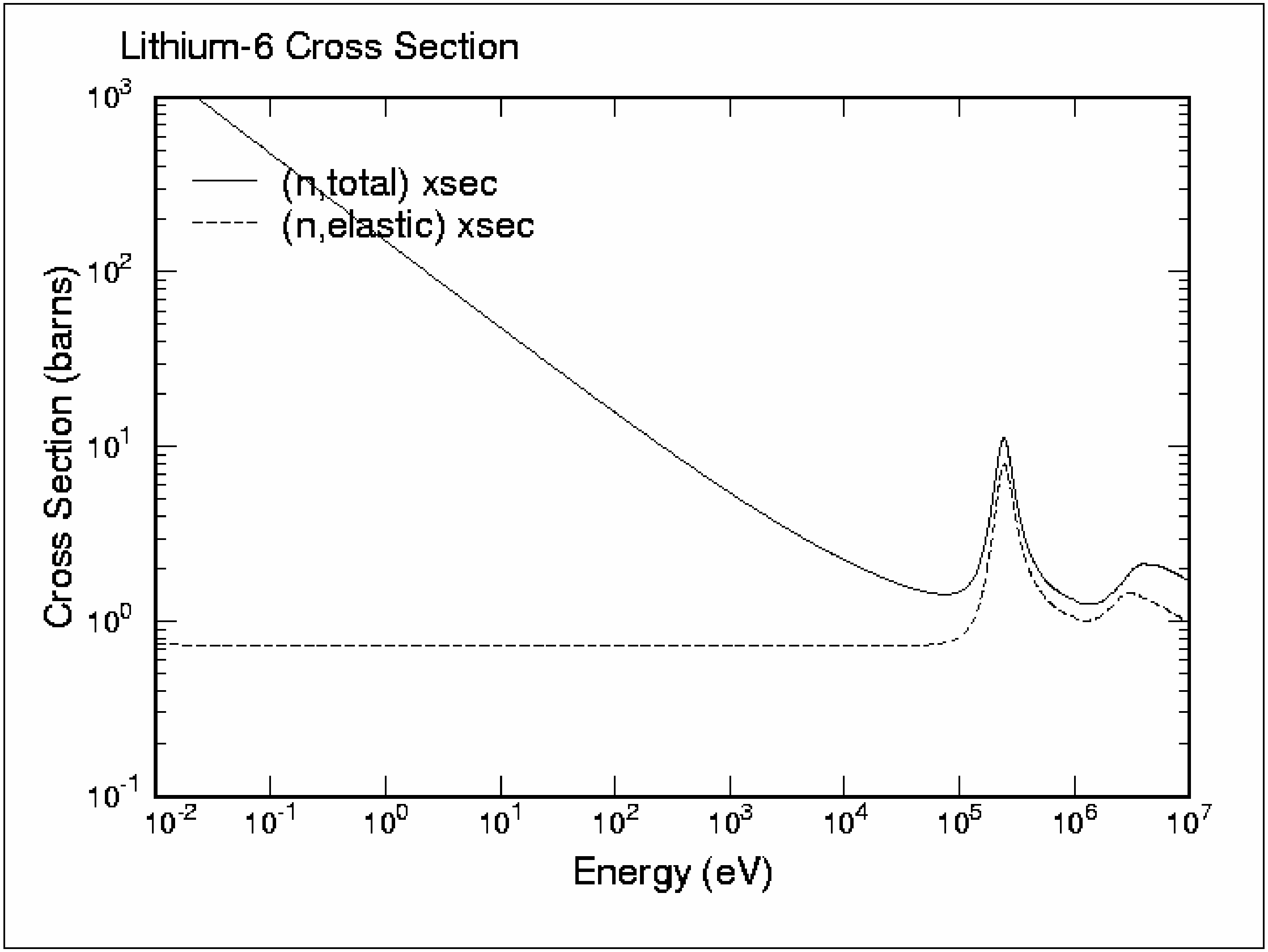
Φ = neutron flux (neutrons / m^2-s)

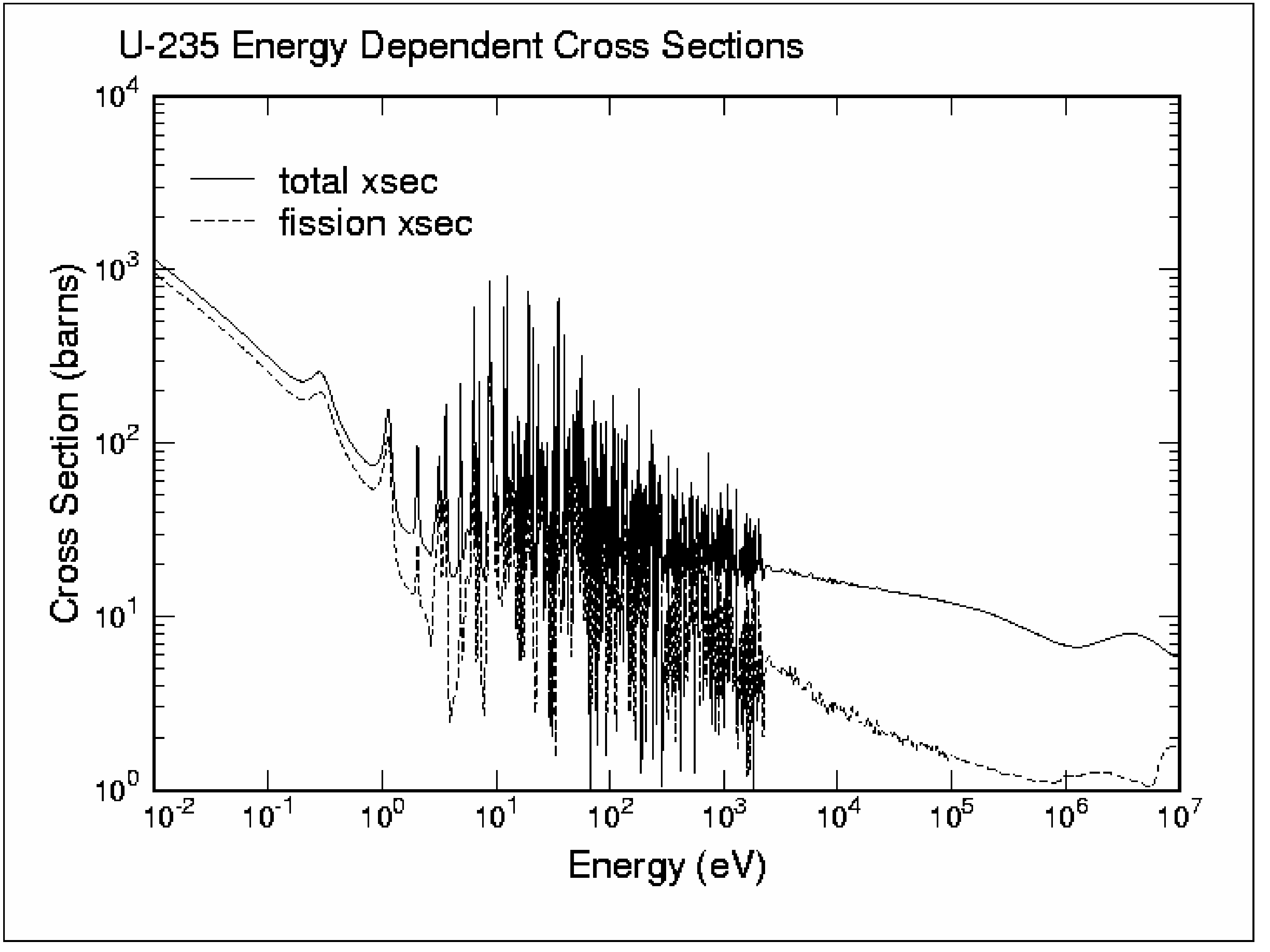
σ = cross section (m^2)

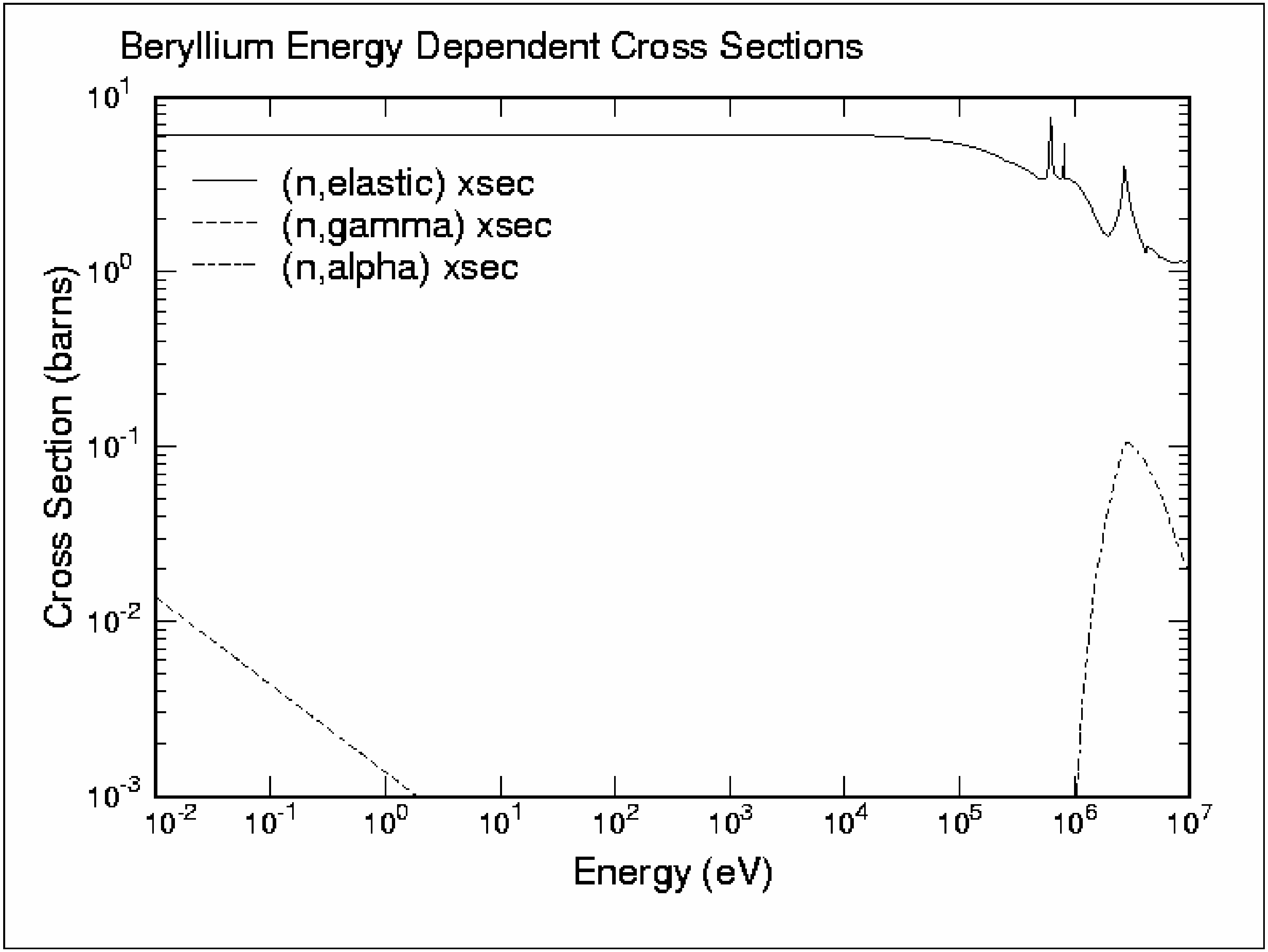
Comparison of Hydrogen and Deuterium Cross Sections






Lithium-6 Cross Section
(n,total) xsec
(n,elastic) xsec
Cross Section (barns)
Energy (eV)
10^3
10^2
10^1
10^0
10^-1
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

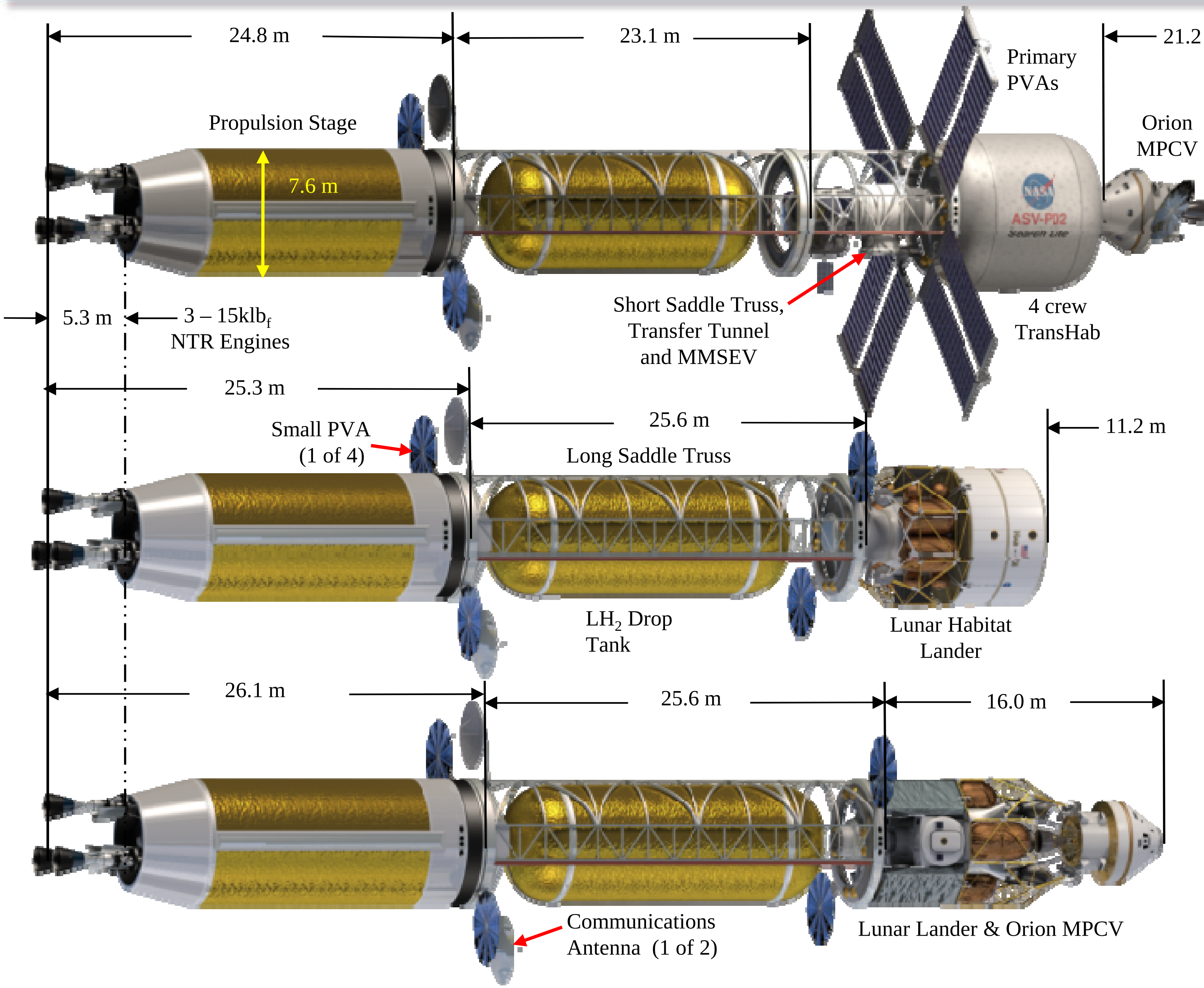

U-235 Energy Dependent Cross Sections
total xsec
fission xsec
Cross Section (barns)
Energy (eV)
10^4
10^3
10^2
10^1
10^0
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7



Beryllium Energy Dependent Cross Sections
(n,elastic) xsec
(n,gamma) xsec
(n,alpha) xsec
Cross Section (barns)
Energy (eV)
10^1
10^0
10^-1
10^-2
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7

NTR Transfer Vehicles for Reusable NEA, Lunar Cargo and Crewed Landing Missions using ~70 t-class SLS

(Courtesy Stan Borowski, NASA GRC)

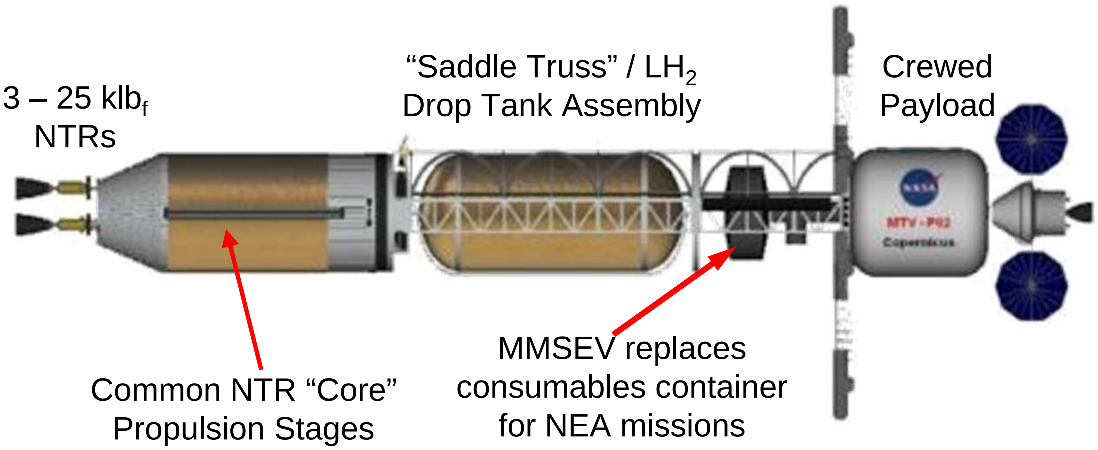


ASV 2000 SG344:
- 4 crew
- 3 – 15 klb$_f$ NTRs
- 7.6 m LH_2 tanks
- IMLEO ~178.7 t
- Max Lift ~67 t

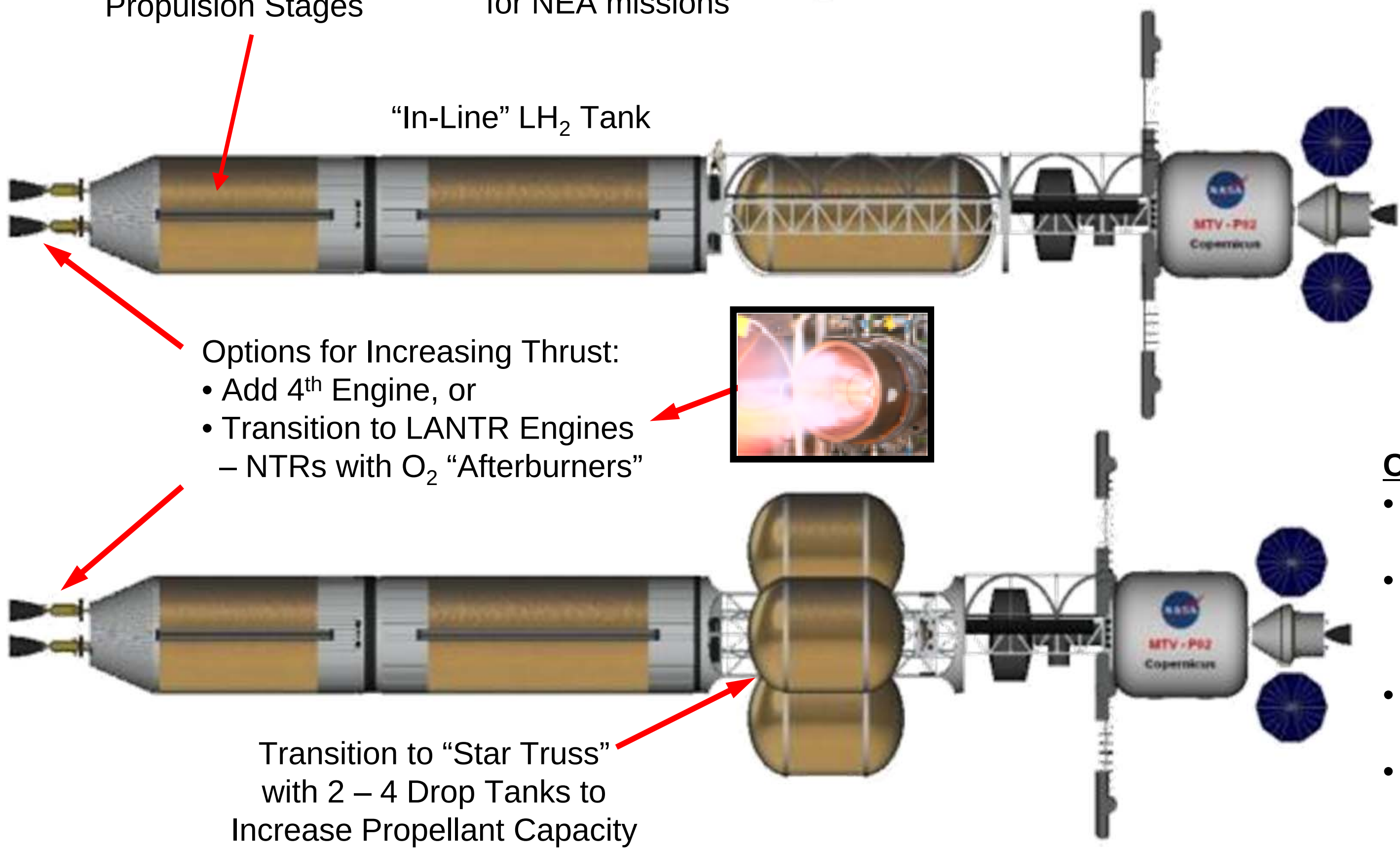
Lunar Cargo:
- 57 t Habitat Lander
- 3 – 15 klb$_f$ NTRs
- 7.6 m LH_2 tanks
- IMLEO ~198 t
- Max Lift ~69.3 t

Lunar Landing:
- 4 crew
- 34.5 t Lunar Lander
- 3 – 15 klb$_f$ NTRs
- 7.6 m LH_2 tanks
- IMLEO ~197.5 t
- Max Lift ~72.8 t

Growth Paths Identified using Modular Components to Increase Vehicle LH_2 Capacity & Mission Applications
(Courtesy Stan Borowski, NASA GRC)



Configuration 1 Applications:
- Fast Conjunction Mars Landing Missions – Expendable
- "1-yr" Round Trip to Large NEAs 1991 JW (2027) and Apophis (2028) – Reusable
- Propulsion Stage & Saddle Truss / Drop Tank Assembly can also be used as:
  - Earth Return Vehicle (ERV) / propellant tanker in "Split Mars Mission" Mode – Expendable
  - Cargo Transfer Vehicle supporting a Lunar Base – Reusable

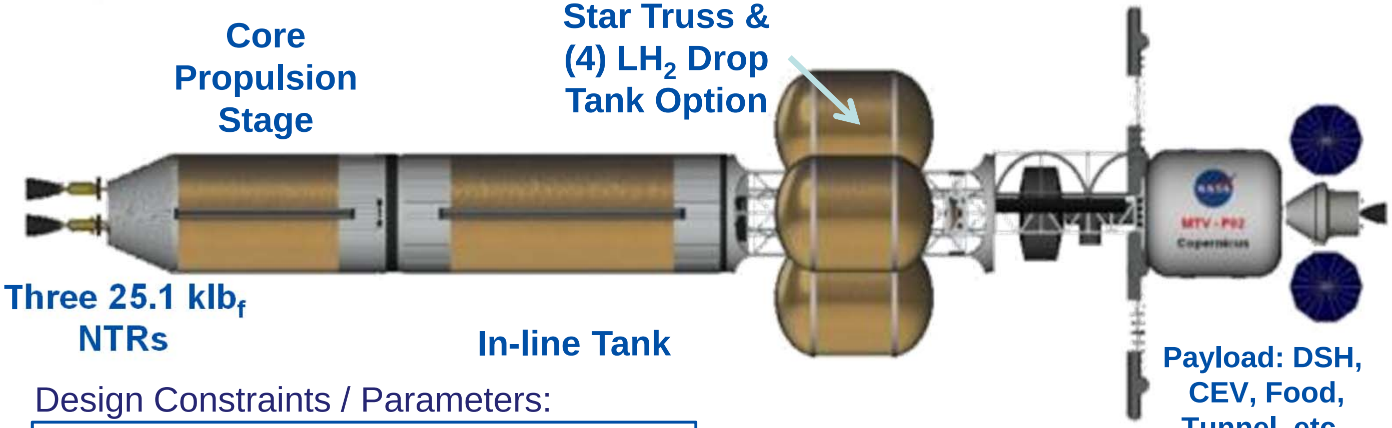


Configuration 2 Applications:
- Fast Conjunction Mars Landing Missions – Reusable
- 2033 Mars Orbital Mission 545 Day Round Trip Time with 60 Days at Mars – Expendable
- Cargo & Crew Delivery to Lunar Base – Reusable

Configuration 3 Applications:
- Fast Conjunction Mars Landing Missions – Reusable or Expendable
- 2033 Mars Orbital Mission 545 Day Round Trip Time with 60 Days at Mars – Reusable
- Some LEO Assembly Required
  – Attachment of Drop Tanks
- Additional HLV Launches

Notional NCPS Mission -- 2033 600 day Mars Piloted Stack
Core Stage, In-line Tank, & Star Truss w/ (2) LH_2 Drop Tanks

(Courtesy Stan Borowski, NASA GRC)



Design Constraints / Parameters:

• # Engines / Type:	3 / NERVA-derived
• Engine Thrust:	25.1 klbf (Pewee-class)
• Propellant:	LH2
• Specific Impulse, Isp:	900 sec
• Cooldown LH2:	3%
• Tank Material:	Aluminum-Lithium
• Tank Ullage:	3%
• Tank Trap Residuals:	2%
• Truss Material:	Graphite Epoxy Composite
• RCS Propellants:	NTO / MMH
• # RCS Thruster Isp:	335 sec (AMBR Isp)
• Passive TPS:	1" SOFI + 60 layer MLI
• Active CFM:	ZBO Brayton Cryo-cooler
• I/F Structure:	Stage / Truss Docking Adaptor w/ Fluid Transfer

Mission Constraints / Parameters:

- 6 Crew
- Outbound time: 183 days (nom.)
- Stay time: 60 days (nom.)
- Return time: 357 days (nom.)
- 1% Performance Margin on all burns
- TMI Gravity Losses: 265 m/s total, f(T/W_0)
- Pre-mission RCS ΔVs: 181 m/s (4 burns/stage)
- RCS MidCrs. Cor. ΔVs: 65 m/s (in & outbnd)
- Jettison Both Drop Tanks After TMI-1
- Jettison Tunnel, Can & Waste Prior to TEI

		Inline	(2) drop	payload	core
	Power Level (kW)	5.25		44.75	7.07
	Tank Diameter (m)	8.90	8.90		8.90
	Tank Length (m)	19.30	13.58		17.10
	Truss length (m)		19	12	
	Liquid LH2	72.18	96.29		62.90
Total	Foodstores			8.01	
6	Crew			0.79	
	Dry weight	17.67	19.30		36.41
	TransHab+Crew Science			34.649	
	Samples			0.25	
	CEV			10.10	
Total	Launch Element Mass (mt)	100.50	121.48	67.93	101.94
	RCS Total Propellant	18.66			
	Total Launched Mass	391.84	mt		

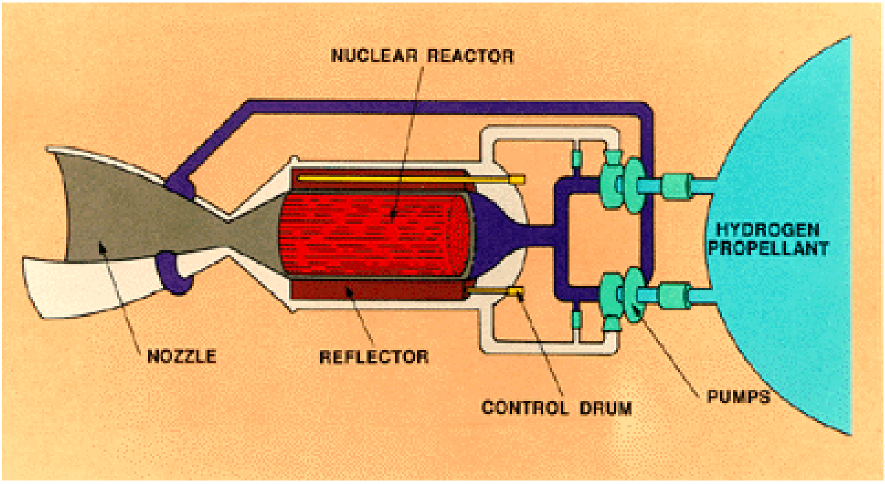
NTP Transfer Vehicle Description:

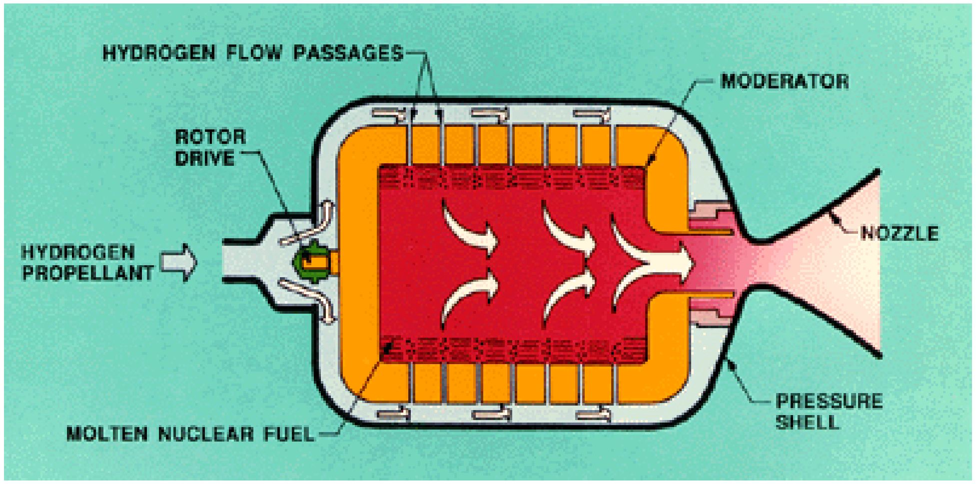
NTP system consists of 3 elements: 1) core propulsion stage, 2) in-line tank, and 3) integrated star truss and dual drop tank assembly that connects the propulsion stack to the crewed payload element for Mars 2033 mission. Each 100t element is delivered on an SLS LV (178.35.01, 10m O.D.x 25.2 m cyl. §) to LEO -50 x 220 nmi, then onboard RCS provides circ burn to 407 km orbit. The core stage uses three NERVA-derived 25.1 klbf engines. It also includes RCS, avionics, power, long-duration CFM hardware (e.g., COLDEST design, ZBO cryo-coolers) and AR&D capability. The star truss uses Gr/Ep composite material & the LH2 drop tanks use a passive TPS. Interface structure includes fluid transfer, electrical, and communications lines.

	ΔV (m/s)	Burn Time (min)
1st perigee TMI + g-loss	2380	39.4
2nd perigee TMI	1445	17.8
MOC	1470	15
TEI	3080	23.5
	8375	95.7

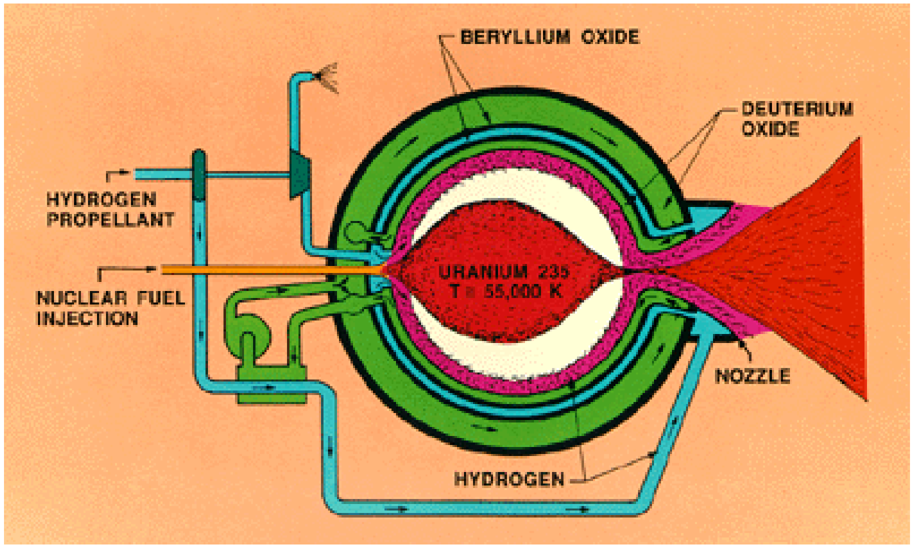
Notional Example of Human Mars Mission

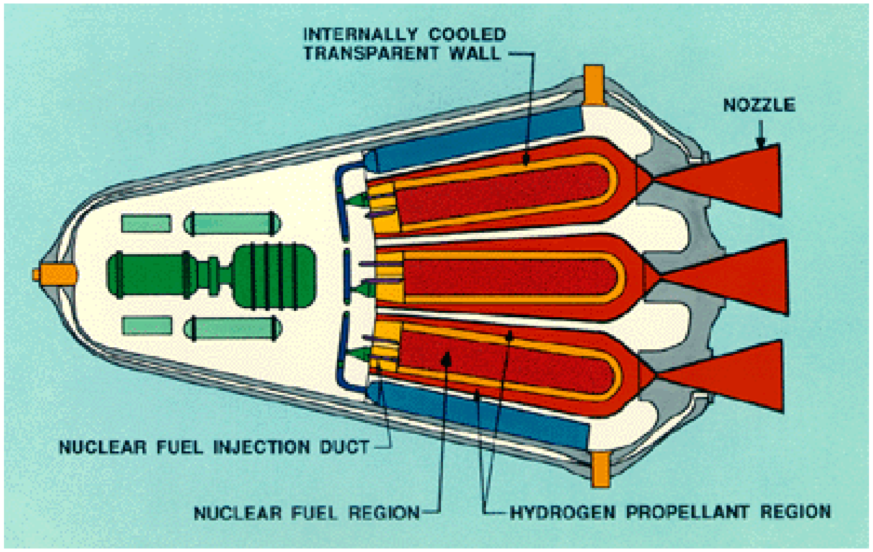
Proposed Types of Nuclear Thermal Propulsion





SOLID CORE NUCLEAR ROCKET





Future Plans / Path Forward

- Space nuclear power and propulsion are game changing technologies for space exploration
- The NASA Nuclear Thermal Propulsion (NTP) project has 1 to 3 years to demonstrate the viability and affordability of NTP
- Participation is encouraged. Please feel free to contact the NTP project with interest or ideas (michael.houts@nasa.gov)