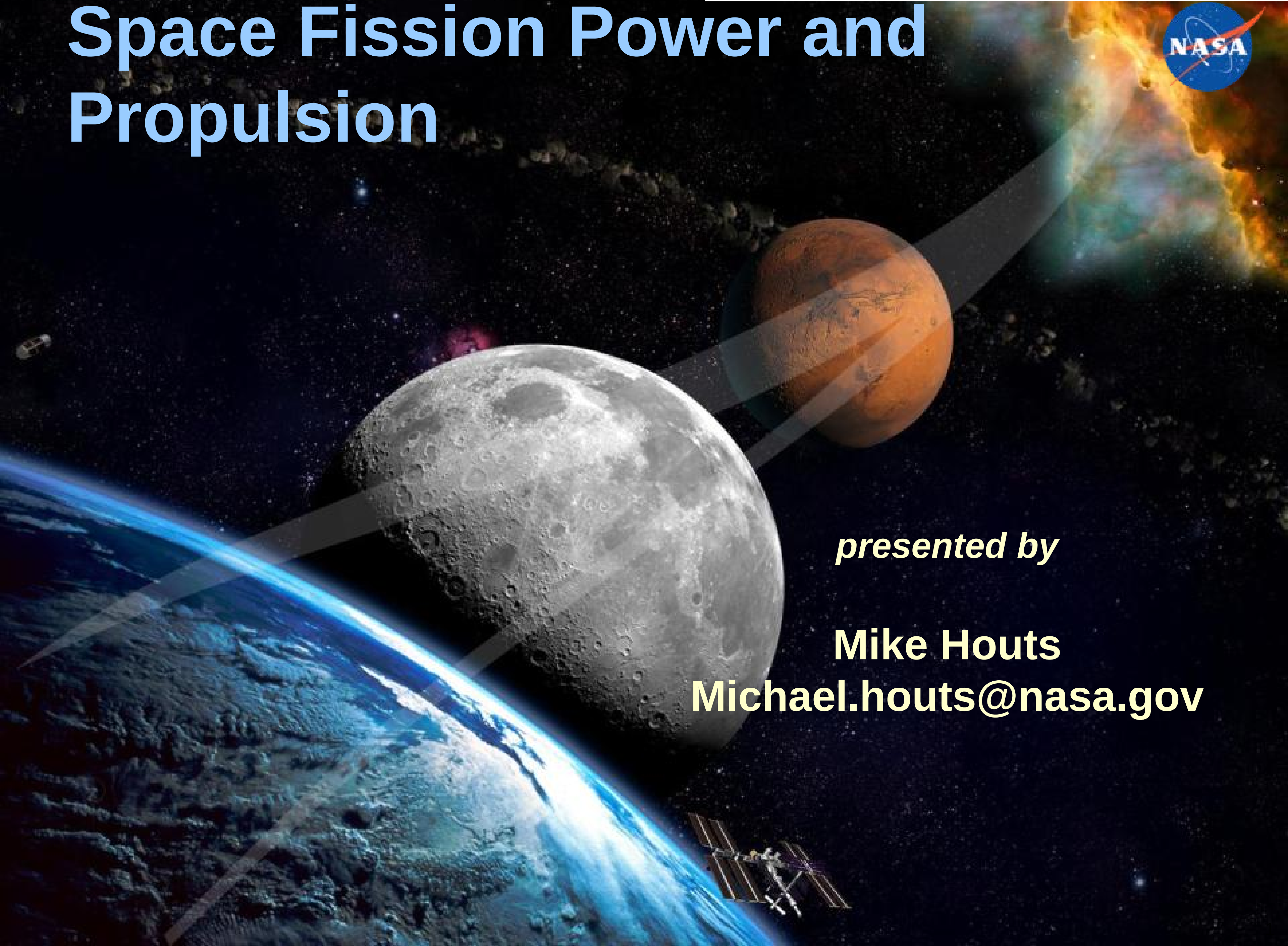
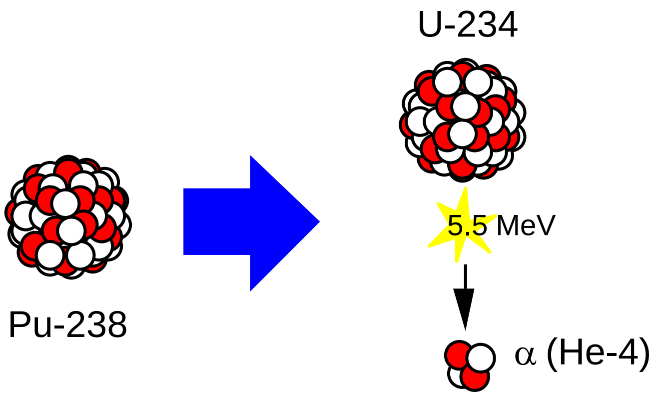
# Space Fission Power and Propulsion



*presented by*

**Mike Houts**
**Michael.houts@nasa.gov**

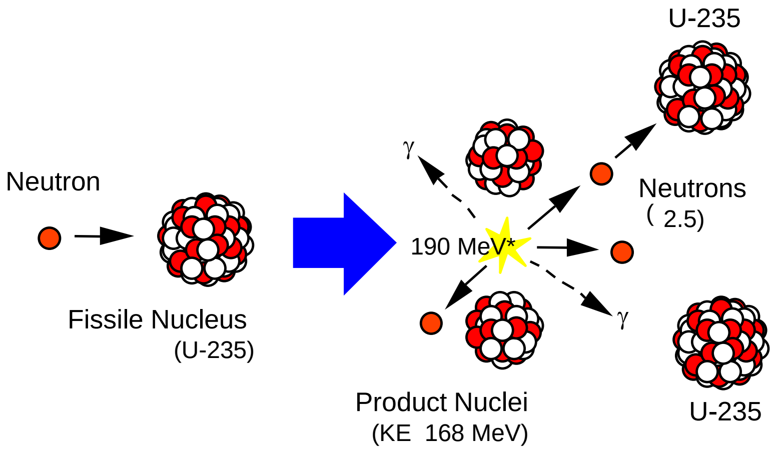
# Basics of Nuclear Systems



*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. since the 1960s
- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
- Used for both thermal management and electricity production

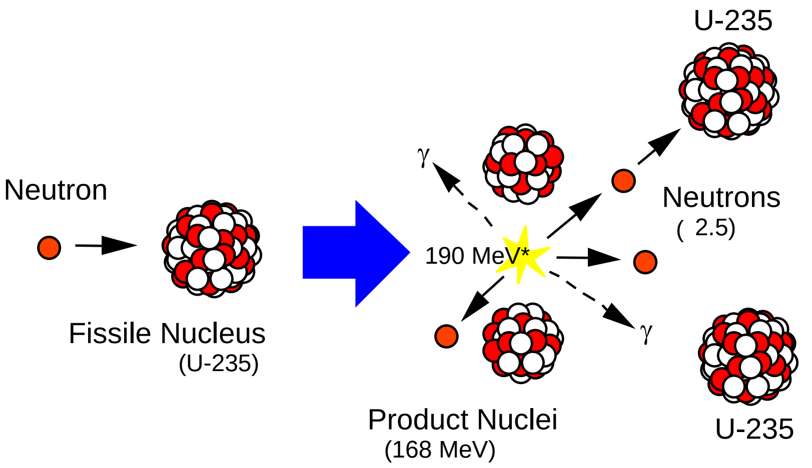


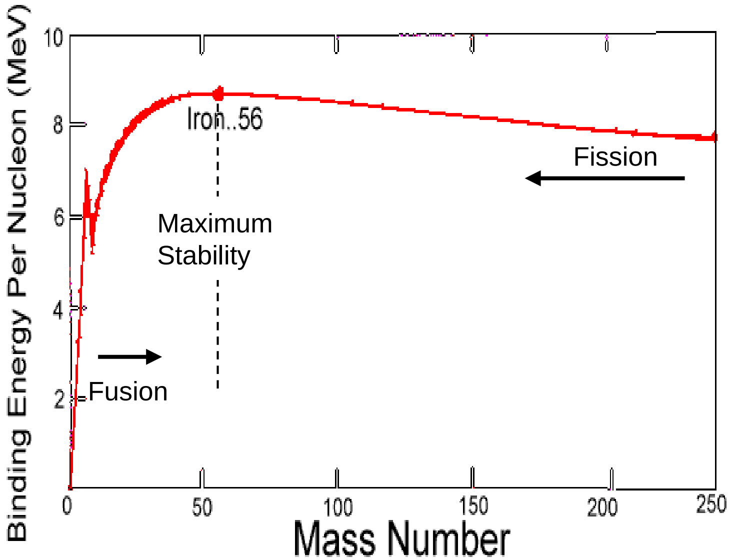
*Heat Energy = 0.851 MeV/nucleon*

*Controllable reaction rate (variable power levels)*

- Used terrestrially for over 70 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

# Nuclear Fission Process





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)

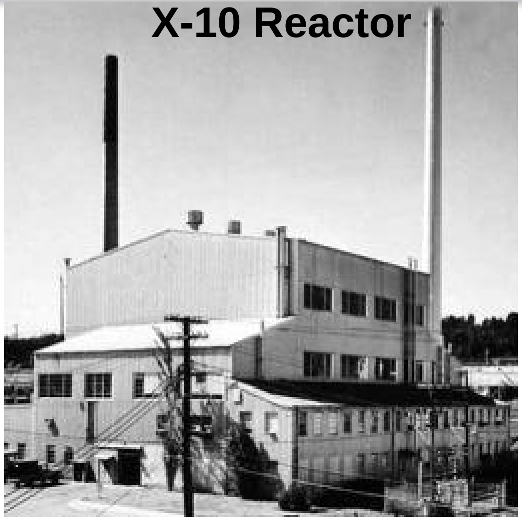
- Neutron absorbed by heavy nucleus, which splits to form products with higher binding energy per nucleon. Difference between initial and final masses = prompt energy released (190 MeV).
  - —*Fissile* isotopes (U-233, U-235 and Pu-239) fission at any neutron energy
  - —Other actinides (U-238) fission 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 from each reaction must cause a subsequent fission in a *chain reaction* process.

# 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***

**X-10 Reactor**



# Fission is Highly Versatile with Many Applications

- Small research reactors
  - Examples include 2000 kWt TRIGA reactor recently installed in Morocco (< $100M)
- 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

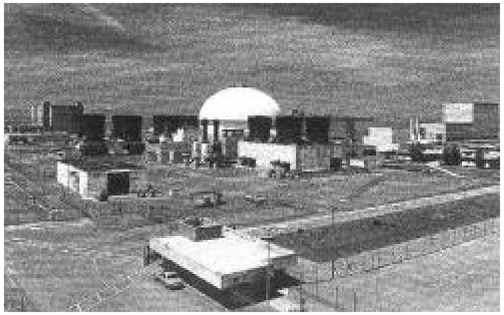
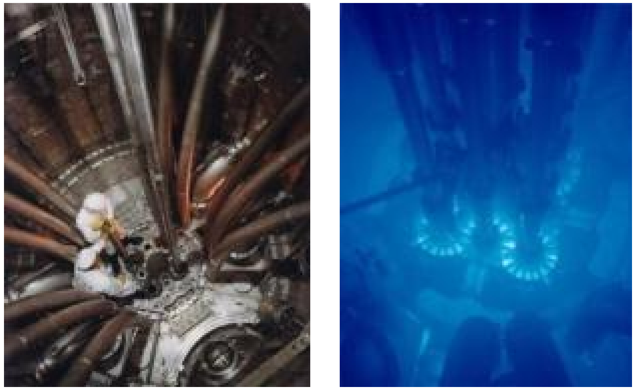


Figure II-92. SNAP 10A Flight System

# Fission is Highly Versatile with Many Applications (continued)

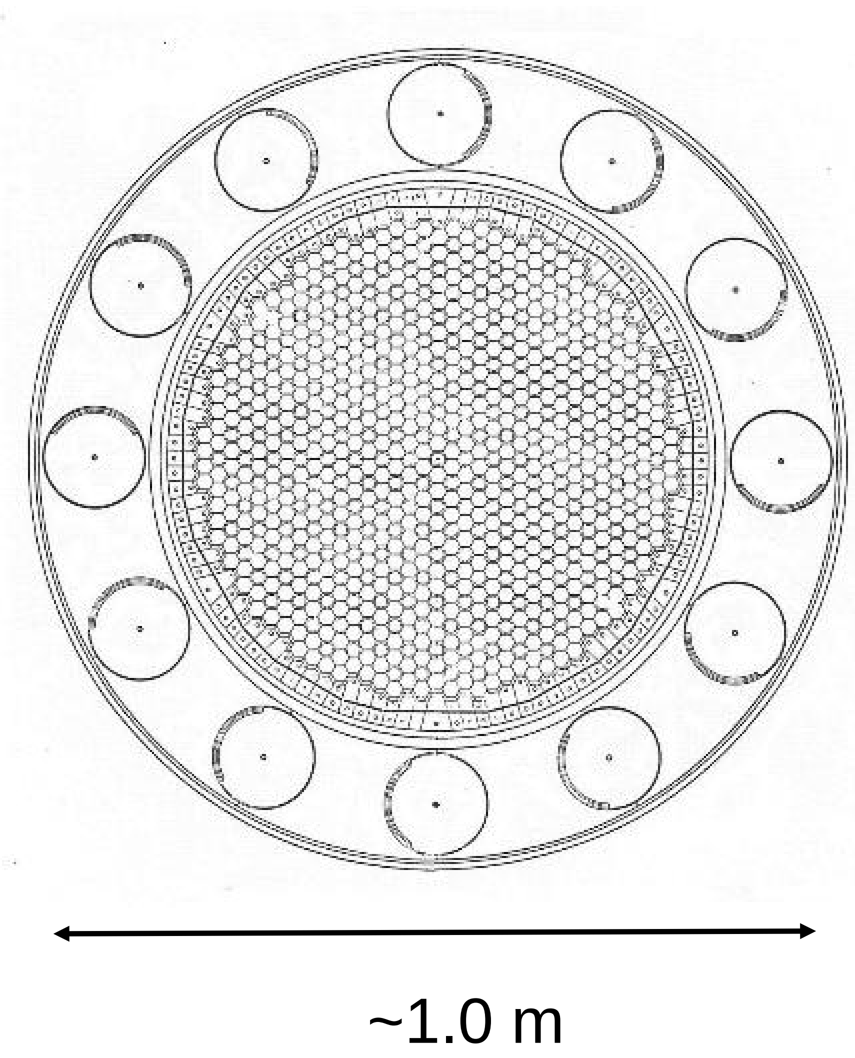
- Naval Reactors
  - Hundreds of submarines and surface ships worldwide
- Production of medical and other isotopes



- 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

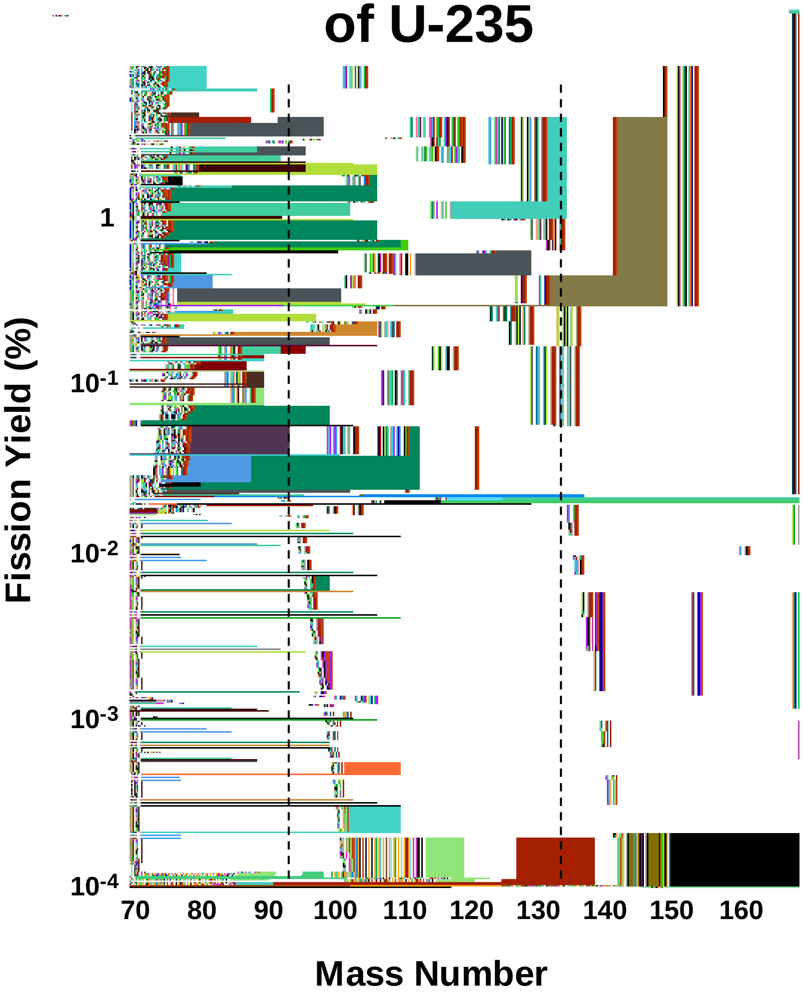


- System power controlled by neutron balance
- Average 2.5 neutrons produced per fission
  - Including delayed
- Constant power if 1.0 of those neutrons goes on to cause another fission
- Decreasing power if < 1.0 neutron causes another fission, increasing if > 1.0
- System controlled by passively and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

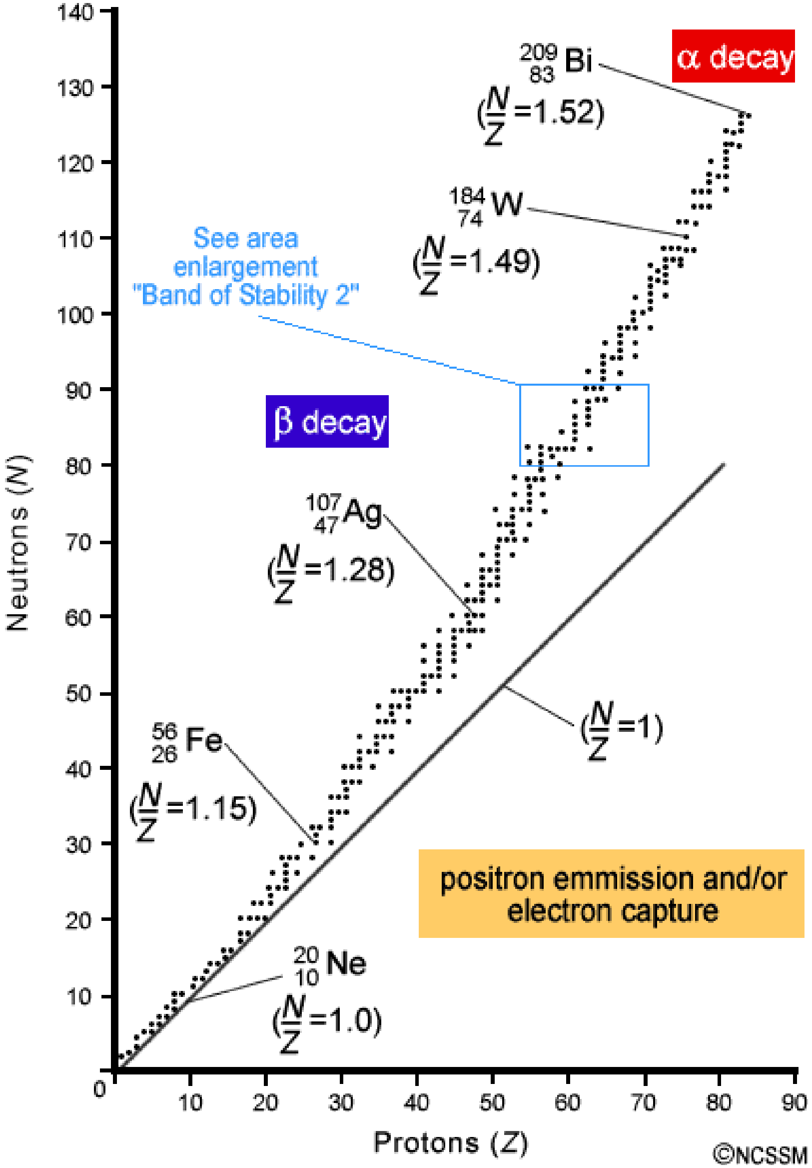
# Fission Products

- 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



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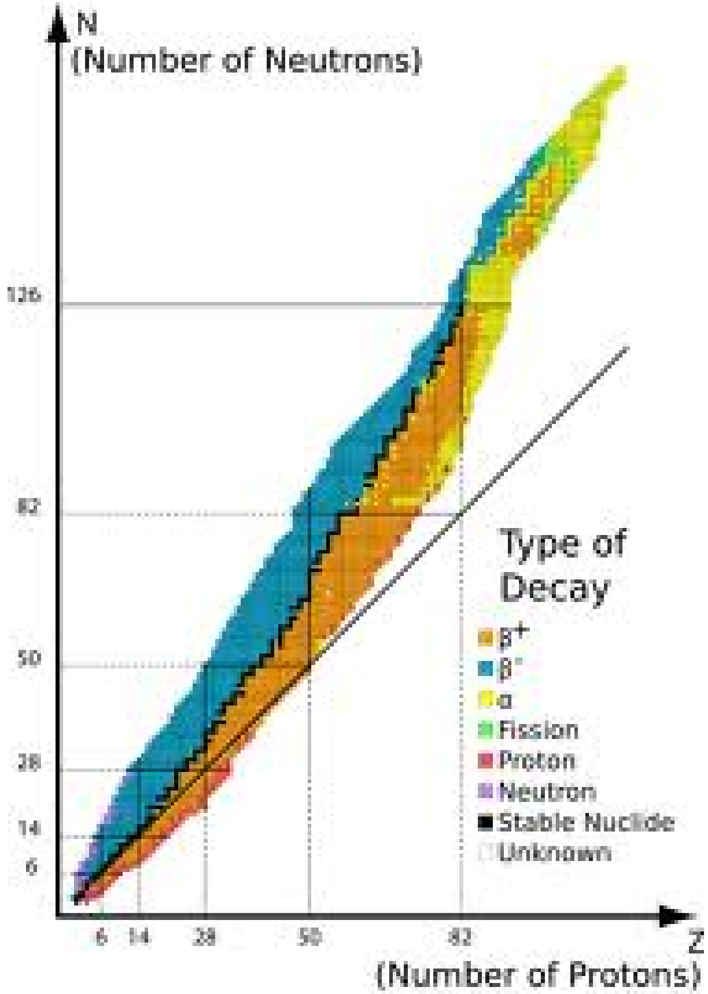


# Gamma Radiation Shielding

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

I = intensity

$I_o$ = initial intensity

B = Buildup Factor

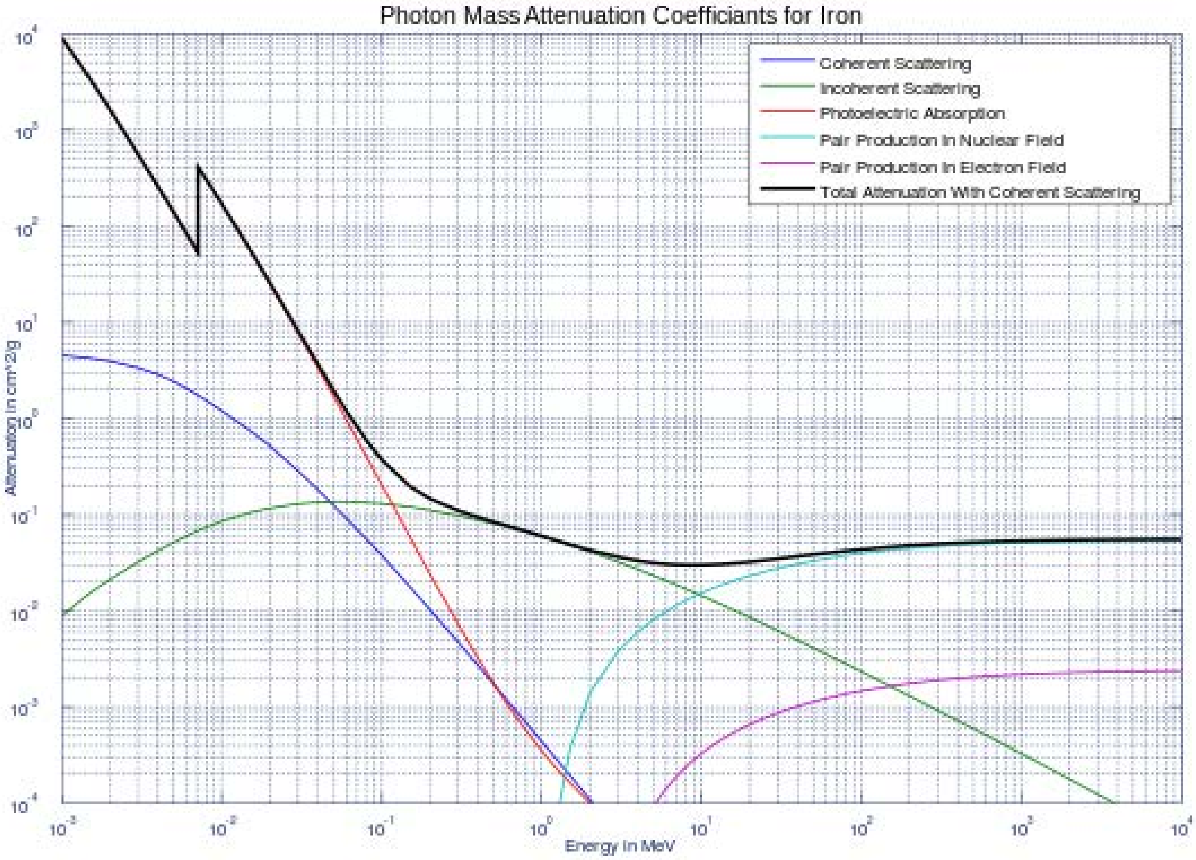
e = 2.71828

$\mu$ = linear attenuation coefficient

$\rho$ = density

$\mu/\rho$ = mass attenuation coefficient

X = shield thickness



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

# Mass Attenuation Coefficient ($\mu/\rho$ $cm^2/g$) 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 “$\sigma$”, common unit is “barn” = $1.0 \times 10^{-28}$ $m^2$

Neutron Flux = nv = $\Phi$

n = neutrons / m3

v = neutron speed (m/s)

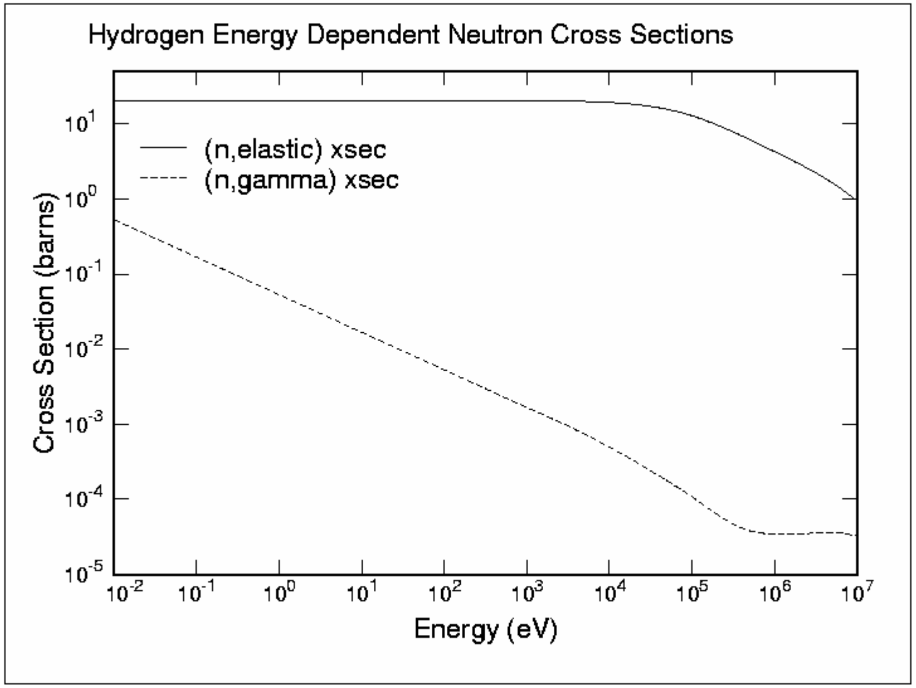
Reaction rate = $\Phi$ N $\sigma$

N = nuclei / $m^3$

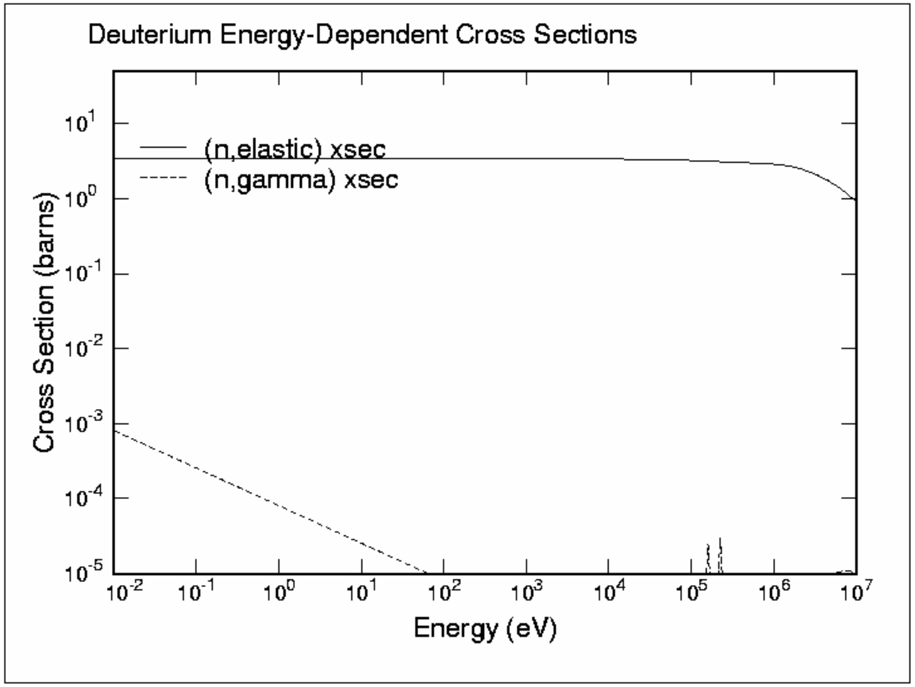
$\Phi$ = neutron flux (neutrons / $m^2$-s)

$\sigma$ = cross section ($m^2$)

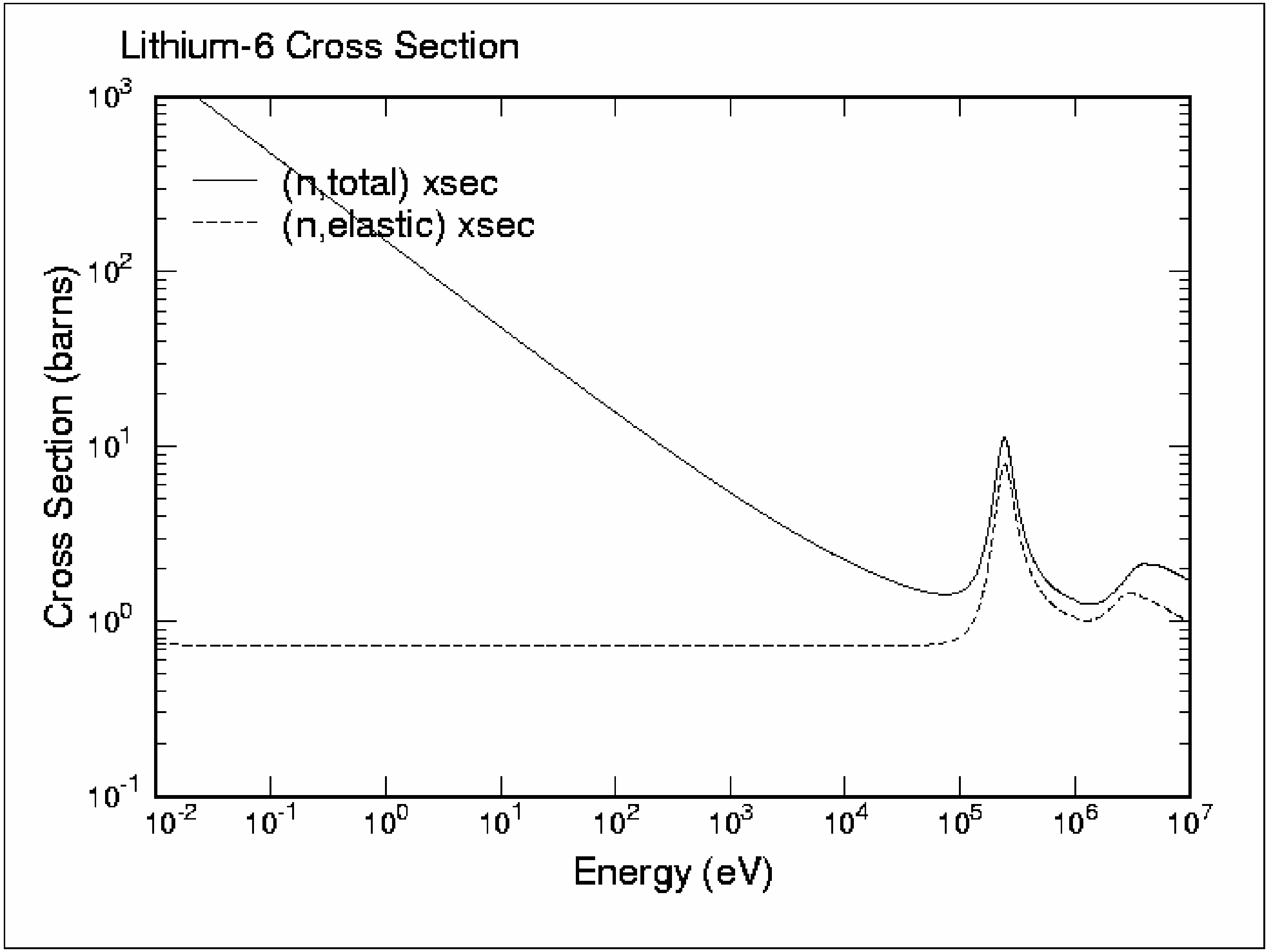
# Comparison of Hydrogen and Deuterium Cross Sections

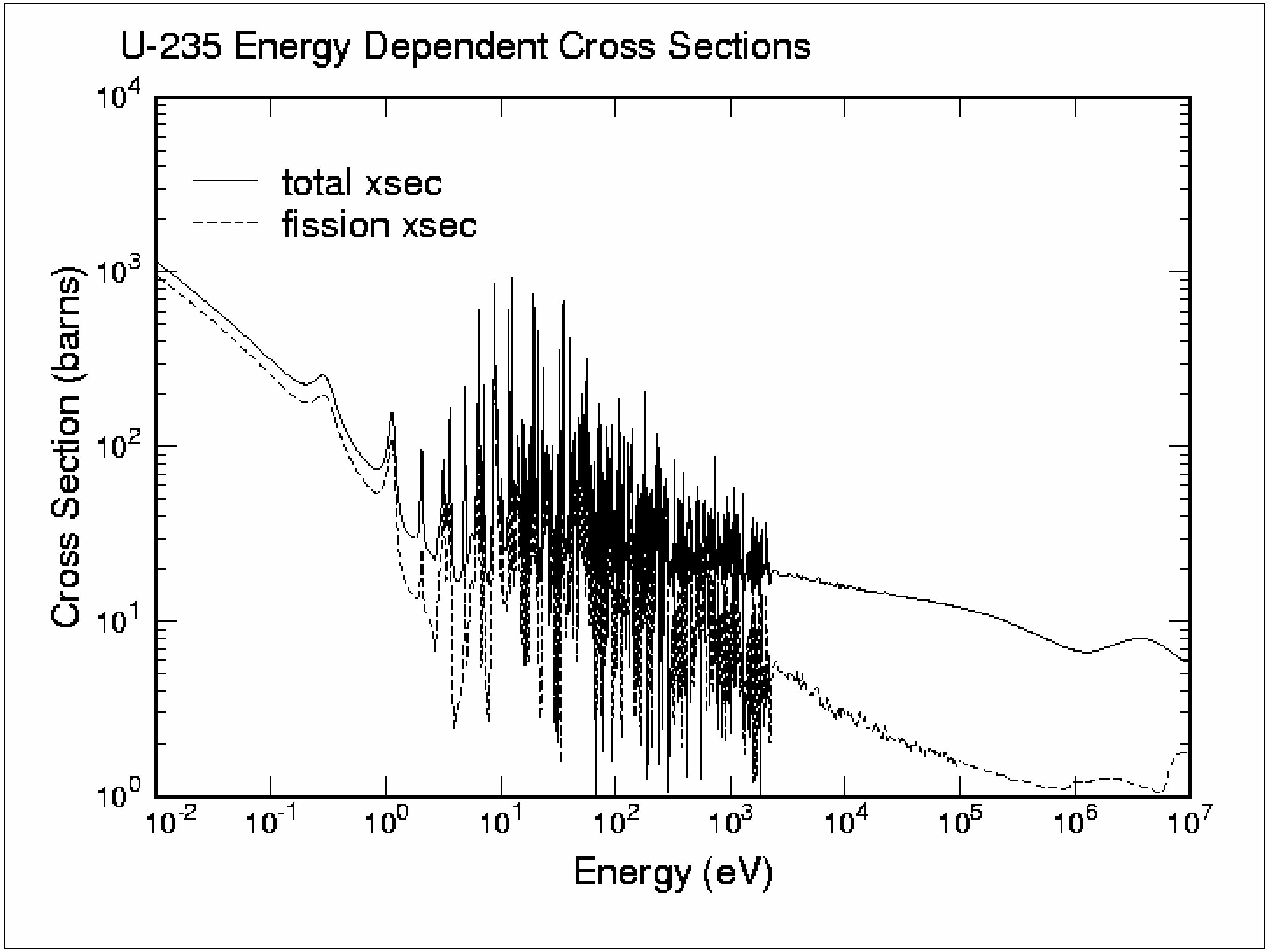


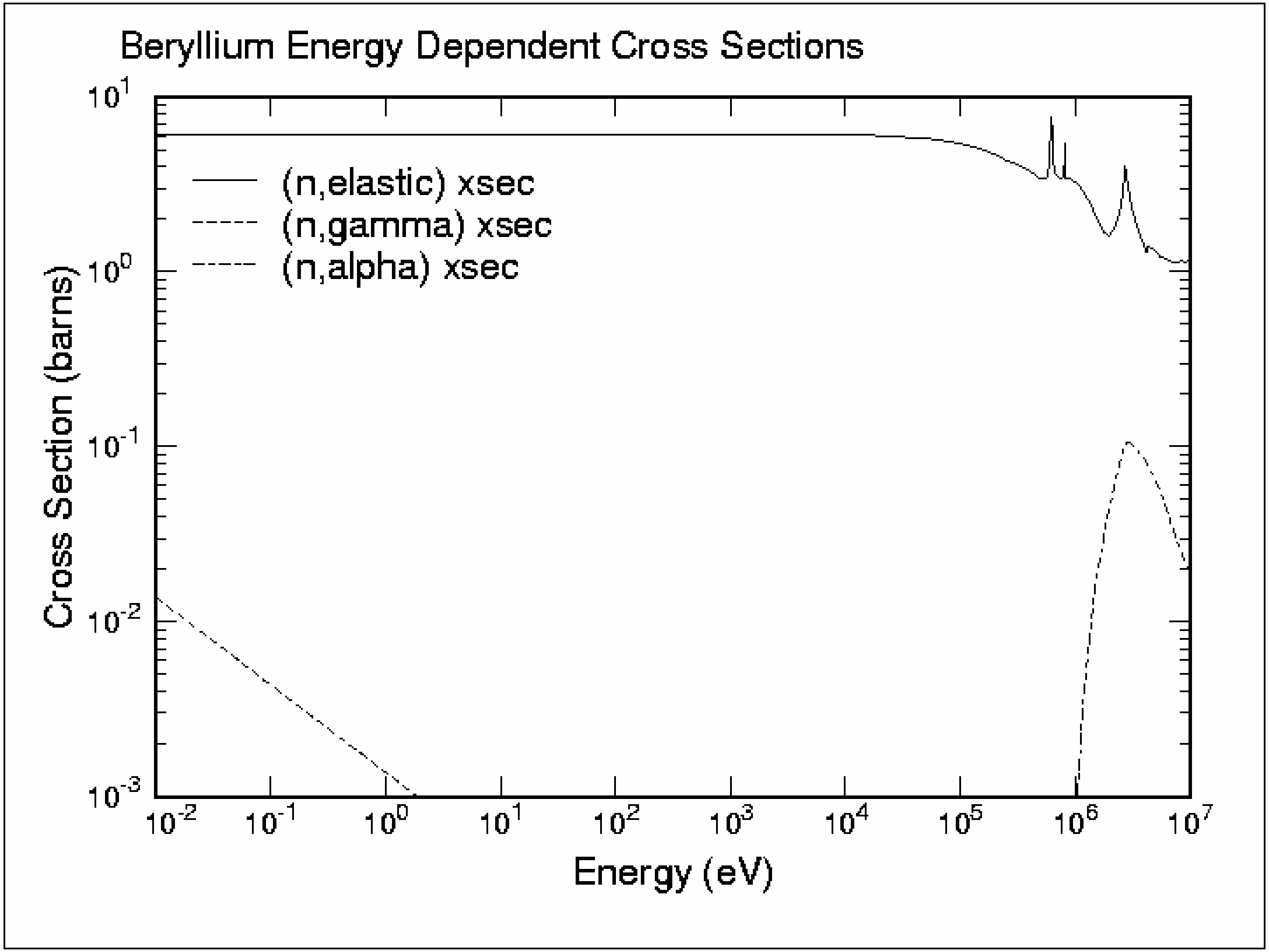
Hydrogen Energy Dependent Neutron Cross Sections



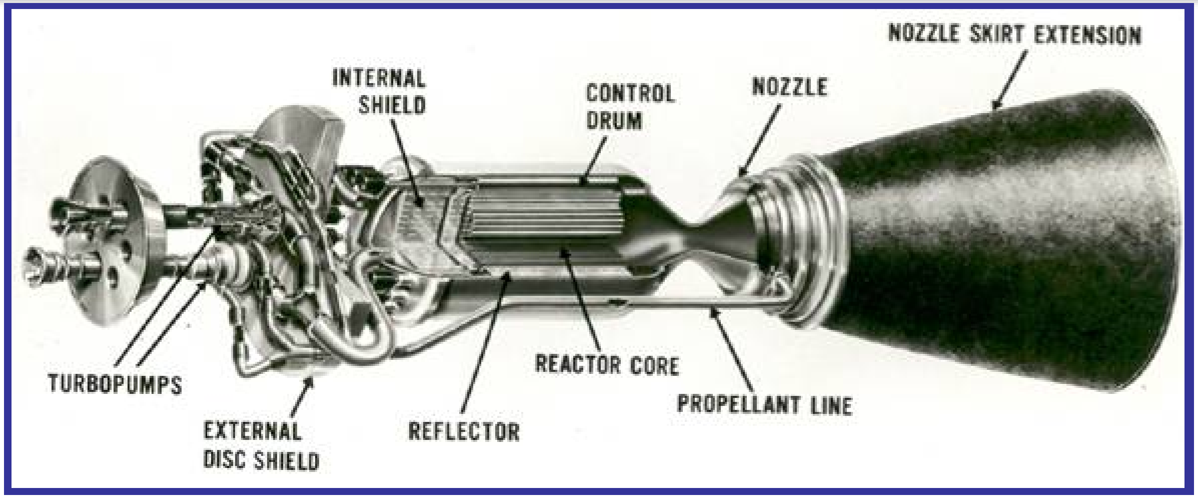
Deuterium Energy-Dependent Cross Sections


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


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

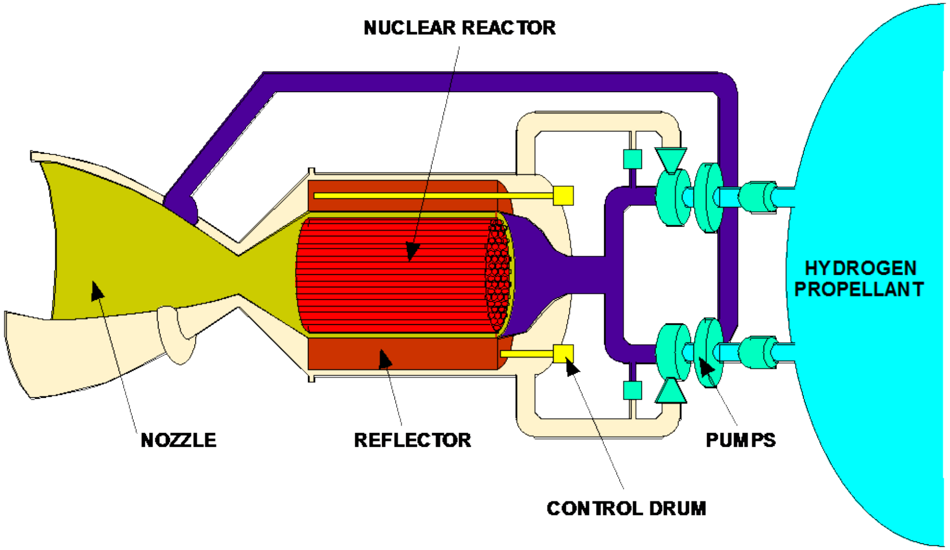
# Nuclear Thermal Propulsion (NTP) Enhances or Enables Advanced Space Missions, Including Human Mars Missions



- 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
- First generation NTP could serve as the “DC-3” of space fission power and propulsion

# How Would Initial NTP Systems Work?

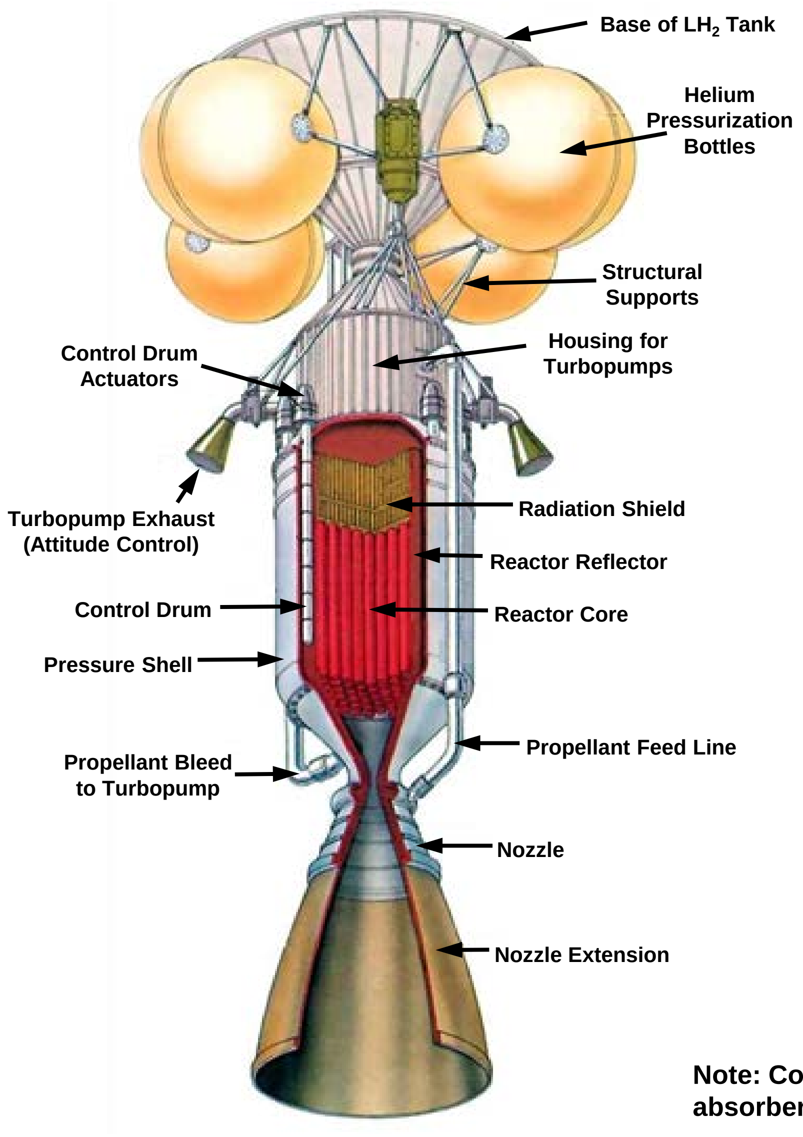
- Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 100,000 N ≈ 450 $MW_{th}$ at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O2/H2 engine actually runs hotter than NTP)

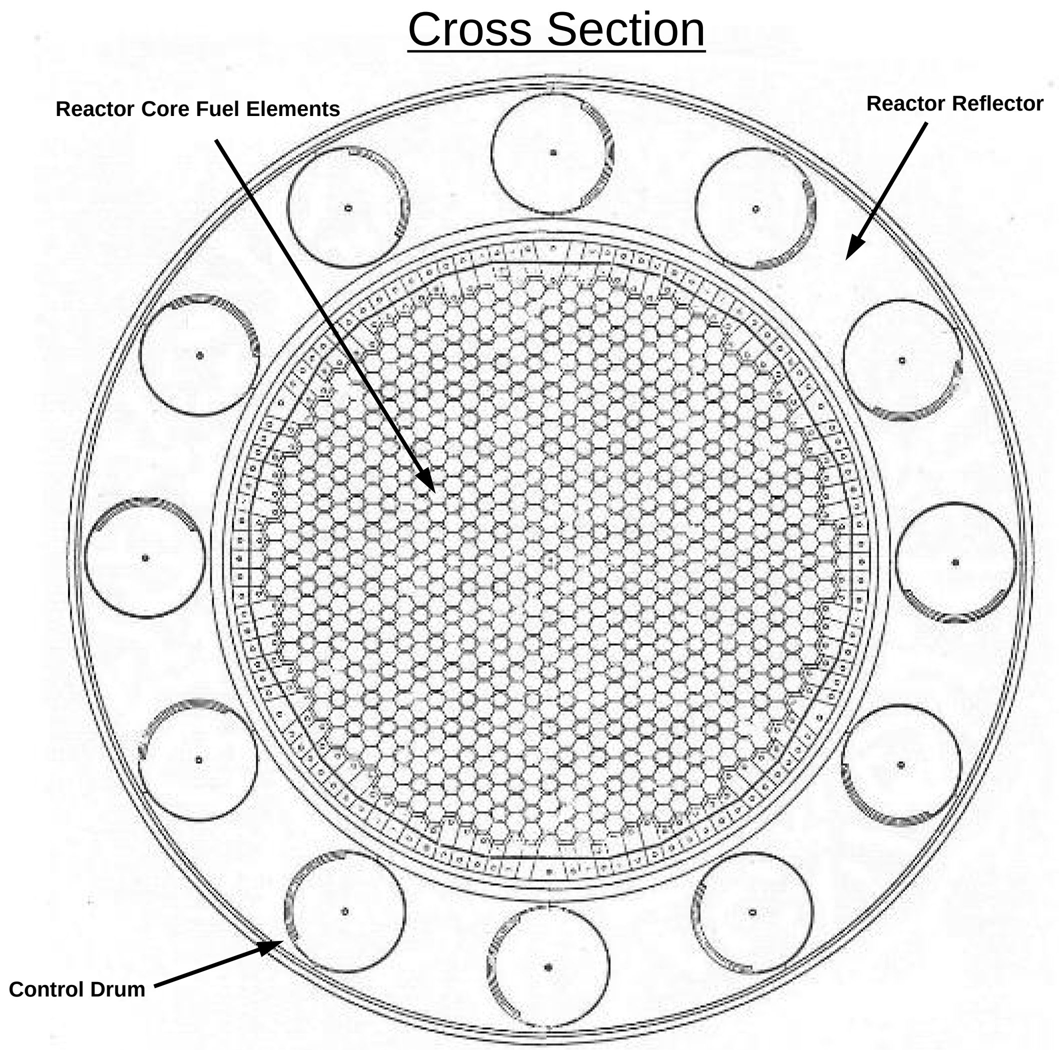


**Major Elements of a Nuclear Thermal Rocket**

**NERVA Nuclear Thermal Rocket Prototype**

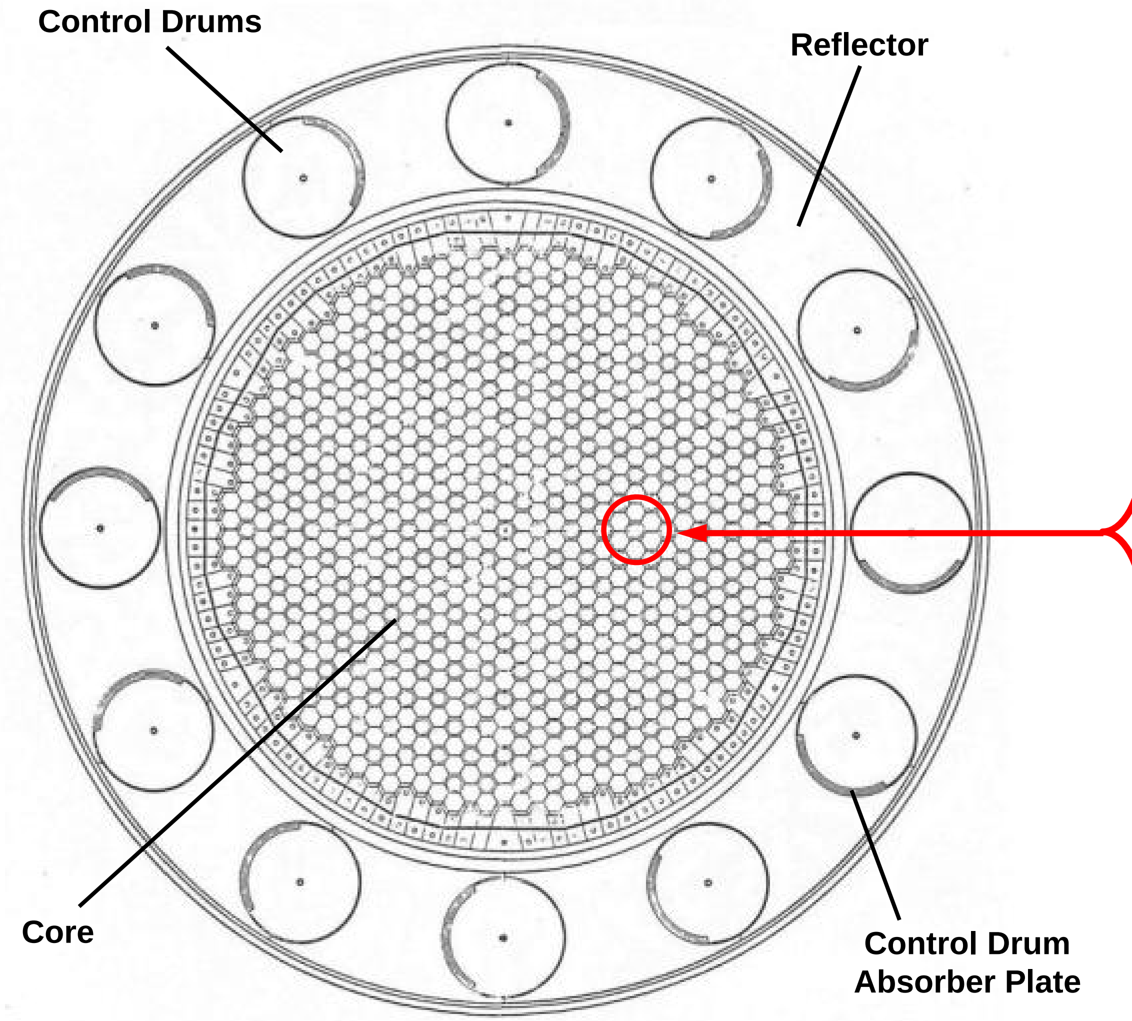
# How Might Initial NTP Systems Work?



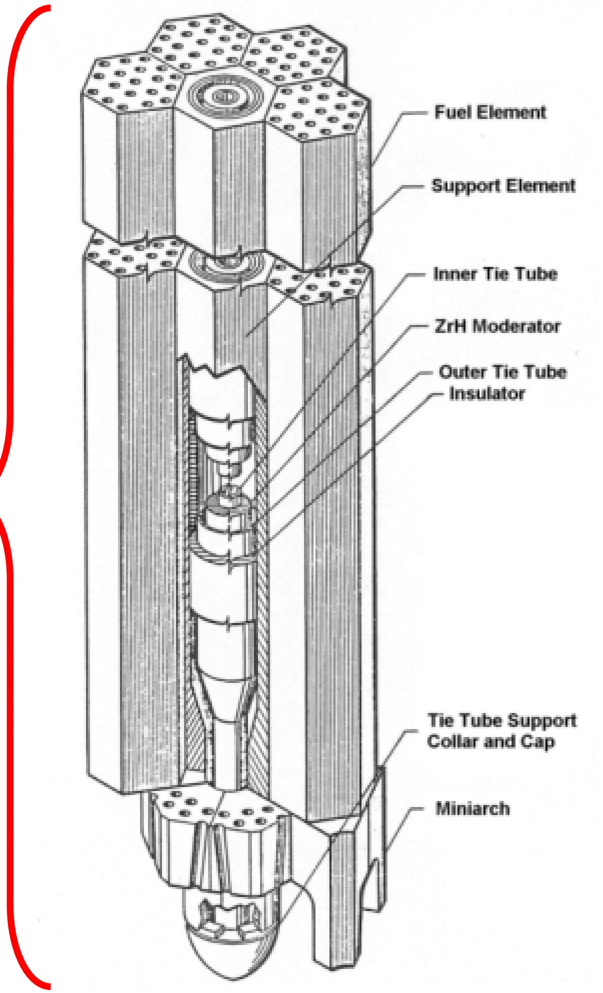


**Note: Control drums rotate to control reactivity. Part of circumference covered with absorber and the rest is a reflector.**

# Previous NTP Engine Designs (Rover / NERVA)

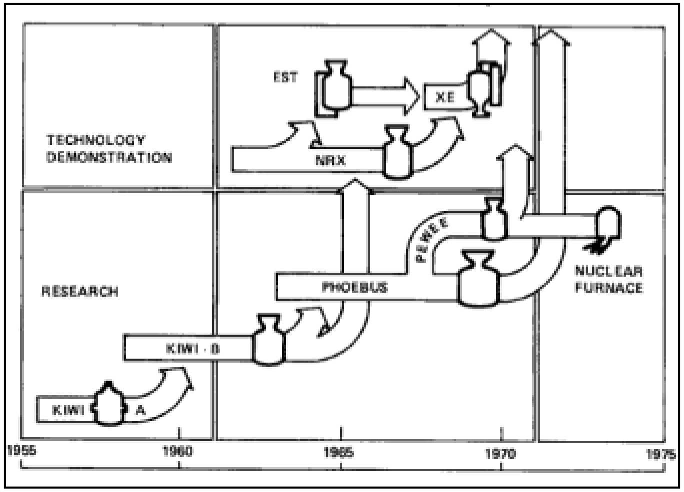


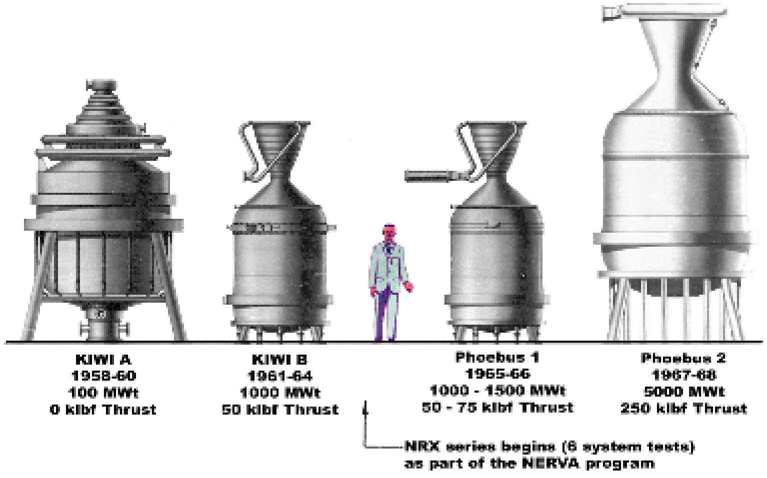
NERVA Reactor Cross Section

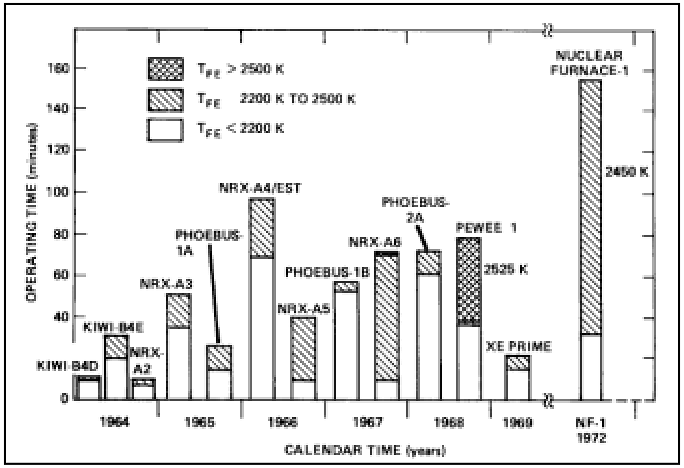


Fuel Segment Cluster

# 20 NTP Engines Designed, Built, and Tested During Rover/NERVA





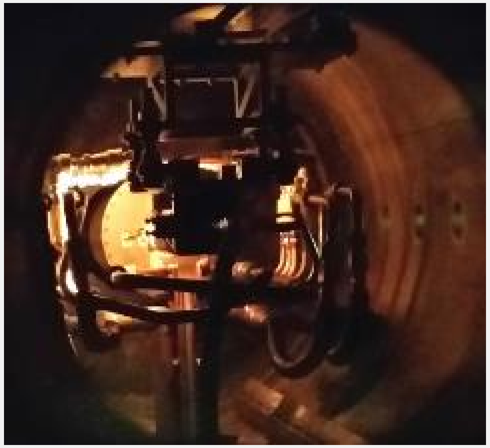


# PHOEBUS 2A NUCLEAR ROCKET ENGINE

**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.**

**NTP reference system is ~0.7 million kilowatts**

# Nuclear Thermal Rocket Element Environmental Simulator (NTREES) Test of ORNL Fuel Element to >2800 K

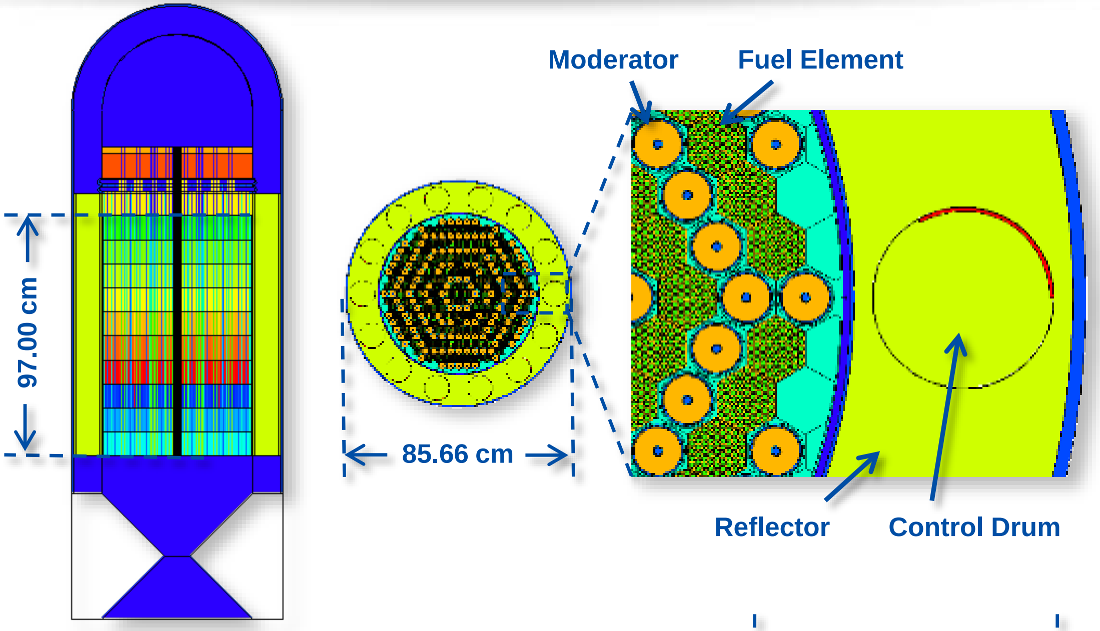


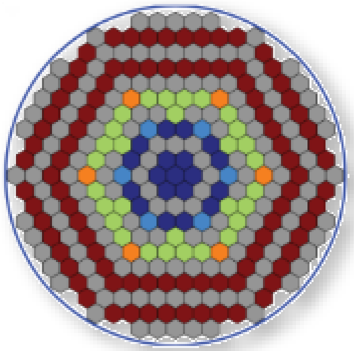
Monitoring testing

Left: John Warren and NTREES designer and lead engineer Bill Emrich watch Mike Schoenfeld (obscured) prepare for testing

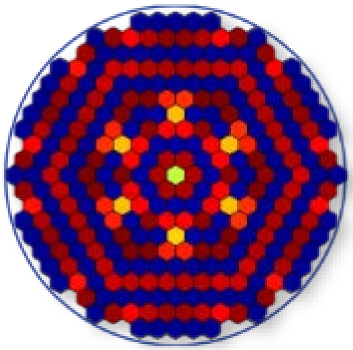
# Space Capable Cryogenic Thermal Engine

## (Baseball Card as of 5/12/15, Rev. 1.0.0)

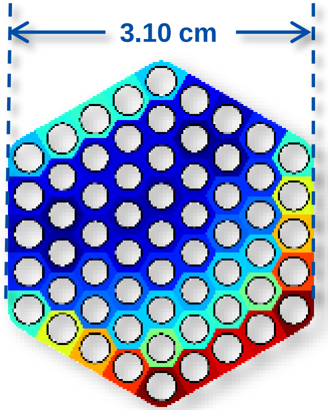




Radial Enrichment Zones (gray is moderator)



Core Power Deposition (Radial peaking factor of 1.089)



Channel by channel power deposition in a fuel element

### General Description

**SCCTE is a A LEU W-$UO_2$ cermet fuel, $ZrH_{1.8}$ moderated nuclear thermal propulsion concept. SCCTE was produced with the Center for Space Nuclear Research's Space Propulsion Optimization Code (SPOC).**

### Reactor System Mass

| | |
|---|---:|
| Fuel Mass (151 Elements) (kg) | 1029.8 |
| Tie Tubes (150 Elements) (kg) | 700.4 |
| Radial Reflector + Control Drums (kg) | 618.6 |
| Axial Reflector (kg) | 165.4 |
| Barrel+Vessel+Other Core Structure (kg) | 308.4 |
| **Total Mass (Excluding Shield) (kg)** | **2822.6** |

### Key Performance Parameters

| | |
|---|---:|
| Nominal Isp (150:1 Nozzle) | 896 |
| Nominal Thrust (kN) | 157.3 (~35k lbsf) |
| Reactor Power (MW) | 709.8 |
| Fuel Temperature Max (K) | 2850.0 |

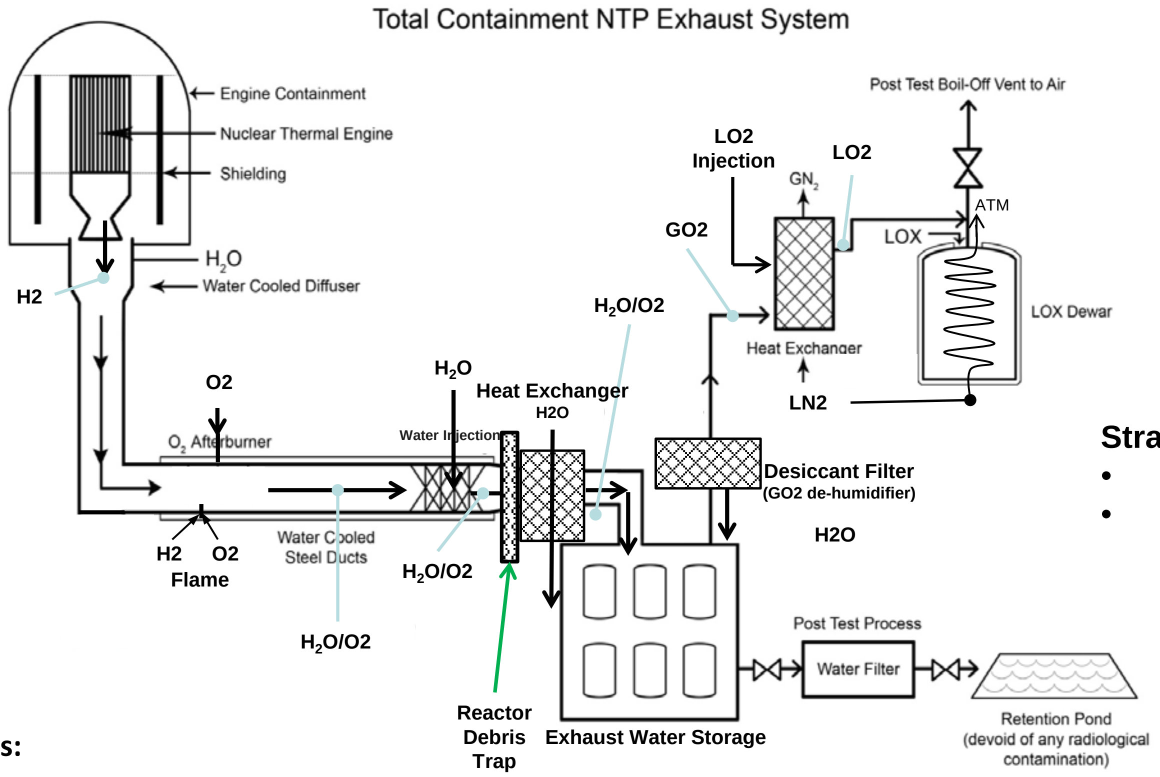
### Engine System Interface Information

| Interface Point | Flow Rate (kg/s) | Pressure (MPa) | Temp. (K) |
|---|---|---|---|
| Core inlet | 17.9 | 6.93 | 291 |
| Core outlet | 17.9 | 4.65 | 2698 |

### Fuel Details

| | |
|---|---|
| Fuel composition | W-$UO_2$-$ThO_2$ |
| Volume loading of Oxide (% vol.) | 60.0 |
| $ThO_2$ in the Oxide (%mol. ) | 6.0 |
| Enrichment of $^{184}$W (% atom) | 98.0 |
| Enrichment of $^{235}$U (% atom) | 19.75 to 13.13 |
| Total Enriched W (kg) | 376.0 |
| Total $^{235}$U (kg) | 45.9 |
| Percent Theoretical Density (% TD) | 97.0 |

# NTP Total Containment Test Facility Concept



**Strategy:**

- Fully Contain engine exhaust
- Slowly drain containment vessels after test

**How it works:**

- Hot hydrogen exhaust from the NTP engine flows through a water cooled diffuser that transitions the flow from supersonic to subsonic to enable stable burning with injected LO2
  - Products include steam, excess $O_2$ and potentially, a small fraction of noble gases (e.g., xenon and krypton)
- Water spray and heat exchanger dissipates heat from steam/O2/noble gas mixture to lower the temperature and condense steam
- Water tank farm collects $H_20$ and any radioactive particulates potentially present in flow.
  - Drainage is filtered post test.
- Heat exchanger-cools residual gases to LN2 temperatures (freezes and collects noble gases) and condenses O2.
  - LOX Dewar stores $LO_2$, to be drained post test via boil-off

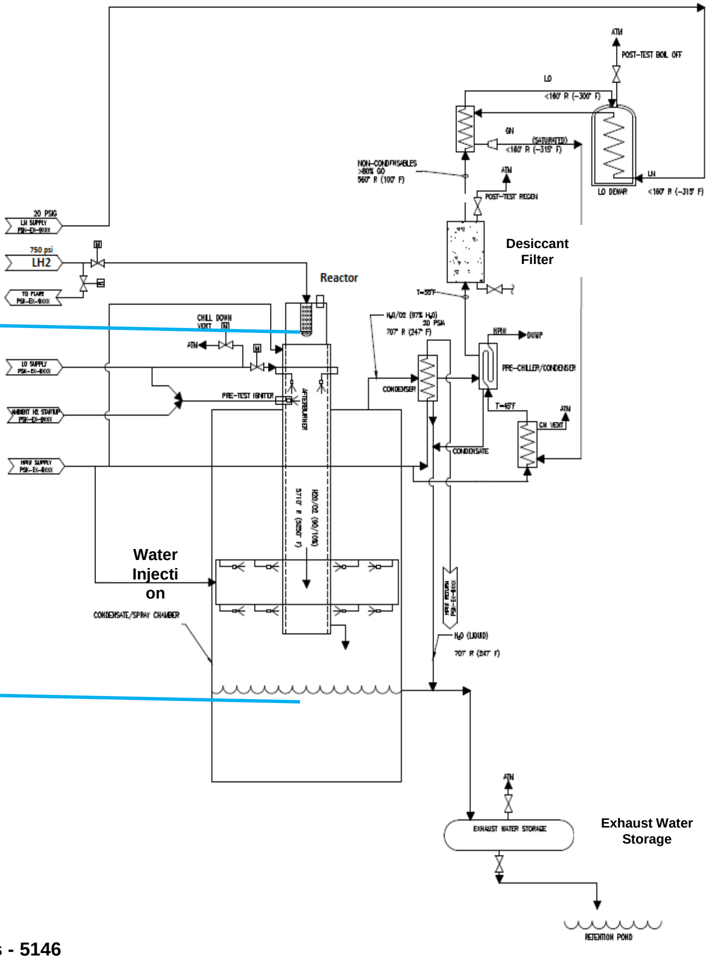
# Total Engine Exhaust Containment

## Conceptual System Design Layout and ROM Cost Estimate

**NTP total containment ground test facility assumed to be located at SSC's A3 Test Stand**

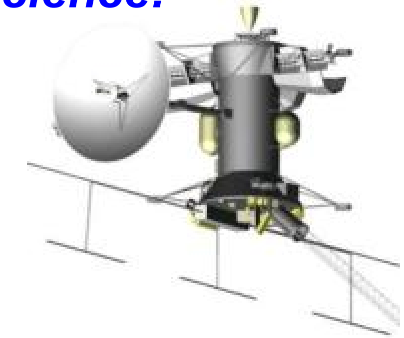
- Most of the infrastructure required by the NTP total containment ground test facility is already in place at A3:
  - Tower, test cell, propellant, HPIW & data and controls infrastructure, the Test Control Center, electric power, etc.
  - Major modifications, procurements, and construction work will be required and are captured in the ROM estimate.

**ROM estimate to prepare stand NTP for engine test: $172.5M, 4 years**

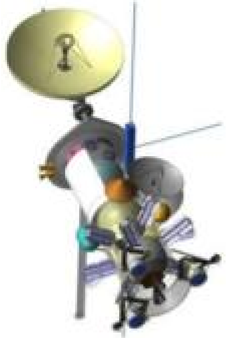


# Safe, Compact, Near-Term Fission Power Systems Could Help Enable Higher Power Fission Propulsion Systems

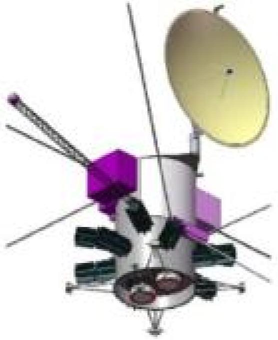
## *Science:*



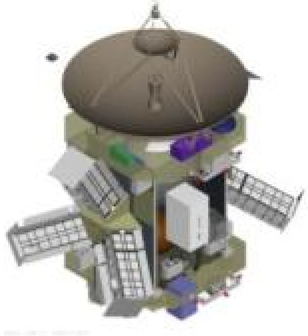
Jupiter Europa Orbiter
~600 We (5 to 6 RPS)



Neptune Systems Explorer
~3 kWe (9 Large RPS)



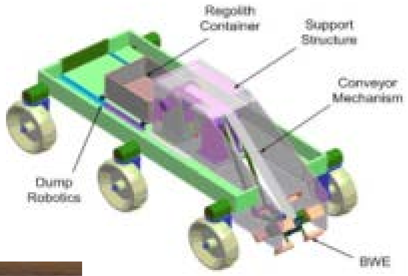
Kuiper Belt Object Orbiter
~4 kWe (9 Large RPS)



Trojan Tour
~800 We (6 RPS)

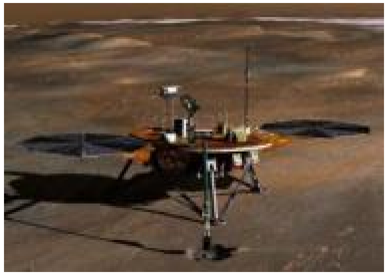
## *Exploration:*

Teleoperated
Rovers

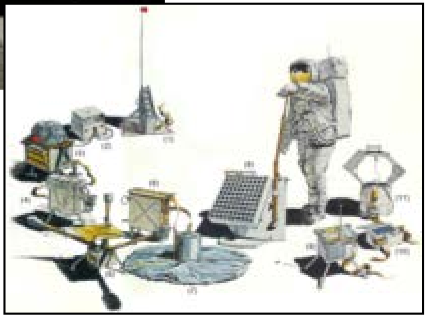


Comm Relay
Stations

ISRU Demo
Plants

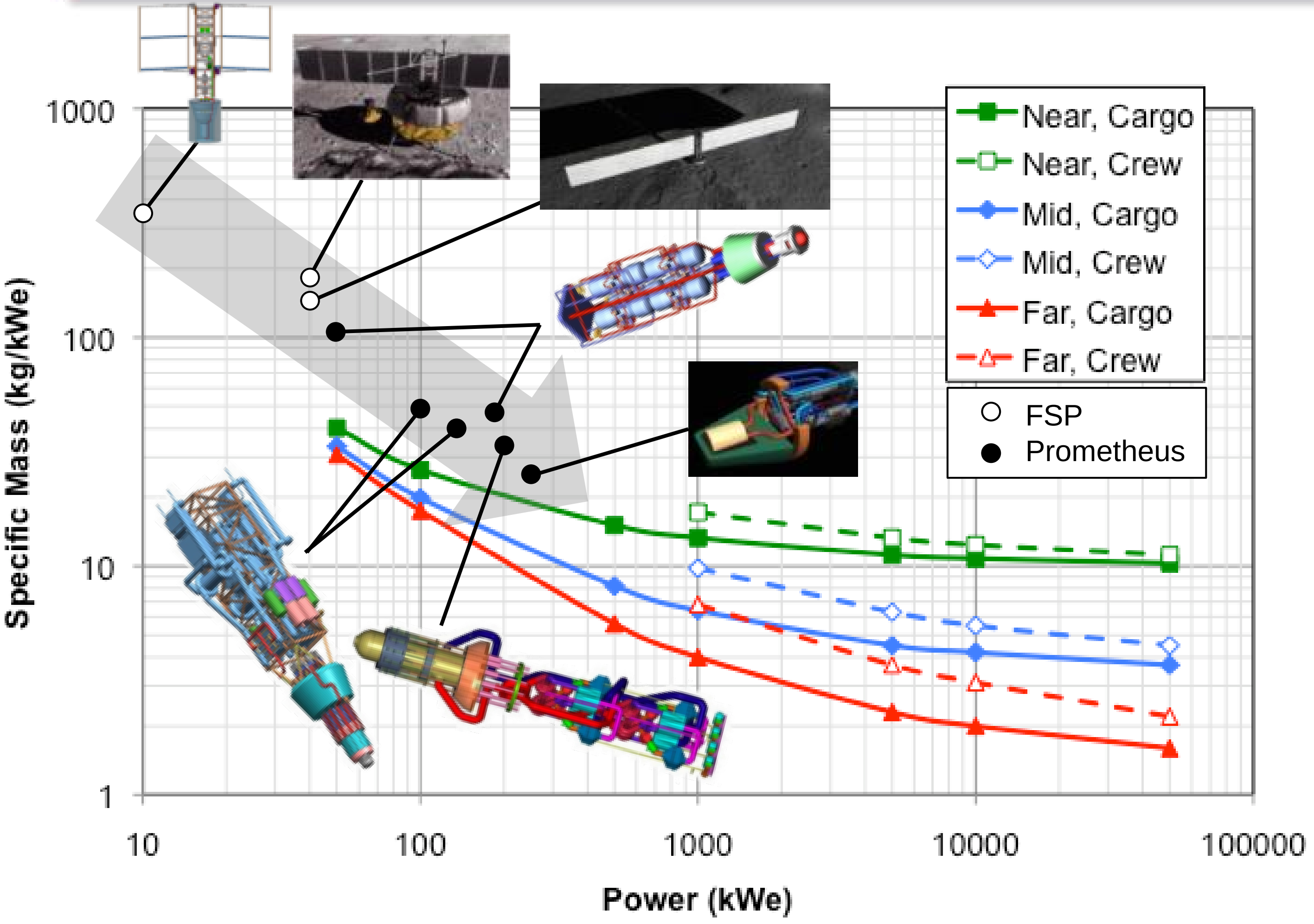


Site Survey
Landers



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

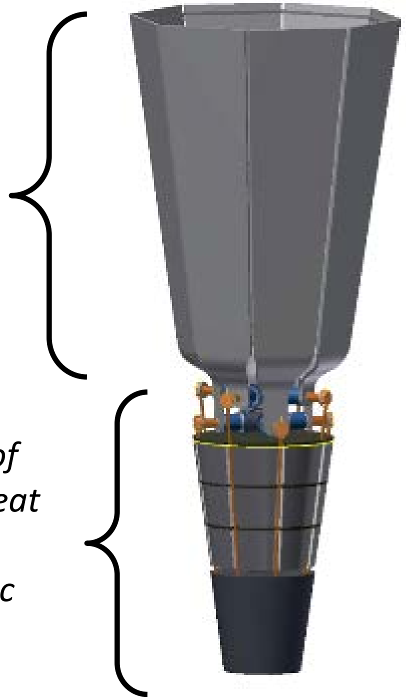
Near=Liq Metal Rx, Brayton, 1300K, 6 kg/m2, 200 Vac (Available ~10 yrs)
Mid=Liq Metal Rx, Brayton, 1500K, 3 kg/m2, 1000 Vac (Available ~ 15-20 yrs)
Far=Liq Metal Rx, Brayton, 2000K, 1.5 kg/m2, 5000 Vac (Available ~ 25-30 yrs)
Cargo=Instrument rated shielding, 1.6x10^15 nvt, 1.2x10^8 rad @ 2 m
Crew=Human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

Chart courtesy
Lee Mason,
NASA GRC

# Kilopower Technology Demonstration – Overall Objectives & Elements

- **Big Idea:**
  - A compact, low cost, scalable fission power system for science and exploration
- **Innovation:**
  - KiloPower: novel integration of available U235 fuel form, passive sodium heat pipes, and flight-ready Stirling convertors
- **Impact:**
  - Provides Modular Option for HEOMD Mars Surface Missions
  - Enables SMD Decadal Survey Missions
  - Reduces NASA dependence on Pu238
- **Goals:**
  - **Nuclear-heated system-level test of prototype U-8Mo reactor core coupled to flight-like Stirling convertors**
  - Detailed design concept that verifies scalability to 10 $\text{kW}_e$ for Mars
  - Prepare for flight test of titanium-water heat pipe radiator on ISS to verify Zero-G performance

**1 to 10 kWe**
**Kilopower Technology**



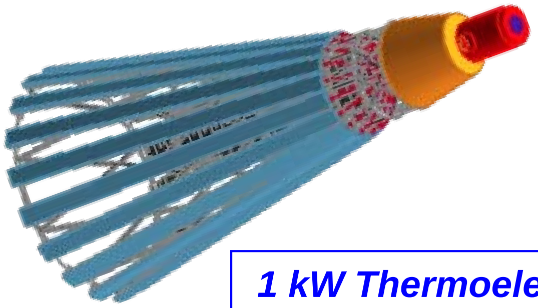
*On-orbit test of variable conductance heat pipe radiator under steady-state & transient conditions*

*Full-scale nuclear test of reactor core, sodium heat pipes, and Stirling convertors at prototypic operating conditions*

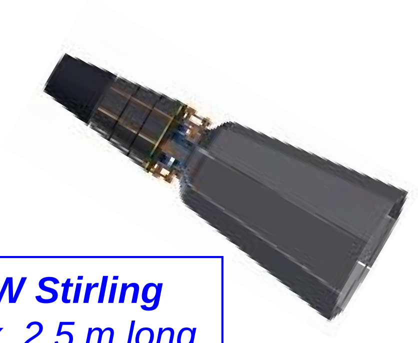
- **10X the power of current RPS**
- **Available component technologies**
- **Tested in existing facilities**

# Kilopower-Enabled Concepts Family

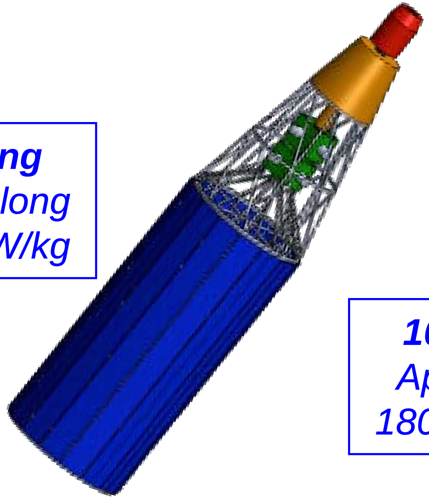
- **Common Design Features include:**
    - 0.5 to 10 kWe; >10 year design life
    - Utilize available UMo reactor fuel from DOE-NNSA
    - Minimize thermal power to simplify reactor design and control
    - Incorporate passive Na heat pipes for reactor heat transport
    - Leverage power conversion technologies from RPS Program (TE, Stirling)
    - Design system so that it can be tested in existing DOE nuclear facilities



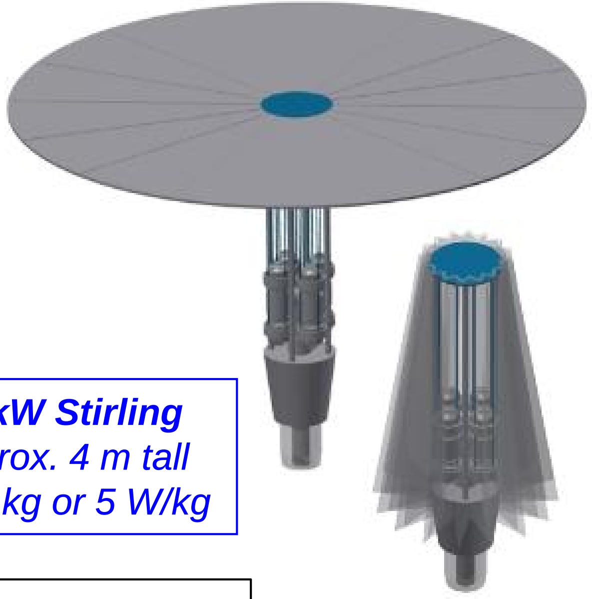
***1 kW Thermoelectric***
*Approx. 4 m long*
*600 kg or 1.7 W/kg*



***800 W Stirling***
*Approx. 2.5 m long*
*400 kg or 2 W/kg*



***3 kW Stirling***
*Approx. 5 m long*
*750 kg or 4 W/kg*



***10 kW Stirling***
*Approx. 4 m tall*
*1800 kg or 5 W/kg*

***1 kWe-class Technology Demonstration establishes foundation for range of systems and capabilities***

# Kilopower Thermal Prototype

- **Kilopower Thermal Prototype is first of three steps to a nuclear ground demonstration**
  - Non-nuclear functional prototype with steel simulated reactor core
  - Non-nuclear prototype with depleted uranium simulated core
  - Nuclear demonstration with uranium reactor core

- **Thermal prototype validates core geometry and heat pipe attachment method prior to build of depleted uranium simulated core**
  - Steel core thermal properties are close enough to uranium to validate heat pipe attachment method under thermal load, and segmentation of core
  - First of two electrically heated trials of heat pipe attachment methods tested at temperature in vacuum

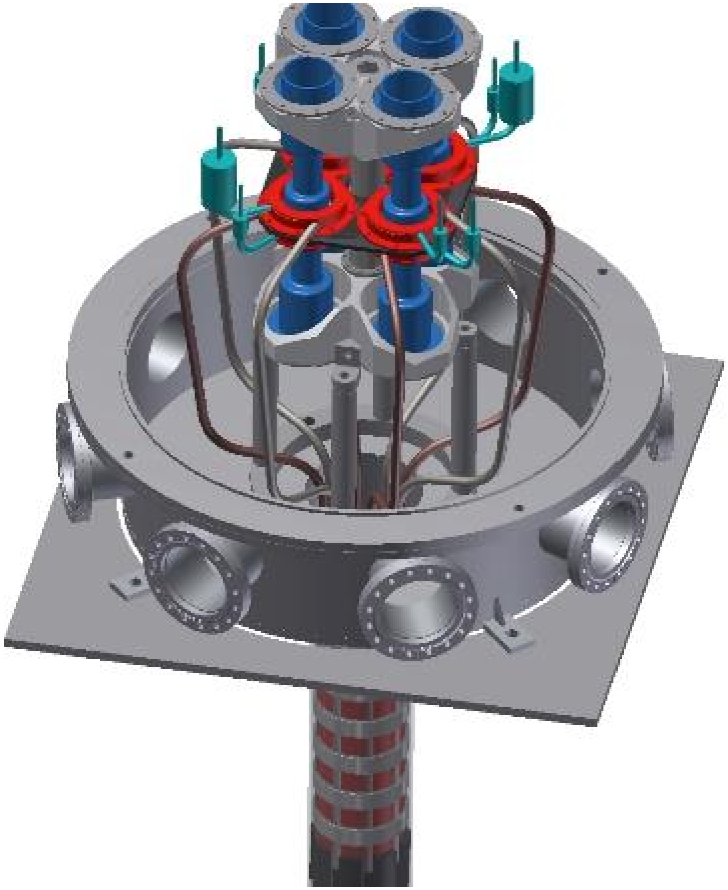
**Stainless Steel Thermal Prototype**

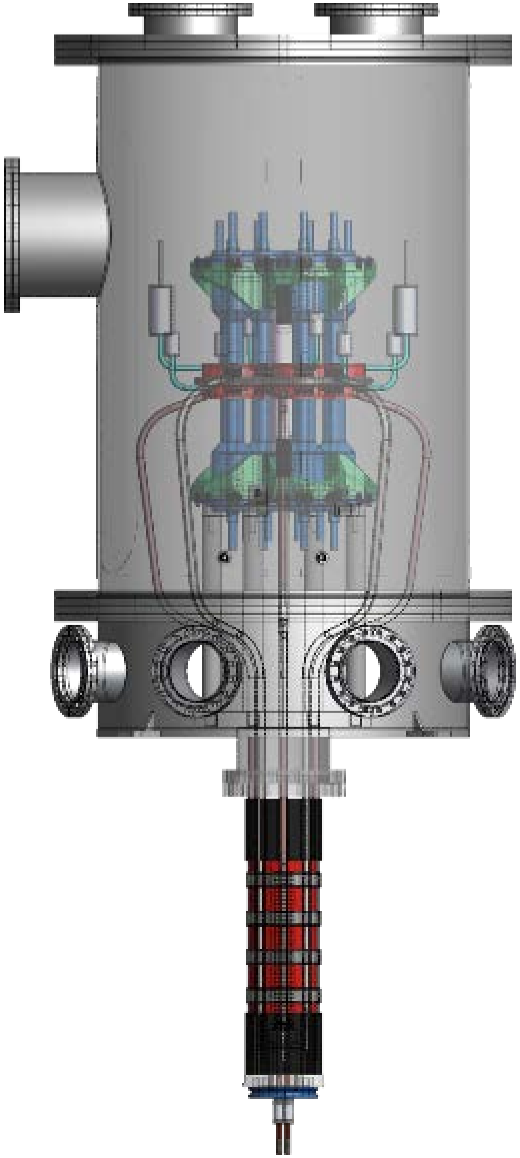
**Vacuum Tank Integration**

**Integrated Assembly**

**Test**

# Latest Configuration of 1 kW$_e$ Krusty Nuclear Demonstration





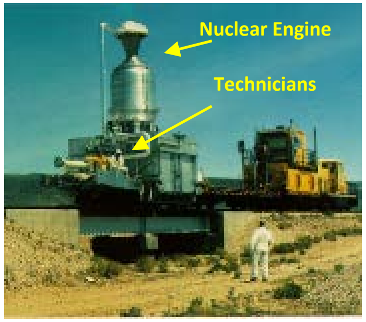
# Partner Organizations Investing in Kilopower

- **DOE / National Nuclear Security Administration (NNSA)**
  - Nevada National Security Site Device Assembly Facility is being provided without cost to NASA
  - NNSA will own, keep, and dispose of Kilopower demonstration reactor core
  - *NNSA is contributing $0.5M in FY16 and $2M in FY17 to Kilopower*
- **HEOMD**
  - Significant interest from HAT for Evolvable Mars Campaign
  - Providing time of Human Spaceflight Architecture Team (HAT) members for Mars Kilopower Concept Development
  - Possible Kilopower use on 2024-26 Mars ISRU Surface Demo
- **Industry: Aerojet/Rocketdyne**
  - Committing Independent Research and Development funds in FY15 for reactor core materials research and testing
  - Interested in continued and broader partnership
- **Other Government Agencies: ARPA-E**
  - Contracts awarded for 1 kWe residential power: GENerators for Small Electrical and Thermal Systems (GENSETS)
  - Two Stirling technology contracts could have direct benefit to Kilopower

# NTP Facts

- The volume of a toy marble could contain the mass of uranium providing the NTP energy for an entire human Mars mission

- Standing next to an NTP engine before launch for one year is less radiation than a diagnostic x-ray



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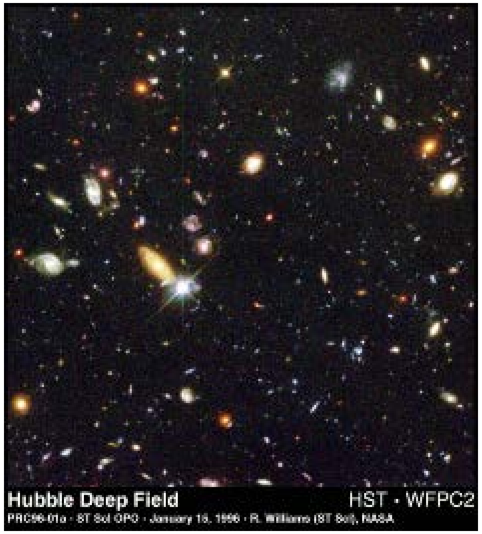
- NTP ground test regulations allow the maximum annual public dose from NTP testing to be equivalent to ~20 hours of plane flight, which is also equivalent to ~25% of the natural radiation from food.

# NTP Facts (Cont'd)

- Crews of nuclear submarines have lower radiation exposure than the general public above the water

- Using NTP for faster trip times to Mars exposes the astronauts to less galactic cosmic radiation



- NTP reactor fission products from the entire Mars mission is about equal to products formed after ~two weeks of runtime from a 10 MW college reactor

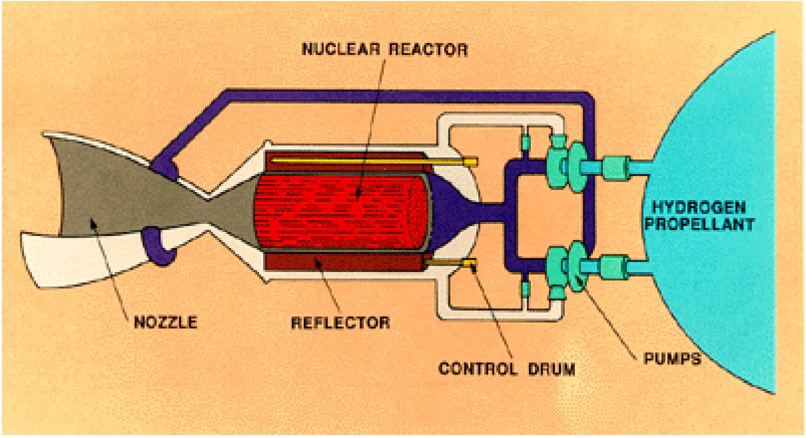
# Deaths by TeraWatt Hours (TWh) *

| Energy Source | Death Rate (per TWh) | Percent - World Energy /Electricity |
|---|---|---|
| Coal (electricity, heating, cooking) | 100 | 26% / 50% |
| Coal (electricity -world average) | 60 | 26% / 50% |
| Coal (electricity, heating, cooking) - China | 170 | |
| Coal (electricity) - China | 90 | |
| Coal - USA | 15 | |
| Oil | 36 | 36% |
| Natural Gas | 4 | 21% |
| Biofuel / Biomass | 12 | |
| Peat | 12 | |
| Solar (rooftop) | 0.44 | 0.2% of world energy for all solar |
| Wind | 0.15 | 1.6% |
| Hydro | 0.10 (Europe death rate) | 2.2% |
| Hydro (world including Banqiao dam failure) | 1.4 (About 2500 TWh/yr and 171,000 Banquio dead) | |
| Nuclear | 0.04 | 5.9% |

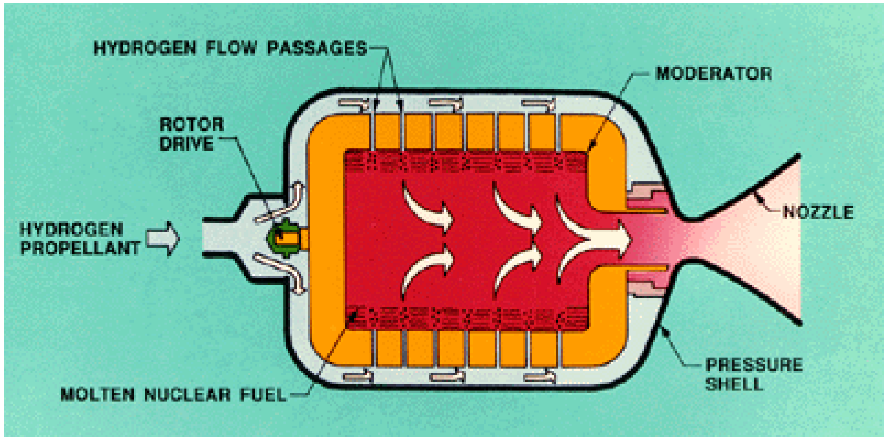
60% for coal for electricity, cooking and heating in China. Pollution is 30% from coal power plants in China for the particulates and 66% for sulfur dioxide. Mining accidents, transportation accidents are mostly from coal for electricity.

*Source: http://nextbigfuture.com/2011/03/deaths-per-twh-by-energy-source.html?m=1 5/13/2011

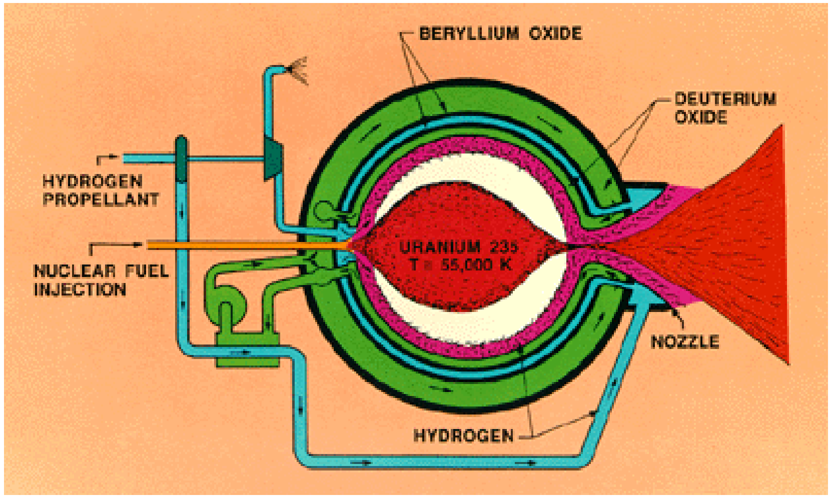
# First Generation NTP Systems Could Help Enable Highly Advanced Propulsion Systems



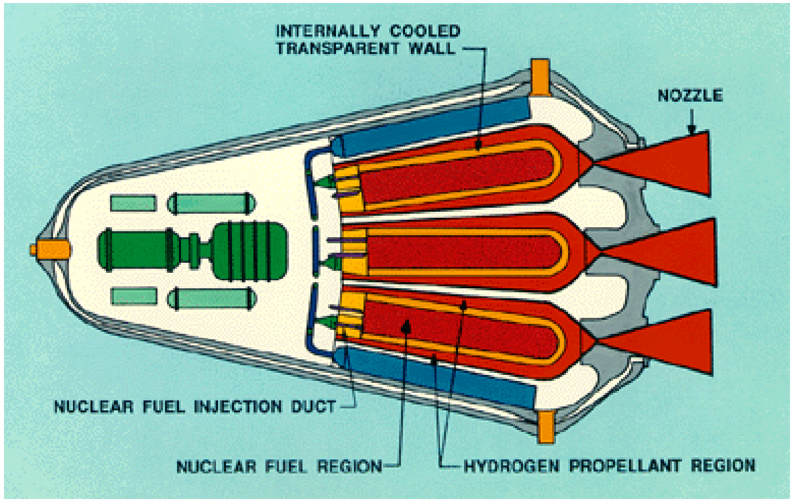
SOLID CORE NUCLEAR ROCKET



LIQUID CORE NUCLEAR ROCKET



Open-Cycle Gas Core Nuclear Rocket



Closed-Cycle Gas Core Nuclear Rocket

# Future Plans / Path Forward

- Space fission power and propulsion systems have the potential to enable ambitious missions throughout the solar system.
- Space fission power and propulsion will only be utilized if affordable and viable development strategies can be devised.
- Ongoing projects are focused on developing and demonstrating those strategies.