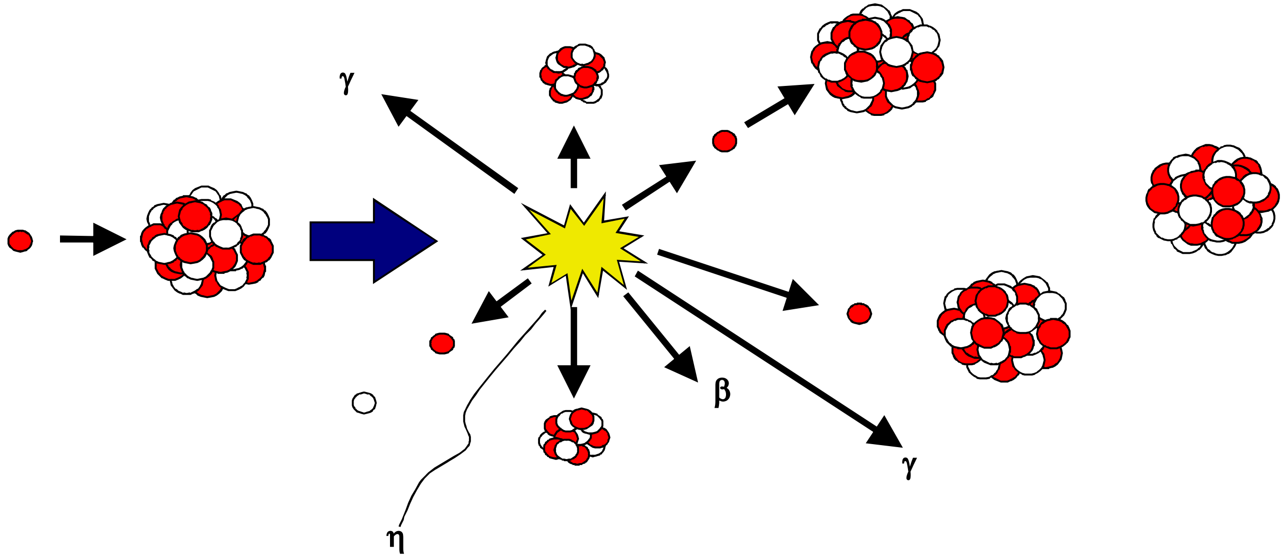
SAND2008-1171P

Principles of Fission Nuclear Power



Joe Harris
Deputy Director
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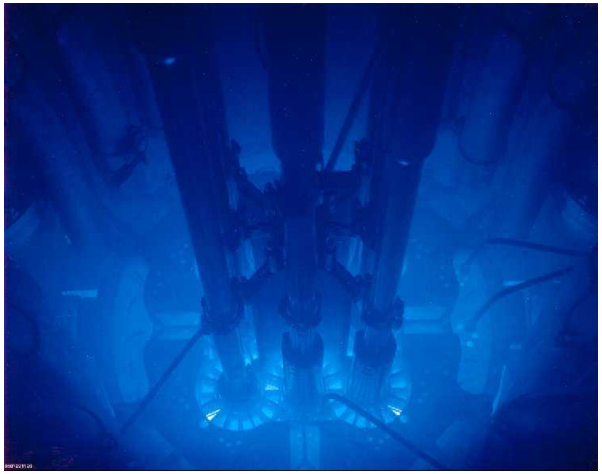
Some Historical Perspective

- 1905: Einstein develops Nobel Prize-winning explanation of the Photoelectric Effect – “photon” and wave phenomena have particle properties; Einstein’s Theory of Special Relativity – energy and mass are equivalent.
- 1924: Prince Louie de Broglie – particles can behave as “waves.”
- 1925: Davisson and Germer – electrons scatter like x-rays off Ni – confirms de Broglie.
- 1925 & 1926: Schrodinger and Heisenberg formulate quantum mechanics.
- 1932: Chadwick interprets the 1930 experiment of Bothe and Becker and discovers the neutron.
- 1939: Hahn and Strassman – discovery of fission.
- 1942: Fermi – first self-sustaining fission chain reaction – CP1.

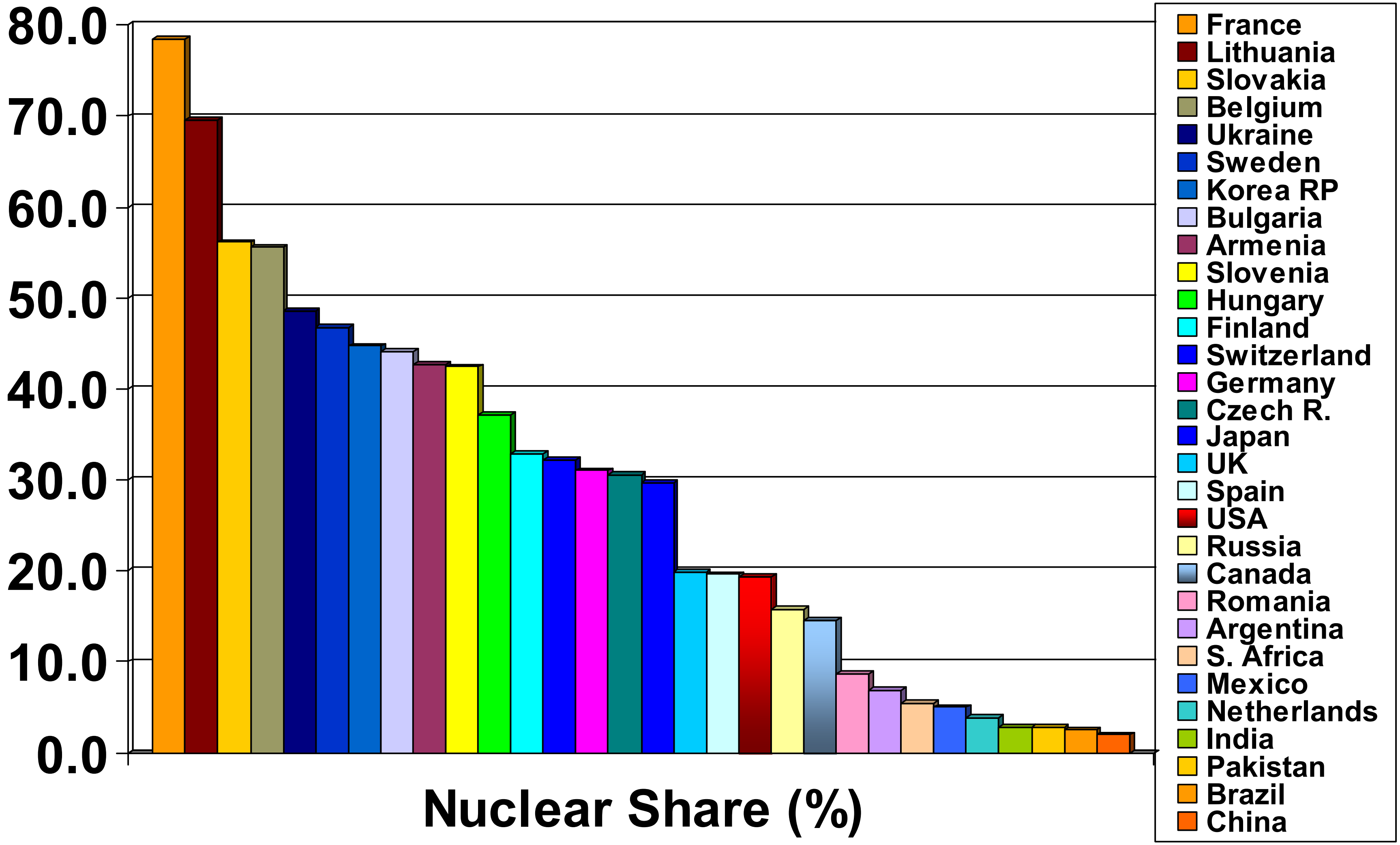
Fission is a Well-Developed, Extensively-Utilized Technology

- **Fission power systems have been operating safely and reliably since 1942.**
- **Fission reactors are used by governments, industry, utilities, and universities.**
- **Fission reactors are currently operating in dozens of countries at power levels up to 2 x 10^9 watts (2 GW).**
- **Existing nuclear fission power plants are the least expensive source of electricity in the US.**
- **Several countries have plans for development and/or utilization of advanced reactors.**



Nuclear Share of Electricity Generation

(as of 31 Dec. 2005)



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Attributes of Fission Systems

= 10 x

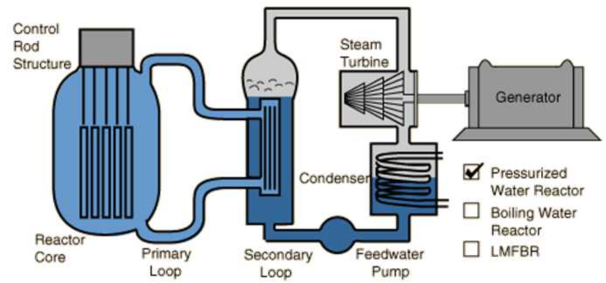
Fissioning 12 fl oz (355 ml) of Uranium yields 10 times the energy contained in the Shuttle Tanks

Uranium Energy Density: 82 billion joules per gram, or approximately 10^6 times that of chemical reactions

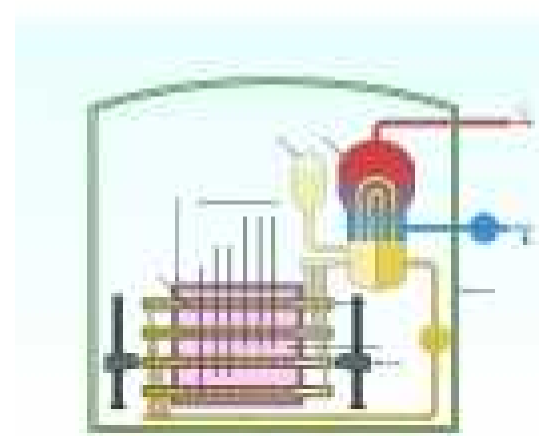
- Fission overcomes limitations of other candidate power sources:
  - Chemical: already near theoretical performance levels;
  - Radioisotopes: versatile and long-lived, but have low power density and a limited Pu-238 supply;
  - Natural sources (e.g., beamed energy, fusion): too immature, may not work, and/or require substantial infrastructure and investment.

Nuclear Reactors

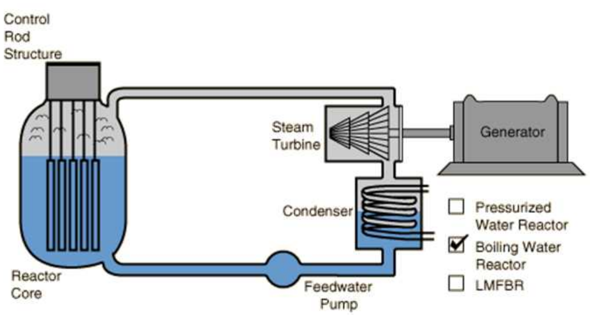
Light-water Pool Reactor



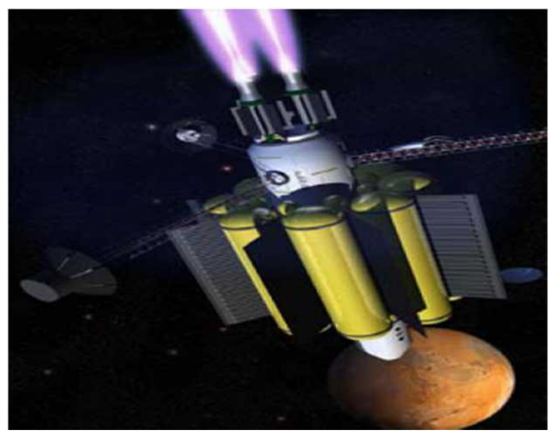
Pressurized Water Reactor



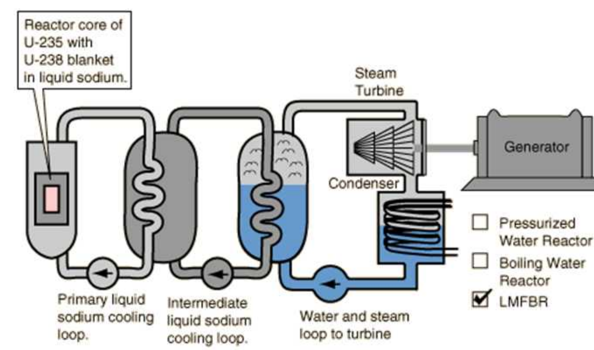
CANDU Reactor



Boiling Water Reactor



Space Reactor



Liquid Metal Fast Breeder Reactor

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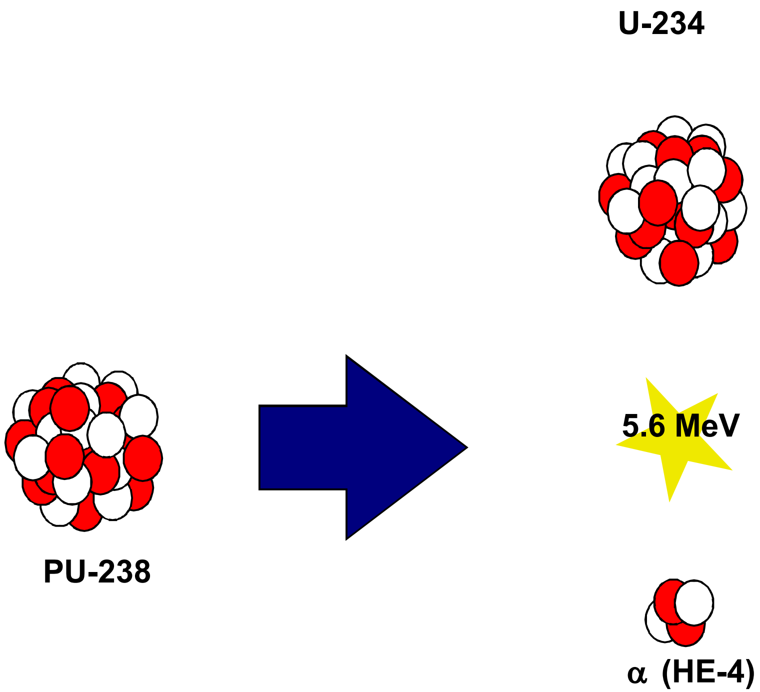
Reactor Types (Abbreviations and Summary)

Full Name	Type Code	Number of Reactors, as of 31 Dec 2005				
		Operational	Construction	Shut Down	Suspended	Cancelled
Advanced Boiling Light-Water-Cooled and Moderated Reactor	ABWR	4	2			
Advanced Gas-Cooled, Graphite-Moderated Reactor	AGR	14		1		
Boiling Light-Water-Cooled and Moderated Reactor	BWR	90		20	2	18
Fast Breeder Reactor	FBR	3	1	6	2	1
Gas-Cooled, Graphite-Moderated Reactor	GCR	8		29		
High-Temperature Gas-Cooled Graphite-Moderated Reactor	HTGR			4		
Heavy-Water-Moderated, Gas Cooled Reactor	HWGCR			3		
Heavy-Water-Moderated, Boiling Light-Water-Cooled Reactor	HWLWR			2	1	
Light-Water-Cooled, Graphite-Moderated Reactor	LWGR	16	1	8		5
Pressurized Heavy-Water-Moderated and Cooled Reactor	PHWR	41	7	9	3	
Pressurized Light-Water-Moderated and Cooled Reactor	PWR	214	4	17	6	27
Water Cooled Water Moderated Power Reactor	PWR-WWR	53	12	10	11	11
Steam-Generating Heavy-Water Reactor	SGHWR			1		
TOTAL		**443**	**27**	**110**	**25**	**62**

Note: Only reactors for which construction had commenced are counted for cancellations and suspensions.

Reactor Types (Abbreviations and Summary)

Radioisotope Power



Radioisotope Decay

- ***Heat Energy = 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 numerous RHUs launched by U.S. during past 40 years**
- **Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)**
- **Small portion of heat energy (5% - 20%) converted to electricity via passive or dynamic processes.**
- **(Note: PU-238 is the preferred isotope for radioisotope thermoelectric generators.)**

Useful Terms

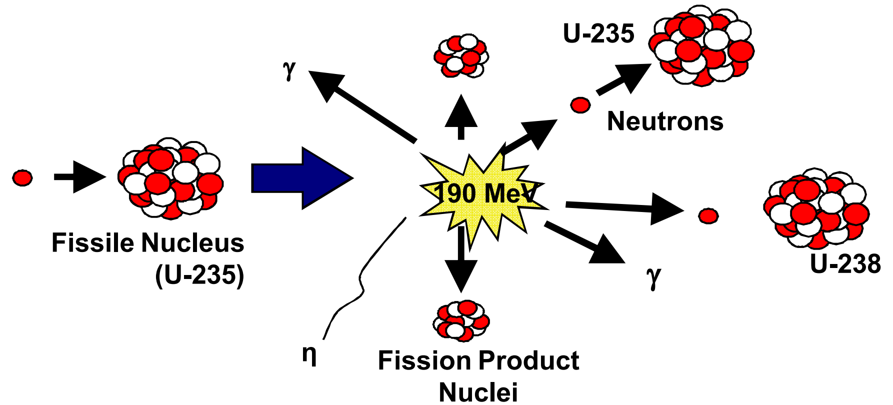
Particles

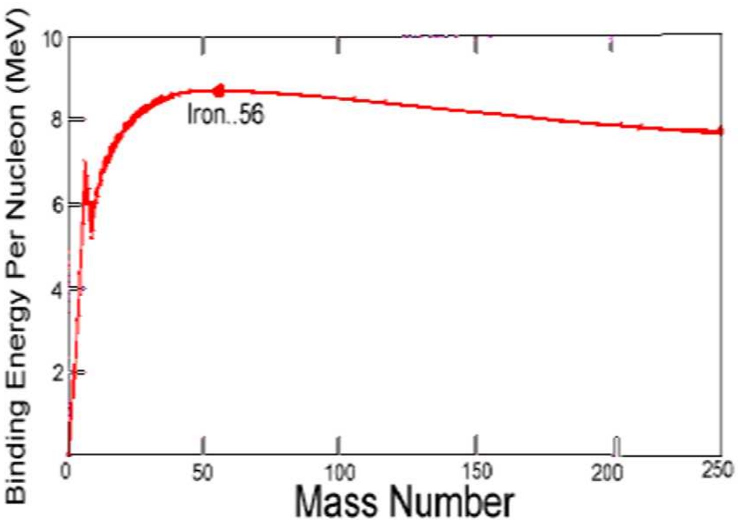
- β^- = electron
- ρ = proton; also a hydrogen nucleus: H
- γ = gamma ray, electromagnetic radiation
- n = neutron, approximately the same weight as ρ, but with no charge
- η = neutrino (don't worry about neutrinos)

Energy/Power

- 1 electron volt = 1 eV = electron energy from acceleration by 1 volt
- 1 MeV = 1×10^{6} eV = 1.602×10^{-13} joules = 1.52×10^{-16} BTU
- 1025 BTU = energy 1 standard cubic foot of natural gas
- 1 watt = 1J/sec

Nuclear Fission Process





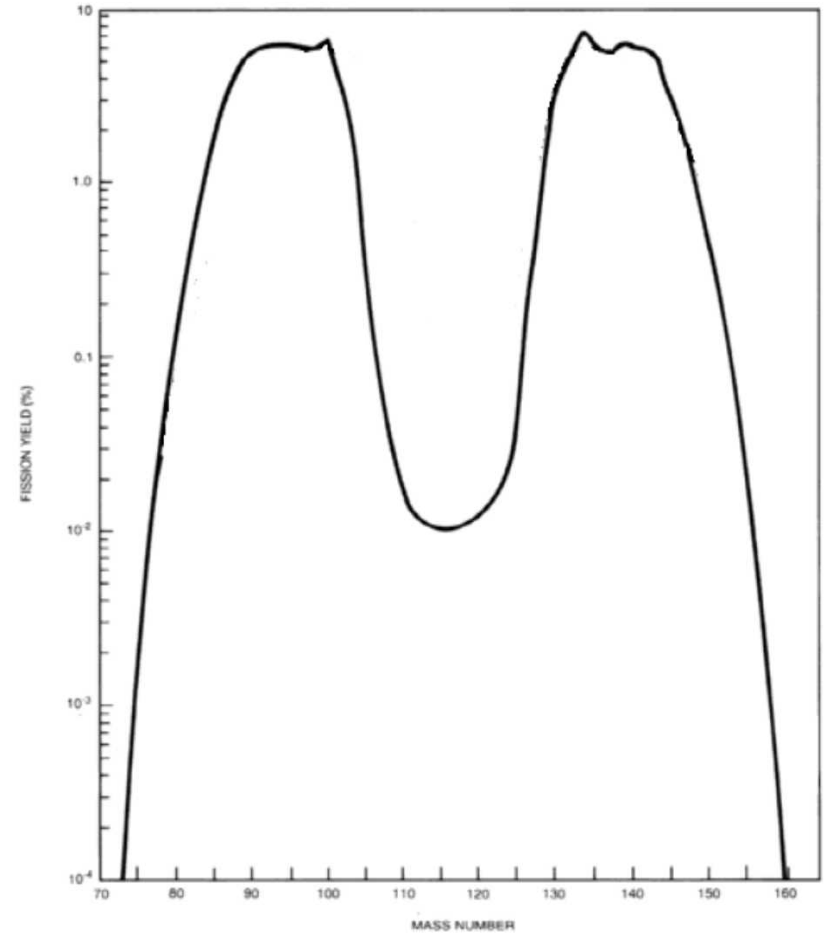
180 MeV prompt useful energy (+ 10 MeV neutrinos) – additional energy released in form of fission product beta particles, gamma rays, neutron capture gammas (~200 MeV total useful).

- 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), Neutrino (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.

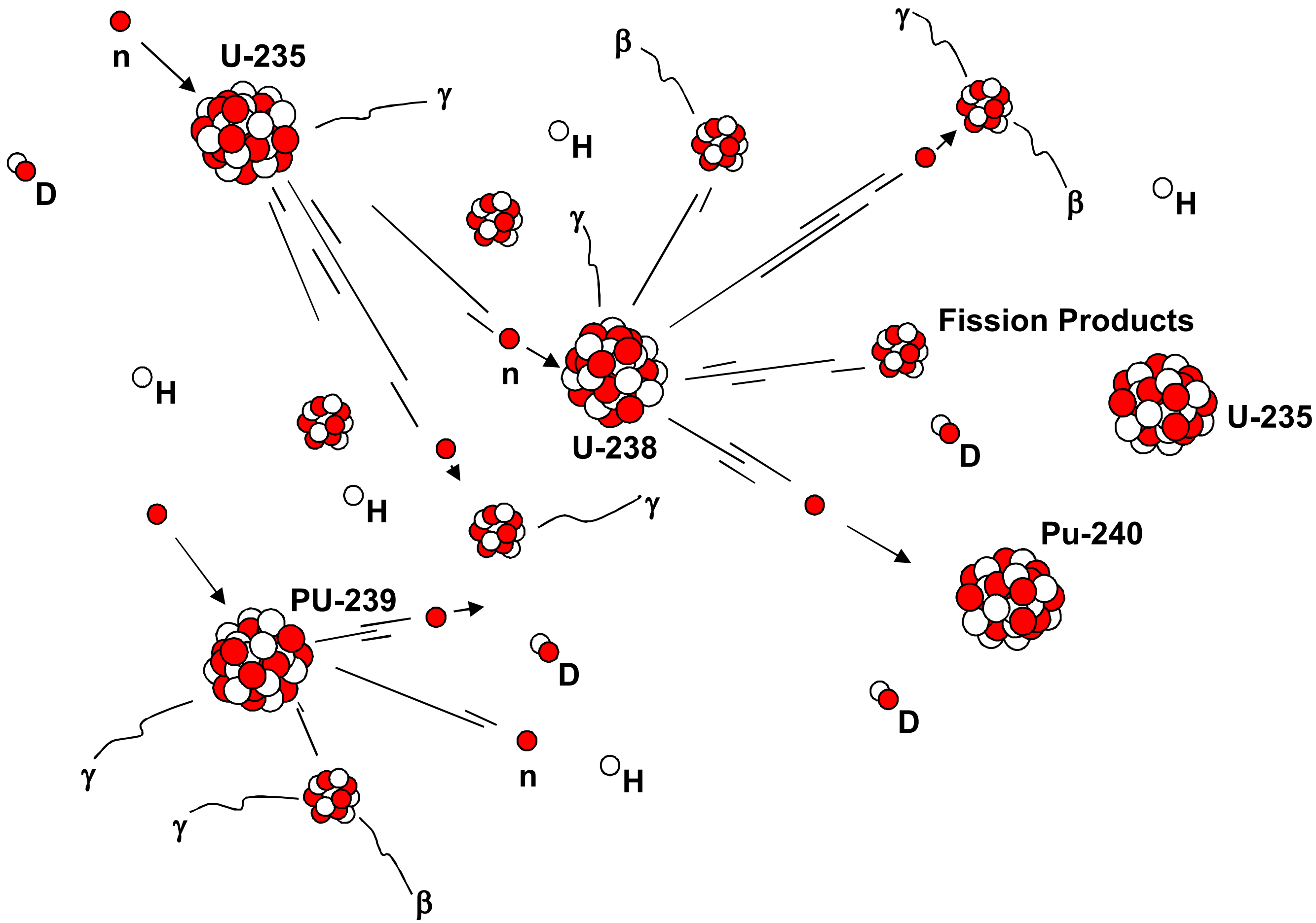
Fission Products

- 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 that 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).

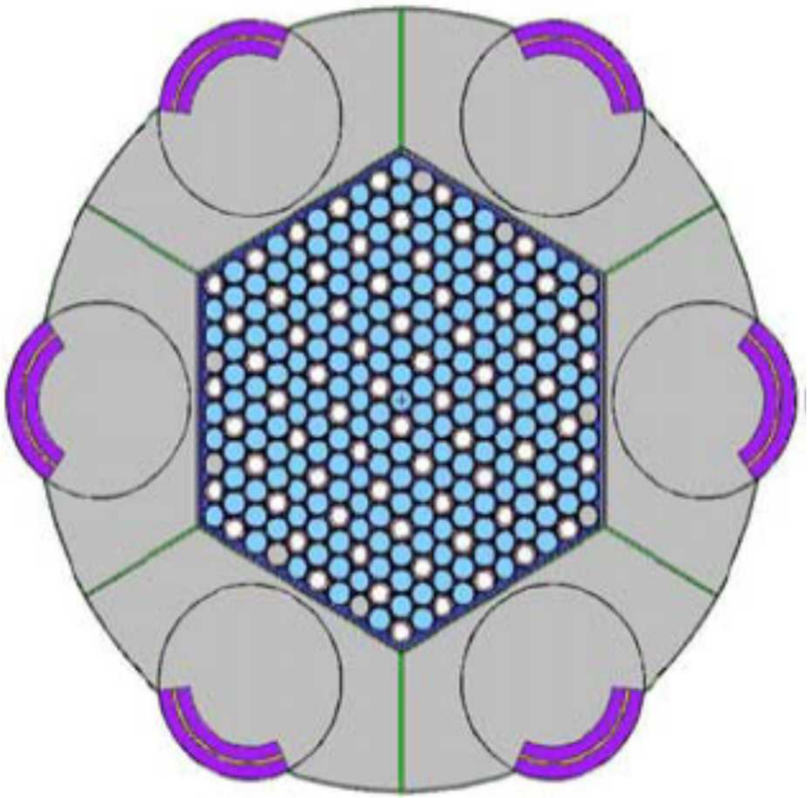
U-235

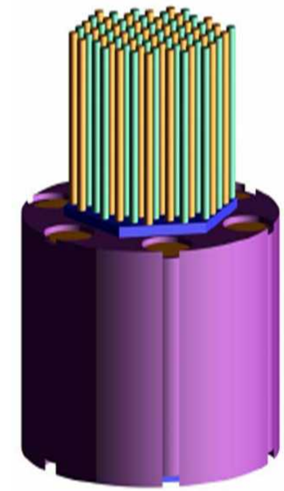


Chain Reaction



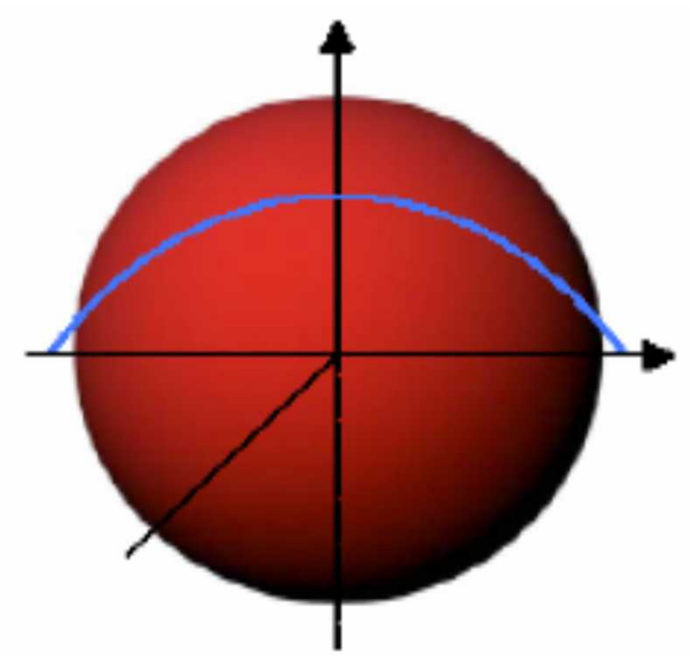
Fission Reactor Operation





- 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 the fraction of neutrons that escape or are captured.
- Burn 1 kg uranium per 1G kW-day.

Nuclear Reactor Basics



Radial neutron flux distribution in spherical core

- Thermal Power $(t) \propto N(t)$ — Core neutron population
- $\frac{dN}{dt} =$ Production Rate − Loss Rate

Production Rate: Fission neutrons

Loss Rate:
Absorption (fission, nonproductive capture)
Leakage (boundaries)

$k \equiv$ Multiplication Factor

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

<1 (subcritical, $dN/dt < 0$)
$=1$ (critical, $dN/dt = 0$)
>1 (supercritical, $dN/dt > 0$)

Delayed Neutrons

Example of Delayed Neutron Precursor

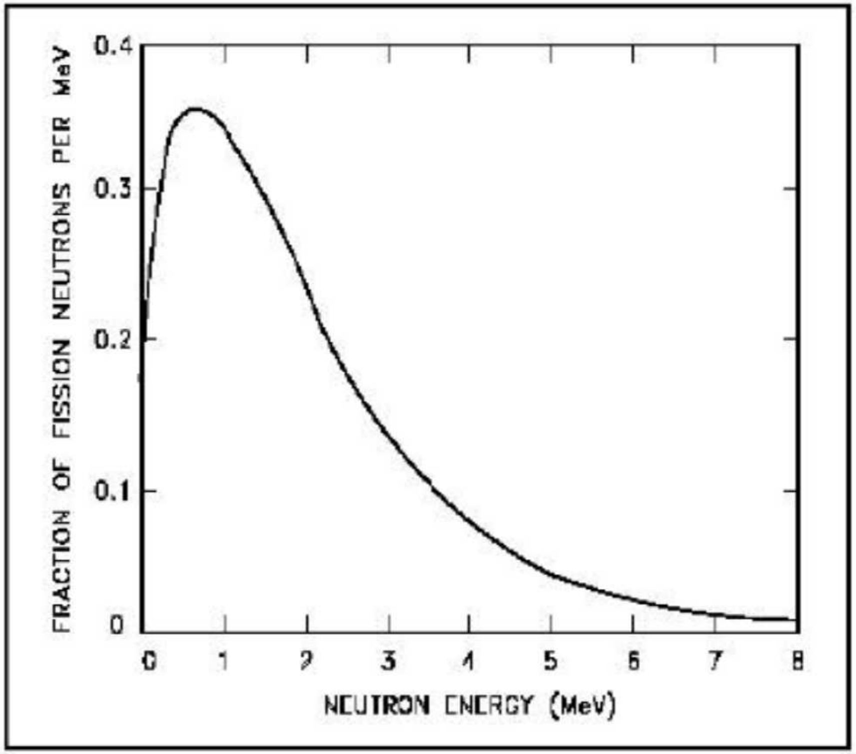
$$^{87}_{35}\mathrm{Br} \xrightarrow[55.9\ \mathrm{sec}]{\beta^-} {}^{87}_{36}\mathrm{Kr} \xrightarrow[\mathrm{instantaneous}]{n} {}^{86}_{36}\mathrm{Kr}_{\mathrm{stable}}$$

Other important neutronic parameters:
Nu = ν average numbers of neutrons liberated per fission
Eta = η = neutrons liberated per neutron absorbed

	ν (0.025 eV)	η (0.025 eV)	ν (1 MeV)	η (1 MeV)
U-233	2.49	2.29	2.58	2.40
U-235	2.42	2.07	2.51	2.35
Pu-239	2.93	2.15	3.04	2.90

Prompt vs. Delayed Neutrons

- >99% of total fission neutrons are prompt neutrons.
- Prompt neutrons released within 1.0 x 10^{-14} s of the instant of fission.
- Most prompt neutrons have energies between 1 and 2 MeV, some > 10 MeV.



Prompt Fission Neutron Energy Spectrum for Thermal Fission of Uranium-235

Prompt vs. Delayed Neutrons (cont.)

- Fraction of delayed neutrons varies with isotope and (slightly) with neutron spectrum.
- Average delayed neutron energy is significantly less than average prompt neutron energy.
- Delayed neutron "importance factor" >1 for compact HEU systems.

Delayed Neutron Fractions for Various Fuels				
Group	**Half-Life (sec)**	**Uranium-235**	**Uranium-238**	**Plutonium-239**
1	55.6	0.00021	0.0002	0.00021
2	22.7	0.00141	0.0022	0.00182
3	6.22	0.00127	0.0025	0.00129
4	2.30	0.00255	0.0061	0.00199
5	0.61	0.00074	0.0035	0.00052
6	0.23	0.00027	0.0012	0.00027
Total	**-**	**0.00650**	**0.0157**	**0.00200**

Reactor Kinetics

Multiplication factor = k = $\frac{\text{\# neutrons in generation n + 1}}{\text{\# neutrons in generation}}$

Reactivity = ρ = (k-1)/k, where k is the effective multiplication factor

Reactivity in "$" = ρ / β

Delayed neutron fraction = β = $\frac{\text{\# delayed neutrons per fission}}{\text{\# total neutrons per fission}}$

Prompt neutron lifetime

$$\boldsymbol{l = 1 / (\nu \Sigma_a (1 + L^2B_g^2))}$$

Where

$\boldsymbol{l}$ = prompt neutron lifetime

$\boldsymbol{\nu}$ = average neutron speed

$\boldsymbol{\Sigma_a}$ = macroscopic absorption probability

$\boldsymbol{1 + L^2B_g^2}$ = nonleakage probability

Prompt neutron lifetime is on order of 10^{-6} s for compact, fast-spectrum system

Reactor Kinetics (cont.)

If there were no delayed neutrons, reactor would be difficult to control

Reactor period = $T_p = l/\rho$

Example: $\rho = 0.00001$, $l = 1$ microsecond => $T_p = 0.01$ s

Delayed neutrons stabilize operation:

$$l_{eff} \approx l + (\beta - \rho)/\lambda$$

where λ = properly weighted average decay constant for six actual delayed neutron groups $\approx 0.08\ s^{-1}$

Actual stable reactor period would be $T_{peff} = (\beta - \rho)/\lambda\ \rho = 800$ seconds in previous example

Reactor Kinetics (cont.)

Delayed neutrons also limit rate at which fission power can be reduced

Prompt Jump (or Prompt Drop):

$$\Phi/\Phi_0 \approx \beta / (\beta - \rho)$$

Where Φ = neutron flux, β = effective delayed neutron fraction, ρ = reactivity

Example: If "full shutdown" gives reactivity extraction of 0.1, then
$\Phi/\Phi_0 \approx 0.0065 / (0.0065 + 0.1) = 0.061$ => 6.1% full power

After a short period of time, power continues to decrease by a factor of "e" every 800 s, with delayed neutrons limiting the rate of decrease.

Photoneutrons can also limit the rate the neutron flux decreases.

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 / m^3

v = neutron speed (m/s)

Reaction rate = $\Phi N \sigma$

N = nuclei / m^3

Φ = neutron flux (neutrons / m^2-s)

σ = cross section (m^2)

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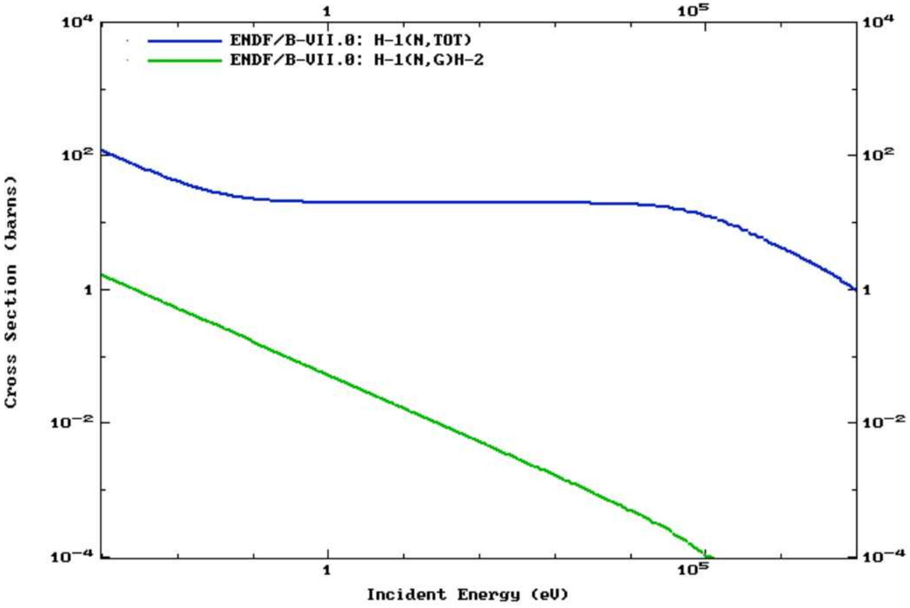
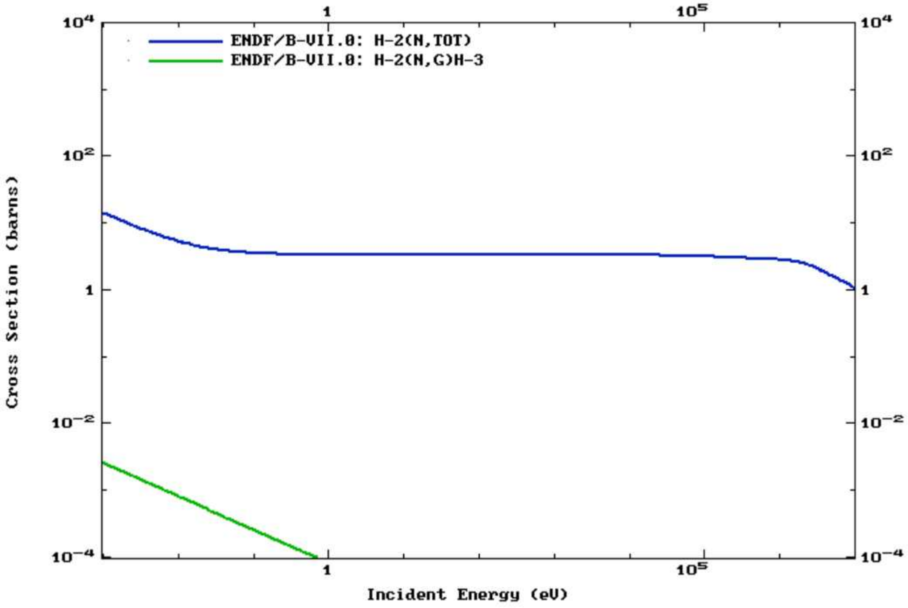
Comparison of Hydrogen and Deuterium Cross Sections

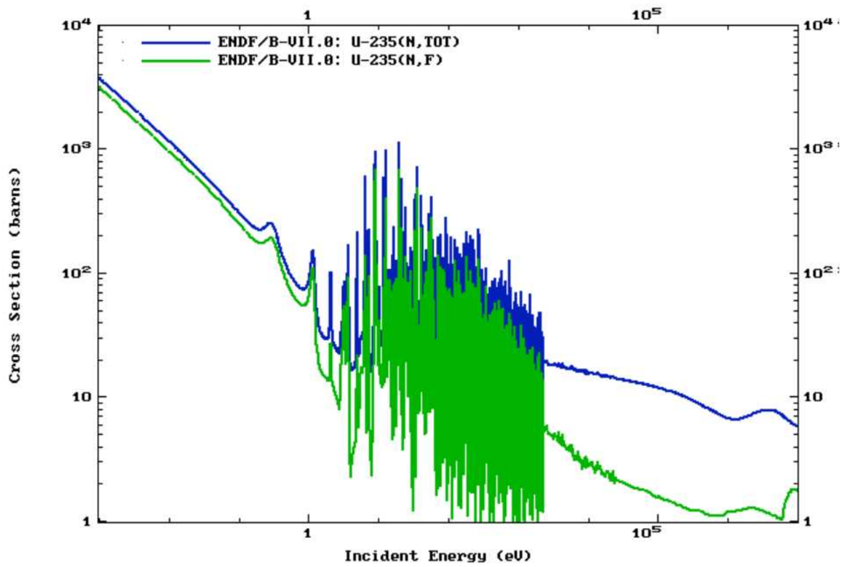


H_1

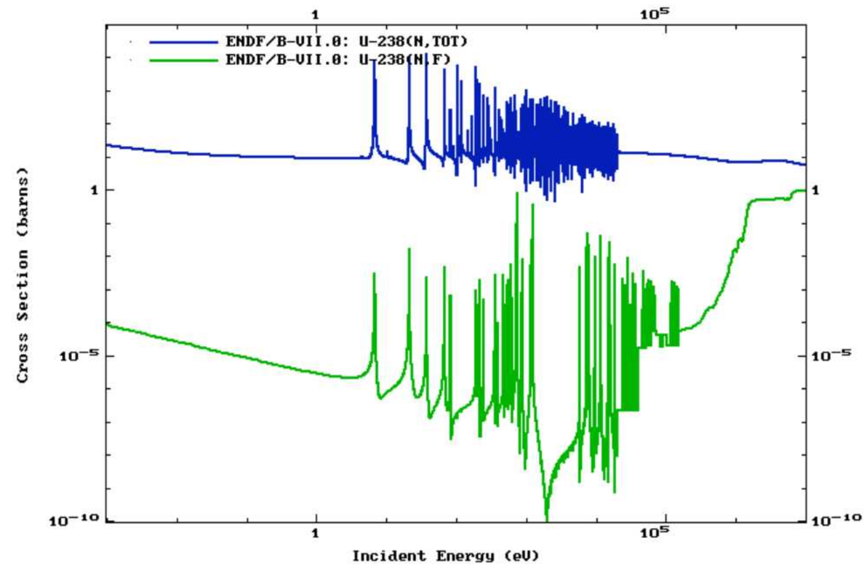


H_2

Uranium Energy Dependent Cross Sections



U-235



U-238

Natural Uranium is 98.3% U-238 and 0.07% U-235

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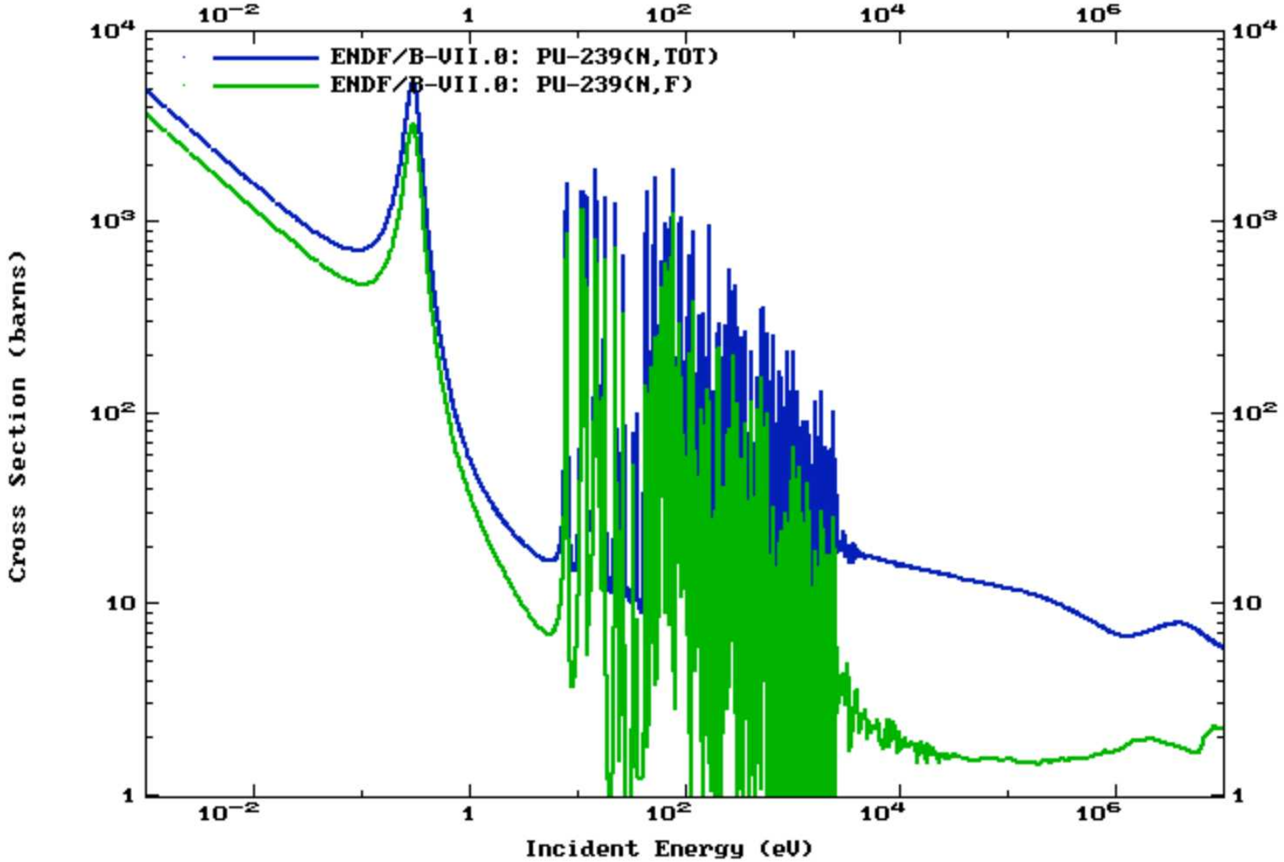
Plutonium Energy Dependent Cross Section



Pu-239

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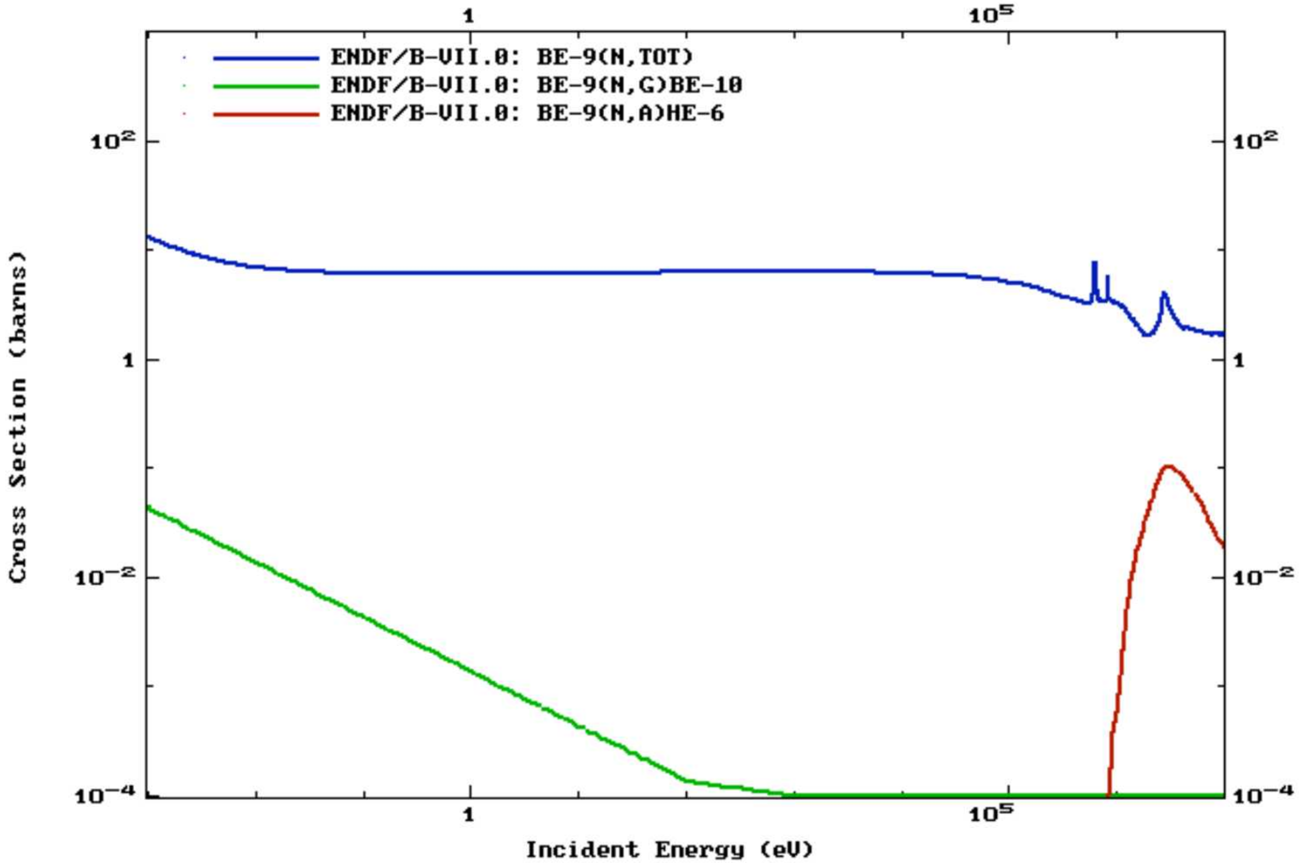
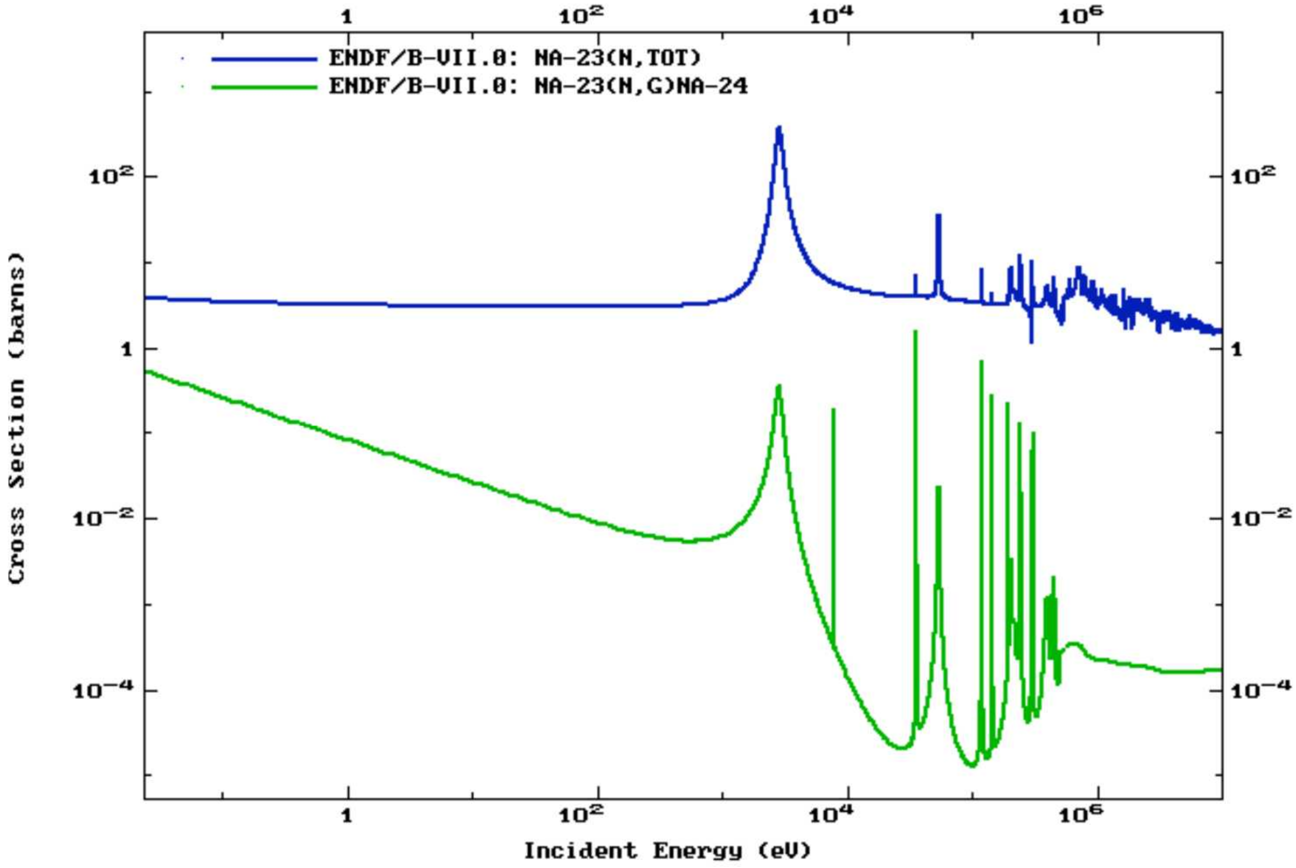
Beryllium Energy Dependent Cross Section



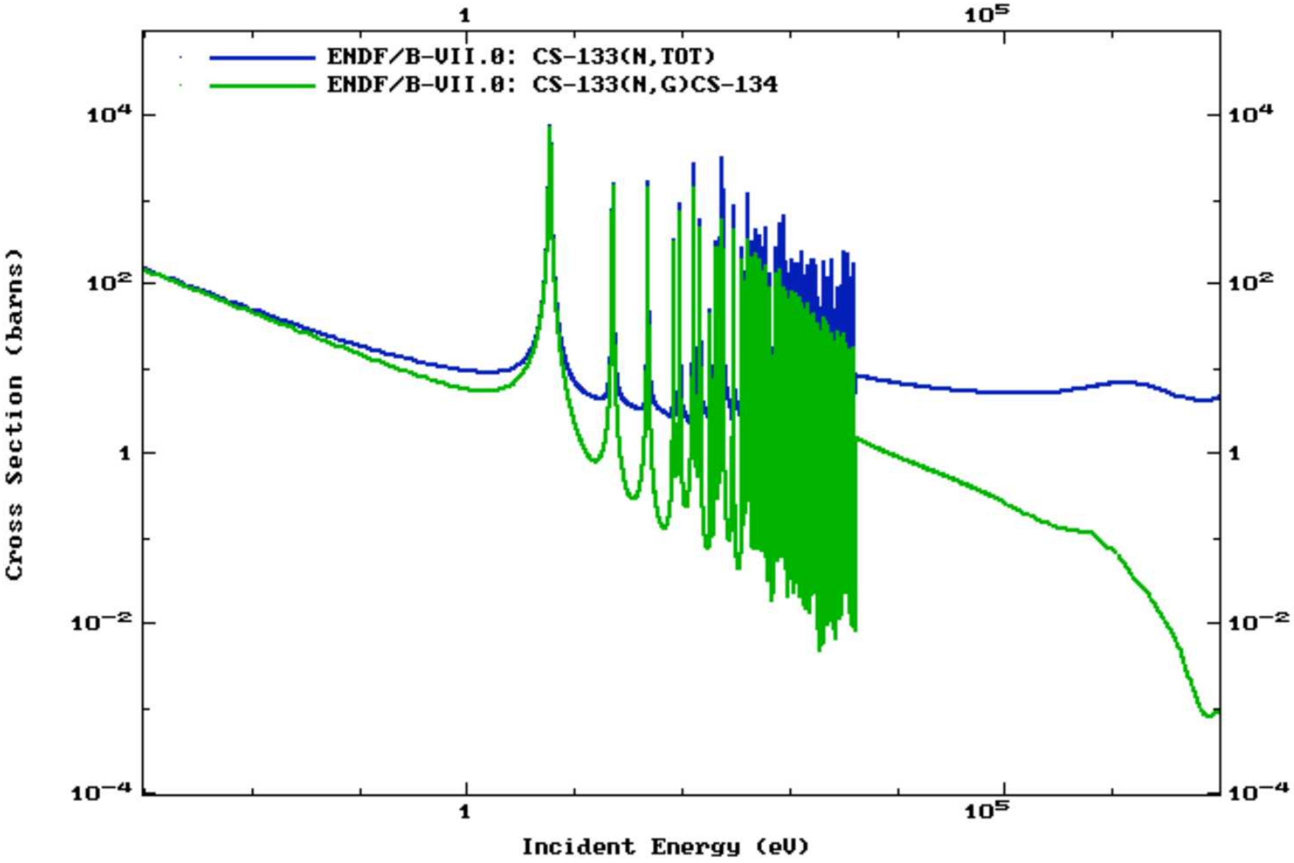
Be-9

Sodium Energy Dependent Cross Section



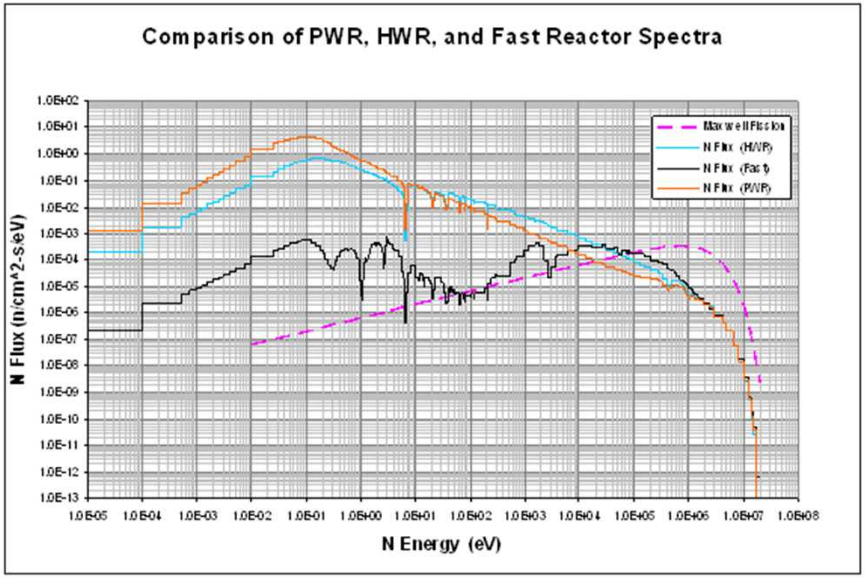
Na-23

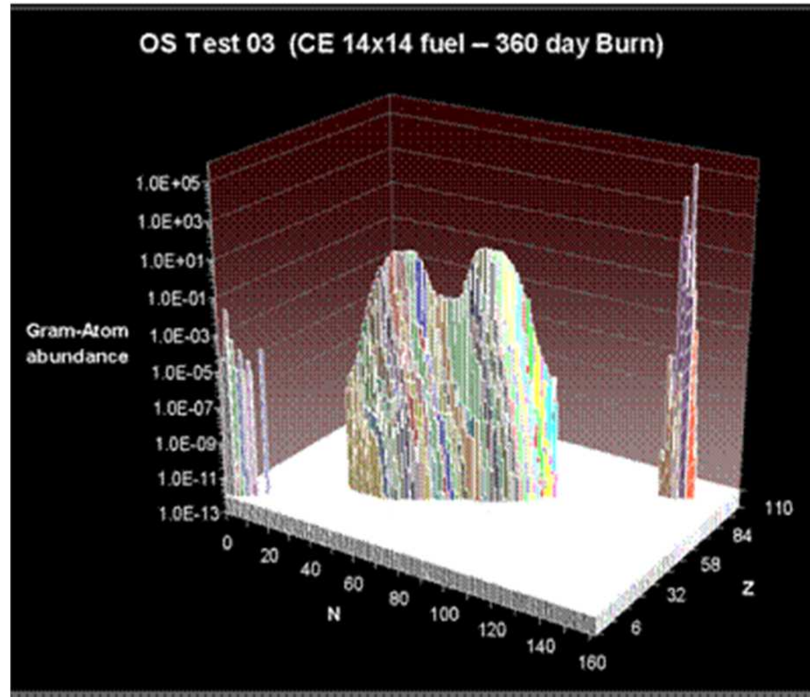
Cesium Energy Dependent Cross Section



Cs-133

Reactor Core Flux and Nuclides





- The neutron flux and nuclide abundance from the combustion engineering 14x14 cell reactor core model.
- Flux is calculated for heavy-water, light-water, and fast reactor configurations.
- Nuclide abundance is for a light-water configuration.

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Conversion and Breeding

Breeding is the conversion of non-fissile nuclides to fissile ones.

Typical Fissile Nuclides: U-233, U-235, Pu-239, Pu-242

Typical Fissionable Nuclides: Th-232, U-238, Pu-240, Pu-242

U-Chain:

$$n + U^{238}_{92} \rightarrow U^{239}_{92} + \gamma \xrightarrow[23m]{\beta^-} Np^{239}_{93} \xrightarrow[23d]{\beta^-} \underset{\text{fissile}}{Pu^{239}_{94}}$$

Pu-Chain:

$$n + Pu^{239}_{94} \begin{cases} \nearrow \ \textbf{fission} \\ \searrow \ P^{240}_{94} \end{cases}$$

$$Pu^{240}_{94} + n \rightarrow \underset{\text{fissile}}{Pu^{241}_{94}} + \gamma$$

Th-Chain:

$$n + Th^{232}_{90} \rightarrow Th^{233}_{90} + \gamma \xrightarrow[2.2m]{\beta^-} Pa^{233}_{91} \xrightarrow[27.4d]{\beta^-} \underset{\text{fissile}}{U^{233}_{92}}$$

Approximately 50% of the power in a CANDU comes from PU, even though there is none in the initial fuel.

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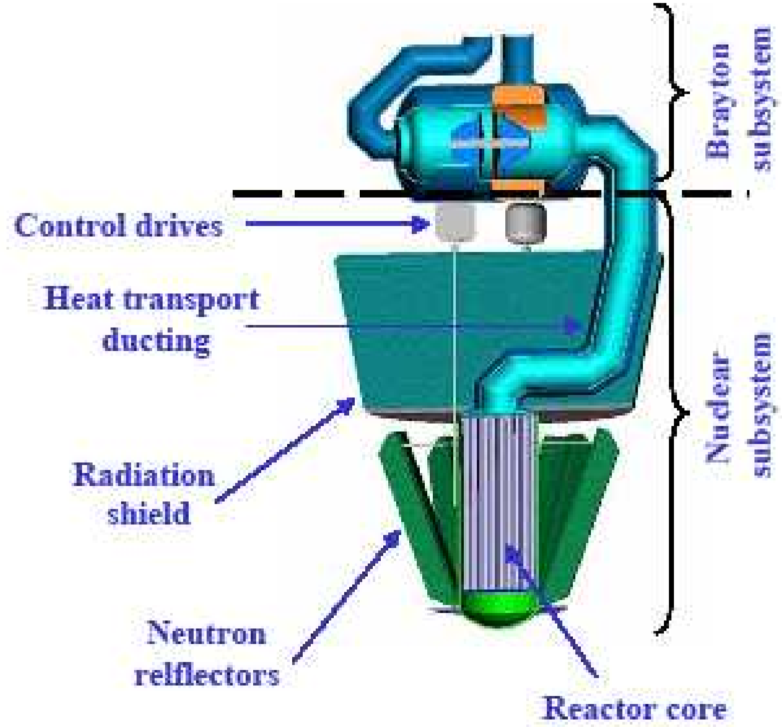
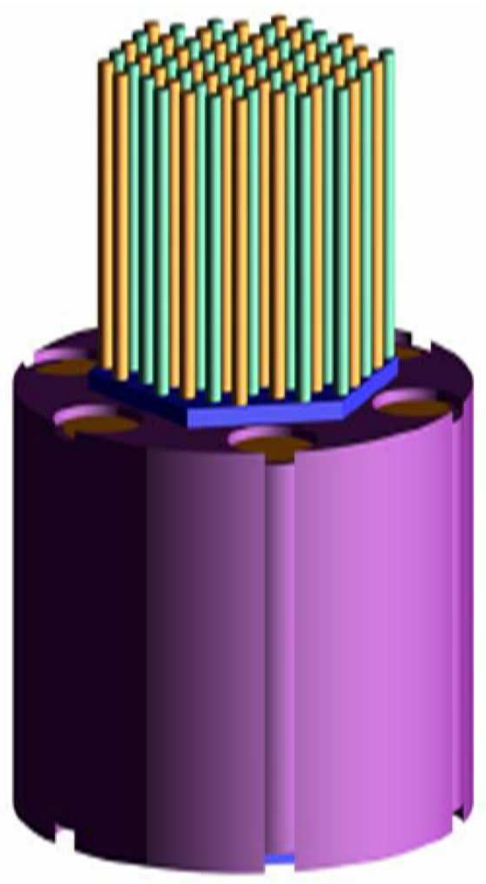
Nuclear Subsystem Functions

- **Reactor Core**
  - Typically consists of an array of fuel pins
  - Produces heat by fissioning of ^{235}U
- **Primary heat transport**
  - Transfers heat from reactor core to power conversion subsystem
  - Gas or liquid metal (loop or Heatpipe)
  - Usually includes an intermediate heat exchanger
- **Radiation shield**
  - Limits gamma and neutron doses to other subsystems and payload
- **Instrumentation and control**
  - Controls fission rate in reactor core
  - Controls startup, shutdown, and other transients
  - Maintains subcriticality under accident conditions
- **Structure**
  - Supports NSS components during all mission phases
  - Provides mounting interface to power conversion subsystem and NEP vehicle



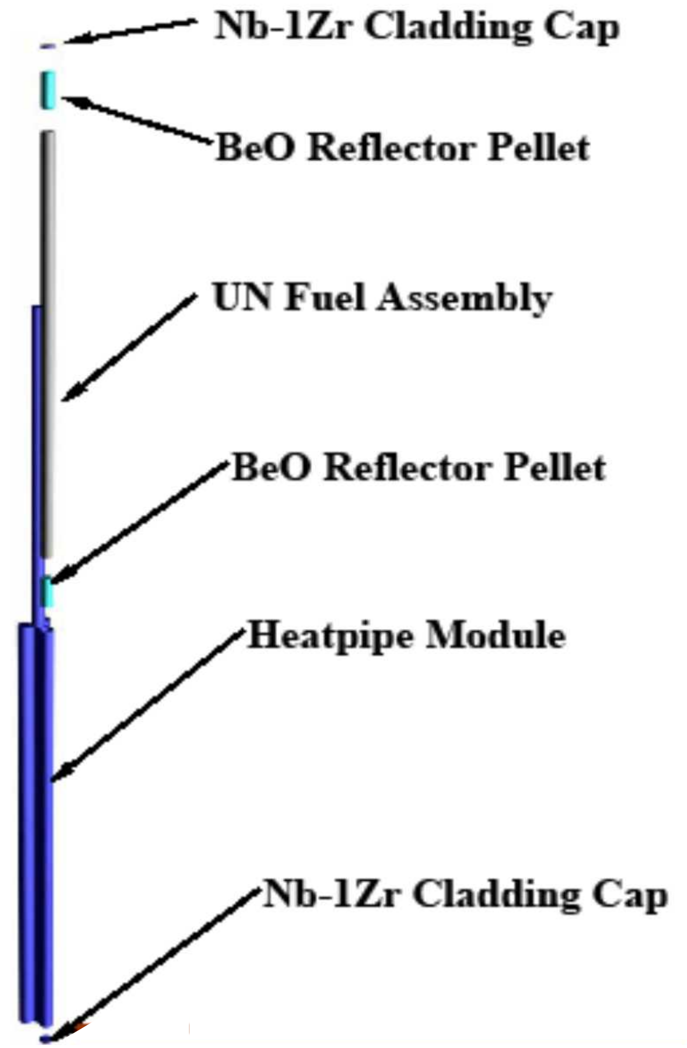
(Gas-cooled direct Brayton example shown)

Principle Nuclear Reactor Elements: Core



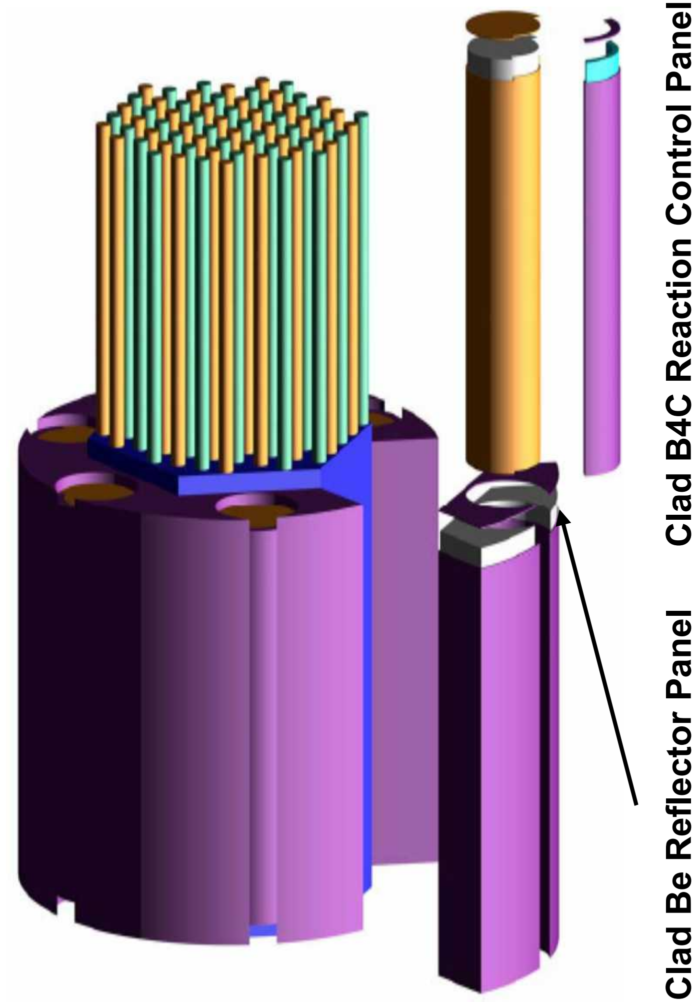
- Designed to maintain stable chain reaction process while delivering power at desired temperature distribution.
- Options for core cooling include heat pipes, pumped gas, and pumped liquid metal. Each has advantages and disadvantages, depending on overall system design and application.
- Core designed for safe, stable operation. Materials and geometry chosen so that power increase results in reactivity decrease.
- Minimum required fissile material mass typically less for moderated reactors than for fast-spectrum reactors. Total system mass may be similar because of other factors.
- Hydrogenous moderators limited to peak operating temperature of 1000 K, potentially limiting power conversion efficiency.

Principle Nuclear Reactor Elements: Fuel



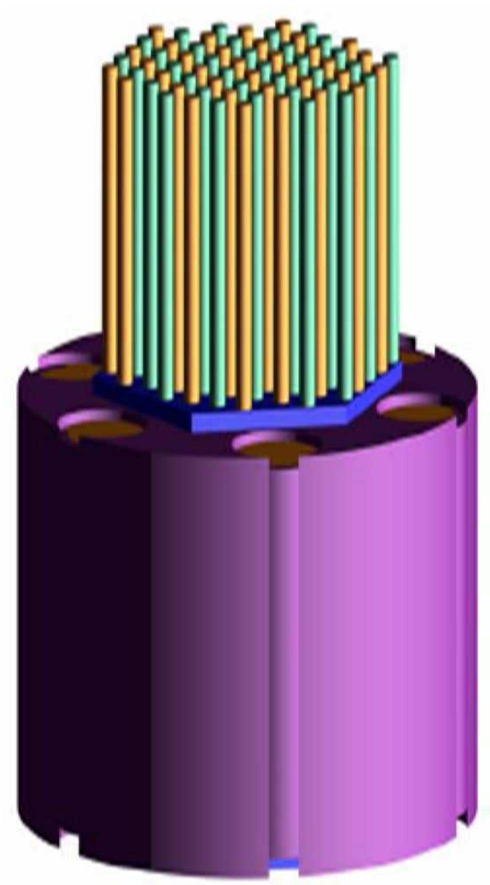
- **Numerous fuel options available. Choices include:**
  - Geometry (e.g., pin, particle, prismatic, foil)
  - Isotope (e.g., U-233, U-235, Pu-239, Am242m)
  - Compound (e.g., U-metal, UZrH, UO_2, UN, UC, UC2, UCZrN, (U,Zr,Nb)C, UF_4)
- **Factors to consider include the following:**
  - Required fuel operating temperature
  - Fuel burnup (fraction of uranium fissioned
  - Fuel operating environment
  - Fabricability / technical risk
  - Desired / required uranium density
  - Core power density
- **Two leading fuel options are UO_2 and UN**
  - UO_2 flown in space (TOPAZ), used by commercial power industry and Navy, available commercially and from National Laboratories
  - UN (current baseline) developed during SP-100 and previous programs. High uranium loading, high thermal conductivity, low swelling/fission gas release

Principle Nuclear Reactor Elements: Moderator/Reflector/Control/Shield



- **Moderator**
  - Hydrogen best moderator material for space systems. UZrH or UZrH good to 1000 K
- **Reflector**
  - Beryllium (Be) and Beryllium Oxide (BeO) best for space systems
  - Be flown in space, easier to fabricate
- **Control**
  - Control by varying neutron capture in reflector region (rotating control drums) or by varying rate of neutron escape (sliding or pivoting reflector)
  - Rotating control drums flown in space. Sliding reflectors potential advantage for certain designs
- **Shield**
  - High-Z material for gamma attenuation (e.g., W)
  - Hydrogenous material for slowing down neutrons
  - Reduce capture-gamma generation (Li-6 or B-10 for absorbing neutrons)
  - Reduce gammas produced by inelastic scatter (layered shield)

Reactor Control and Safety



- **Design for inherent stability**
  - Negative temperature and power reactivity feedback coefficients
  - Neutron escape dominates in small, fast-spectrum system
- **Provide redundant and diverse shutdown mechanisms**
  - Reflector control (e.g., drums, sliders)
  - Reflector ejection
  - In-core control rods
- **Minimize mission-ending single point failures in control system**
  - System remains operational following single or multiple control system failures
- **Prevent inadvertent system start**
  - Preclude inadvertent system start during all credible launch accidents
  - System essentially non-radioactive at launch

Reactor Lifetime

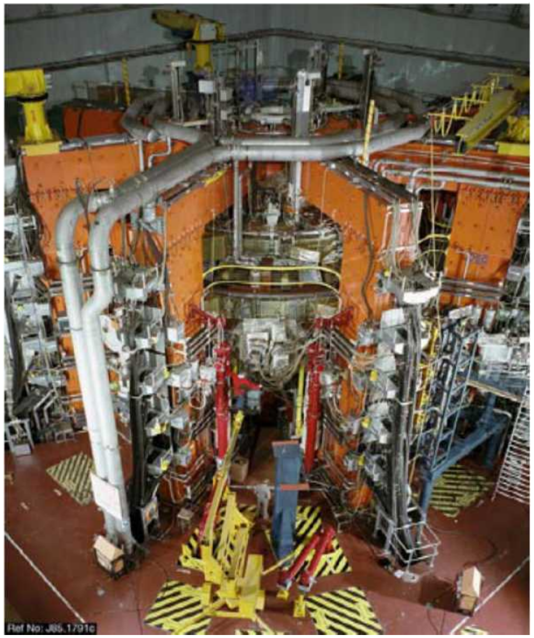
- A reactor power plant's lifetime and reliability are determined by a complex set of material engineering tradeoffs:
  - Corrosion
  - Radiation damage, swelling
  - Creep, stress effects
  - Thermal loads
- The oldest operating power reactor is the 230 MW(e) GCR Dungeness-A1, which began commercial operation in October 1965.
  - EBR II ran for 32 yr producing 20 MW(e) power.
- One of the shortest operating commercial reactor was the 94 MW(e) Fermi I, which began commercial operation from August 7 until October 5, 1966, and July 18, 1970, through November 1972.

Beyond Fission: Potential Futuristic Nuclear Energy Sources

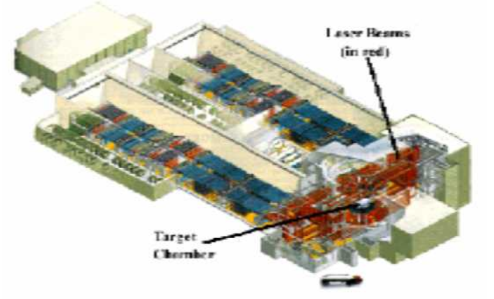
Fusion. The performance potential of lightweight, high-gain fusion propulsion systems operating with aneutronic fuels (e.g., $p\text{-}^{11}B$) theoretically exceeds that of fission by an order of magnitude.

Fundamental Issues to Resolve:

1. **Aneutronic Fuels.** The performance potential of fusion propulsion systems operating with deuterium- or tritium-bearing fuels (e.g., D-T, D-D, or $D\text{-}^{3}He$) is severely limited because of waste heat production from neutron kinetic energy, and the additional waste energy released when a neutron of any energy is captured. The use of aneutronic fuels (e.g., $p\text{-}^{11}B$) will be required for high performance.
2. **High Gain.** Recent studies (Chakrabarti, et al., 2001) have shown that high engineering gain (Q>50) is needed to minimize the mass of the fusion reaction driver and enable high performance.
3. **Compact Systems.** Tens of billions of dollars and five decades have been spent on research related to controlled fusion. While the two leading approaches for achieving engineering breakeven are extremely massive, knowledge and experience from the ongoing terrestrial fusion effort may be useful in devising compact systems suitable for space propulsion applications.



Photograph Courtesy of EFDA-JET



National Ignition Facility

Beyond Fission: Potential Futuristic Nuclear Energy Sources (cont.)

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

Fundamental Issues to Resolve:

1. **Production.** Antiproton production rates must increase by several orders of magnitude, and the cost per antiproton must decrease correspondingly.
2. **Storage.** Effective methods for long-term antiproton storage and transportation must be developed.
3. **Thrust Production.** Effective methods for converting energy stored as antimatter into high specific impulse thrust must be devised.

Antiproton Decelerator at CERN

High Performance Antiproton Trap (HiPAT) at NASA MSFC