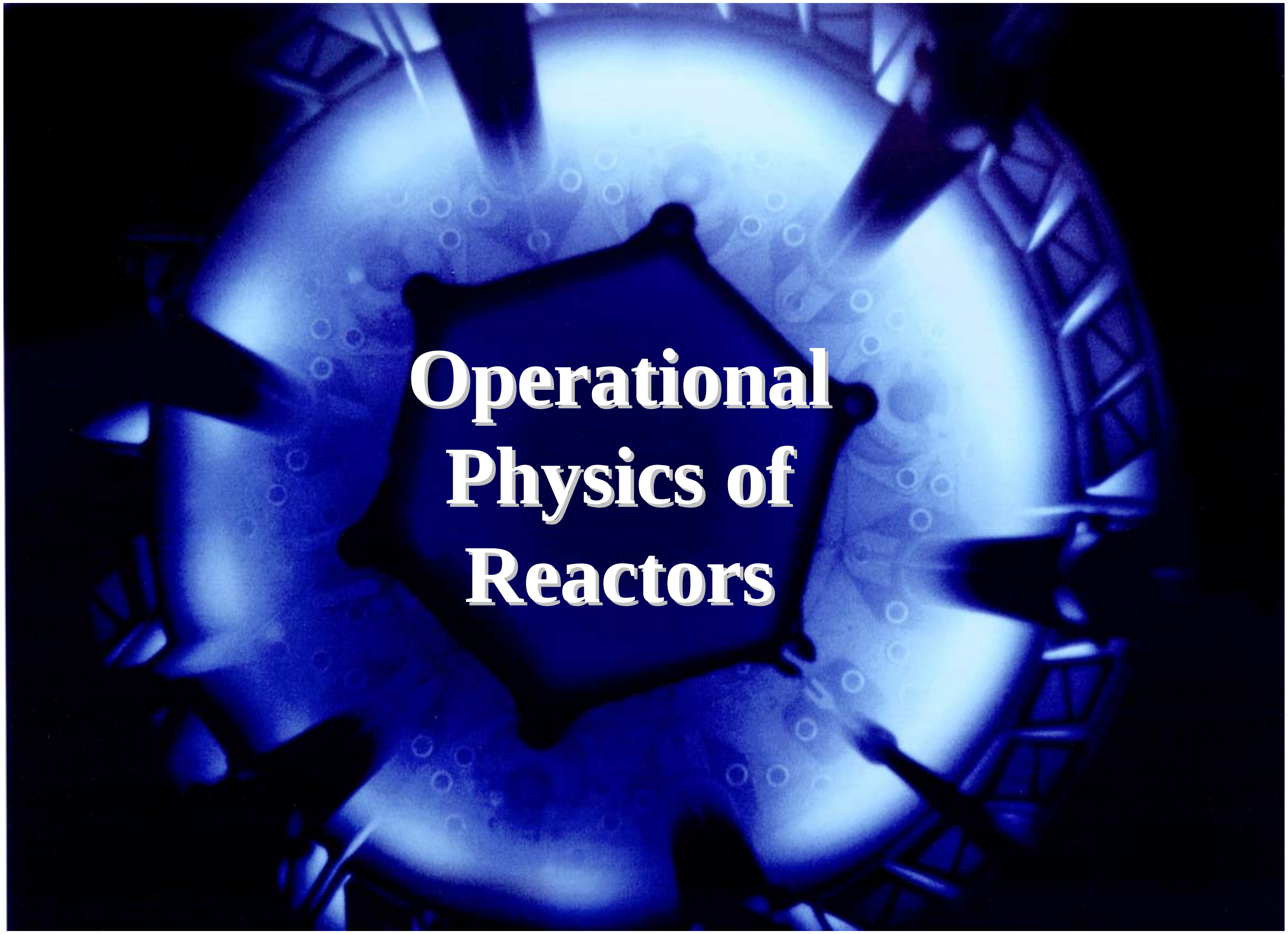
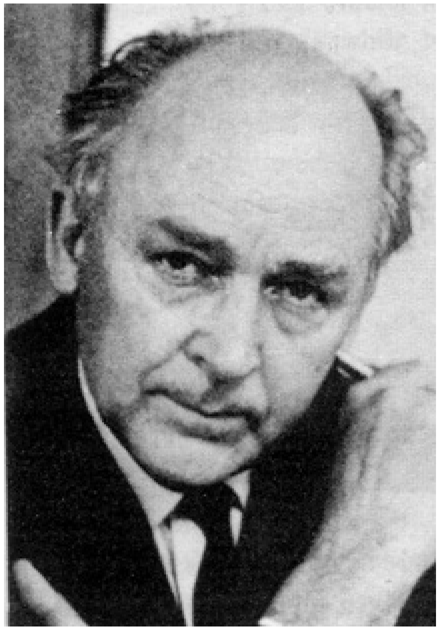

Operational
Physics of
Reactors

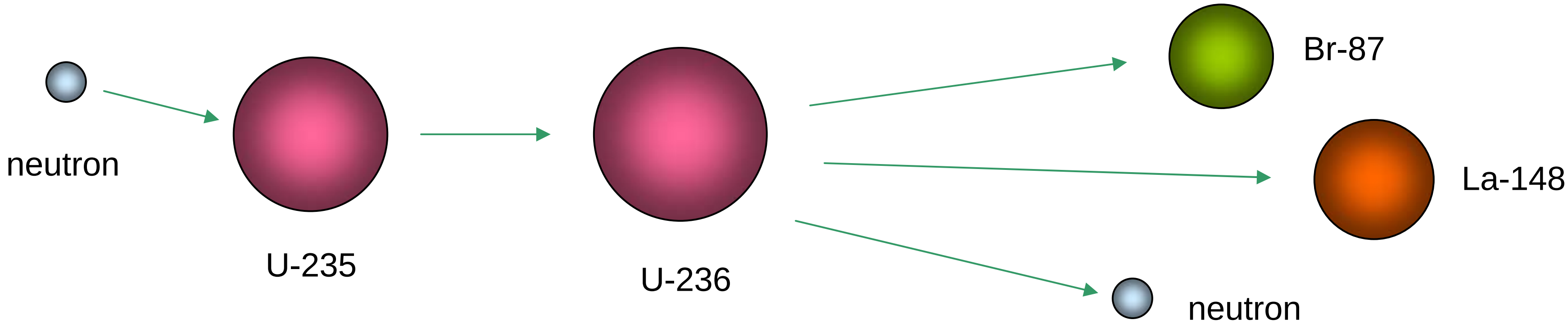
Discovery of Fission



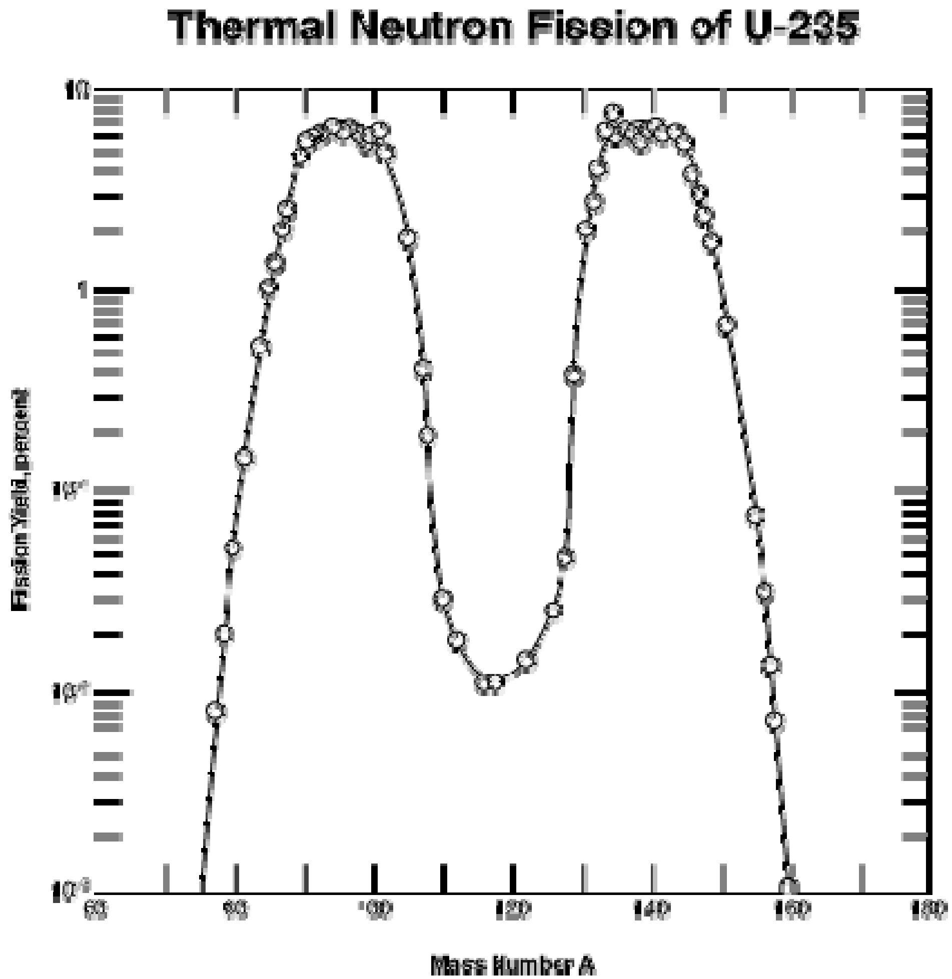
In 1939, Hahn (left) and Strassman (right) discovered that neutrons react with uranium nuclei to cause fission in which the heavy nucleus splits into two smaller and not necessarily equal nuclei plus "debris" such as neutrons, gamma-rays, electrons, etc.

Many fission reactions are possible. Below is an example.

$$ {}_{0}^{1}n + {}_{92}^{235}U \rightarrow {}_{35}^{87}Br + {}_{57}^{148}La + {}_{0}^{1}n $$

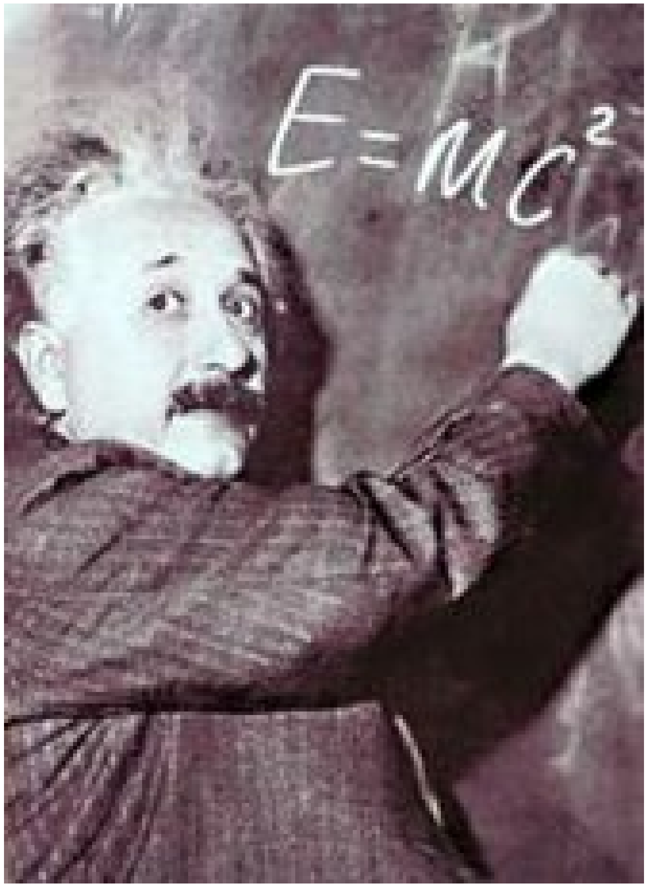


Fission Yield



Graph used with permission of Prof. Chung (Peter) Chieh of the University of Waterloo.

This graph demonstrates the likelihood of various fission fragments resulting from U-235 thermal neutron fission. Note that the two peak yields occur around atomic masses of 94 and 140.



Conservation of Mass

In the equation below, the number of nucleons balance and the charges balance.

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{87}_{35}Br + {}^{148}_{57}La + {}^{1}_{0}n $$

However, what happens when you try to balance the mass?

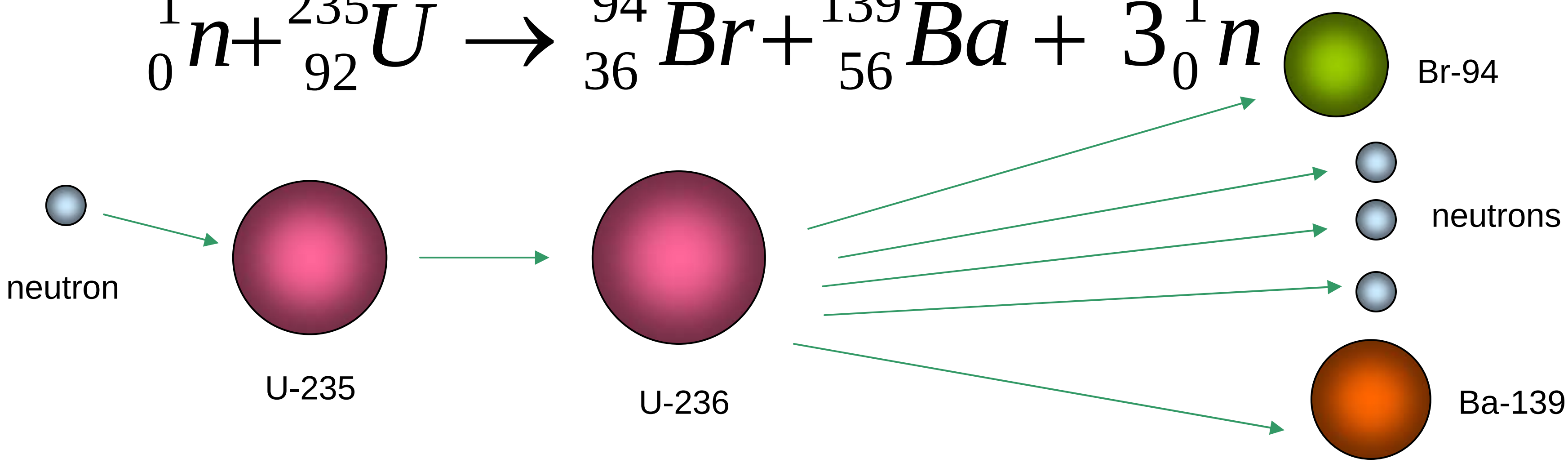
Mass of Input	Mass of Output
235.11240	86.95722
	147.98930
235.11240	234.94652

Using Einstein's mass-energy equivalence, the loss of .16588 atomic mass units implies that an extra 155 MeV of energy is created because of the laws of conservation of mass. This is often termed "binding energy."
(c^2 = 931.494 MeV/amu)

U-235 Specific Fission

Around the same time as Hahn and Strassman's work, Otto Frisch (left) and Lise Meitner (right) showed that U-235 fission yielded at least two neutrons per neutron absorbed in the interaction. Because of the production of more than one neutron per neutron absorbed, a chain reaction is possible.

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{94}_{36}Br + {}^{139}_{56}Ba + 3\,{}^{1}_{0}n $$

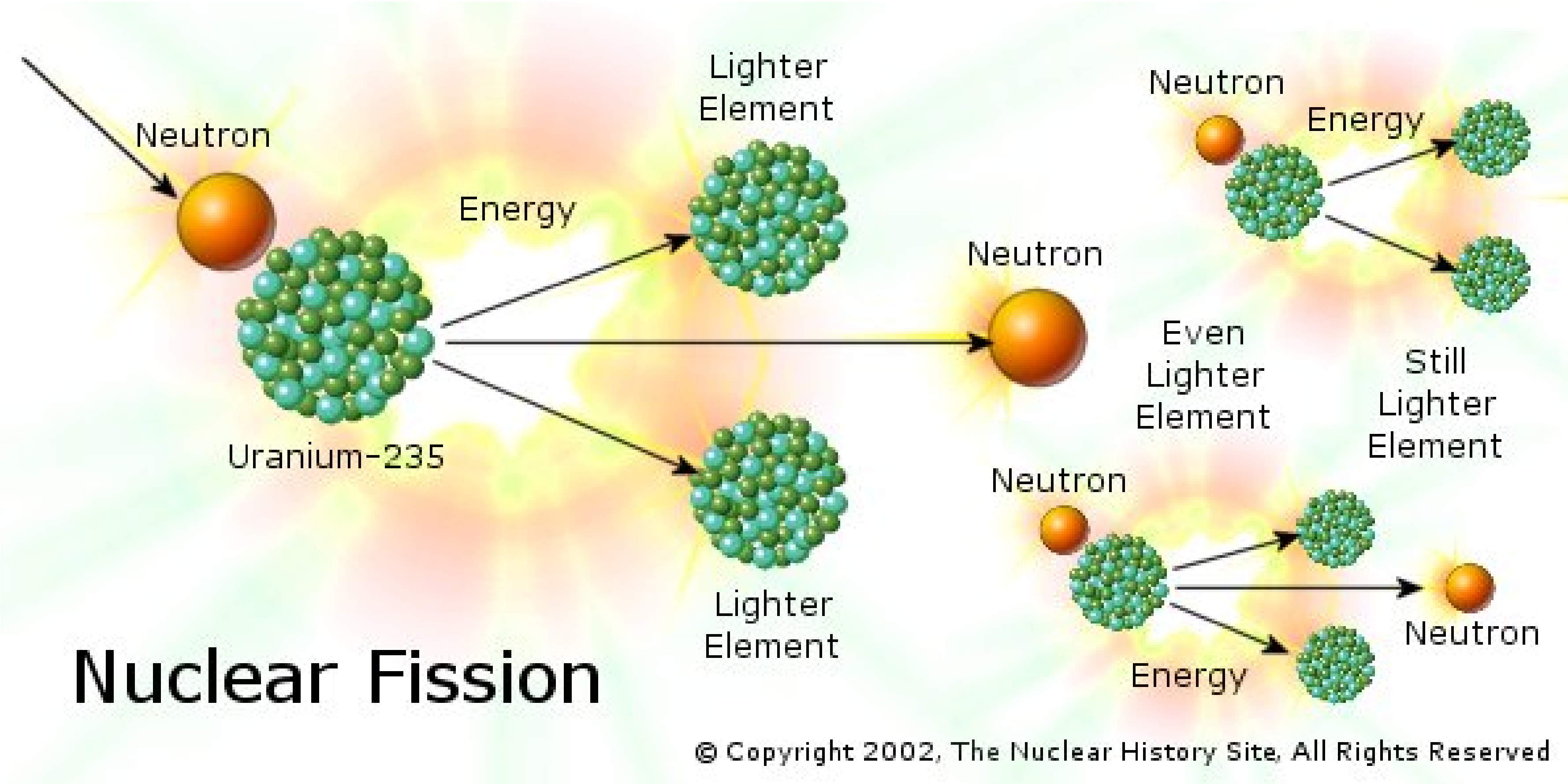


Fuel Comparison for Different Fissile Nucleui

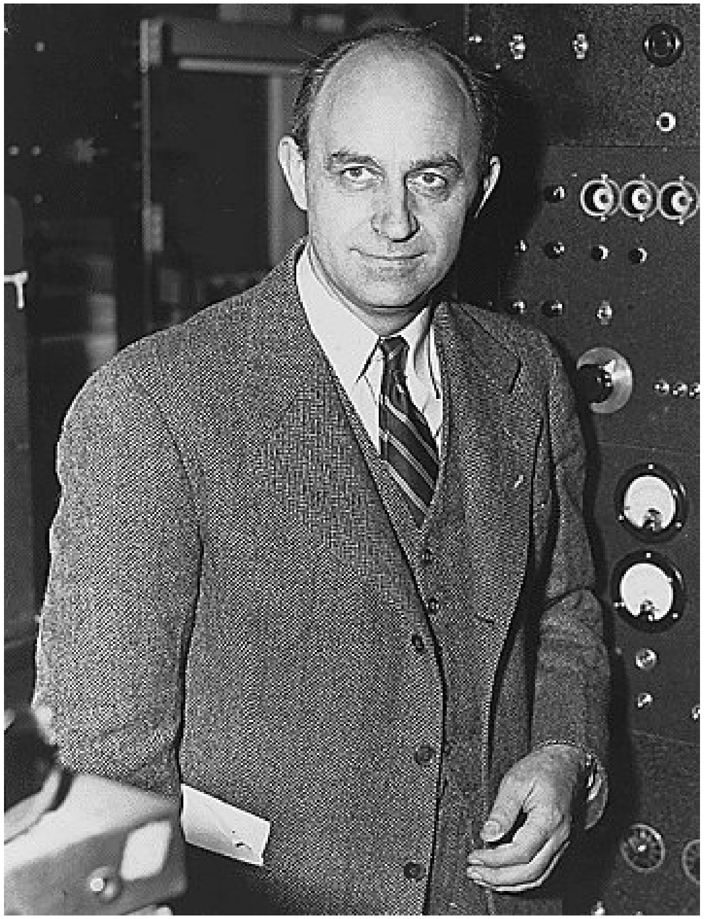
Nuclide	ν (Number of Neutrons Produced Per Fission Event)
U-233	2.50
U-235	2.43
Pu-239	2.90

Following Frisch and Meitner’s work, other potential fissile nucleui were characterized in order to determine their suitability for reactor fuel. This table describes the fuel reproduction ability (ability to sustain a chain reaction) for potential fuel sources. It is important to note that sometimes neutrons are absorbed in a nucleui without producing a fission.

Nuclear Energy is Possible!



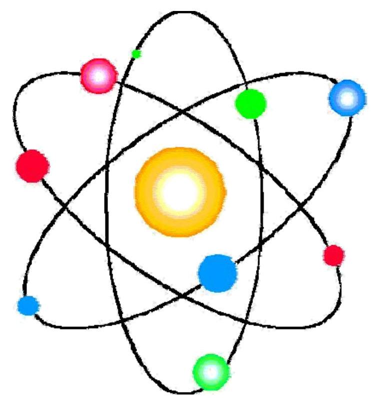
A single fission event can produce over 200 million times the energy of the incident neutron. Note that the average recoverable energy released per fission is 200 MeV as opposed to 1 - 10MeV for other decay chains and ~ 1 eV for chemical reactions.



"The Italian navigator has landed"

Enrico Fermi was the Italian "navigator" who sent the wartime-coded message announcing the successful first operation of a nuclear reactor. At 3:25 pm on December 2, 1942, in a laboratory constructed in an abandoned handball court under the grandstands of the University of Chicago's Stagg Field Stadium, a 28-minute nuclear chain reaction was started, controlled, and stopped. The reactor consisted of uranium and uranium oxide lumps spaced in a cubic lattice imbedded in graphite. A schematic is depicted on the next slide.

The Atomic Age had begun.



Scale Model of the First Nuclear Reactor

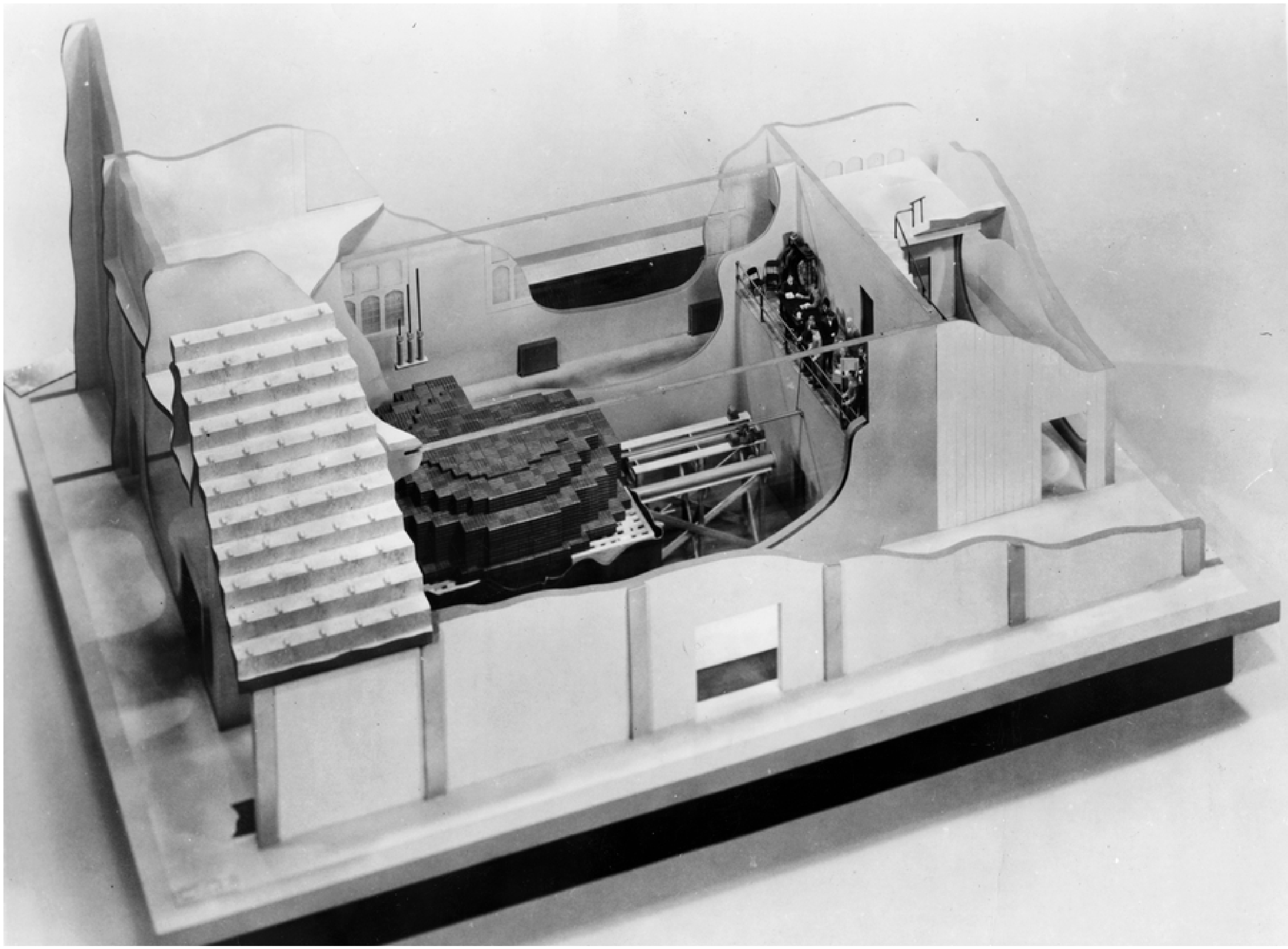


Photo Courtesy of Archival Photofiles, [apf2-00504], Special Collections Research Center, University of Chicago Library

How much energy is required for the incident neutron to cause a fission event?

The binding energy of fissionable target nuclei (*e.g.*, U-235) is so low that when a neutron is captured, the energy released by the formation of the new isotope exceeds its binding energy. The nucleus is no longer stable and must shed the excess energy by splitting into two fragments. The critical energy (E_c) required for fission must be greater than or equal to the binding energy difference (Q) between the target nucleus (*e.g.*, U-235) and the compound nucleus (*e.g.*, U-236) as well as the kinetic energy of the incident neutron. In the case of U-235, no extra energy is required for fission to occur so thermal neutrons (KE is ~0) or low-energy neutrons cause fission.

$$Q + KE_n \geq E_c$$

$$Q = \Delta BE = [m_{U\text{-}235} + m_n - m_{U\text{-}236}]c^2$$

$$= [235.11240 + 1.0086647 - 236.0455619] * 931.494$$

$$= 70.33\ MeV$$

When does the incident neutron become captured (absorbed) without causing fission?

Sometimes, the incident neutron is merely captured by the target nuclei without causing fission because there is not enough energy present to overcome the critical energy (E_c). Let's look at our equation again and use U-238 as our target nuclei. Experimentally, E_c is ~6 MeV for U-238 to fission. Therefore, the incident neutron must have some energy in order to cause fission. This is sometimes termed "fast fission" because it requires a higher energy neutron.

$$Q + KE_n \geq E_c$$

$$Q = \Delta BE = [m_{U\text{-}238} + m_n - m_{U\text{-}239}]c^2$$

$$= [238.0507826 + 1.0086647 - 239.054278] * 931.494$$

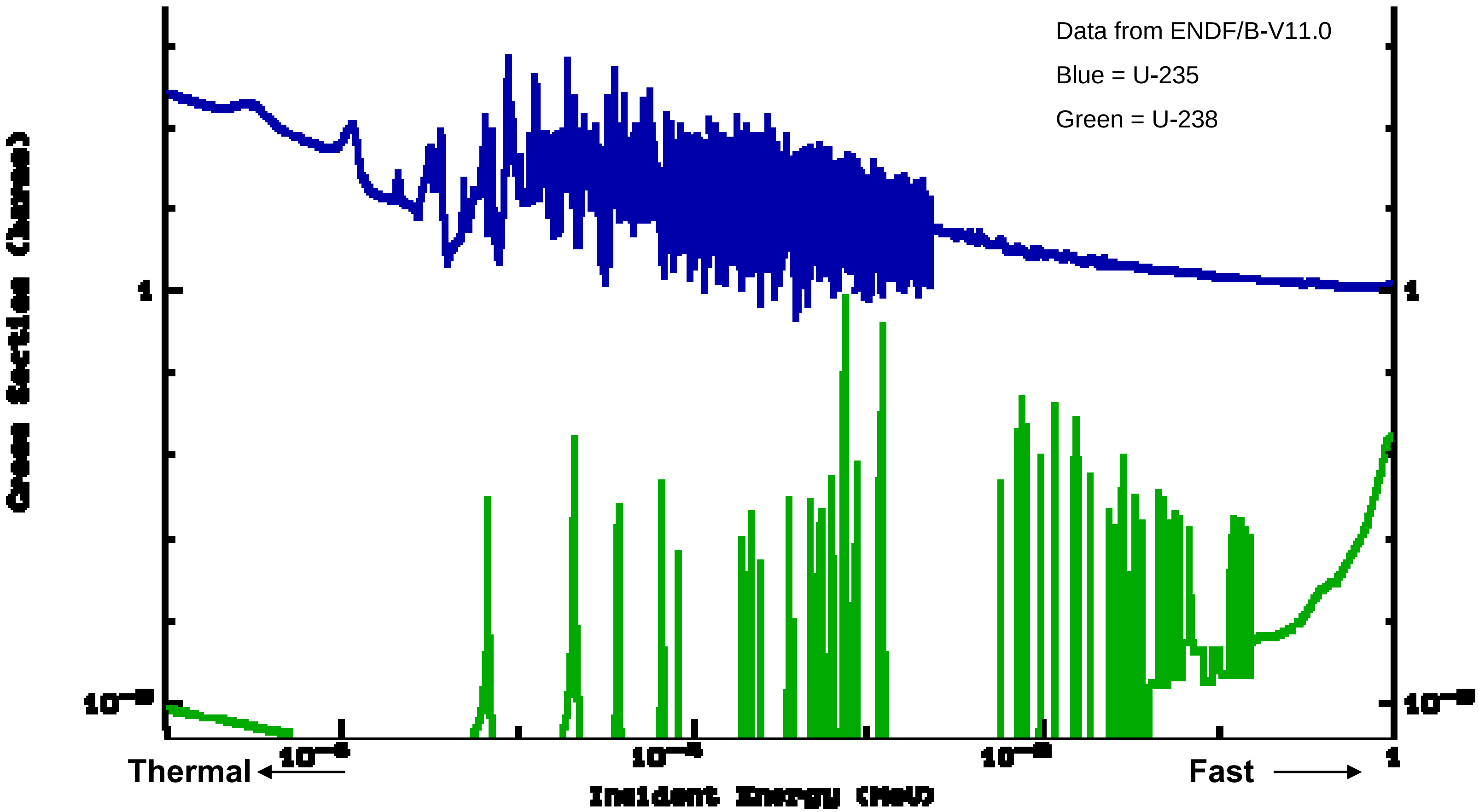
$$= 4.76\ MeV$$

Microscopic Cross Sections (σ)

The efficiency of neutrons in causing fission events varies with neutron energy and is identified as the fission cross section. The fission cross section is the probability that a fission event will occur. (Note: Cross sections can be described for any type of reaction: scattering, absorption, fission, etc.) Cross sections are typically given in the unit "barns." 1 "barn" is equal to 1 x 10^{-24} cm^2. The reason that the unit is an area is that it literally describes the effective target area of a given nucleus for an interaction with an incident neutron. The table below identifies the thermal neutron cross sections in barns for two types of reactions with fissionable nucleui.

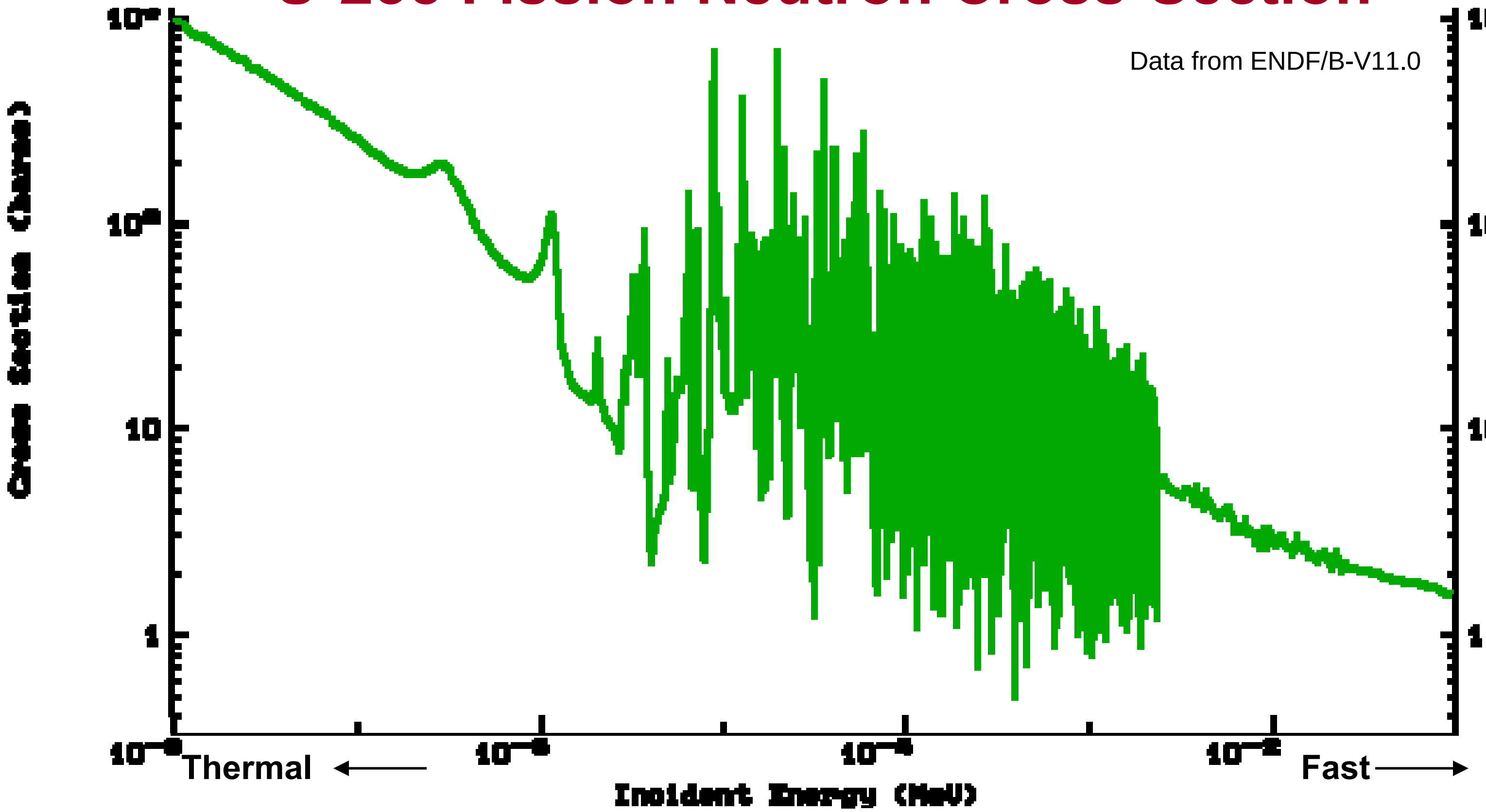
Nuclide	$\sigma_{fission}$	$\sigma_{capture}$	Capture/Fission Ratio
U-233	527	54	.102
U-235	577	106	.183
U-238	----	2.7	-----
Pu-239	742	287	.386

Compare U-235 and U-238 Fission Cross-Sections



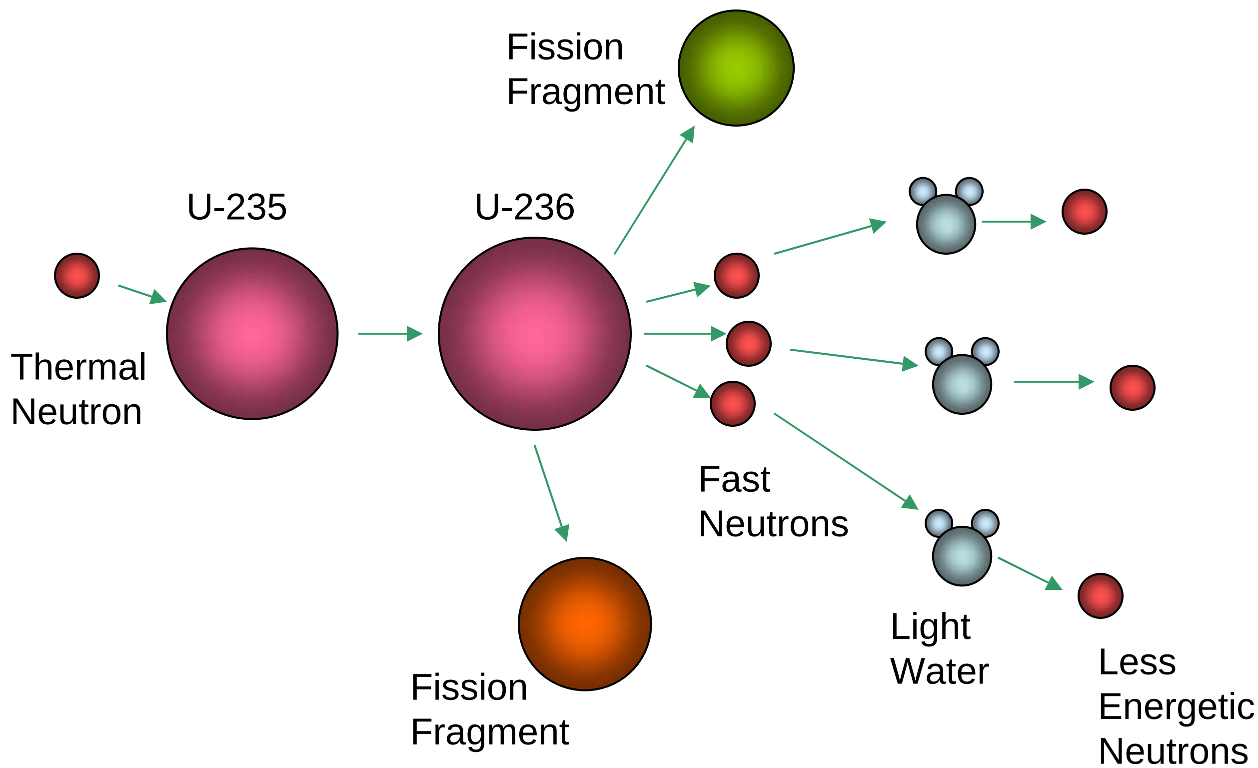
As previously noted, thermal neutrons cannot effectively cause fission in U-238 because they do not have enough energy to overcome the critical energy threshold. However, fast neutron fission occurs in U-238 as well as in sharply-defined points in the "resonance" region (the green peaks).

U-235 Fission Neutron Cross-Section



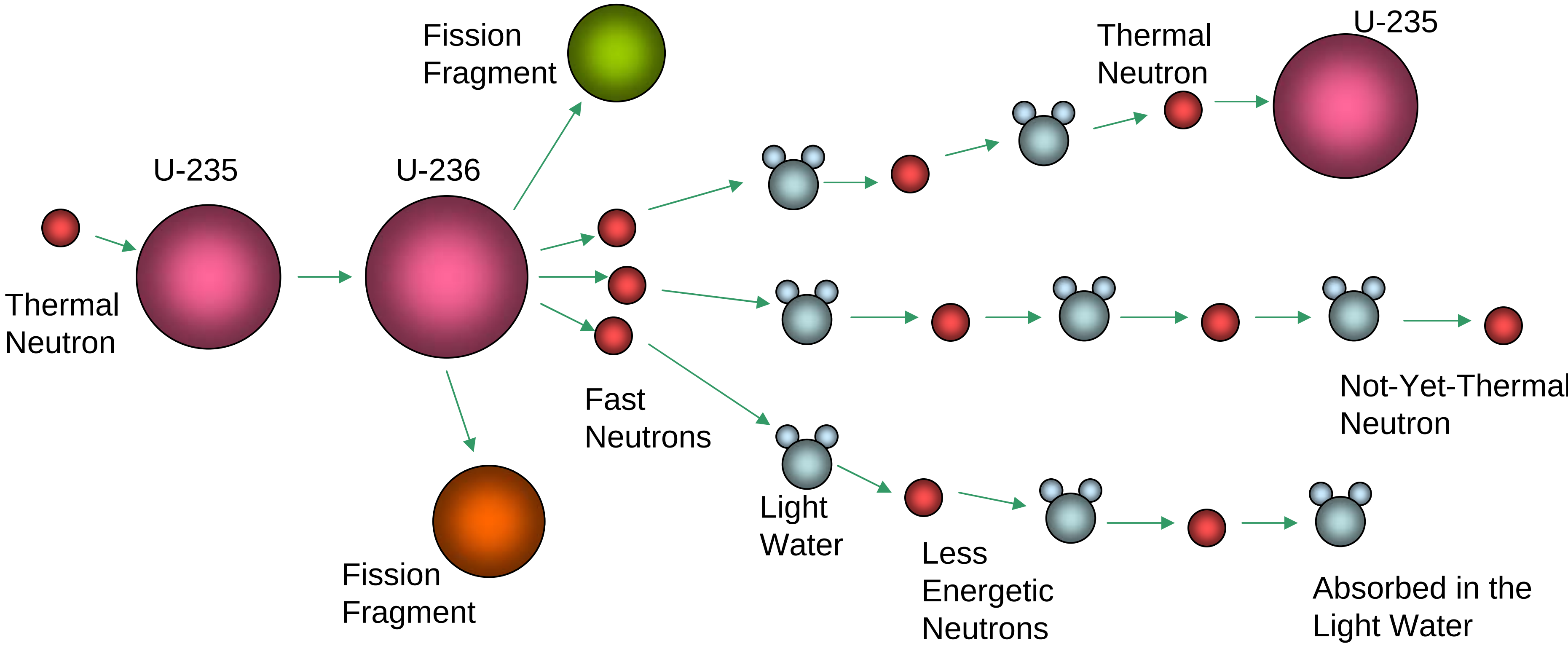
The fission of U-235 is more likely to occur (note the much higher cross-section) with a low energy or "thermal" neutron (~0.025 eV). A fast neutron is not efficiently captured by a U-235 atom so neutrons must be slowed down or thermalized to increase their fission probability and continue the chain reaction.

Neutron Slowing-Down (Moderation)



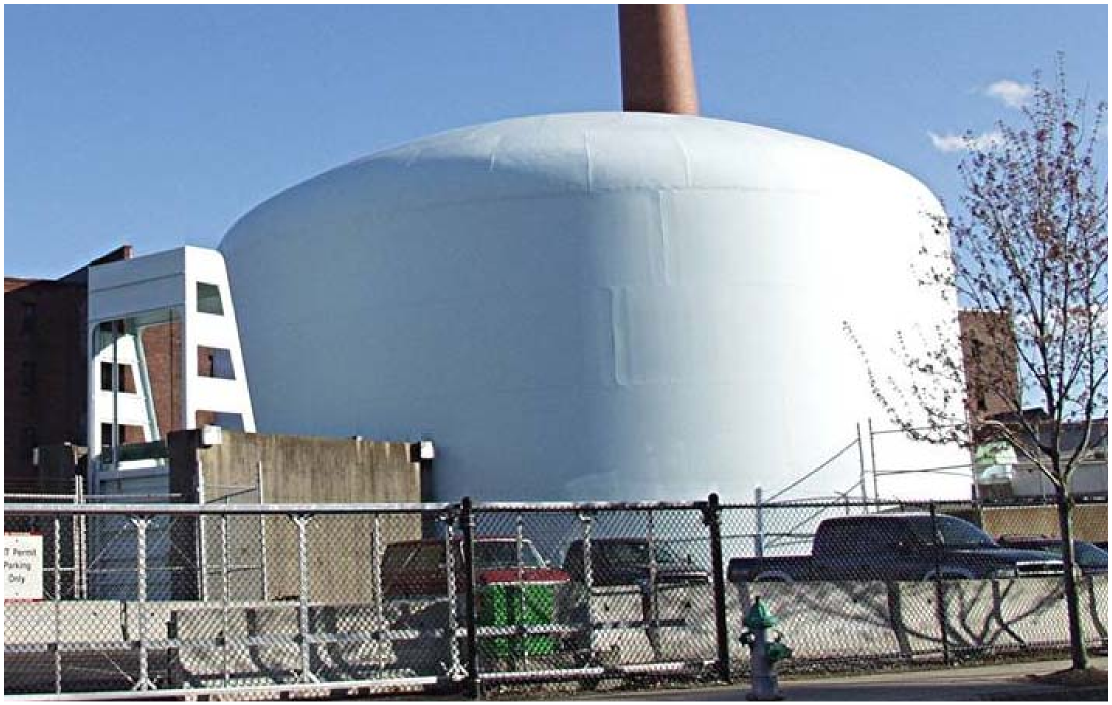
To thermalize or moderate fast neutrons, they must collide with other targets. Remember conservation of momentum? This process is optimized when the target has a similar mass because there is a maximum transfer of energy as a result of the collision. Therefore, hydrogen-rich targets make the best moderators. In reactors, light water is used as a moderator.

Using Moderators to Sustain the Chain Reaction



On average, ~18 scattering events with hydrogen nuclei will reduce the neutron energy from 1.5 MeV to a typical thermal energy of 0.025 eV. Neutrons may also leak out of a reactor core (if they are still too fast) or be absorbed in the moderator. The equilibrium is characterized by the physical temperature (and thus density) of the moderator.

Types of Nuclear Reactors



Nuclear Reactors are generally classified by their purpose. Research Reactors (like MIT's) produce neutrons for use in scientific and medical studies. Power Reactors produce energy that is utilized for electrical power. Production Reactors transmute natural uranium (U-238) into the fissionable isotope Pu-239 for use in weapons production.

Key Features of any Nuclear Reactor

1. **Fuel** – Typically enriched U-235 in the form of uranium oxide or alloyed with aluminum and clad (sealed) in aluminum or zircaloy.

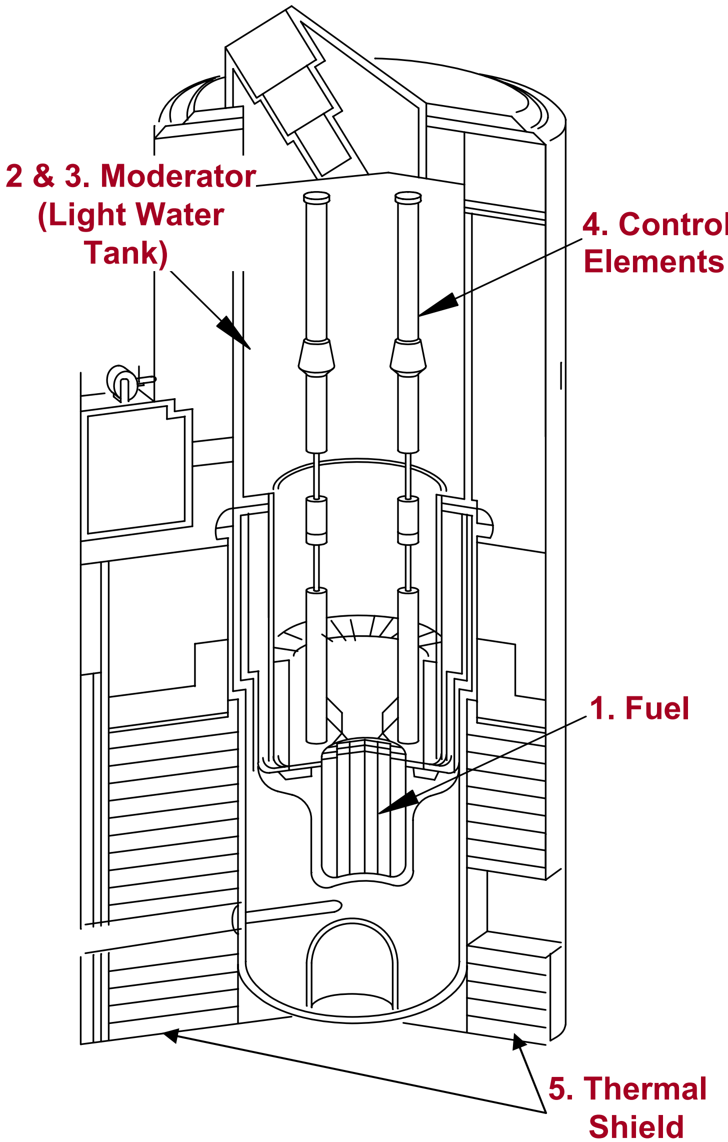
2. **Moderator** – Typically light water, but heavy water and graphite are also used.

3. **Heat Transfer Mechanism** – Removes the heat generated from the kinetic energy of the fission fragments (which are retained in the cladding)

4. **Control Elements** – Neutron Absorbers that are used to control the fission chain reaction and therefore, the power output. Typically made of boron or cadmium.

5. **Thermal and Biological Shield** – Contains the intense neutron and gamma radiation produced by decay of the fission products.

Key Features Arrangement in the MIT Reactor



1. **Fuel** – We use highly enriched U-235 in an aluminum-alloy with aluminum cladding.
2. **Moderator** – We use light water. The fuel elements are submersed in it.
3. **Heat Transfer Mechanism** – In addition to using light water to moderate the nuclear reaction, we also use it to cool the fuel elements. The primary water removes heat.
4. **Control Elements** – We use 6 boron-impregnated stainless shim blades and 1 cadmium regulated rod for fine adjustments. These control elements are attached to drive motors to control their movement.
5. **Thermal and Radiological Shield** – We have a dense concrete shield surrounding the core tank.

View of the MIT Reactor in the Light Water Tank