

Reactor Physics

Neutron Behavior, Fission, Fusion, & Reactor Materials

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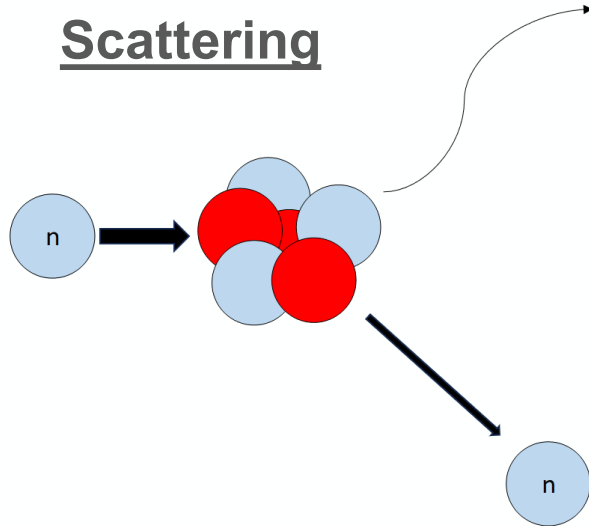
School of Nuclear Engineering

Key Concepts to Understand

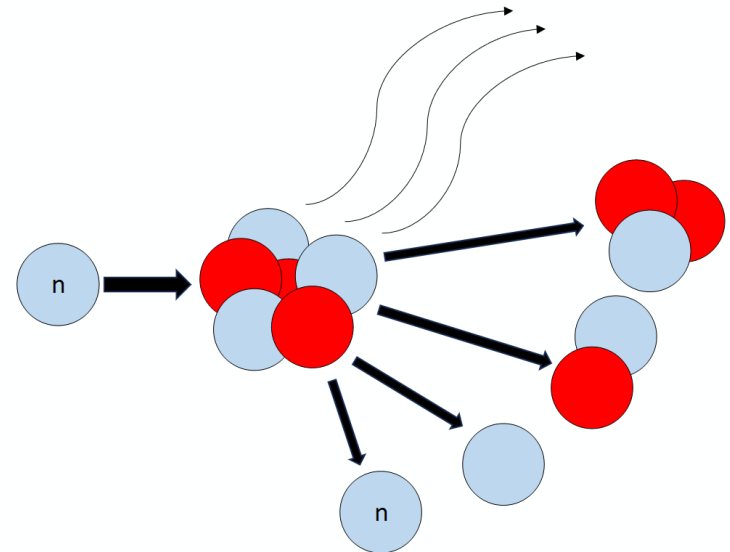
- **Neutron Interactions**
- **Neutron Energy**
- **Moderation**
- **Fertile vs. Fissile**
- **Prompt vs. Delayed Neutrons**
- **Criticality**
- **Supercritical vs. Subcritical**
- **Reactor Design Principles**
- **Neutron Population Life Cycle**
- **Fusion Concepts & Technologies**

Review of Neutron Interactions

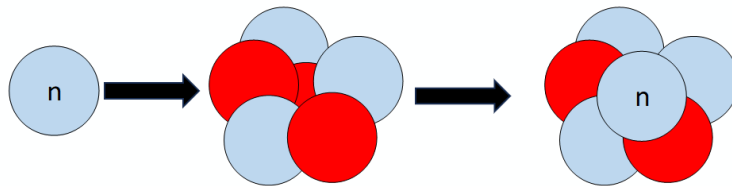
Scattering



Fission



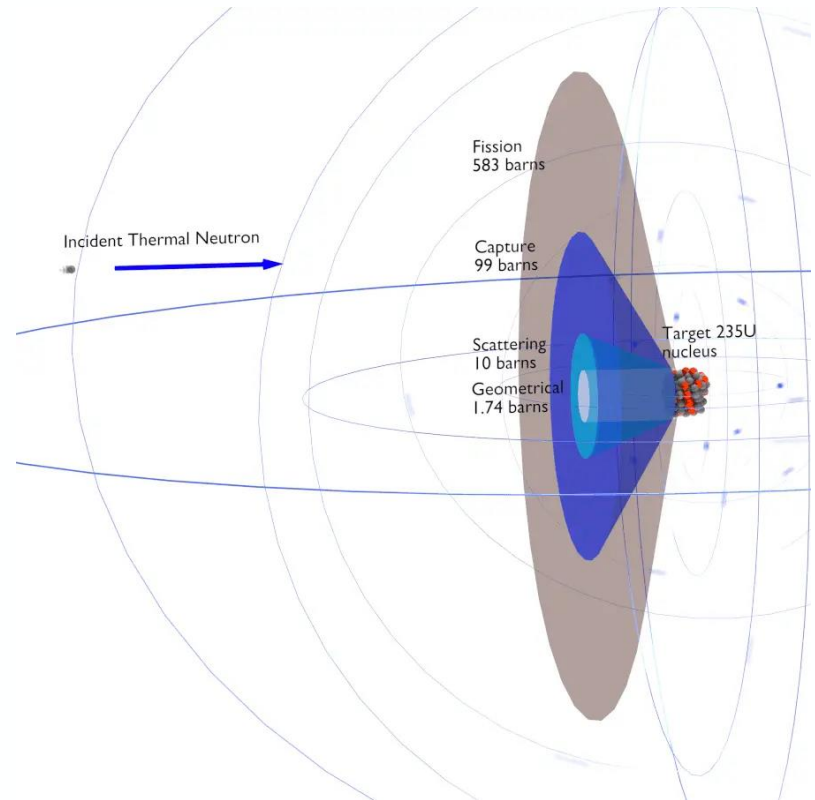
Absorption



Interaction Cross Section

Cross Sections

- Cross section is a measure of probability, not actual geometric cross section of the nucleus
- Microscopic cross-section (σ)
 - The intrinsic probability of interaction of a given isotope
 - Every isotope has its own σ
 - Units of barns (b) or (cm^{-2})
 - 1 barn = $10^{-24}cm^{-2}$
- Macroscopic cross-section (Σ)
 - Probability of interaction for bulk material
 - Considers the density of material
 - Units of (cm^{-1})
 - $\Sigma = \sigma N$
 - $N = \frac{\rho N_A}{M} (cm^{-3})$
 - $\rho = \text{material density } \left(\frac{g}{cm^3}\right)$
 - $N_A = \text{avagadro's number } (mol^{-1})$
 - $M = \text{atomic molar mass } \left(\frac{g}{mol}\right)$

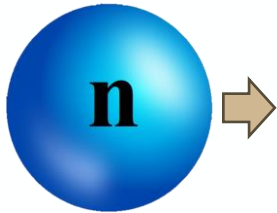


Source: <https://www.nuclear-power.com/nuclear-power/reactor-physics/nuclear-engineering-fundamentals/neutron-nuclear-reactions/microscopic-cross-section/>

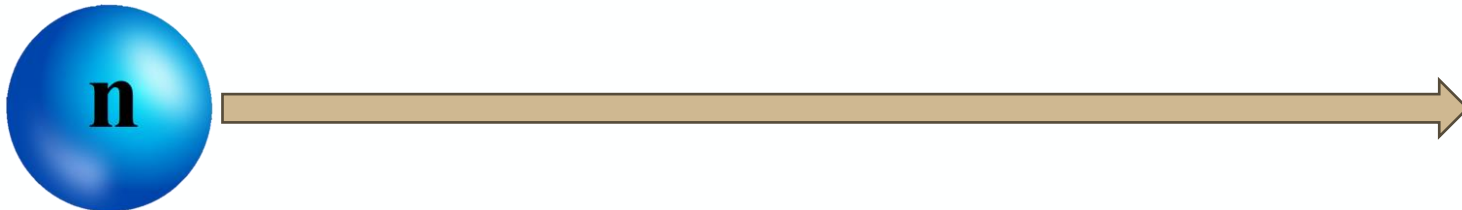
Neutron Energy

In Nuclear Engineering, the thing we care the most about pertaining to neutrons is their energy.

Neutrons with low energy, **below 0.025 eV**, travel at **roughly 2.2 km/s** and are called "**Thermal**" neutrons since they have similar energy to air at 20°C.



Neutrons with high energy, **above 0.1 MeV**, move at speeds **up to 14000 km/s** and are defined as "**Fast**" neutrons.

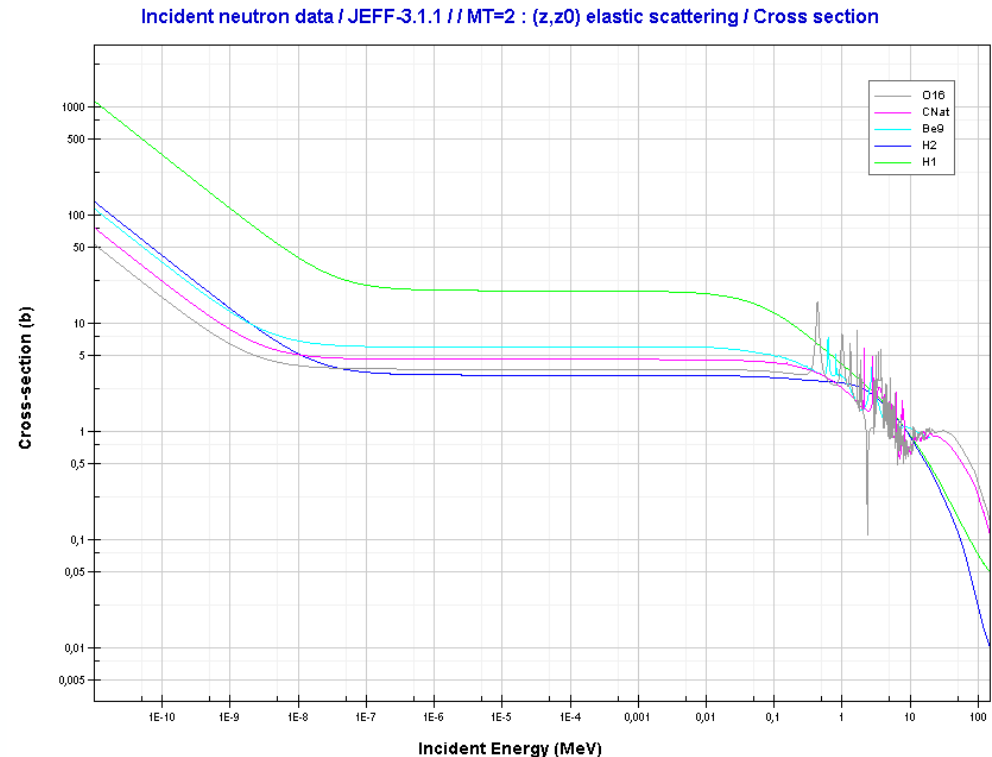


Effect of Neutron Energy on Scattering Interactions

The energy of neutrons determines the cross-section for each possible interaction, or the likelihood of the interaction occurring.

On average, the cross-section for scattering remains relatively constant for most energy ranges.

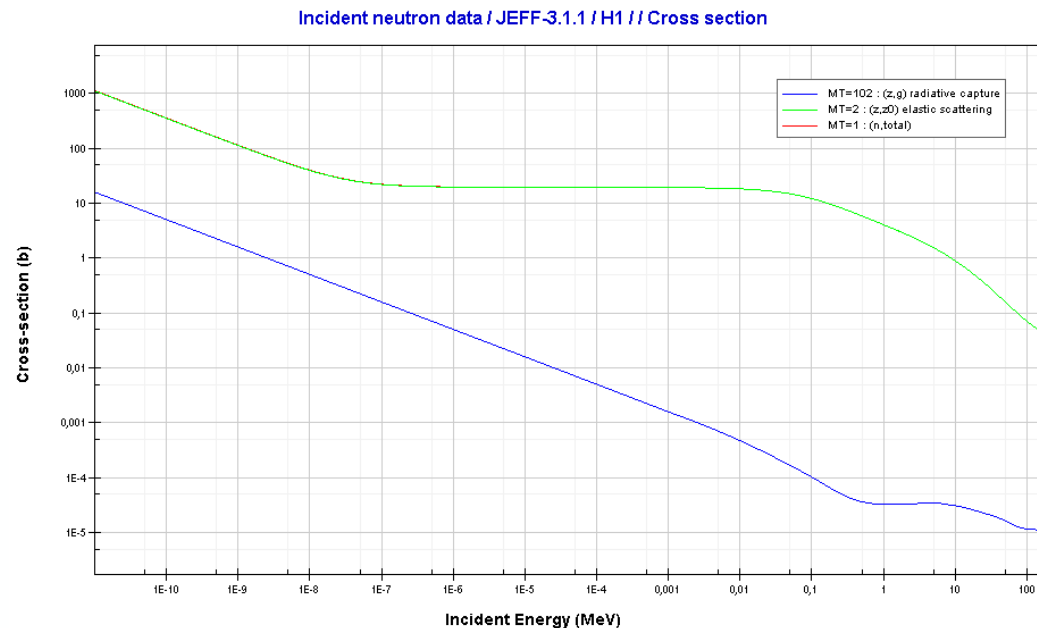
Cross-section data a few materials shown on the right.



<https://www.nuclear-power.com/nuclear-power/reactor-physics/nuclear-engineering-fundamentals/neutron-nuclear-reactions/neutron-elastic-scattering/>

Effect of Neutron Energy on Absorption Interactions

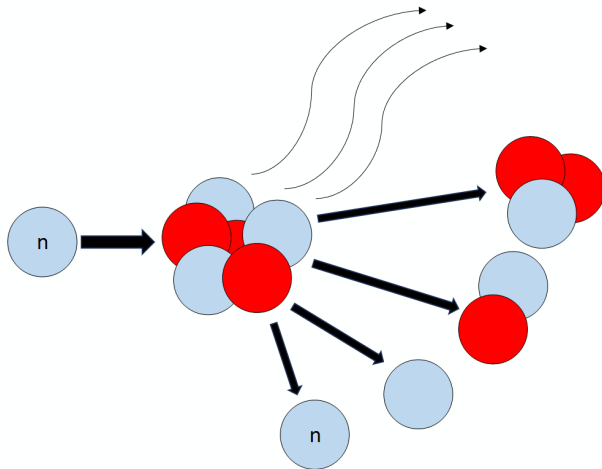
- For absorption cross-sections, there is an inverse relationship between neutron energy and absorption.
- The cross-sections decrease by orders of magnitude for increasing energy.
- Since the cross-section for absorption is so small for all but the smallest energies, absorption cross-sections are usually reported for only the thermal range of neutrons.
- Right figure shows example data showing both absorption (radiative capture) and elastic scattering of hydrogen.



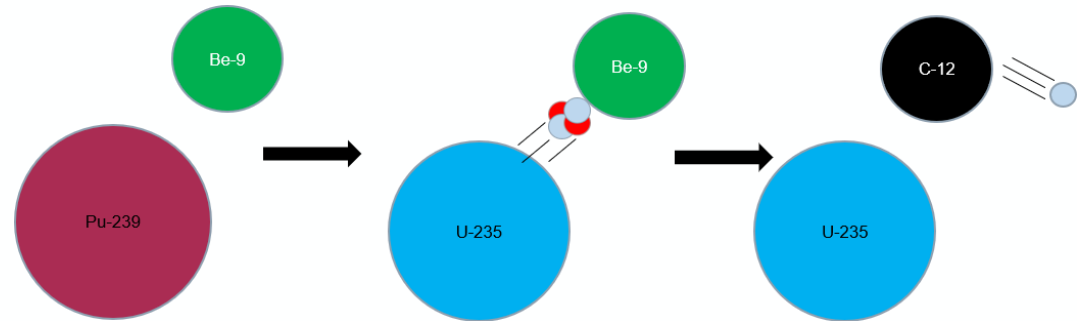
<https://www.nuclear-power.com/nuclear-power/reactor-physics/nuclear-engineering-fundamentals/neutron-nuclear-reactions/neutron-absorption/neutron-absorption-cross-section/>

The Source of Free Neutrons

Fission



Source

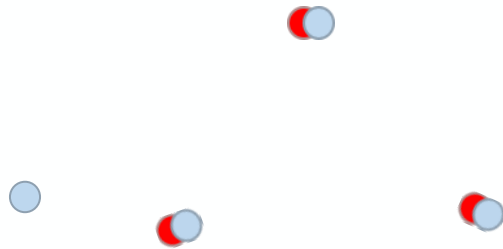


Neutron Moderation

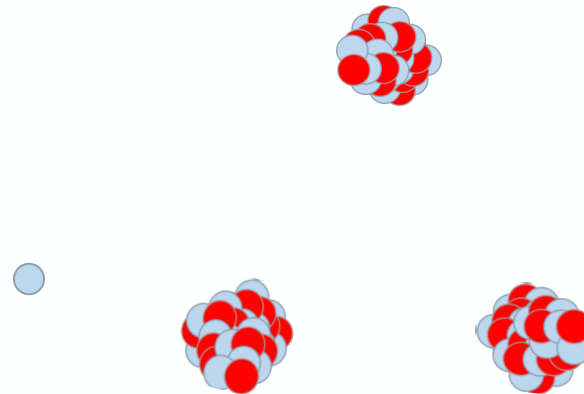
How do we get thermal neutrons?

When neutrons scatter off nuclei, they transfer some energy to the incident nuclei. The lighter the nucleus, the greater the energy transfer.

Low Mass Nuclei



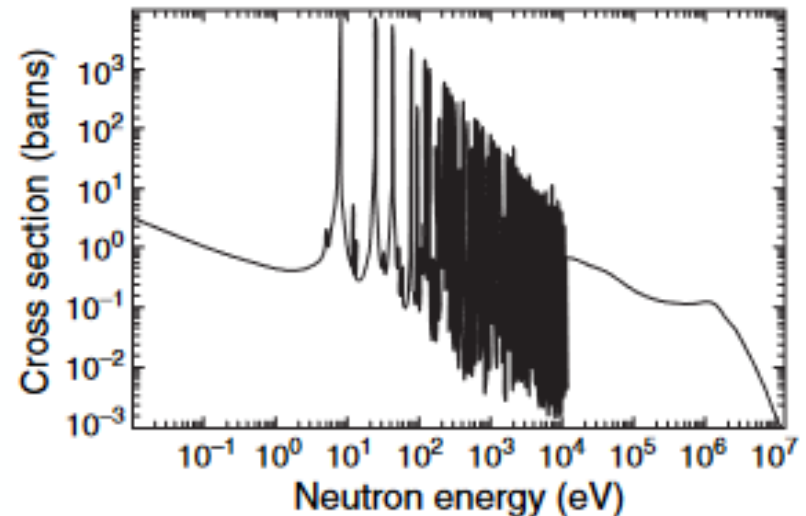
High Mass Nuclei



Neutron Resonance Absorption

Resonance Peaks

- Each nuclei has intrinsic energy levels that they can be excited to or emit gamma rays from.
- If a neutron happens to have excess energy equal to those energy levels, the cross-section of absorption sharply increases.



Neutron Resonance Absorption

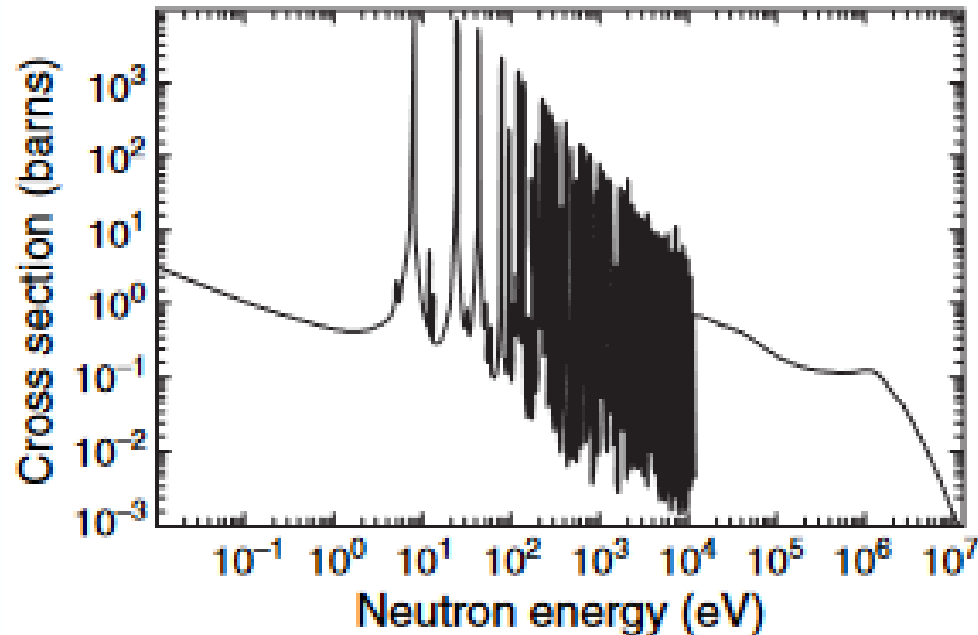
Interpreting the Resonance Peaks

So what do the resonance peaks tell us about this isotope?

Small energy ranges where neutrons are likely to be lost to absorptions

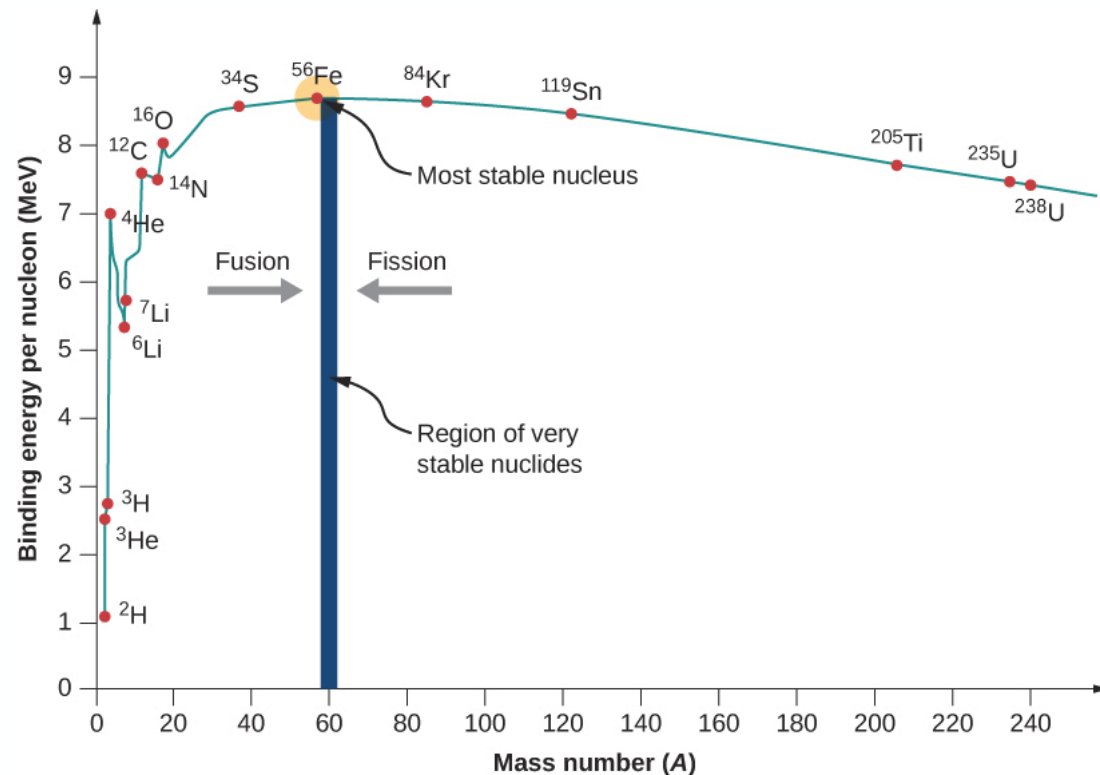
Why is it important to understand?

Getting absorbed in resonance peaks during moderation



Nuclear Fission and Fusion

- Binding energy is the energy of the bonds holding the nucleus of an atom together.
- At Mass Numbers below 56, the Binding Energy increases with the Mass Number and fusion is the dominant reaction.
- At Mass Numbers above 56, the Binding Energy decreases with the Mass Number and fission is the dominant reaction.



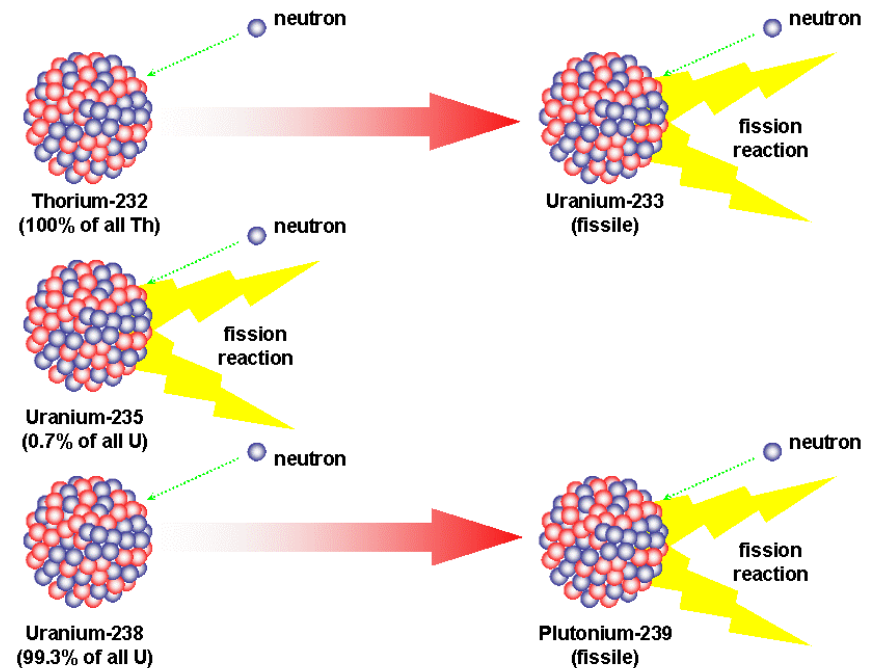
https://phys.libretexts.org/Bookshelves/University_Physics/University_Physics_%28OpenStax%29/University_Physics_III_-_Optics_and_Modern_Physics_%28OpenStax%29/10%3A_Nuclear_Physics/10.03%3A_Nuclear_Binding_Energy

Nuclear Fission: Fissile vs Fertile

When designing a fission reactor's fuel, the materials are labeled based on their ability to fission.

A fissile material can go through fission spontaneously or will fission after neutron absorption.

A fertile material can't fission but becomes a fissile material after neutron absorption.



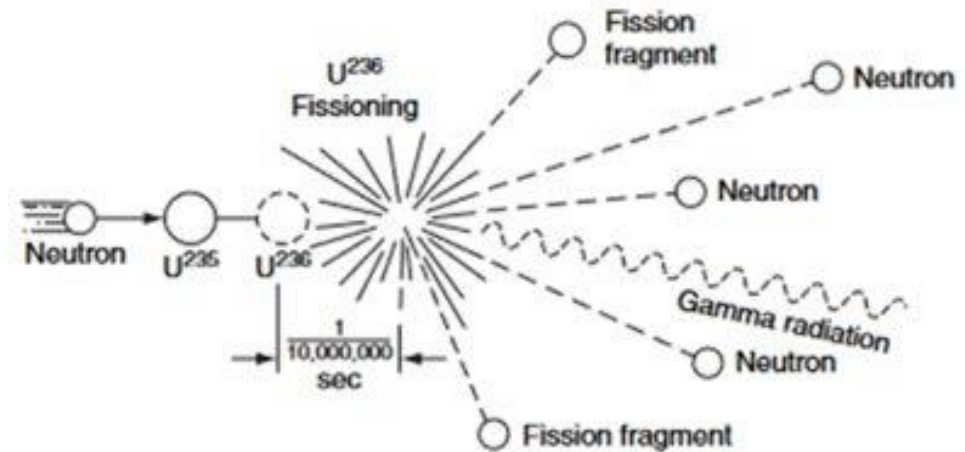
<https://steemit.com/chemistry/@pinkspectre/the-mighty-thorium>

Nuclear Fission

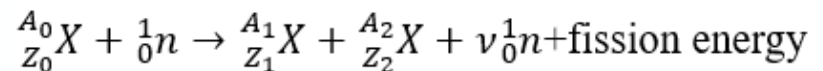
When the nucleus' bonds are broken, the binding energy is expelled as gamma rays.

If you want to find how much energy is emitted as gammas, you can subtract the mass of the products from the mass of the original atom and nucleus and convert that to energy.

The equation to compute that energy is shown below



<https://rajras.in/ras/mains/paper-2/physics/nuclear-fission-and-fusion/>



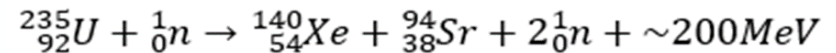
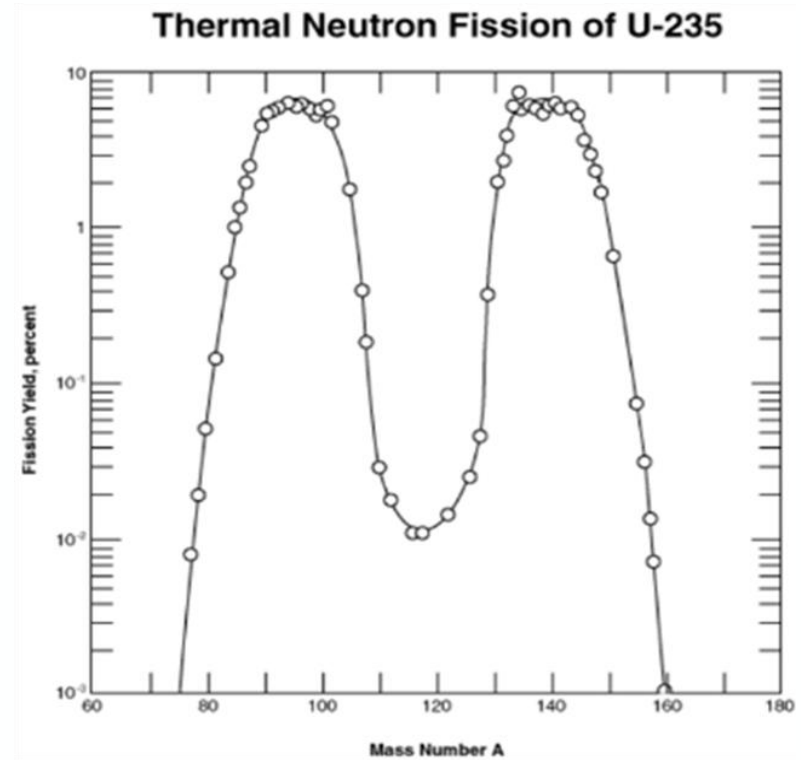
$$\left[M({}_{Z_0}^{A_0}X) - M({}_{Z_1}^{A_1}X) - M({}_{Z_2}^{A_2}X) - (\nu - 1)M_n \right] c^2$$

Fission Fragments

The isotopes created from the fission of U-235, called fission fragments, have an average atomic mass of 118 amu, but the distribution is bimodal.

The most prominent atomic masses are centered around 95 amu and 137 amu.

A complete nuclear fission equation with fission fragments would look like this:



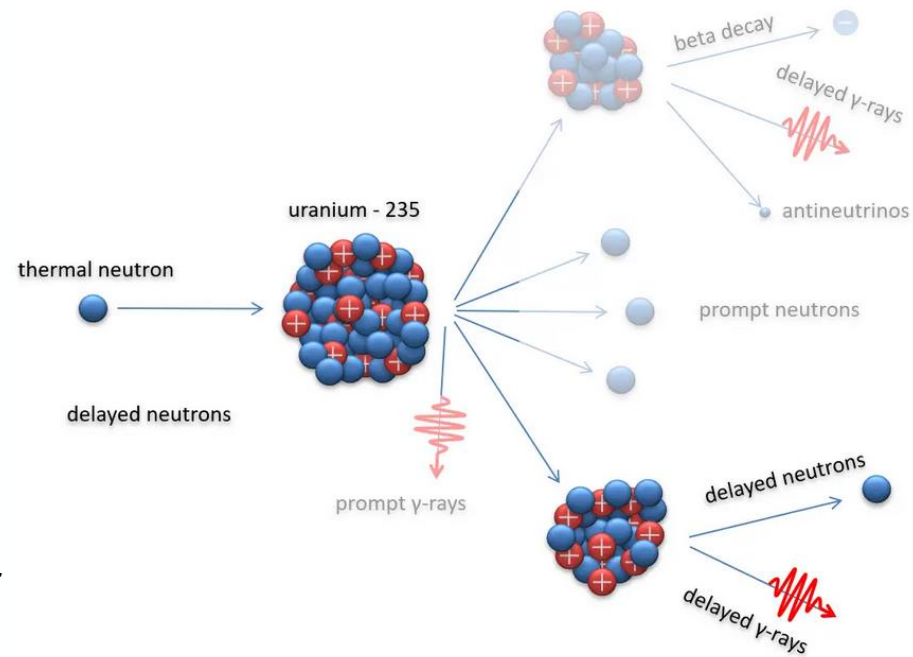
Prompt and Delayed Neutrons

Prompt neutrons are the neutrons produced from the fission reaction and are emitted 10^{-14} seconds after the neutron absorption

Delayed neutrons are neutrons emitted by the unstable fission fragments after they decay, taking a range of milliseconds to minutes

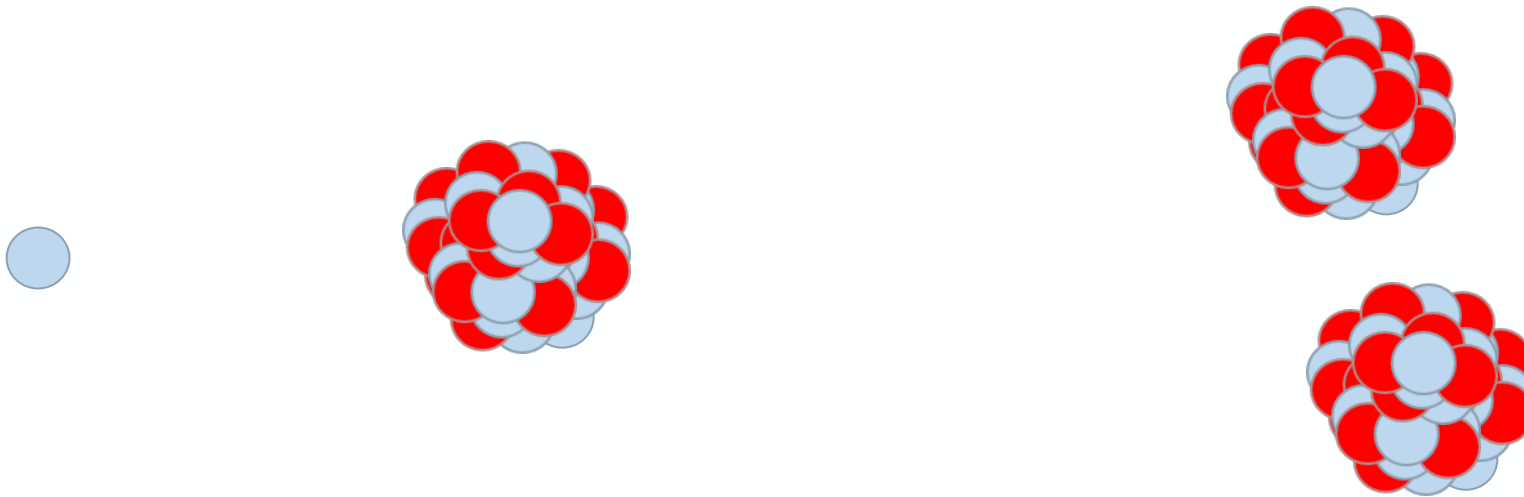
On average, prompt neutrons have higher energy and wider energy range upon emission than delayed.

2 MeV vs 0.4 MeV



<https://www.nuclear-power.com/nuclear-power/fission/fission-fragments/>

Prompt and Delayed Neutron Animation



Prompt Criticality

Prompt neutron generation time:

$$t = 10^{-4} s \rightarrow \frac{1}{t} = 10,000 s^{-1}$$

Reactor criticality

$$k = 1.001$$

$$P = P_0(k)(k)(k) \dots 10,000 \text{ generations} = P_0(k)^{10,000}$$

Reactor power:

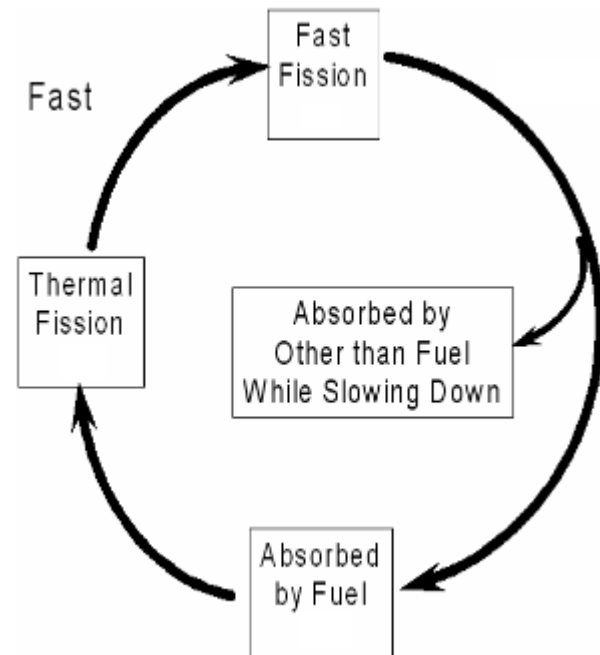
$$\frac{P}{P_0} = (k)^{10,000} = (1.001)^{10,000} = 21,916$$

Prompt and Delayed Neutron Distribution

More than 99% of neutrons produced from fission are prompt neutrons

Despite the difference in population, the average time for neutron generation increases from 10^{-5} seconds to roughly 0.1 second when including delayed neutrons into the calculation.

As a result, the reaction rate is slow enough to be able to adjust it in real-time using control rods



Delayed Critical

Total averaged neutron generation time:

$$l_d = \frac{(1 - \beta_{eff})l_p + \beta_{eff}\tau}{(1 - \beta_{eff}) + \beta_{eff}} \approx 0.1 \text{ s}$$

Reactor power change:

$$\frac{P}{P_0} = (k)^{10} = (1.001)^{10} = 1.01$$

REACTOR PHYSICS

Key Vocab

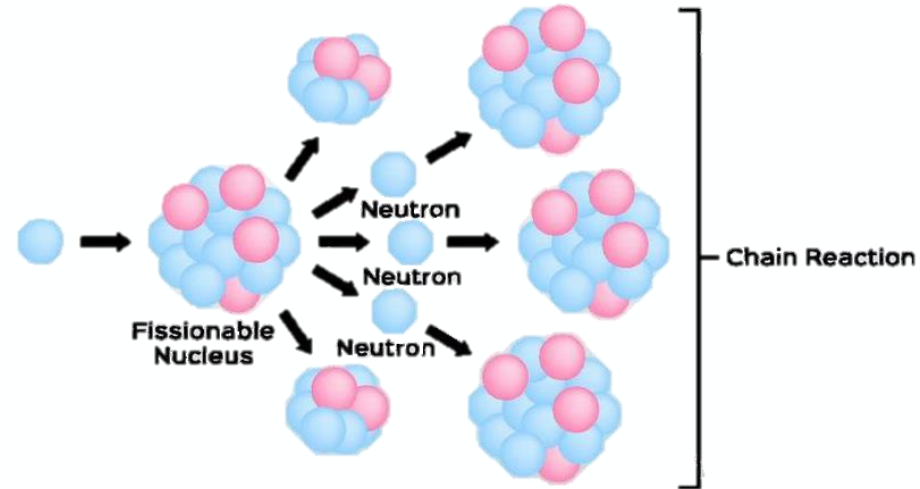
Fuel: The fissionable radioactive isotopes, either Uranium or Plutonium, that absorb and produce neutrons to sustain a chain reaction. For a fusion reactor, hydrogen isotopes are used as fuel.

Moderator: A material with low atomic number and high likelihood for neutron interactions used to lower the energy of neutrons. Most common moderators are light water (H-1), heavy water (H-2), and graphite

Enrichment: The fraction of fissile materials out of all fuel materials, usually increased than the natural abundance of isotopes to increase reactivity. In Uranium fuel, the fissile material is U-235 and the rest is primarily U-238.

Criticality

- The metric that the net change in number of neutrons, or the **Criticality** of the reactor, is measured by is the **Multiplication Factor “k”**.
- Reactor design is centered around controlling the rate at which neutrons are produced from fission removed through absorption or escape
- For power production, its necessary to maintain enough neutrons in the core so that the chain reaction is sustained.



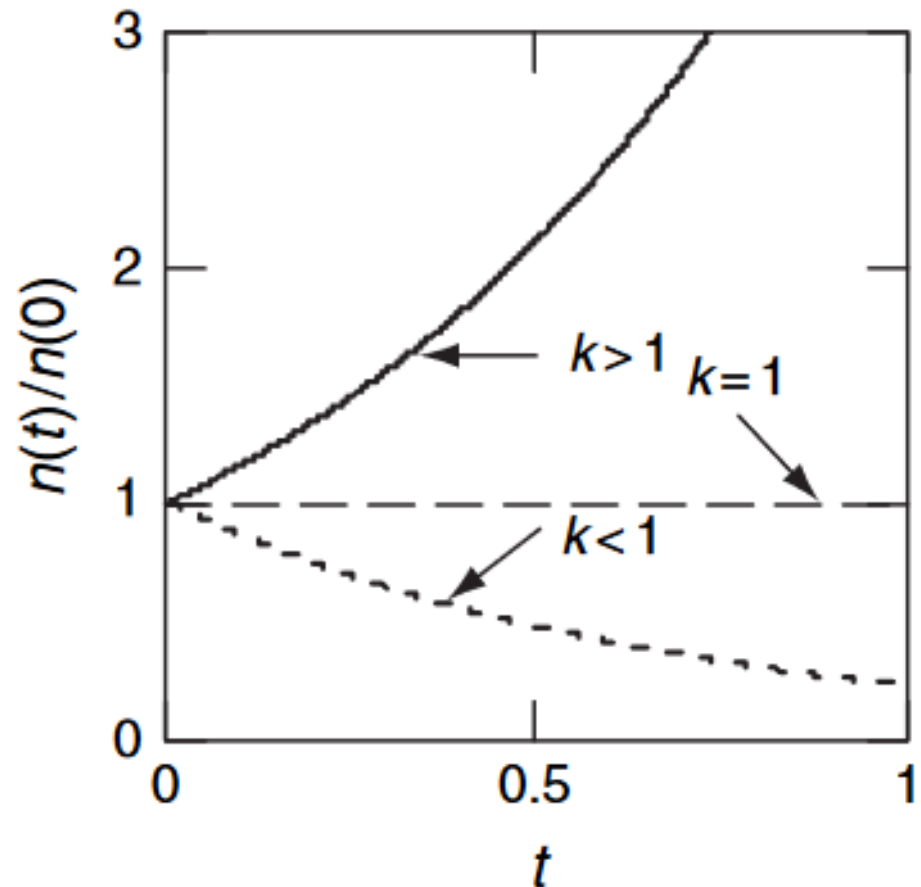
The Multiplication Factor - k

- The **Multiplication Factor** measures the total rate of change of the number of neutrons in the core

$$k = \frac{\text{total neutron production rate}}{\text{total neutron loss rate}}$$

- A “critical” core is producing neutrons at the same rate they are lost to the environment and has a k of 1.

- To compute k for a reactor core, we can use the equation $k = k_{\infty} P_{NL}$, where P_{NL} is the **Non-leakage Probability**.

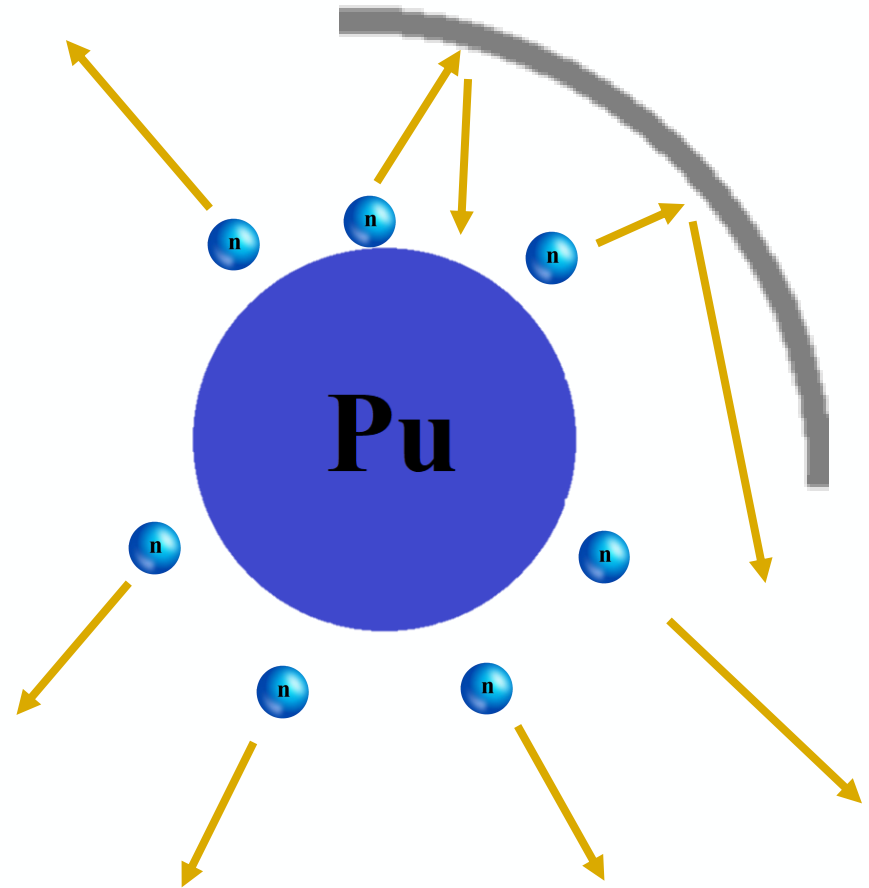


Subcriticality

When $k < 1$, the reactor is **Subcritical** and is losing more neutrons than its producing

Without an outside source of neutrons, the neutron population will continue to decrease until the chain reaction ends.

When a reactor is shutting down, the operator inserts the control rods with high neutron absorption cross-sections.

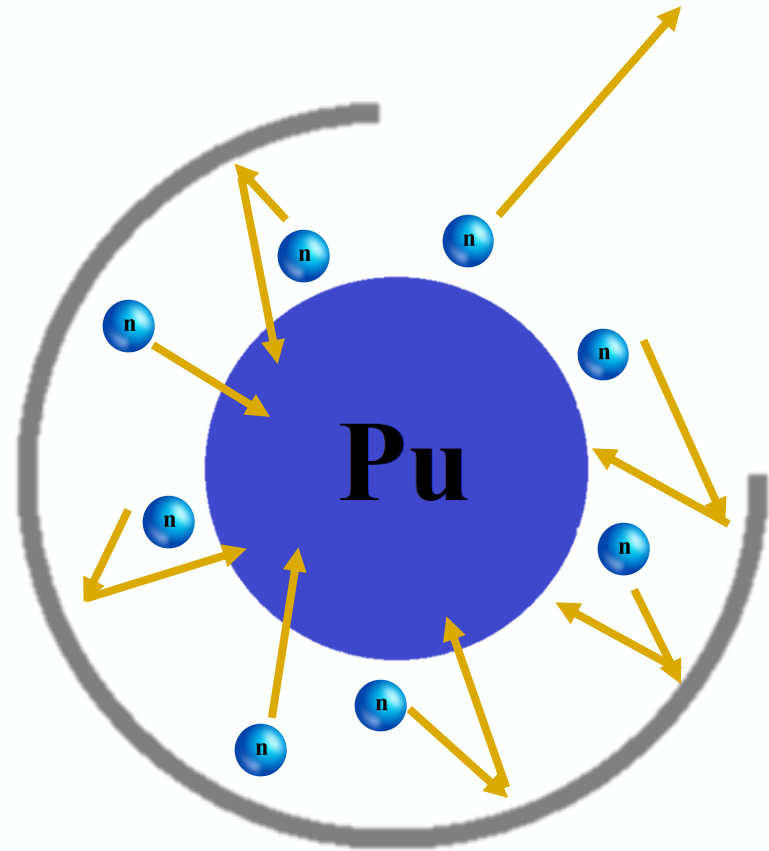


Supercriticality

When $k > 1$, the reactor is **Supercritical** and is producing more neutrons than are being lost to absorption

During start-up, the reactor needs to be supercritical to increase the reaction rate and power output

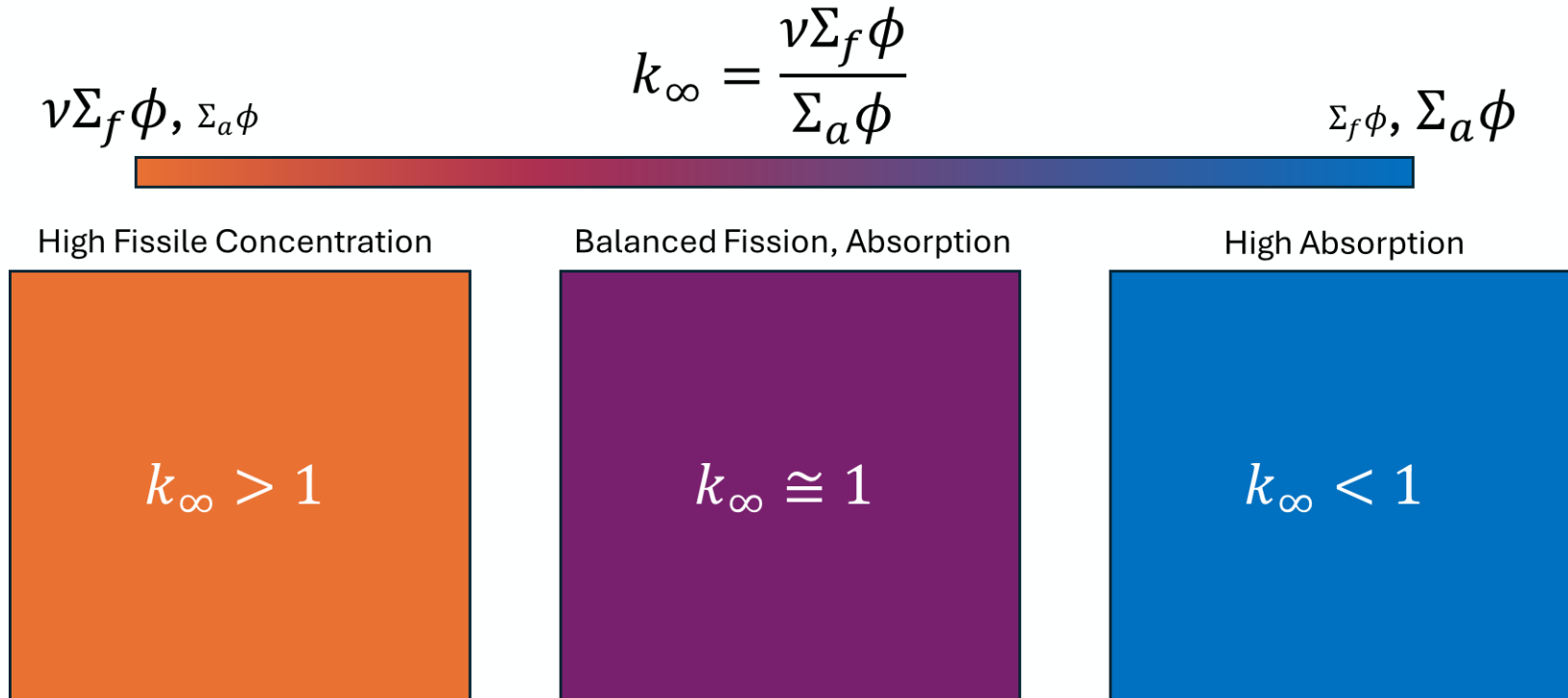
A k that far exceeds 1 is dangerous since the chain reaction can become uncontrollable and expel lethal amounts of radiation to the environment.



Going Supercritical



Neutron Multiplication in Materials



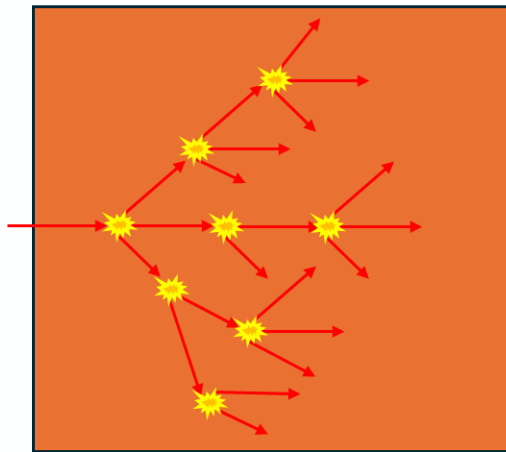
Neutron Multiplication in Materials

$$k_{\infty} = \frac{\nu \Sigma_f \phi}{\Sigma_a \phi}$$

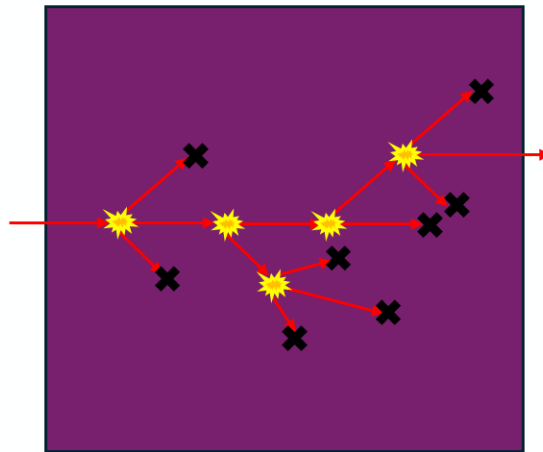
$\nu \Sigma_f \phi, \Sigma_a \phi$ $\Sigma_f \phi, \Sigma_a \phi$



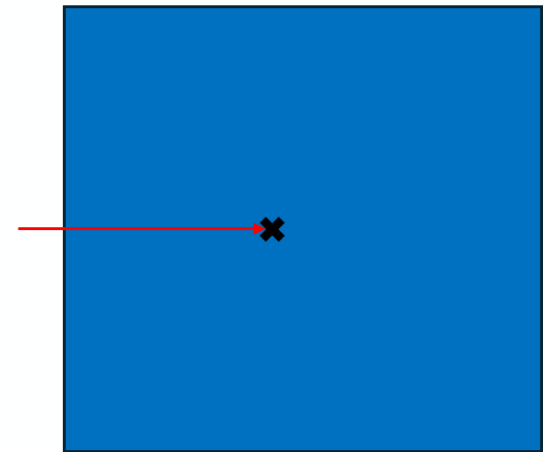
High Fissile Concentration



Balanced Fission, Absorption



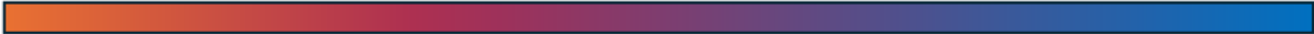
High Absorption



Let's Build a Reactor!

$$k_{\infty} = \frac{\nu \Sigma_f \phi}{\Sigma_a \phi} \quad \text{■} - \Sigma_s \phi$$

$\nu \Sigma_f \phi, \Sigma_a \phi$ $\Sigma_f \phi, \Sigma_a \phi$



Fuel Material



Fuel often contains materials that have both high absorption and high fission cross-sections.

The k_{∞} of the fuel material can differ depending on its enrichment and composition.

Depending on the energy of the neutron population, the fuel may be considered more absorbing.

Control Material



Highly absorbing material in reactors serve as control material for adjusting reactor power.

One typical material is boron, which may take the form of a solute within coolant or more often control rod material.

Moderator

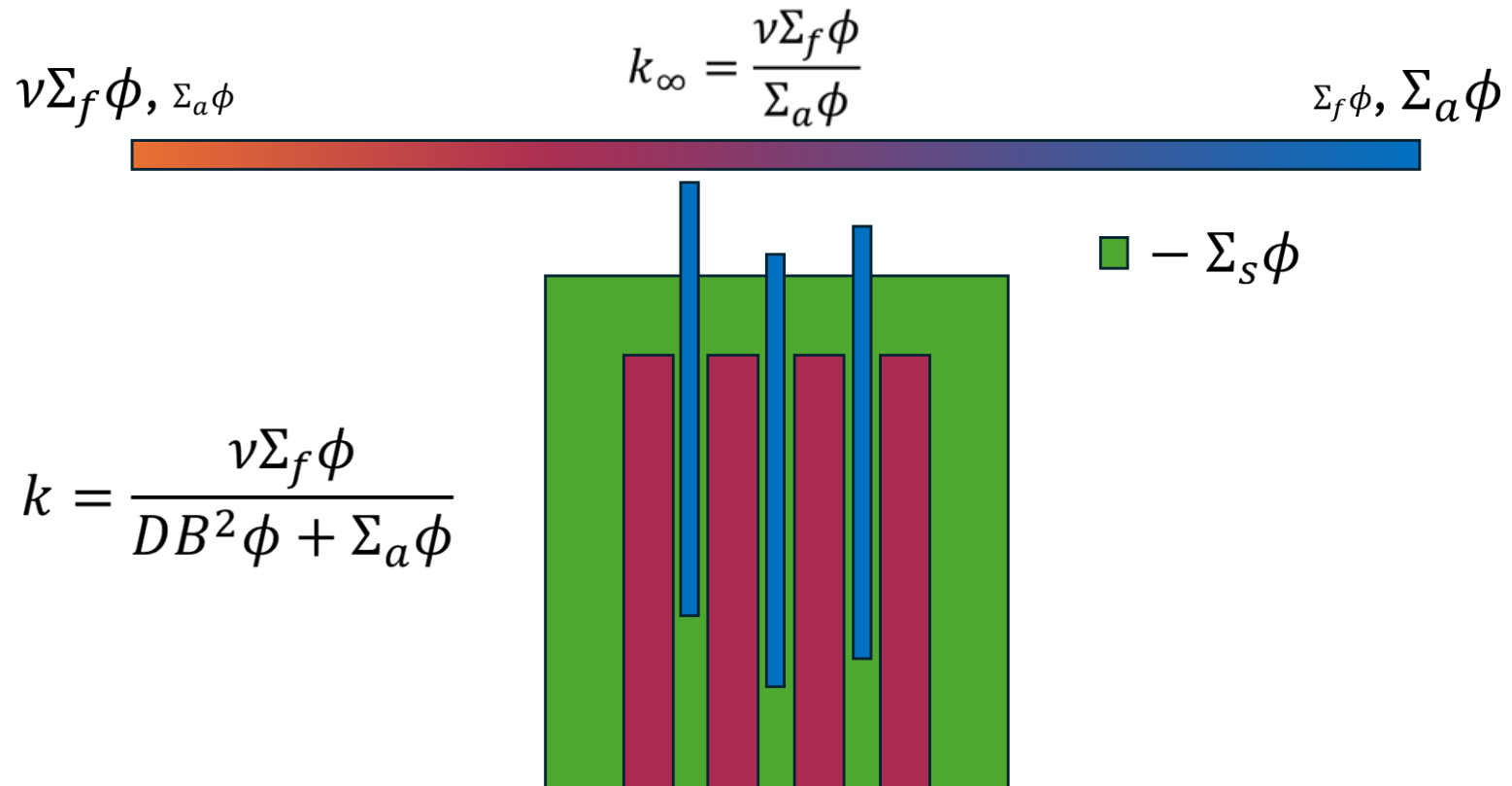


A moderator serves to adjust the energy spectrum of the neutron population towards lower energies.

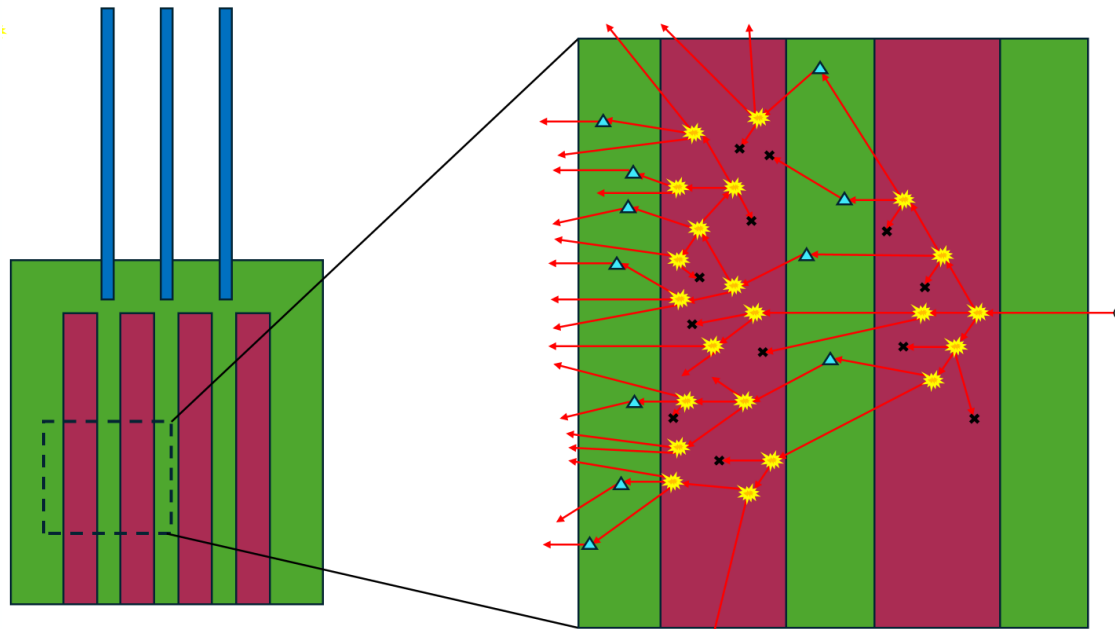
The moderator may also be used as coolant in many cases.

Lower Z material moderators are used for reactors using thermal neutrons (water reactors)

Let's Build a Reactor!



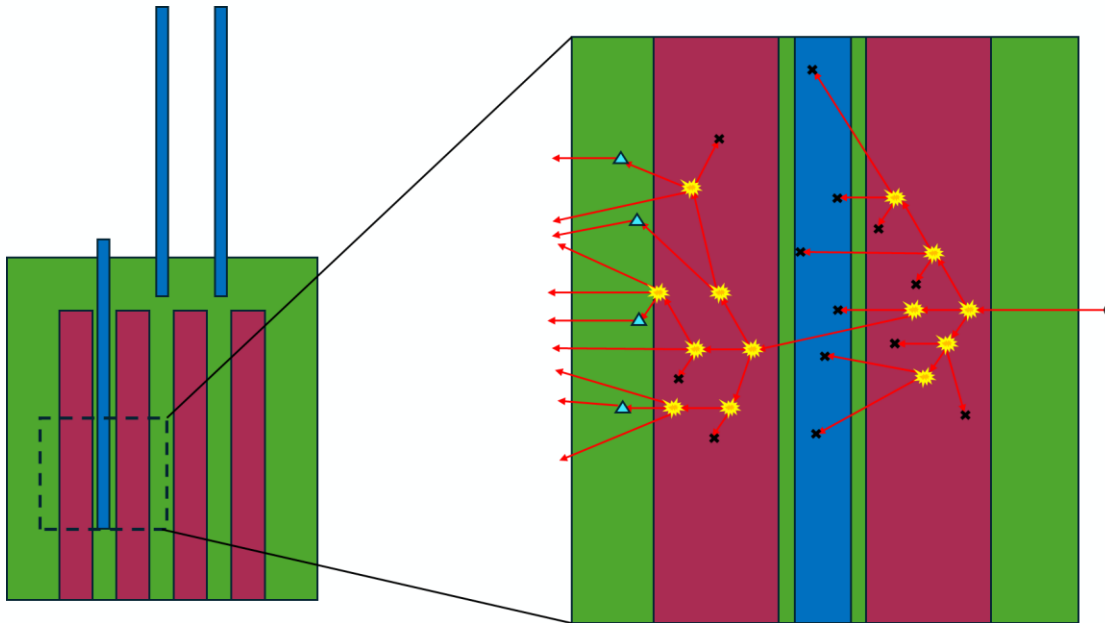
Reactor Control: Fast Reactor Concept



Q: What is the criticality of this system?

Q: How does the criticality affect the neutron population?

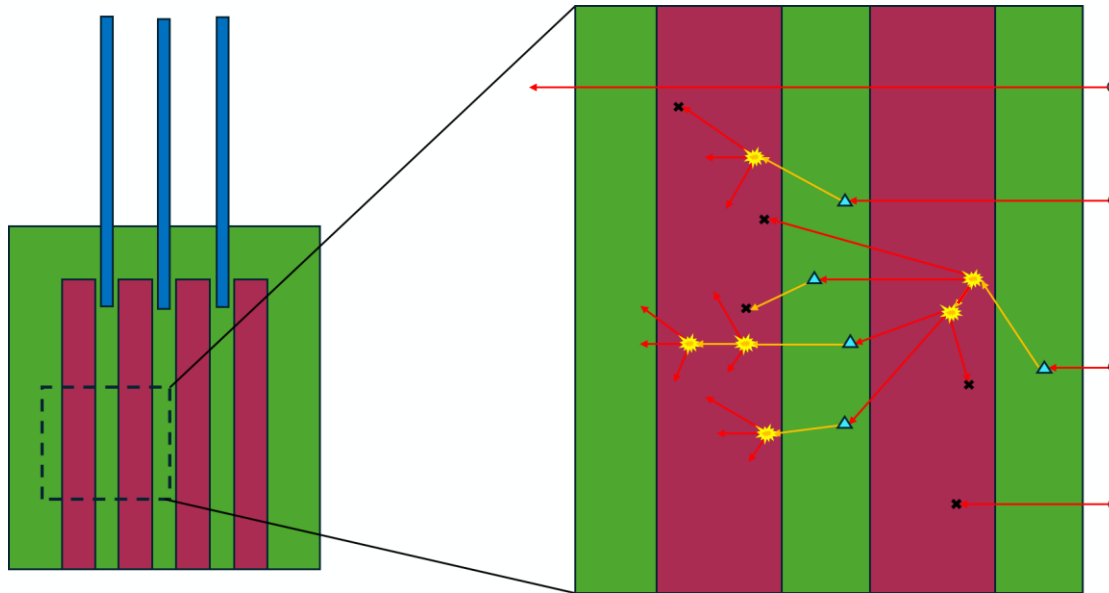
Reactor Control: Inserting Control Rods



Q: How does the criticality of this system compare to before?

Q: How does the criticality affect the neutron population?

Reactor Control: Thermal Reactors



Q: How does this example differ conceptually from the others?

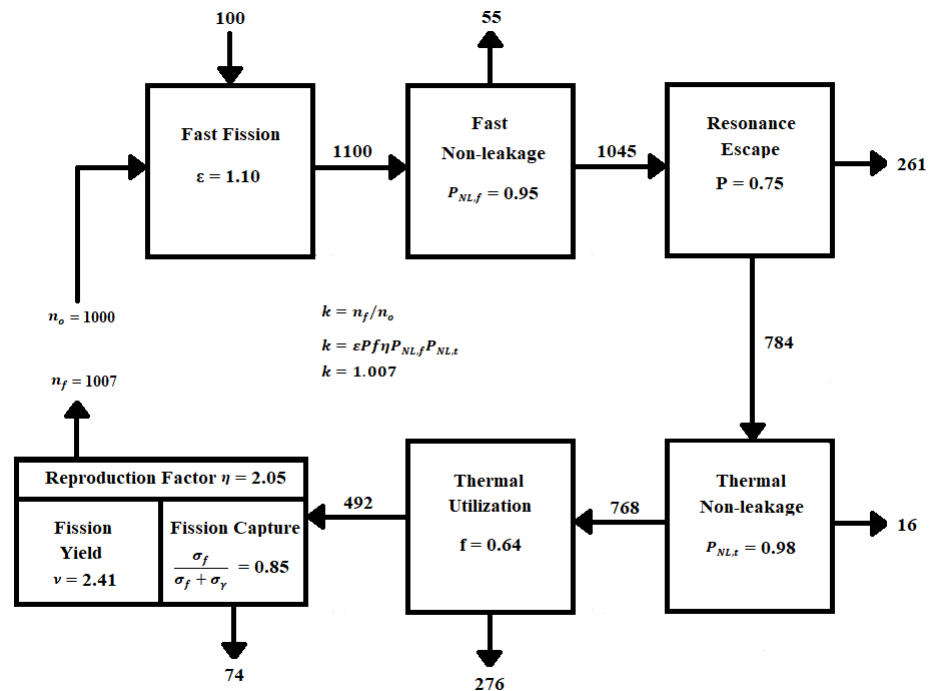
Q: For a reactor containing low enriched uranium (5% U-235), what is the purpose of a moderator material?

Neutron Population Cycle: 4 & 6 Factor Formulas

- There are many possible interactions a neutron can go through before causing thermal fission which can increase or decrease the neutron population
- We can quantify the change in population from the most prominent reactions with factors dependent on the physical characteristics of the core
- To find the total change in population for a reactor, we first find k with the assumption of an infinite medium, k_∞ , so boundary effects and leakage aren't considered

$$k_\infty = \eta f p \varepsilon$$

$$k_{eff} = \eta f p \varepsilon P_{NL}^t P_{NL}^f$$



Neutron Population Cycle: 4 & 6 Factor Formulas

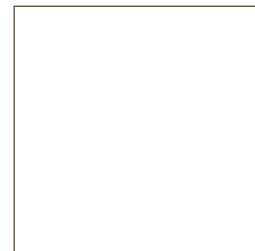
- There are many possible interactions a neutron can go through before causing thermal fission which can increase or decrease the neutron population
- We can quantify the change in population from the most prominent reactions with factors dependent on the physical characteristics of the core
- To find the total change in population for a reactor, we first find k with the assumption of an infinite medium, k_{∞} , so boundary effects and leakage aren't considered

$$k_{\infty} = \eta f p \varepsilon$$



Q: What does k infinite represent?

$$k_{eff} = \eta f p \varepsilon P_{NL}^t P_{NL}^f$$



Q: When is a reactor considered infinite? When is it not?

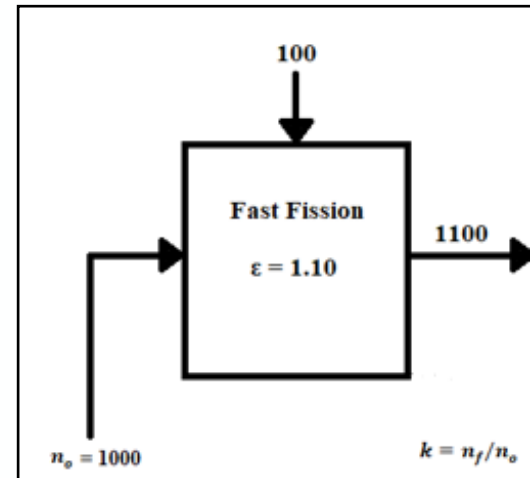
The Fast Fission Factor: ϵ

The **Fast Fission Factor** ratio of the total fission neutrons produced to fission neutrons produced by thermal fission

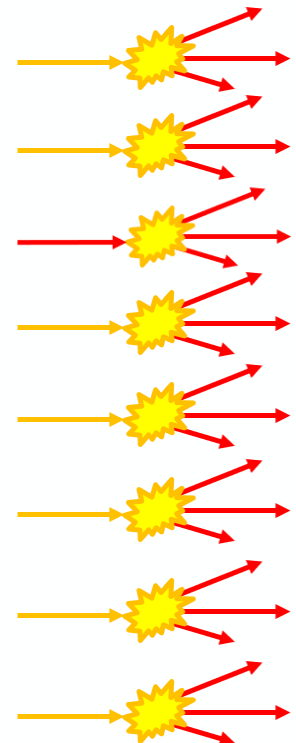
Utilized due to initial assumptions of only thermal fission events. This is a correction factor.

$$\epsilon = \frac{\text{Total Fission Neutrons Produced}}{\text{Fission Neutrons from Thermal Fission}}$$

The increase from this is relatively small, ranging from 1.02x to 1.3x, since cross-sections for fast fission are usually much smaller than the cross-sections for thermal fission



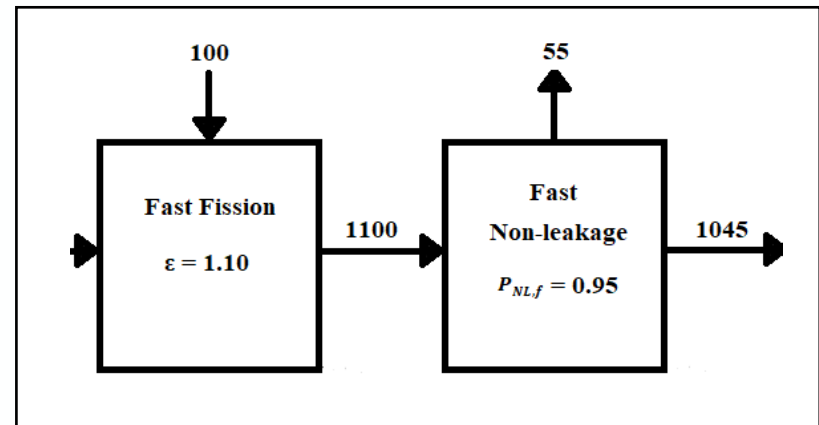
Isotope	fission cross-section	
	0.025eV / 2MeV	
235U	585	1.27
238U	0.000027	0.57
233U	531	1.98
239Pu	747	1.93
241Pu	1 012	1.76



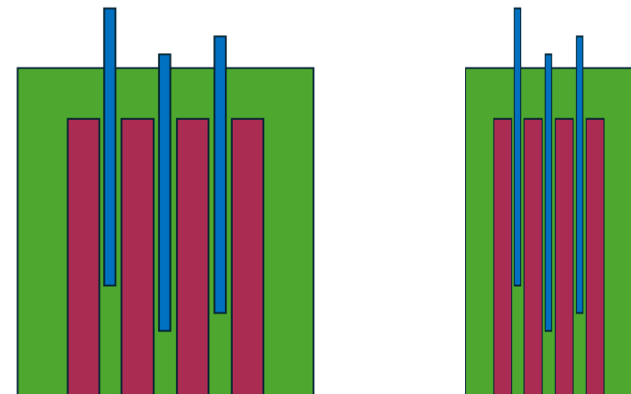
The Nonleakage Probability P_{NL}

The dimensions of the reactor determine the distribution of neutrons within. In general, the larger the vessel, the less leakage.

- The **Nonleakage Probability** is the probability that neutrons will remain in the core and not leak outside through scattering.
- The likelihood of leakage is influenced by the shape and size of the reactor vessel as well as the materials used in the vessel and moderator.



Q: Which reactor will have a higher non-leakage probability?

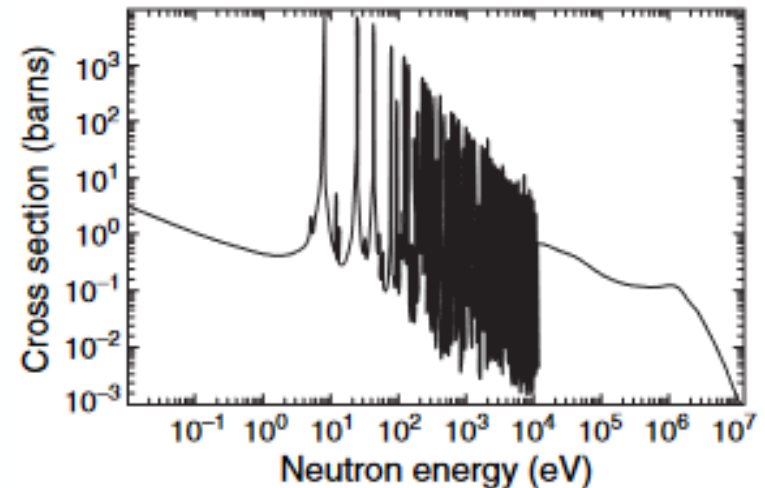
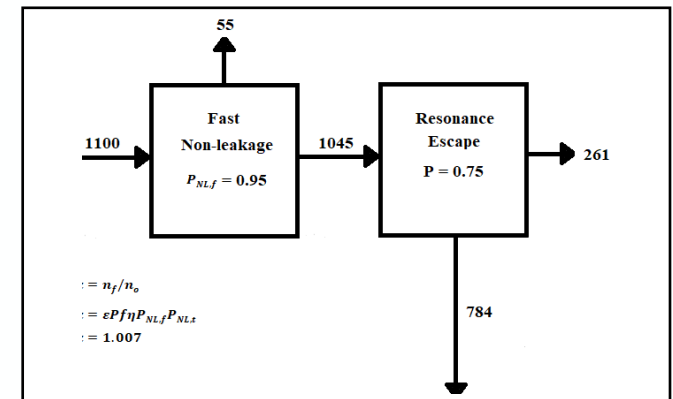


Resonance Escape Probability - p

The **Resonance Escape Probability** is the probability that a neutron won't be absorbed at resonance energy by the fuel or moderator and reach thermal energies.

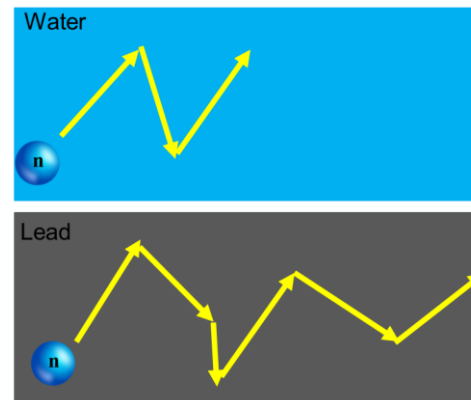
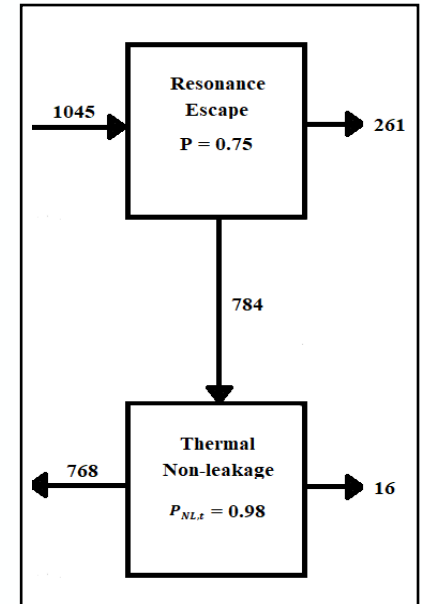
$$p = \frac{\text{Thermal Neutrons Absorbed}}{\text{Intermediate and Thermal Neutrons Absorbed}}$$

Since the resonance energy and cross-sections are unique to every isotope, this factor is dependent on materials used in the reactor core



The Nonleakage Probability P_{NL}

- The **Nonleakage Probability** is the probability that neutrons will remain in the core and not leak outside through scattering.
- The likelihood of leakage is influenced by the shape and size of the reactor vessel as well as the materials used in the vessel and moderator.
- The moderator determines how far neutrons can scatter before absorption. The farther they can travel, the more capable they are of leaking through the walls of the reactor

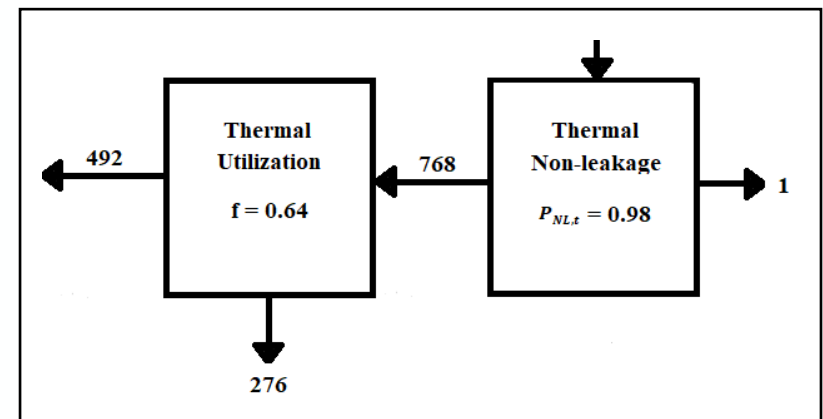
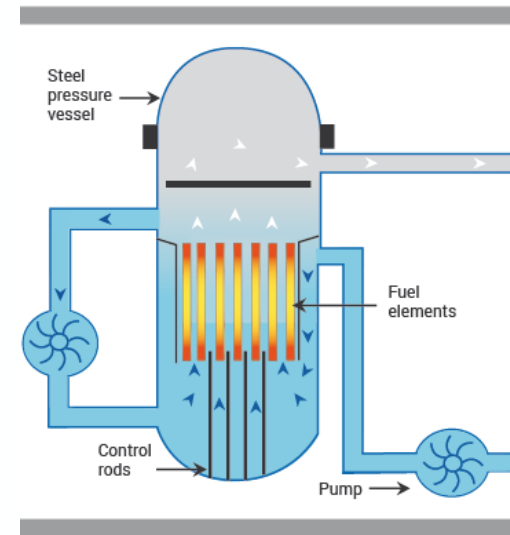


Thermal Utilization Factor - f

The **Thermal Utilization Factor** is fraction of thermal neutrons absorbed by the fuel out of all neutrons absorbed

$$f = \frac{\text{Thermal Neutrons Absorbed by Fuel}}{\text{Thermal Neutrons Absorbed}}$$

Any parts of the vessel, moderator, and control rods may absorb thermal neutrons and lower the neutrons available for fission



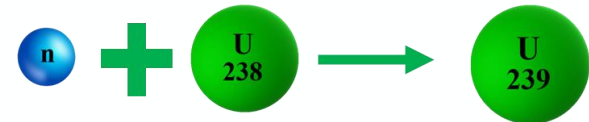
Reproduction Factor - η

▪The **Reproduction** Factor is the average number of fission neutrons produced per fission caused by neutron absorption

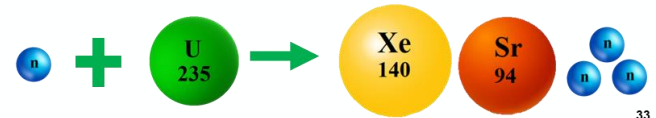
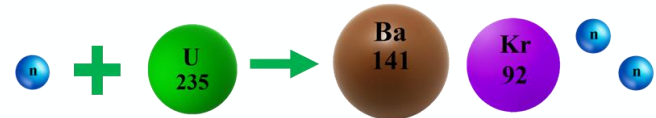
$$\eta = \frac{\text{Average Fast Neutrons Produced from Fission}}{\text{Thermal Neutrons Absorbed in Fuel}}$$

▪The reproduction factor varies depending on the average fission neutron yield and the fission capture cross section of the fuel used

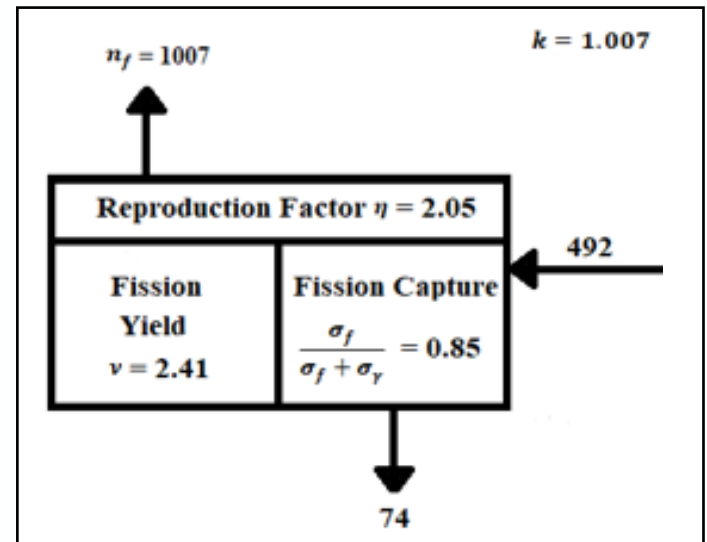
Fertile Absorption: No Neutrons Produced



U-235 Fission: 2-3 Neutrons Produced



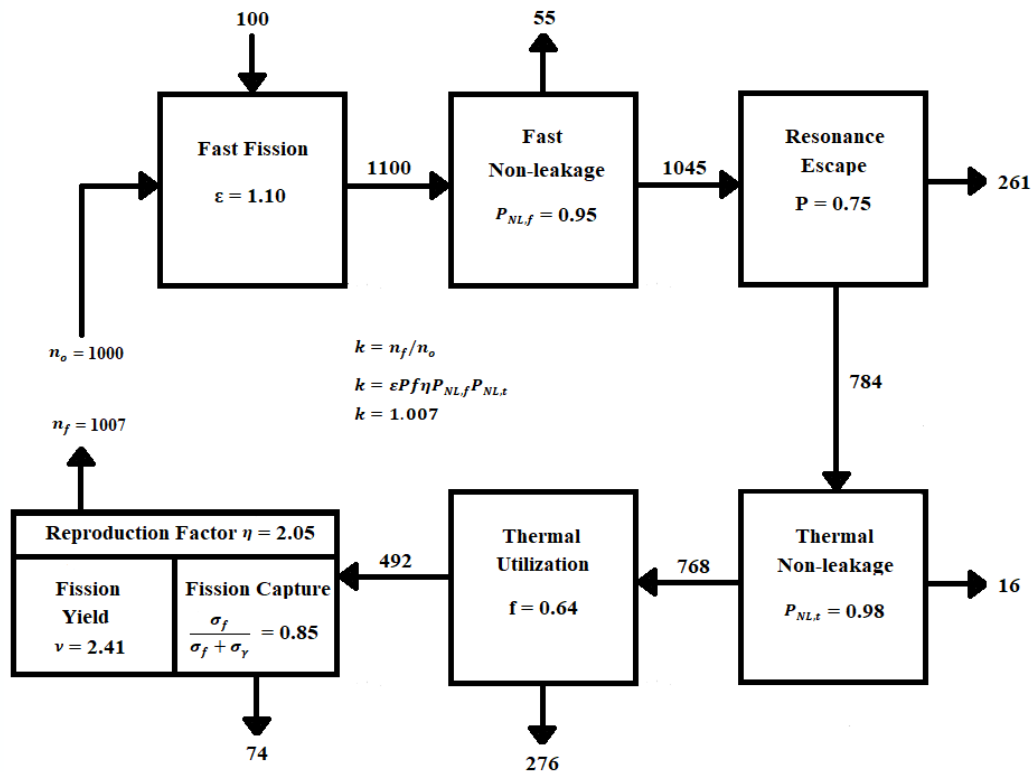
33



Neutron Population Cycle

$$k_{\infty} = \eta f p \varepsilon$$

$$k_{eff} = \eta f p \varepsilon P_{NL}^t P_{NL}^f$$

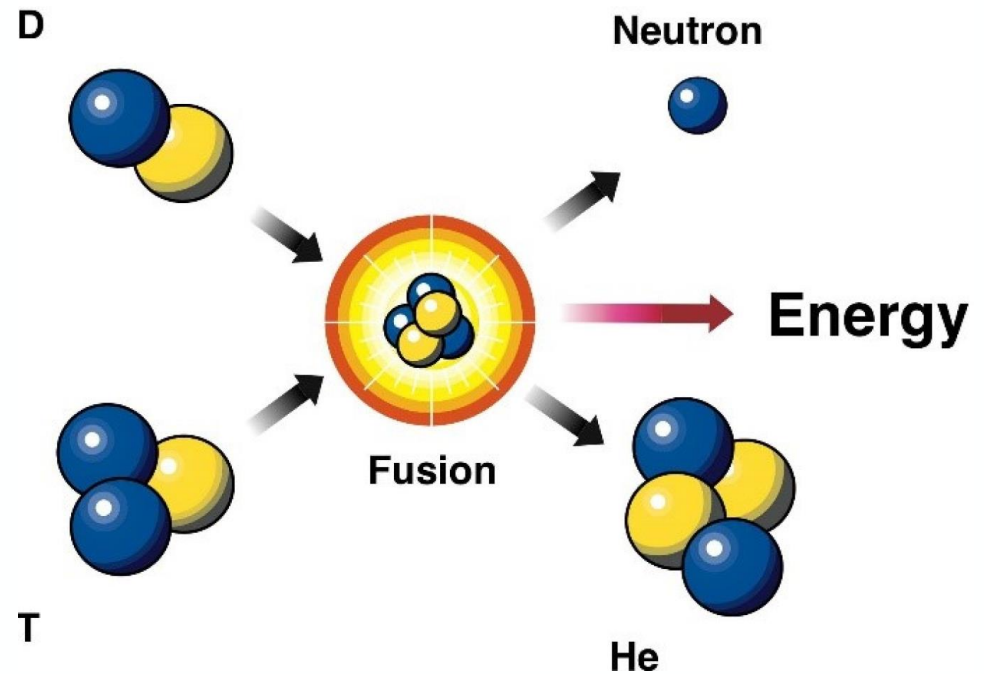


Nuclear Fusion

Fusion is where nuclei combine to form a new isotope of higher mass than either nuclei individually.

The excess mass from the nuclei is then converted to energy.

Most fusion interactions we learn about in Nuclear Engineering are with hydrogen or helium isotopes

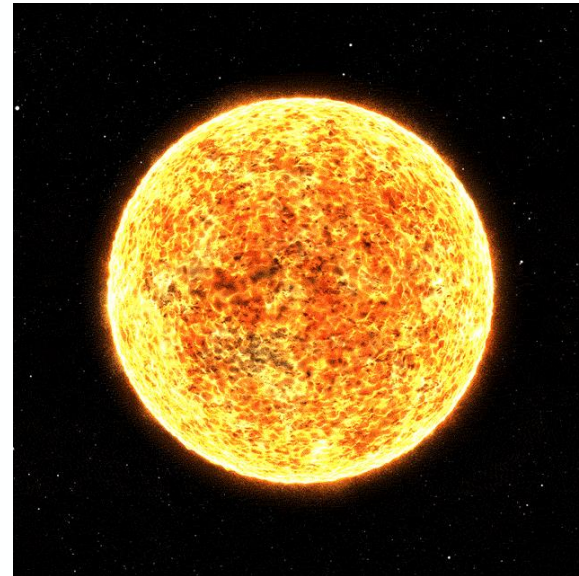


<https://www.energy.gov/science/doe-explainsfusion-reactions>

Fusion: The Lawson Criteria

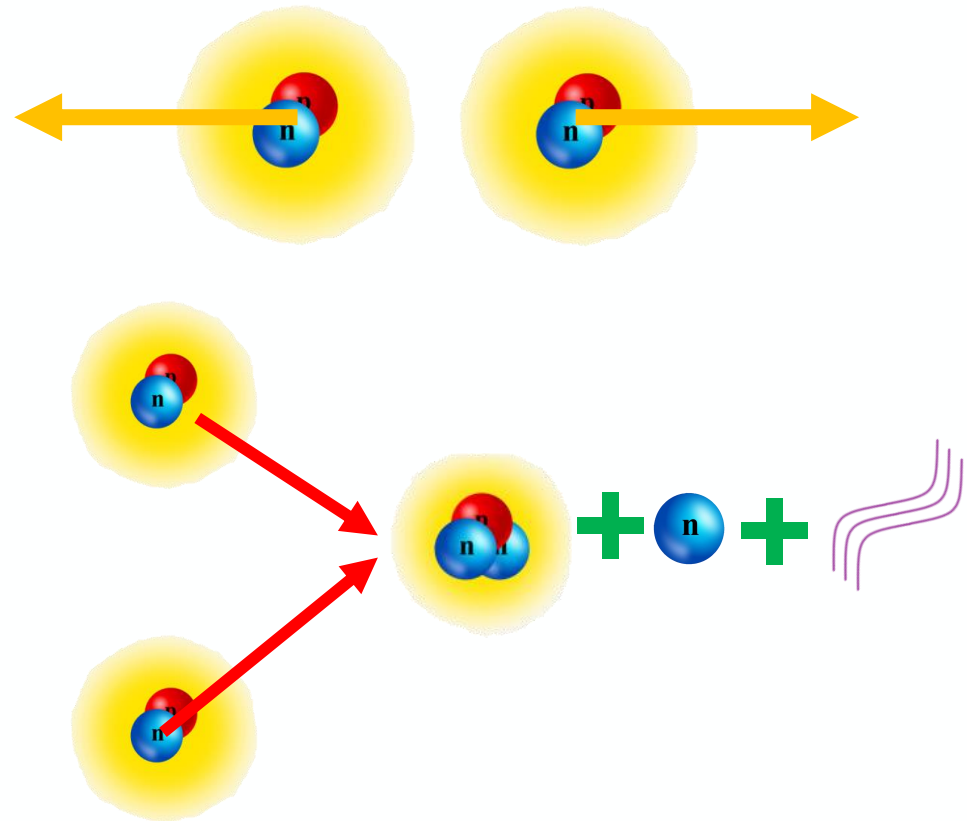
The variables that determine whether fusion is possible, known as the Lawson Criteria, are Temperature, Density, and Time.

- The only place in the world where fusion occurs naturally is in stars which are extremely dense, millions of degrees hot, and are kept together due to their gravitational force.



Fusion: The Lawson Criteria

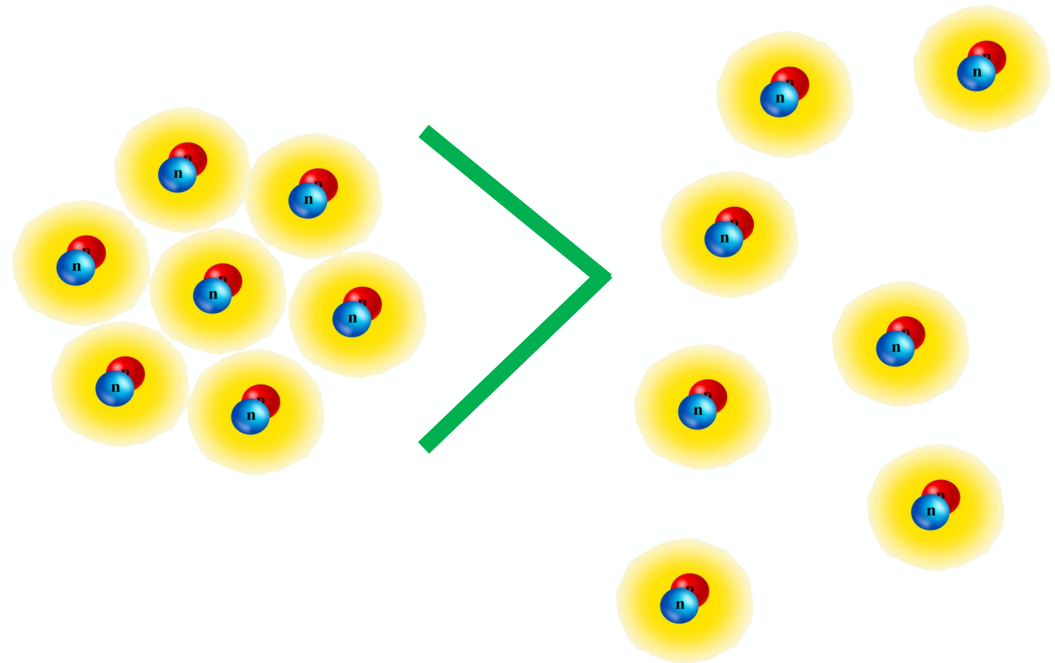
- To fuse, the atoms need to overcome the electrical repulsion of the positively charged nuclei
- Extremely high temperatures provide the energy to nuclei so they can surpass the force of electrical repulsion



Fusion: The Lawson Criteria

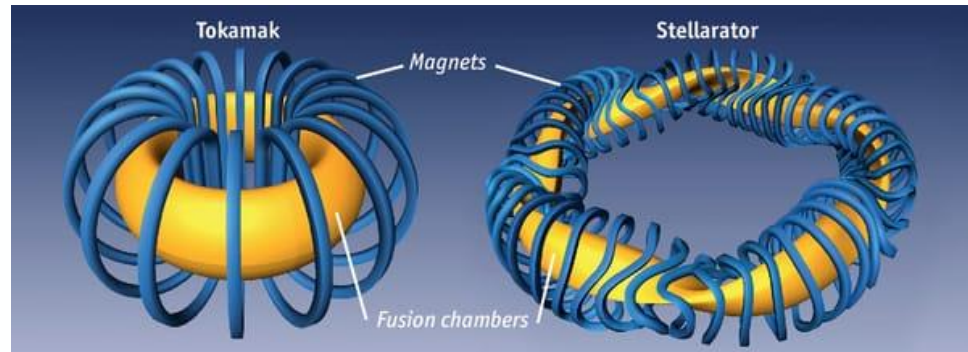
An extremely dense material forces nuclei closer to one another and increases the likelihood of an interaction as they move

Similarly, the longer the nuclei are kept at high temperatures and densities, the more opportunities there are for fusion to occur

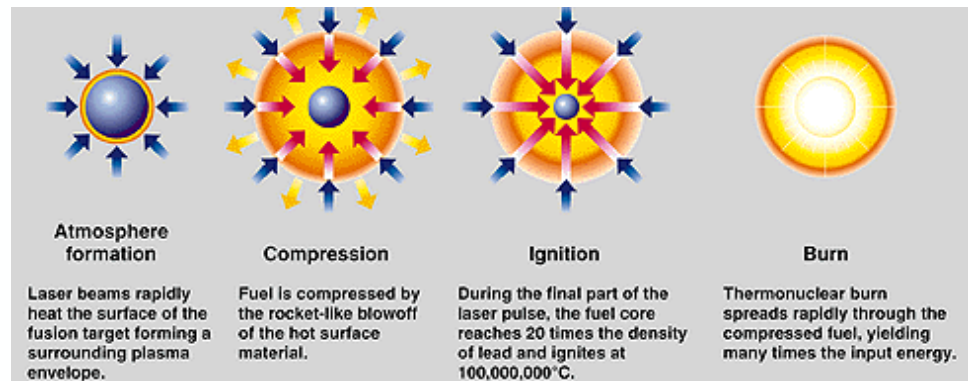


Fusion Technologies

- Fusion requires extremely high temperatures to achieve
 - Create plasma
 - Force atoms in the plasma together long enough for them to react
- Magnetic confinement
 - Use strong magnetic fields to trap the plasma
 - Tokamak – Uses strong magnetic fields to ensure plasma does not touch walls
 - Stellarator – Similar, but twisted to reduce the magnetic field required
- Inertial confinement
 - Use a powerful laser to compress a fuel pellet
 - Pellet's own inertia holds it together long enough for fusion to occur



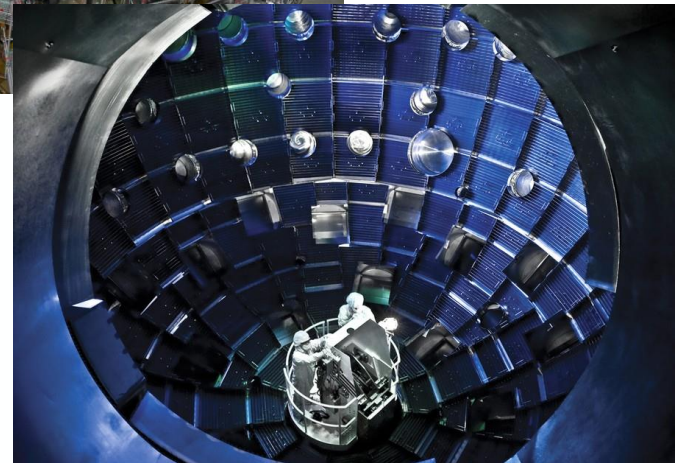
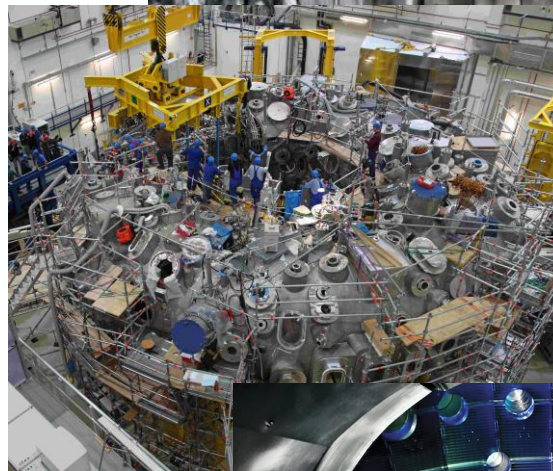
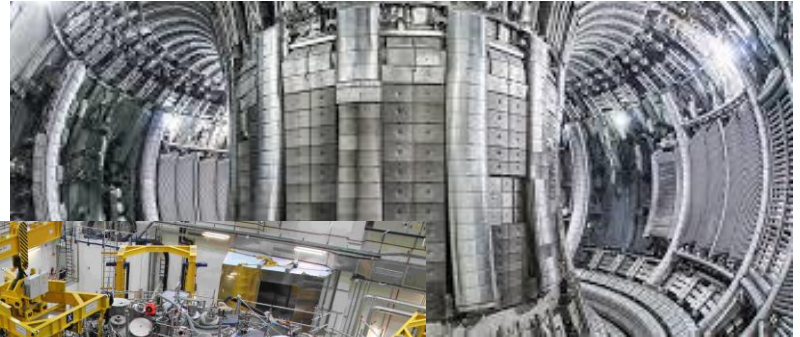
<https://www.economist.com/science-and-technology/2015/10/24/stellar-work>



<https://www.sciencedirect.com/topics/mathematics/inertial-confinement>

Notable Fusion Projects

- ITER (France) — The world's largest tokamak, built by a 35-nation collaboration, designed to demonstrate fusion power at power-plant scale
- Wendelstein 7-X (Germany) — The world's largest stellarator, designed to test steady-state plasma confinement
- NIF — National Ignition Facility (USA) — A laser-driven inertial confinement facility that achieved $Q > 1$
- Over 30 companies (both established and startups) exploring fusion technology



Thank You



School of Nuclear Engineering