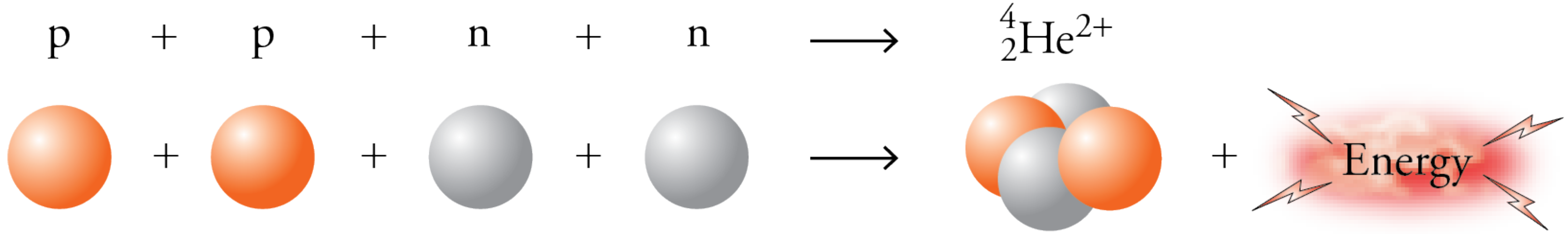
Nuclear Stability and Binding Energy

- ***Binding energy*** = the amount of energy released when a nucleus is formed.
- When two protons and two neutrons combine to form a helium nucleus, energy is released. This is the total binding energy for the helium nucleus.

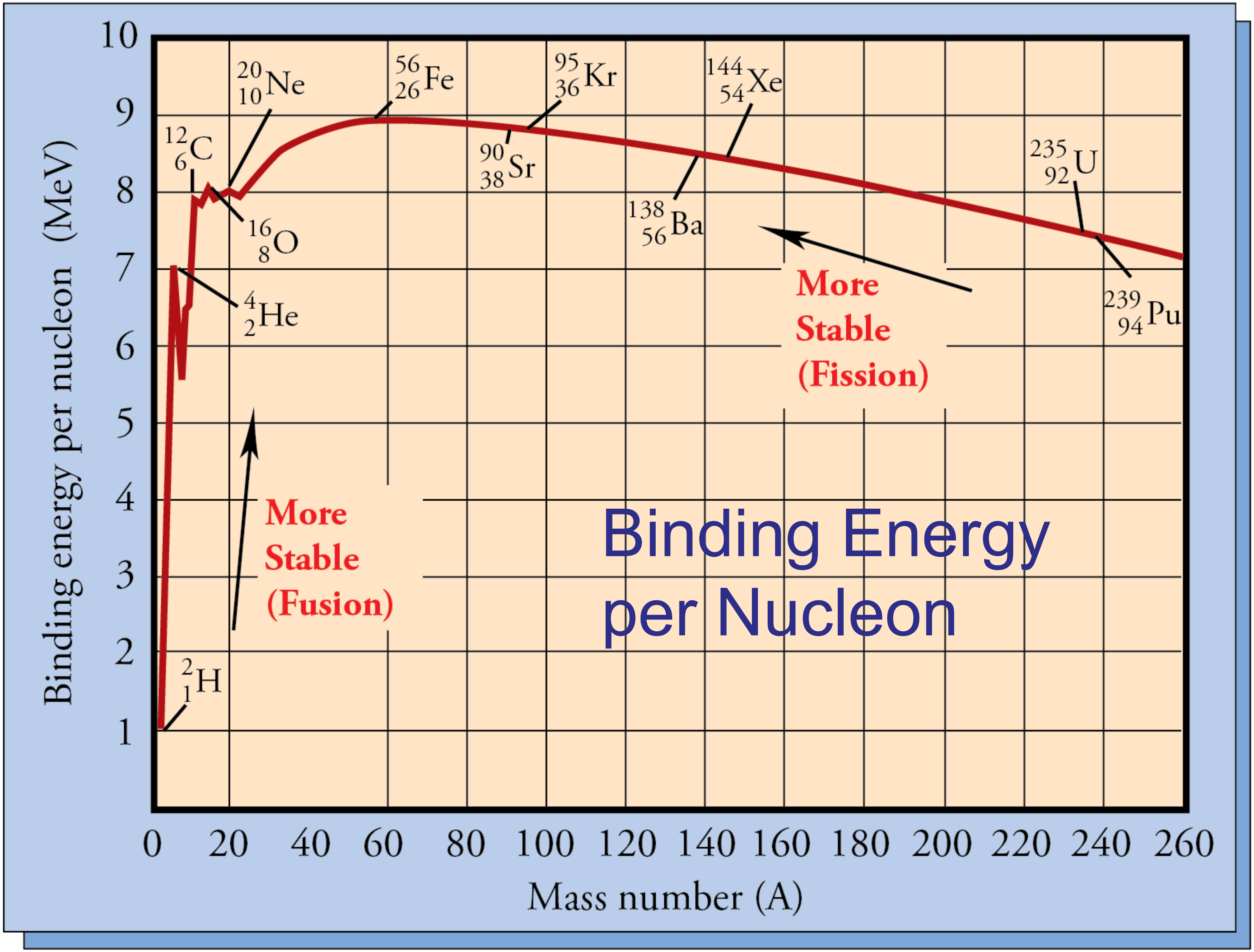


$$p + p + n + n \longrightarrow {}^{4}_{2}\mathrm{He}^{2+}$$

Nuclear Energy

- The **binding energy per nucleon**, which is the total binding energy divided by the number of nucleons (protons and neutrons), is a good indication of nuclear stability.
- For example, because a uranium-235 atom has many more nucleons than an iron-56 atom, it has a much larger total binding energy, but an iron-56 atom is significantly more stable than a uranium-235 atom. This is reflected in the higher binding energy per nucleon for iron-56.
- Binding energy per nucleon generally increases from small atoms to atoms with a mass number around 56.
- Binding energy per nucleon generally decreases from atoms with a mass number around 56 to larger atoms.

Binding Energy per Nucleon



Nuclear Energy

- Because binding energy per nucleon generally increases from small atoms to atoms with a mass number around 56, fusing small atoms to form larger atoms (***nuclear fusion***) releases energy.
- Because binding energy per nucleon generally decreases from atoms with a mass number around 56 to larger atoms, splitting large atoms to form medium-sized atoms (***nuclear fission***) also releases energy.

Nuclear Fusion

$$
\begin{array}{ccccccc}
{}^{2}_{1}\mathrm{H} & + & {}^{3}_{1}\mathrm{H} & \longrightarrow & {}^{4}_{2}\mathrm{He} & + & {}^{1}_{0}\mathrm{n} \\
\text{Deuterium} & + & \text{Tritium} & \longrightarrow & \text{Helium} & + & \text{Neutron}
\end{array}
$$

- Products are much more stable than reactants, so products have much lower PE, and a lot of energy is released.

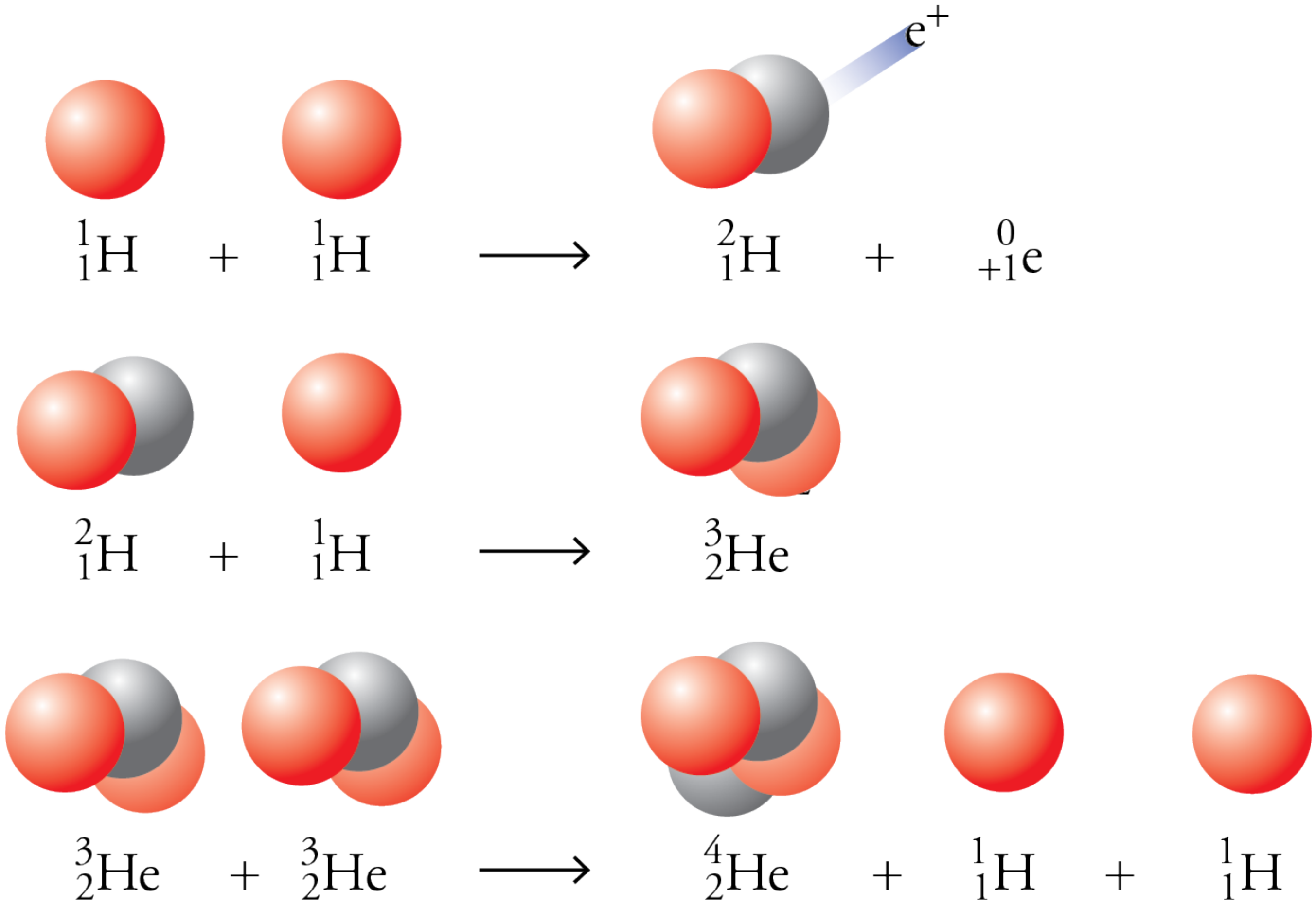
Nuclear Fusion

$$^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

$$\text{Deuterium} + \text{Tritium} \longrightarrow \text{Helium} + \text{Neutron}$$

- Requires a very high temperature (about 10^6 ºC) to initiate the fusion.
  - The electromagnetic repulsion between the positive nuclei is felt at a relatively long range.
  - The strong force attraction is only significant when the nuclei are very close.
  - Therefore, unless the nuclei are rushing together at a very high velocity (very high temperature), the +/+ repulsion slows the nuclei down, stops them, and accelerates them away from each other before they are close enough for the strong force to play a role.

Nuclear Fusion Powers the Sun

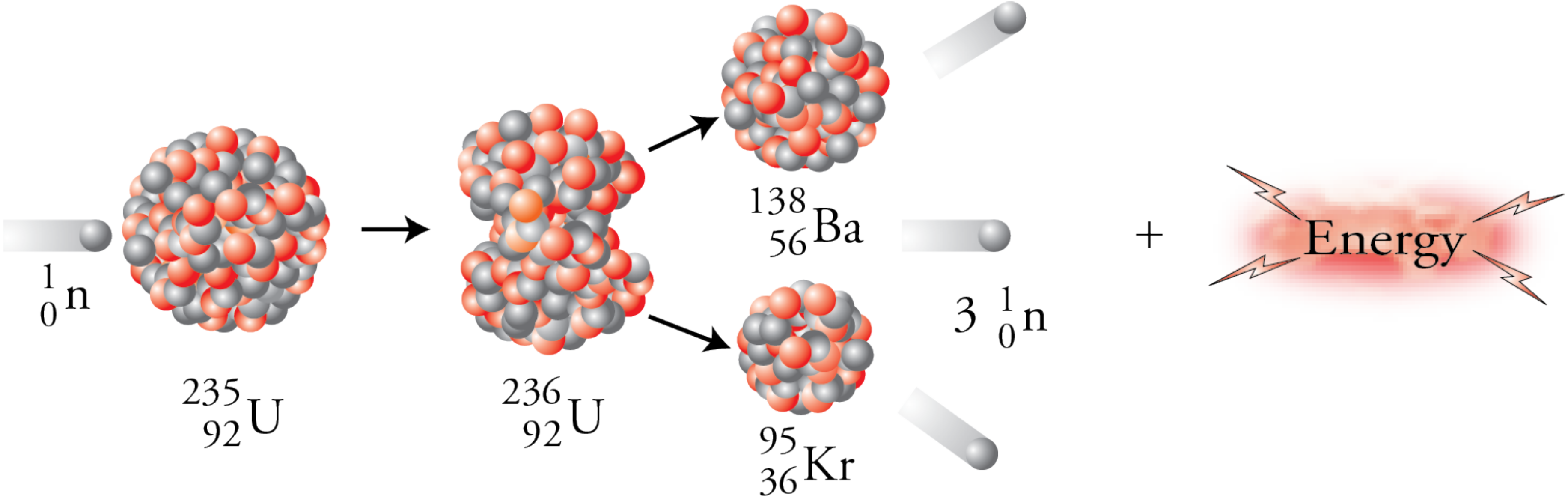


$$^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{2}_{1}\mathrm{H} + {}^{0}_{+1}\mathrm{e}$$

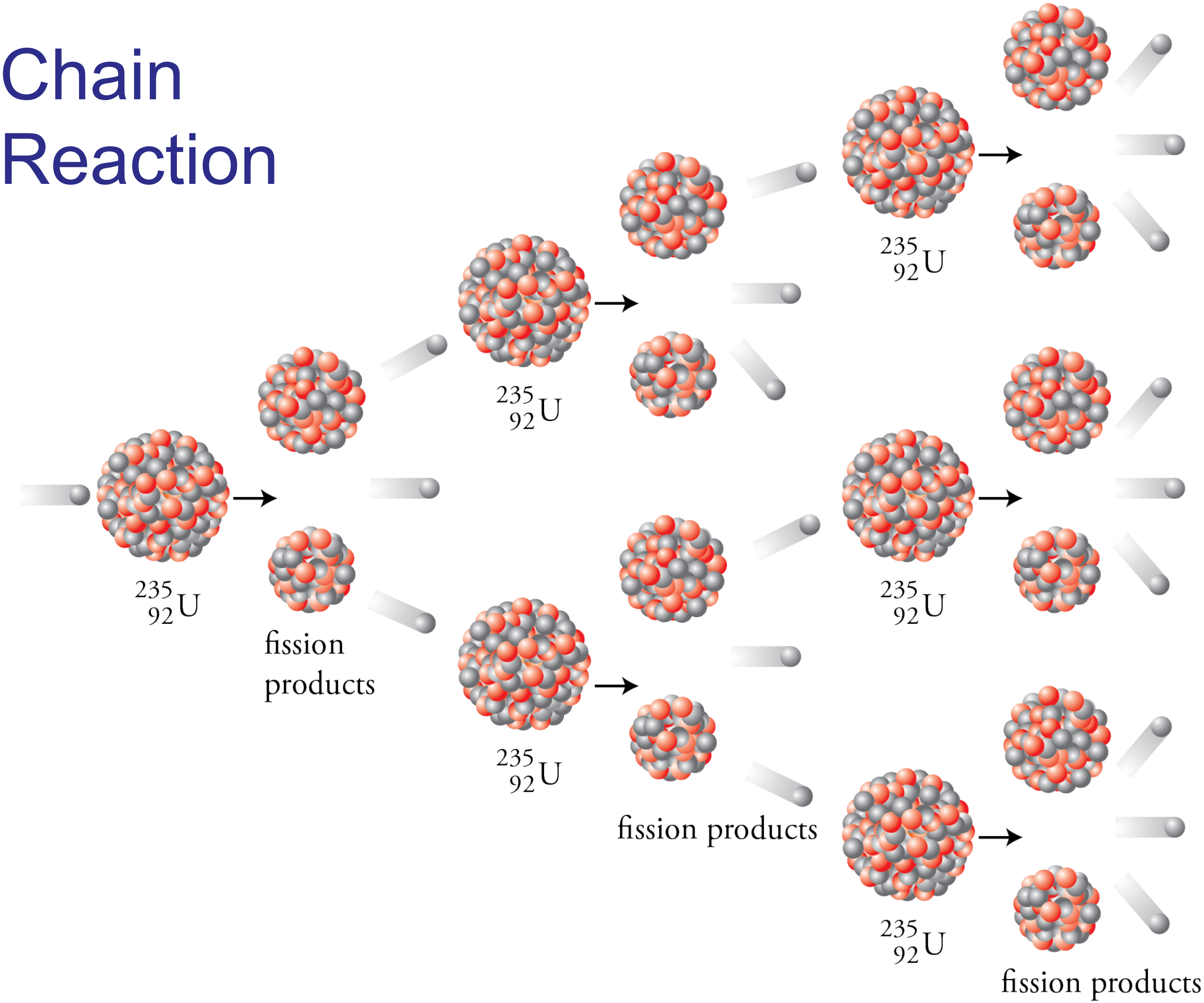
$$^{2}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H} \longrightarrow {}^{3}_{2}\mathrm{He}$$

$$^{3}_{2}\mathrm{He} + {}^{3}_{2}\mathrm{He} \longrightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{H}$$

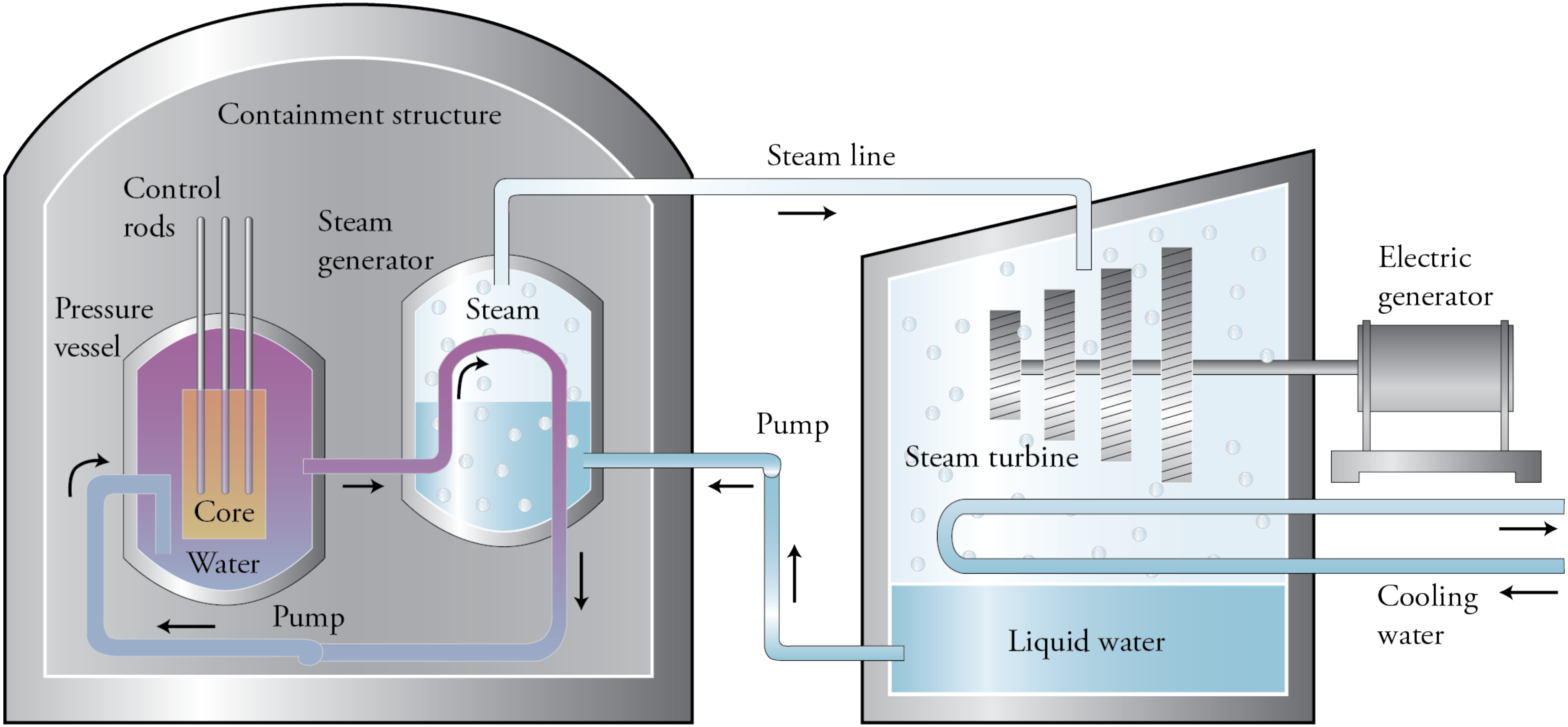
Nuclear Fission



Chain Reaction

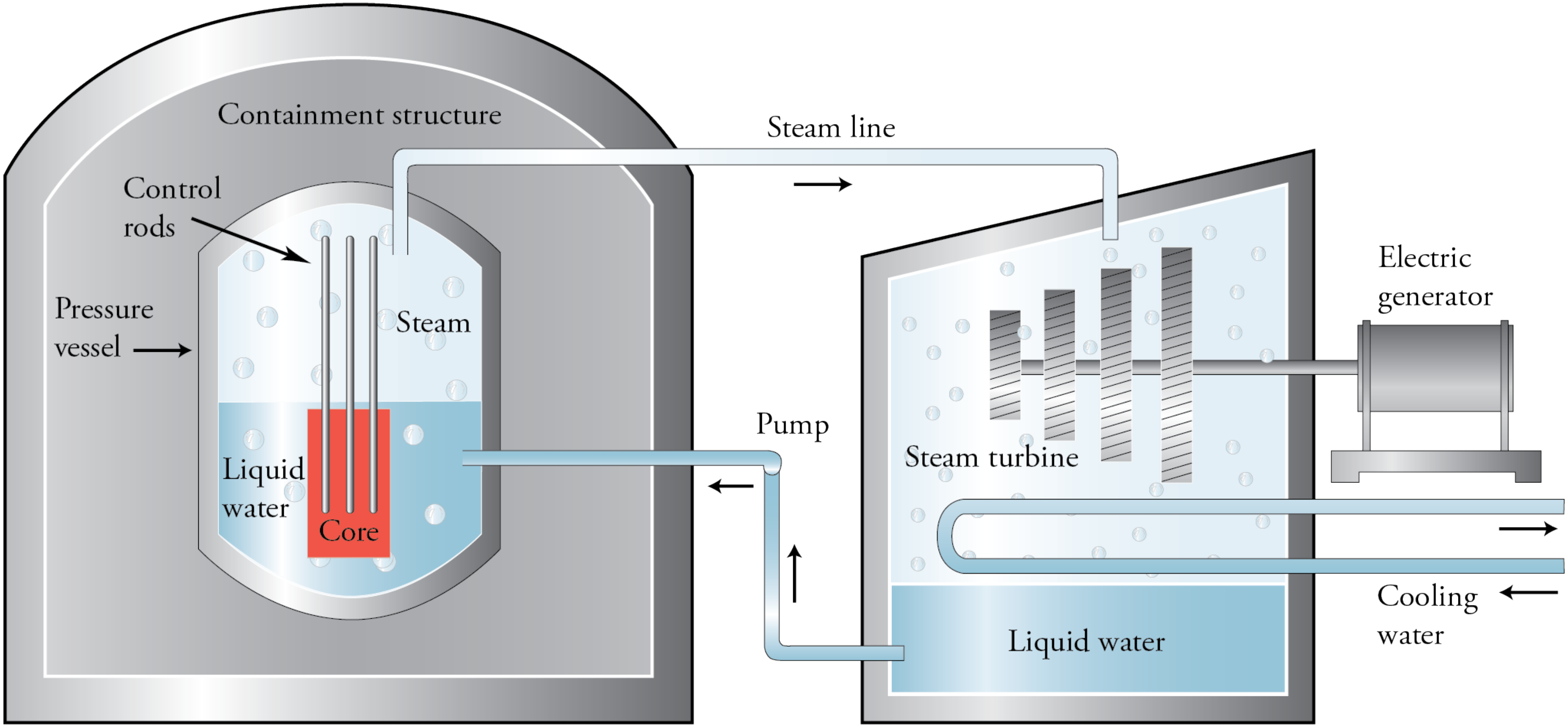


Nuclear Power Plant



Pressurized Water Reactor (PWR)

Nuclear Power Plant



Boiling Water Reactor (BWR)

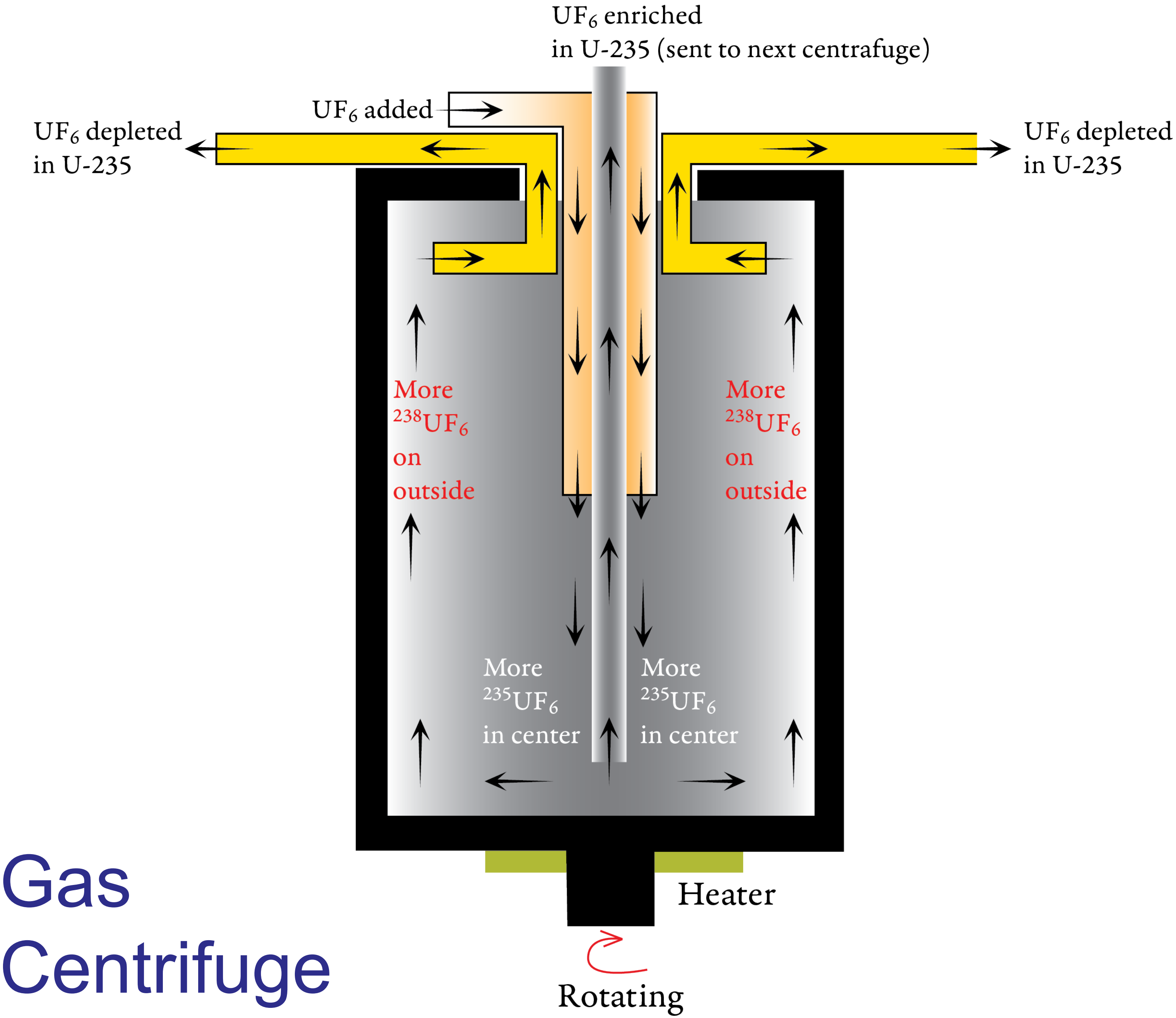
Nuclear Power Plant (2)

- To get a sustained chain reaction, the percentage of ^{235}U must be increased to about 3%, in part because the unfissionable ^{238}U absorbs too many neutrons.

$$^{238}_{92}\text{U} + ^{1}_{0}\text{n} \rightarrow ^{239}_{92}\text{U}$$

$$^{239}_{92}\text{U} \rightarrow ^{239}_{93}\text{Np} + ^{0}_{-1}\text{e}$$

$$^{239}_{93}\text{Np} \rightarrow ^{239}_{94}\text{Pu} + ^{0}_{-1}\text{e}$$



Gas Centrifuge

Nuclear Power Plant (3)

- Fuel rods
  - A typical 1000-megawatt power plant will have from 90,000 to 100,000 kg of enriched fuel packed in 100 to 200 zirconium rods about 4 meters long.
- Moderator slows neutrons
  - ^{235}U atoms are more likely to absorb slow neutrons.
  - Can be water

Nuclear Power Plant (4)

- Control Rods
  - Substances, such as cadmium or boron, absorb neutrons.
  - Control rate of chain reaction
  - Dropped at first sign of trouble to stop fission reaction