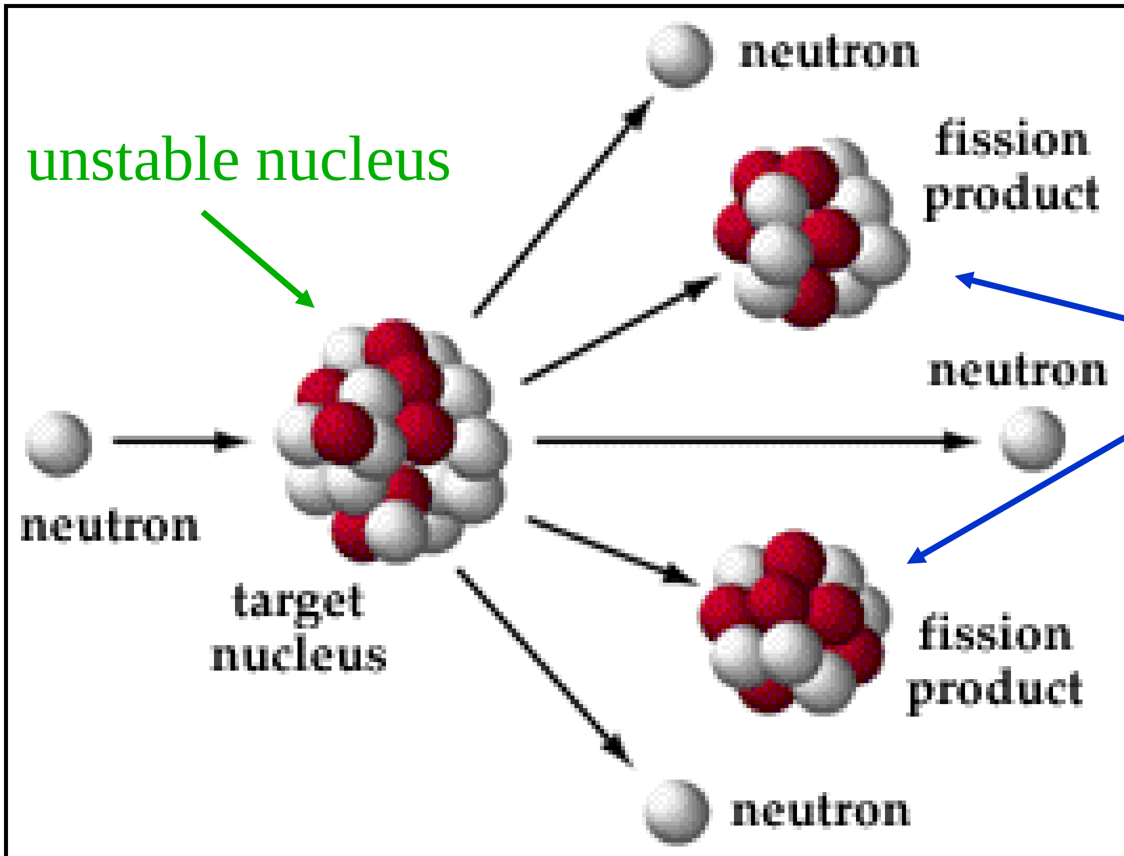
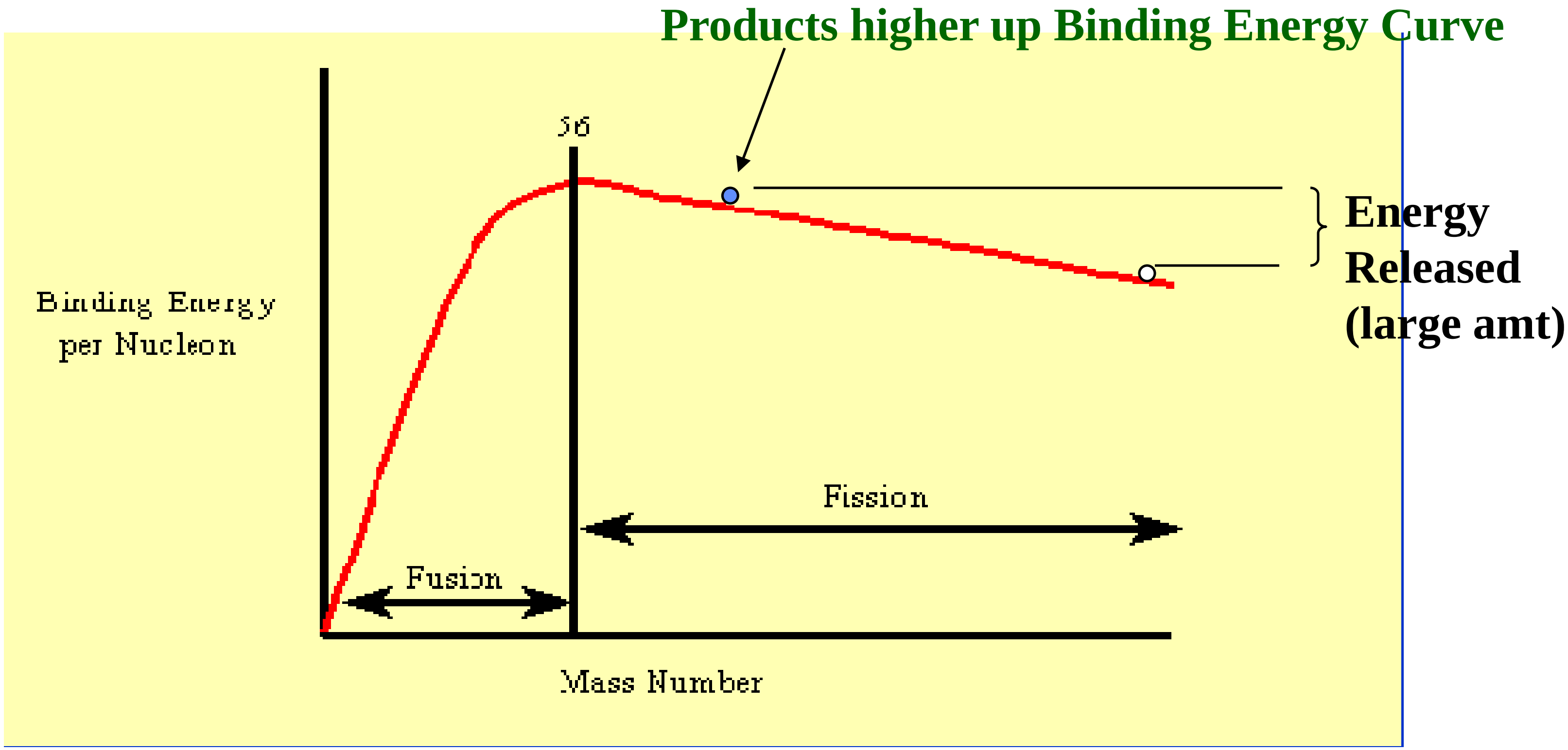
Splitting The Atom

Nuclear Fission

The Fission Process



mass closer to 56



- Sum of the masses of the resulting nuclei ~ 0.1% less than original mass
- "Missing mass" is converted into energy

Energy Released By A Fission

- ^{235}U + n --> fission + 2 or 3 n + 200 MeV

3.2×10^{-11} j

- Production of one molecule of CO_2 in fossil fuel combustion only generates 4 ev or 6.5×10^{-19} j of energy

- This is 50,000,000 times more energy

1MeV (million electron volts) = 1.609 x 10-13 j

Energy Released By A Fission

^{235}U + n --> fission + 2 or 3 n + 200 MeV

3.2×10^{-11} j (per U atom)

50,000,000 times more energy

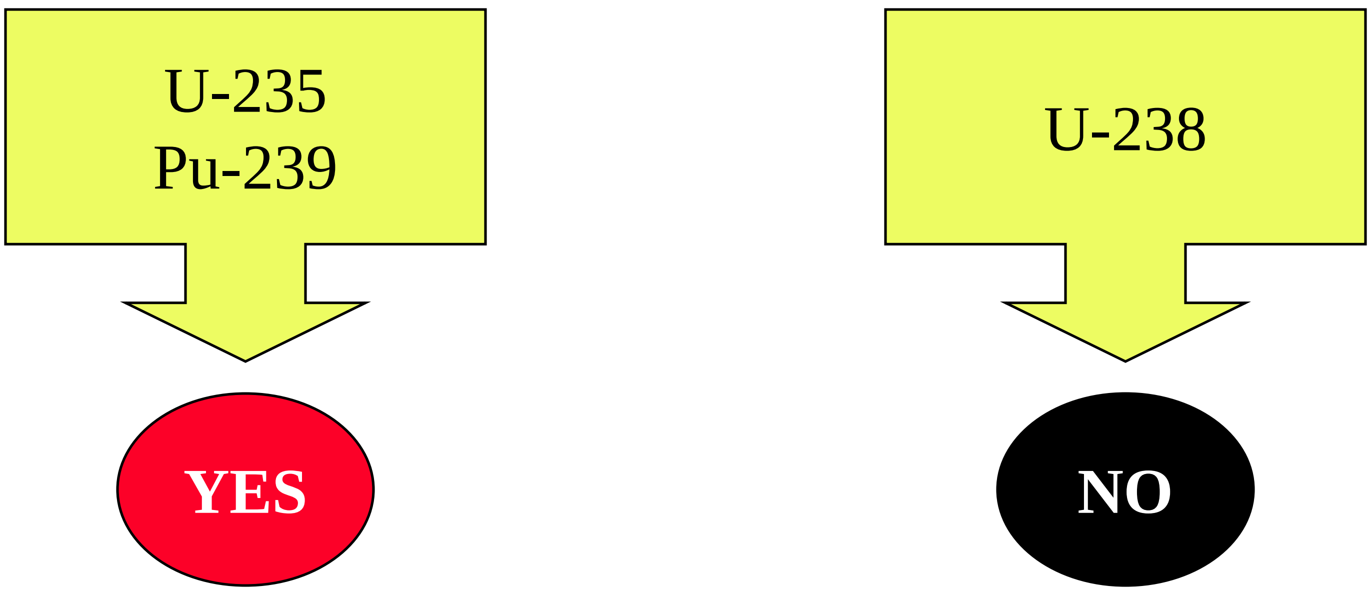
Fossil Fuel —combustion→ CO_2 + 4 ev

6.5×10^{-19} j (per CO_2 molec)

1MeV (million electron volts) = 1.609×10^{-13} j

Fissile Nuclei

- Not all nuclei are capable of absorbing a neutron and then undergoing a fission reaction (induced fission)



The Fission of U-235

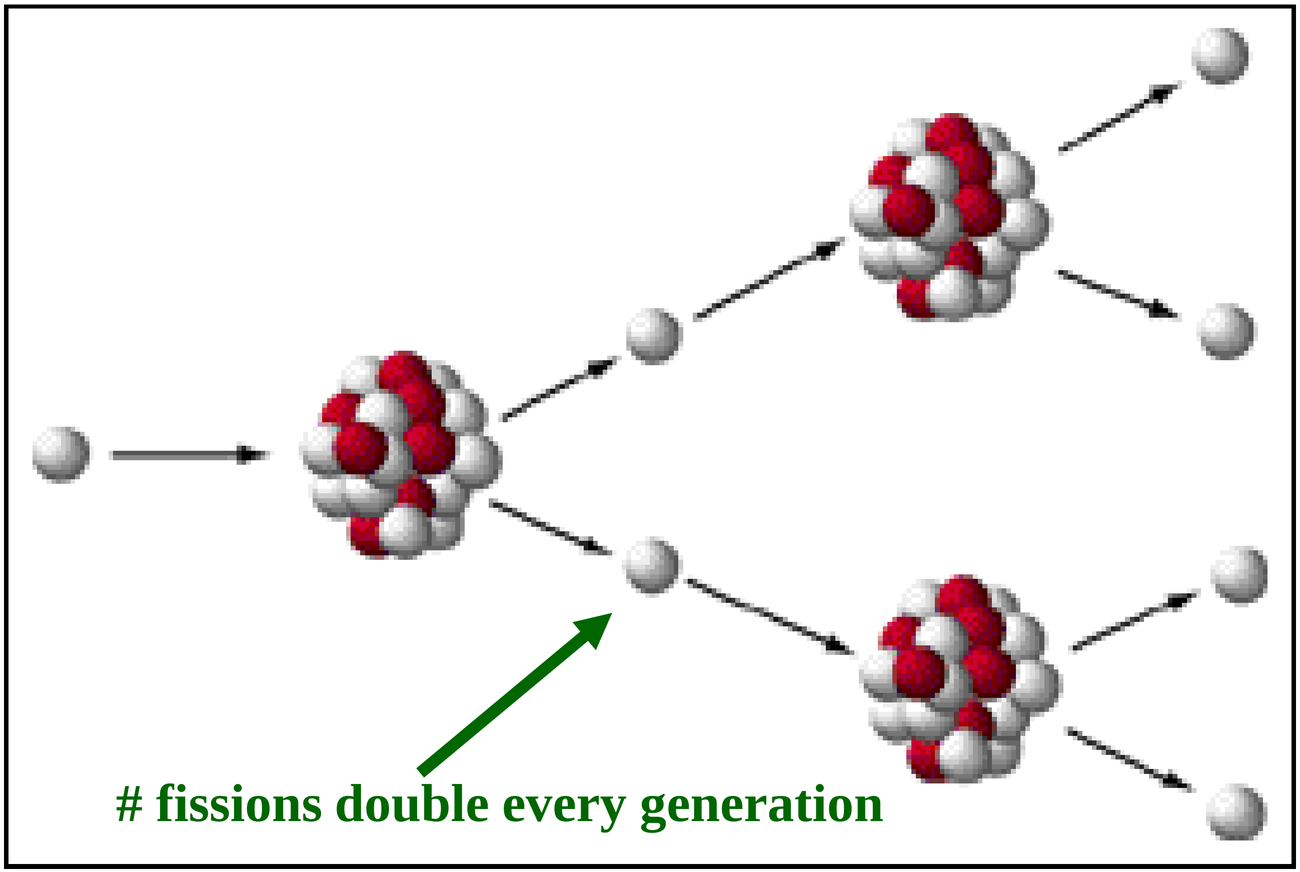
$$^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathrm{U}$$

$$^{236}_{92}\mathrm{U} \rightarrow {}^{140}_{54}\mathrm{Xe} + {}^{94}_{38}\mathrm{Sr} + 2\,{}^{1}_{0}\mathrm{n}$$

$$^{236}_{92}\mathrm{U} \rightarrow {}^{132}_{50}\mathrm{Sn} + {}^{101}_{42}\mathrm{Mo} + 3\,{}^{1}_{0}\mathrm{n}$$

$$^{236}_{92}\mathrm{U} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\,{}^{1}_{0}\mathrm{n}$$

Nuclear Chain Reaction



10 generations ⟶ 1024 fissions

80 generations ⟶ 6 x 1023 fissions

Critical Mass

When the amount of fissile material is small

- many of the neutrons don't strike other nuclei
- chain reaction stops

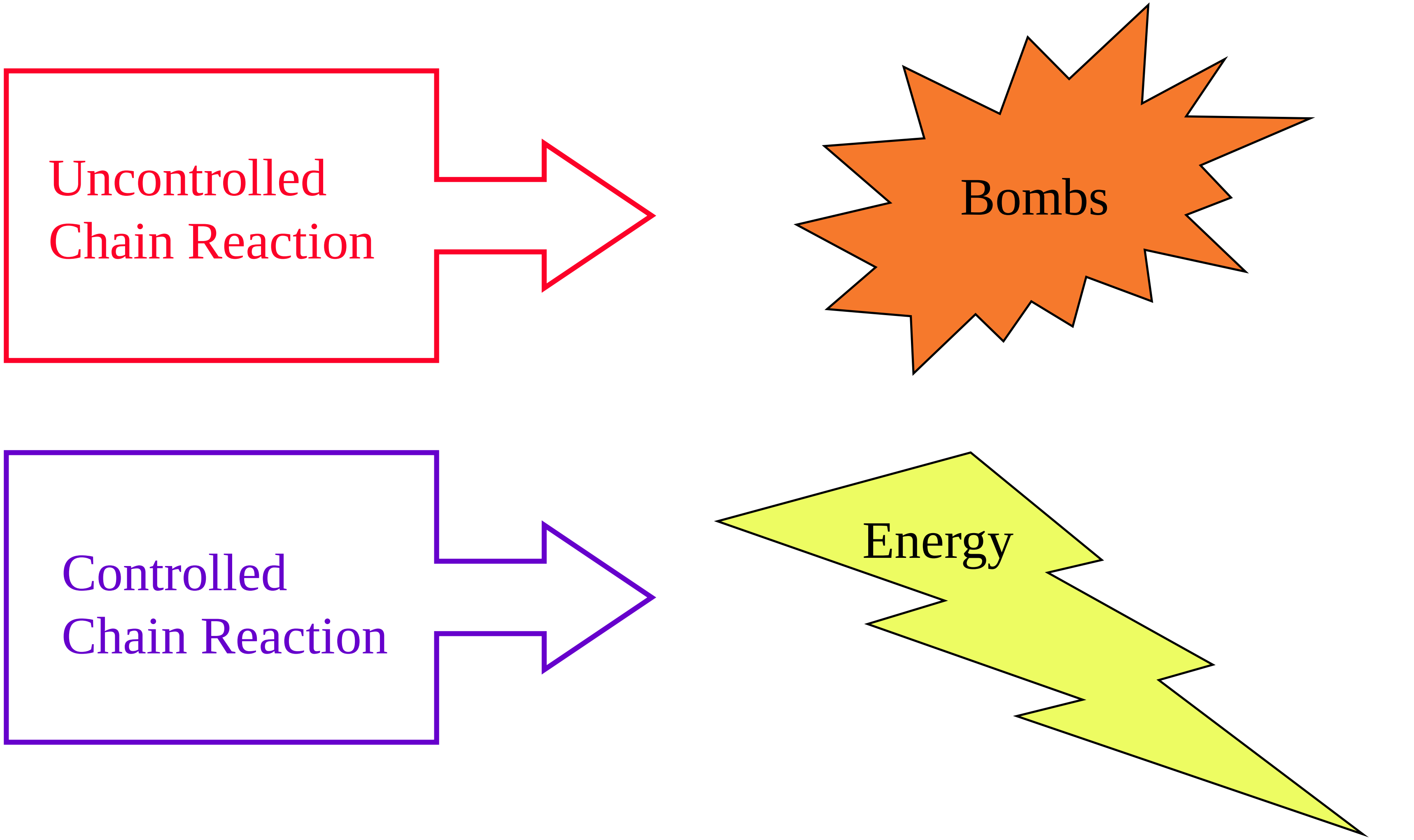
critical mass

the amount of fissile material necessary for a chain reaction to become self-sustaining.

Nuclear Chain Reactions

- An uncontrolled chain reaction is used in nuclear weapons
- A controlled chain reaction can be used for nuclear power generation

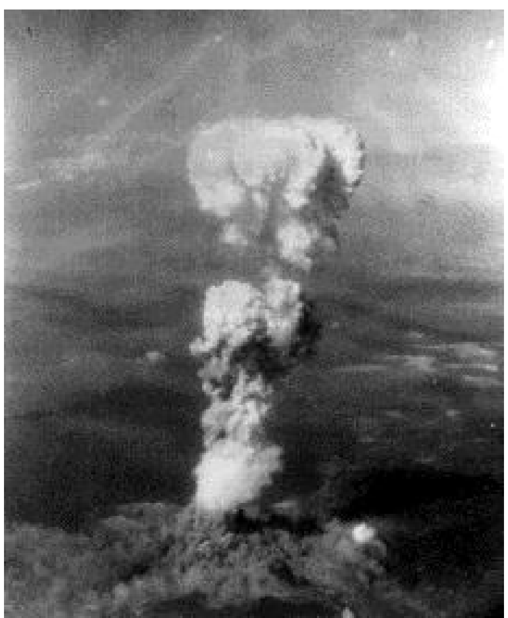
Nuclear Chain Reactions



Uncontrolled Chain Reactions

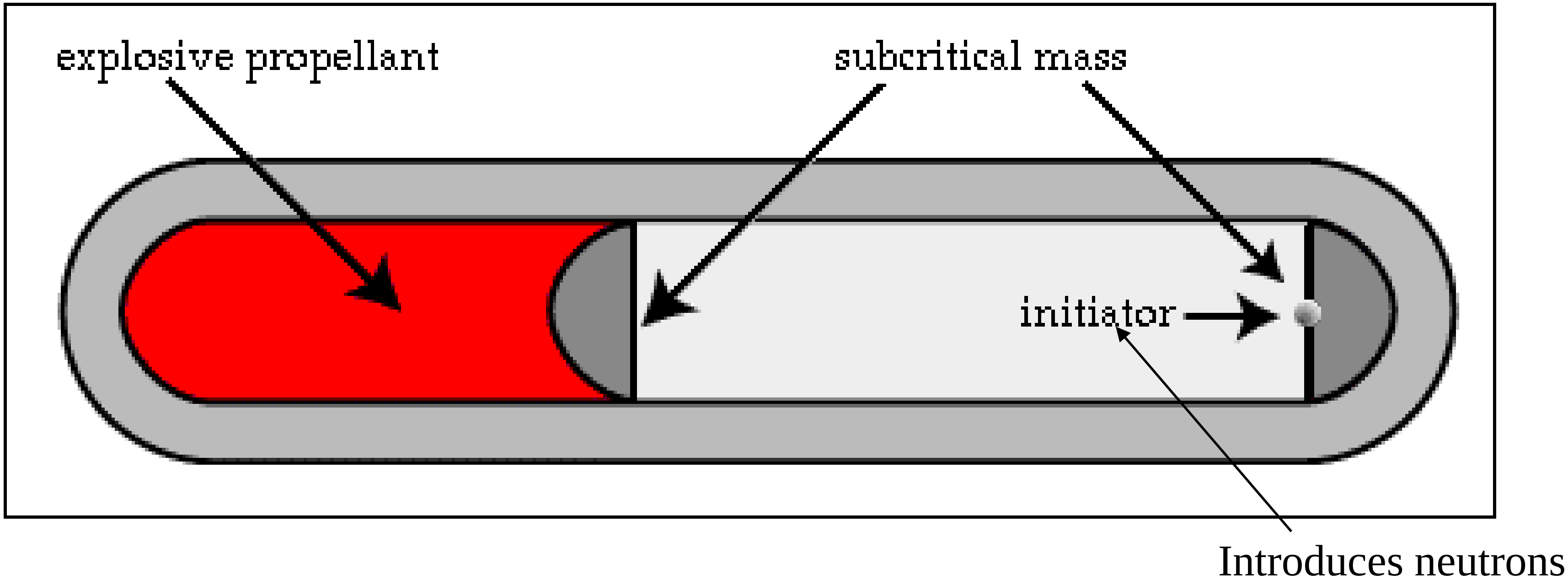
The Atomic Bomb

Little Boy Bomb

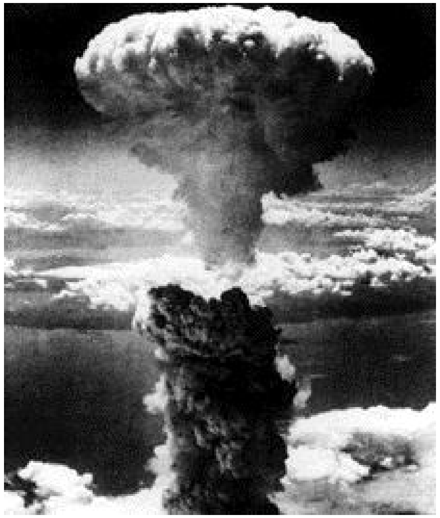


- Dropped on Hiroshima August 6, 1945
- U-235 gun-type bomb
- Between 80,000 and 140,000 people killed instantly

The Gun-Type Bomb

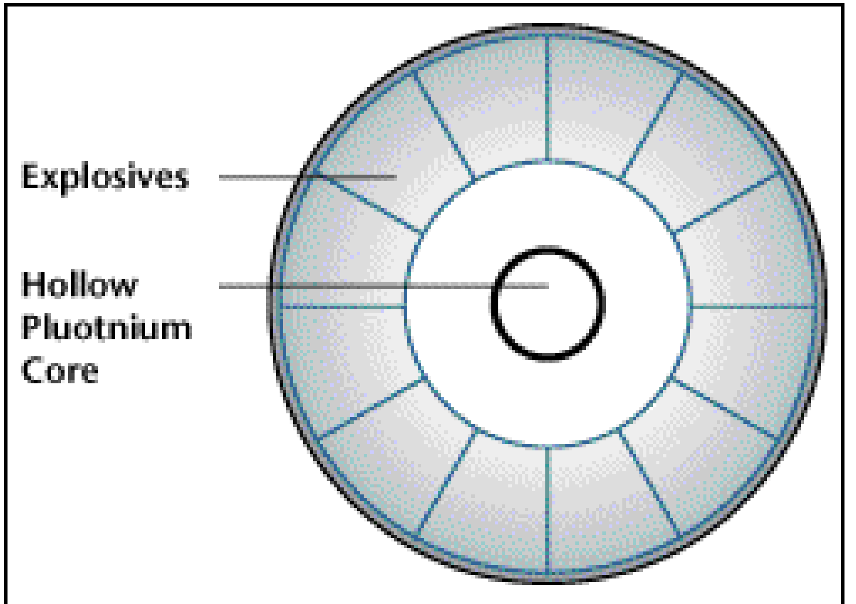


Fat Man



- Plutonium implosion-type bomb
- Dropped on Nagasaki August 9, 1945
- 74,000 killed and 75,000 severely injured

Plutonium Implosion-Type Bomb



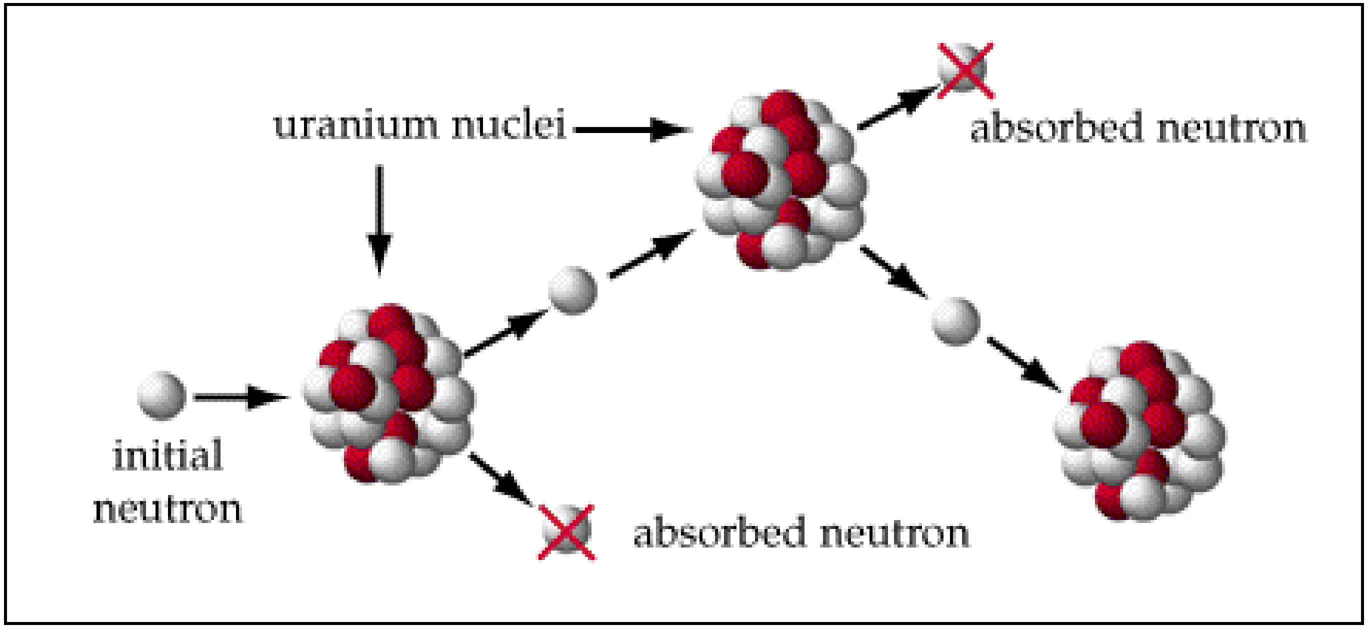
Fat Man Schematic

Explosive charges compress a sphere of plutonium quickly to a density sufficient to exceed the critical mass

Controlled Chain Reactions

Nuclear Energy Production

Controlled Nuclear Fission



Requirement:

only one produced neutron per generation can strike another uranium nucleus

Controlled Nuclear Fission

Produced neutrons : used neutrons < 1

Rxn unsustained

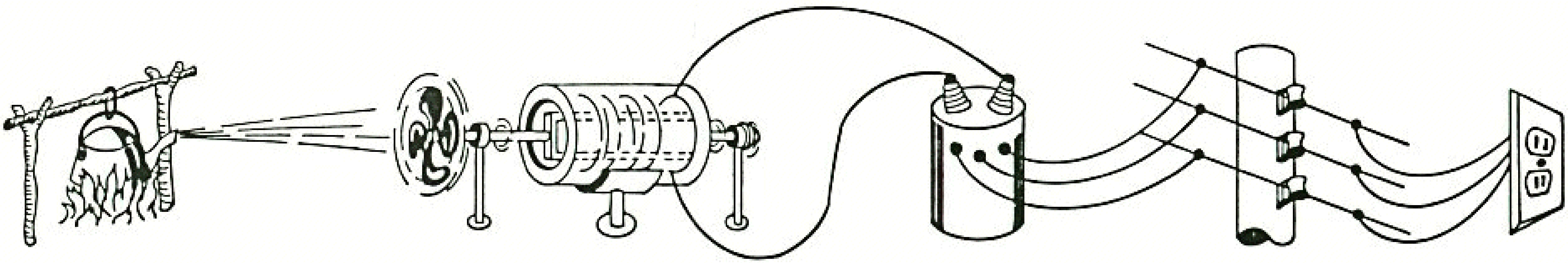
Produced neutrons : used neutrons > 1

BOOM

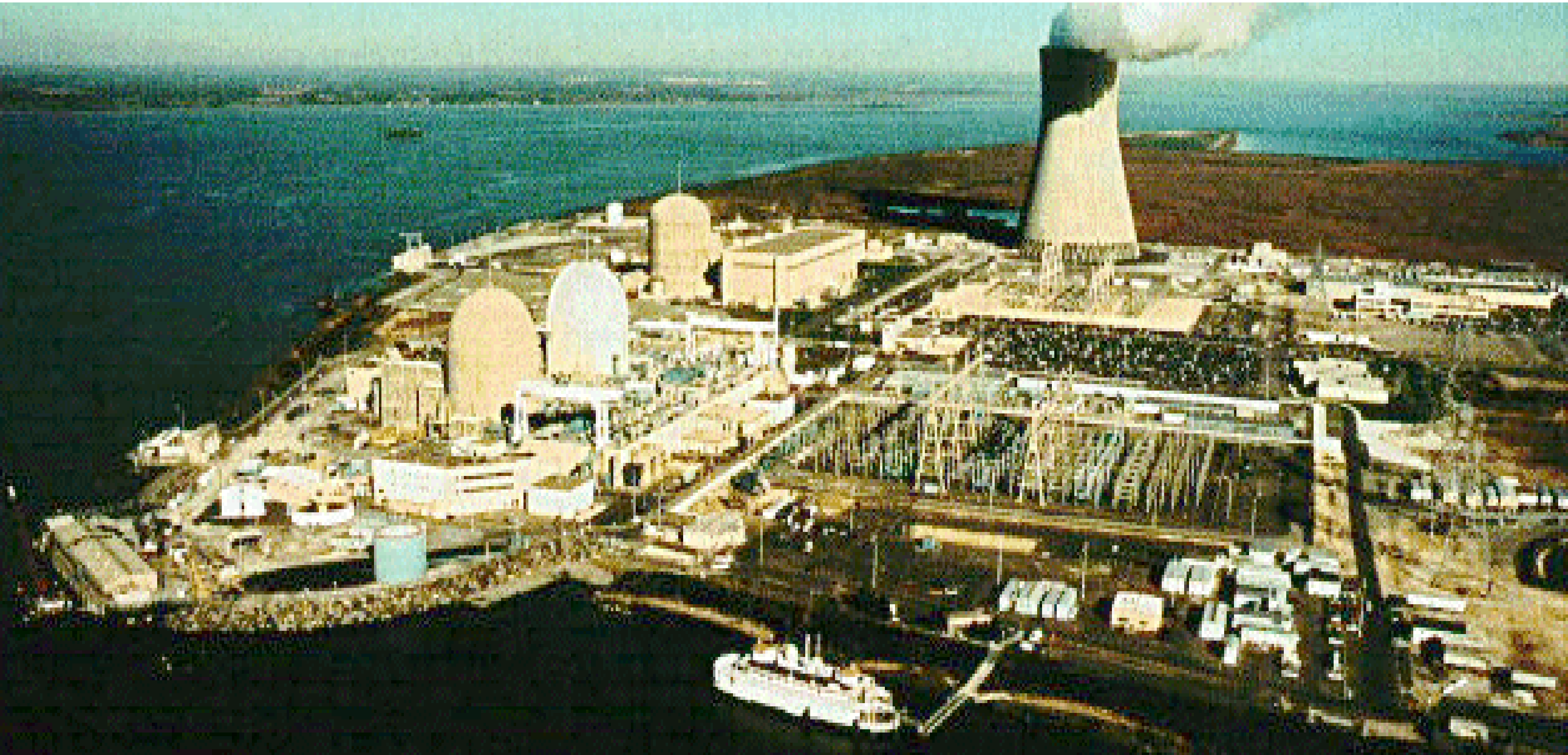
Neutron-absorbing material used to control the chain reaction

graphite

From Steam To Electricity



- Different fuels can be used to generate the heat energy needed to produce the steam
  - Combustion of fossil fuels
  - Nuclear fission
  - Nuclear fusion



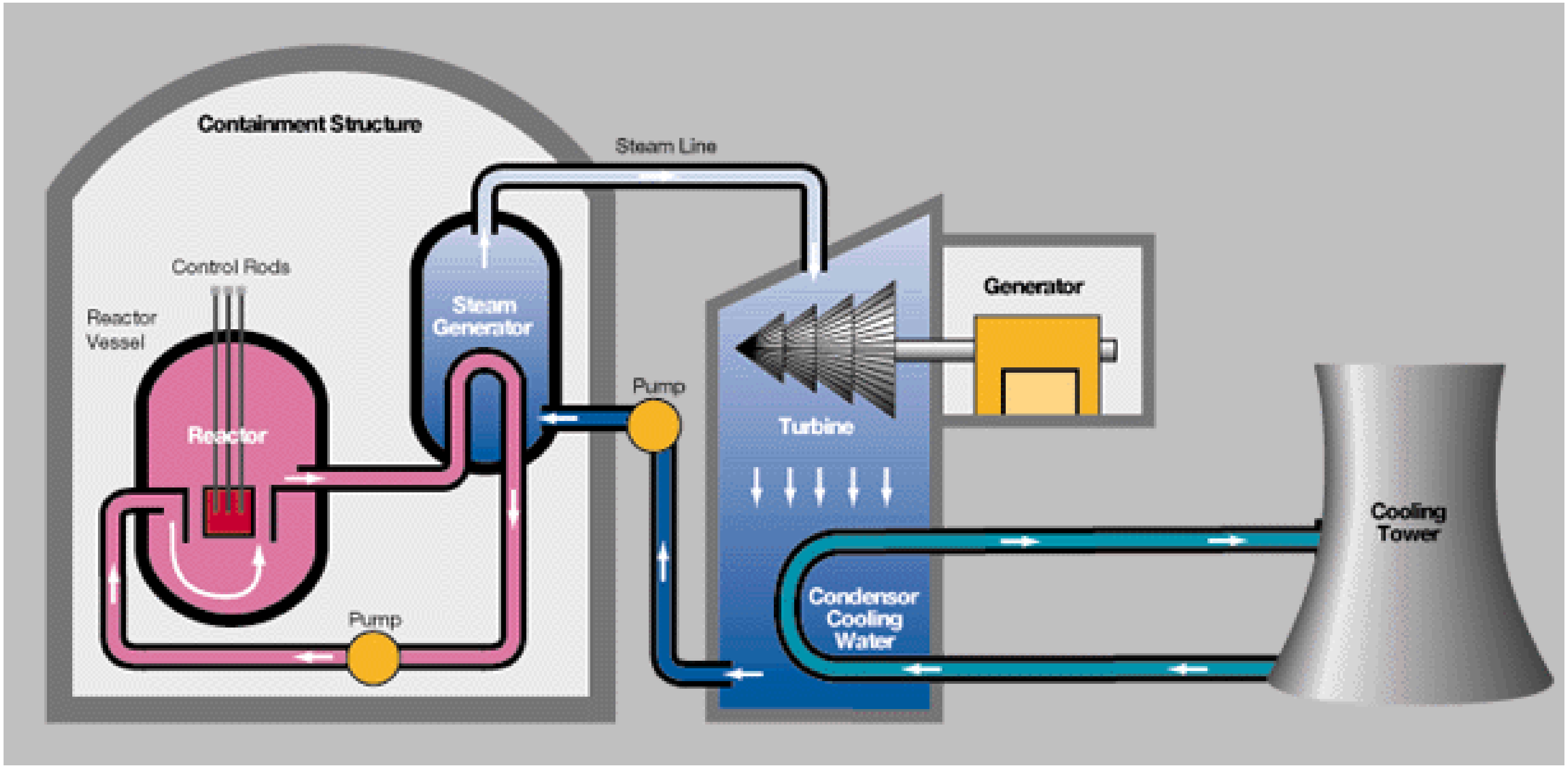
Types of Fission Reactors

- Light Water Reactors (LWR)
  - Pressurized-light water reactors (PWR)
  - Boiling water reactors (BWR)
- Breeder reactors

Light Water Reactors

- Most popular reactors in U.S.
- Use normal water as a coolant and moderator

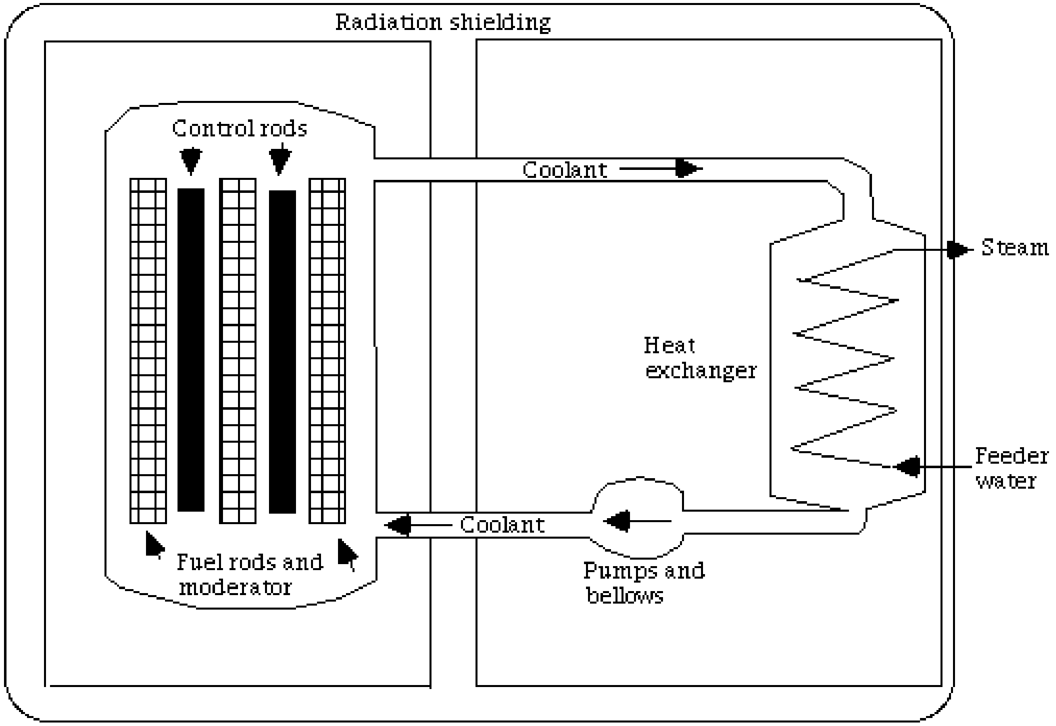
Pressurized Water Reactor



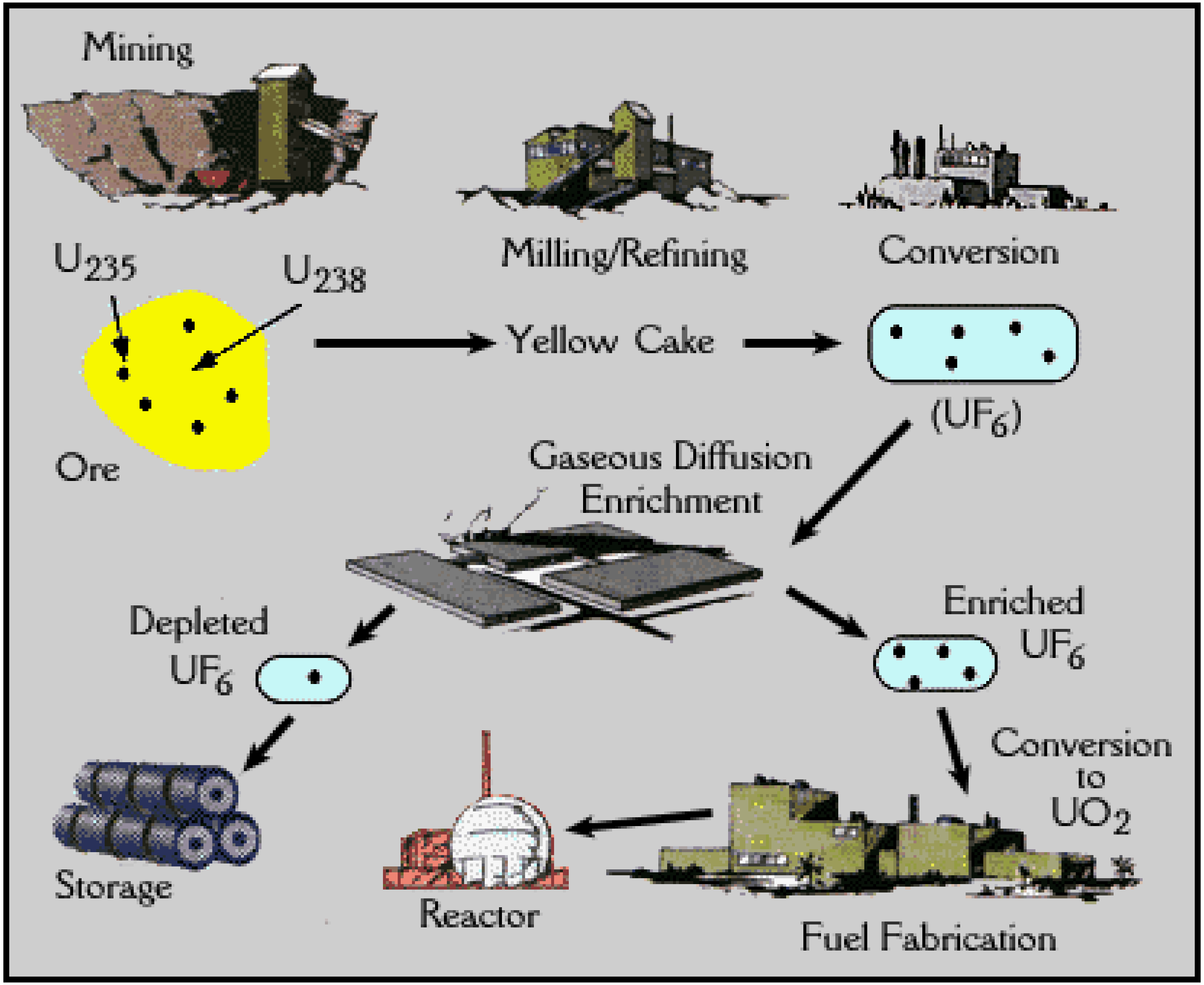
- The PWR has 3 separate cooling systems.
- Only 1 should have radioactivity
  - the Reactor Coolant System

Inside Containment Structure

Simple Nuclear Reactor

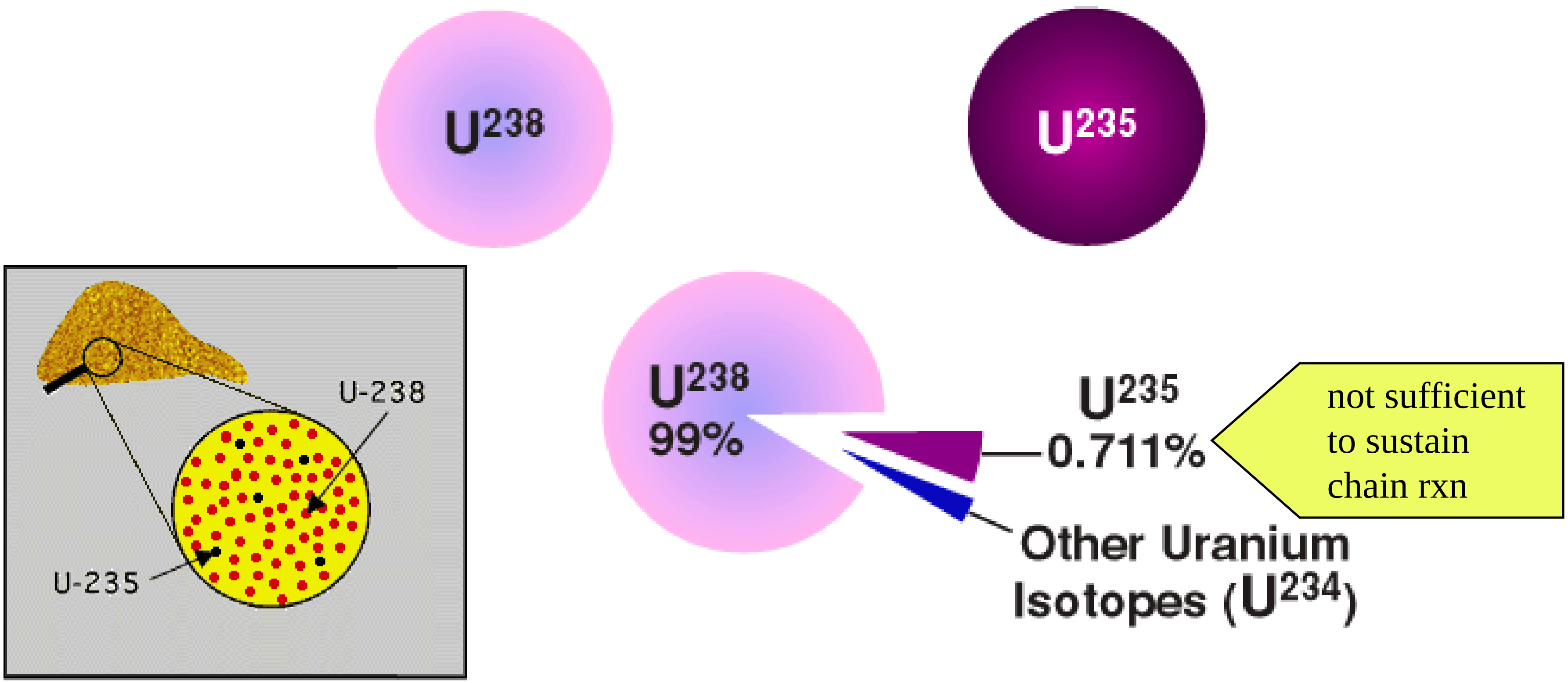


- Fuel Rods
  - U (3-5% enriched in U-235)
  - Pu in alloy or oxide form
- Control rods
  - Cd or graphite
    - Raised/lowered to change rate of reaction


Mining
U_{235}
U_{238}
Ore
Milling/Refining
Conversion
Yellow Cake
(UF_6)
Gaseous Diffusion Enrichment
Depleted UF_6
Enriched UF_6
Storage
Reactor
Conversion to UO_2
Fuel Fabrication

All Uranium Is Not Created Equal!

A sample of any given element usually contains different kinds of atoms of that element. These atoms have different masses. These are called isotopes.



Processing required to increase the concentration of U-235

Uranium Enrichment

Rate of Diffusion & Effusion

Diffusion

rate at which two gases mix

Effusion

rate at which a gas escapes through a pinhole into a vacuum

Rate inversely proportional to $\sqrt{MW}$

Effusion of a mixture of two gases:

$$\frac{v_1}{v_2} = \sqrt{\frac{m_2}{m_1}}$$

Graham's Law

For a mixture of H_2 and He:

$$\frac{v_{H_2}}{v_{He}} = \sqrt{\frac{m_{He}}{m_{H_2}}} = \sqrt{\frac{4}{2}} = 1.414$$

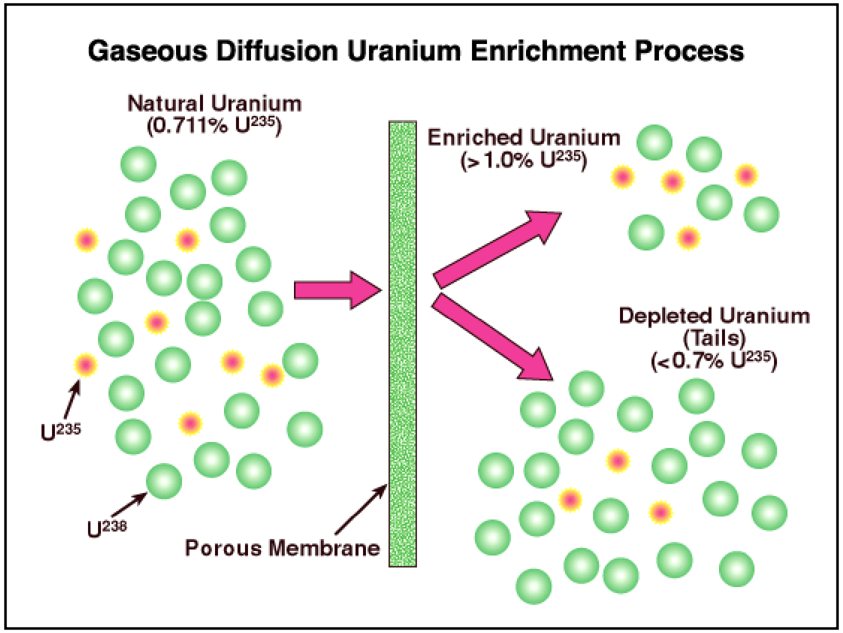
H_2 will leave container faster

U-235 Enrichment

enrichment one pass

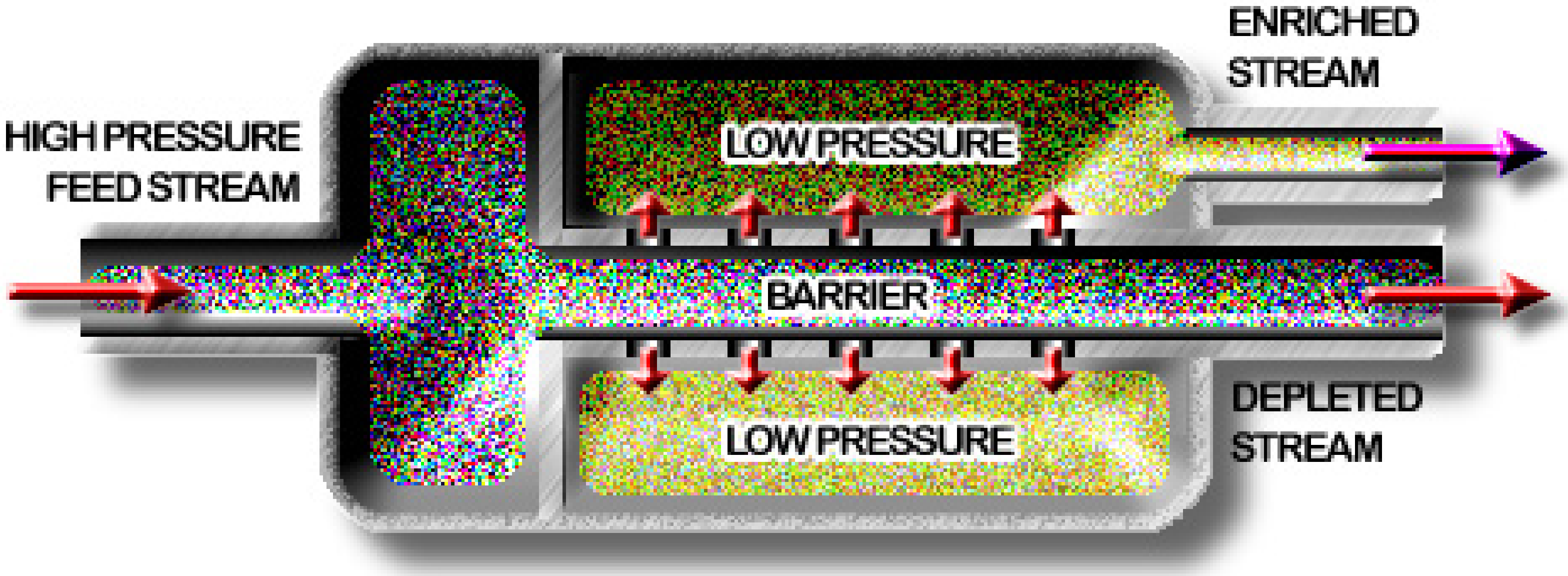
$$\frac{v_{U-235}}{v_{U-238}} = \sqrt{\frac{352}{349}} = 1.004$$

UF_6 is source of gaseous uranium



enrichment after passing through n diffusion barriers is $(1.004)^n$

GASEOUS DIFFUSION STAGE



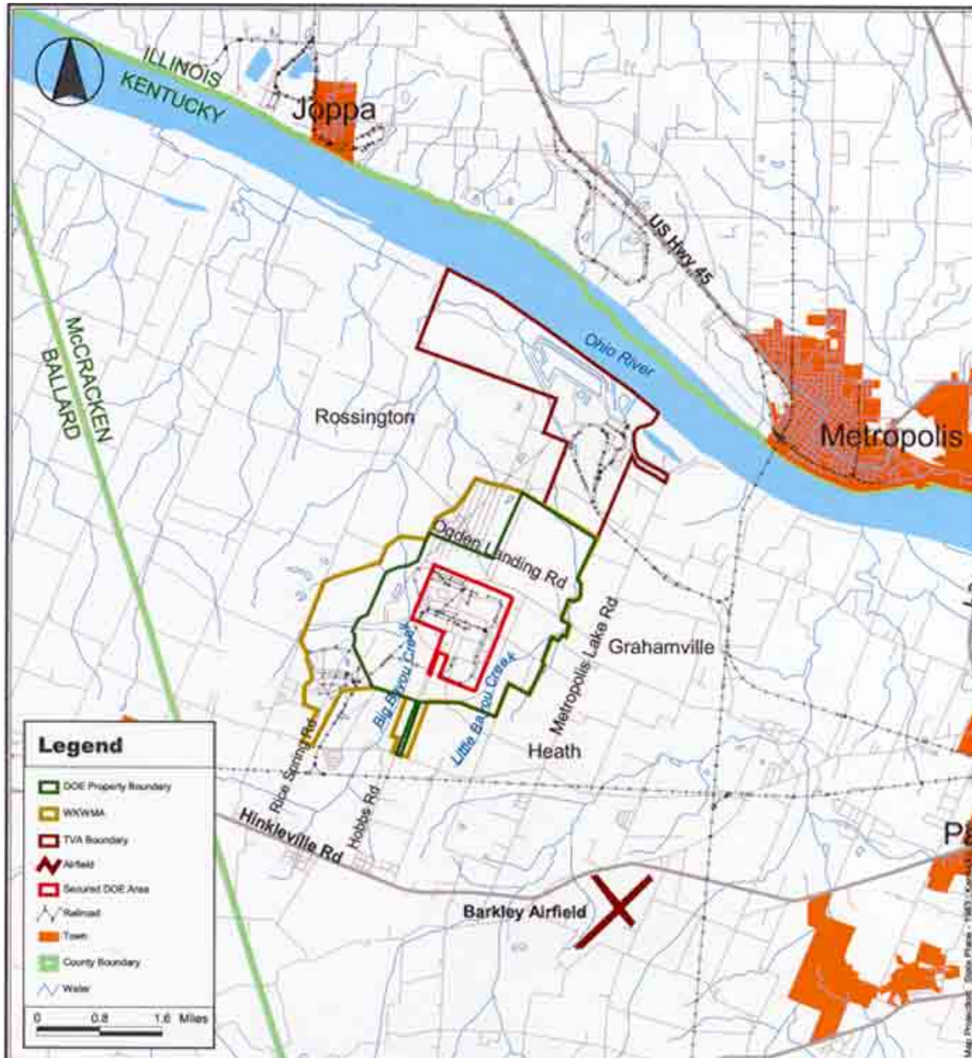
Need 2.1% U-235 to run LWR

3x natural concentration

$(1.004)^{\mathbf{263}} = 3$

263 diffusion stages!

large amount of energy needed to push U through so many barriers



Paducah Gaseous Diffusion Plant

Paducah, Kentucky

CERCLIS No. KY8890008982

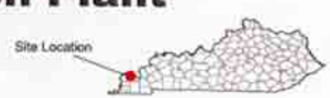


Figure 1: Plant Location and Vicinity

McCracken County, Kentucky

SAAGIS

converter contains separating barriers and gas cooler

Process Buildings
house the motors, compressors and process piping used to enrich uranium

up to 12 million gallons of water lost daily via steam-off from the cooling towers

water from Ohio River replaces what is lost as steam

http://www.nukeworker.com/nuke_facilities/North_America/usa/DOE_Facilities/Paducah/index.shtml

The large Tricastin enrichment plant in France (beyond cooling towers)
The four nuclear reactors in the foreground provide over 3000 MWe power for it

http://www.uic.com.au/nip33.htm

Commercial Nuclear Fuel

Mining

Uranium ore is mined from the earth.

Milling

Uranium ore is processed to produce a form of uranium known as "yellowcake."

Conversion

Yellowcake is converted to uranium hexafluoride.

Enrichment

This step increases the concentration of the isotope U-235 from its naturally occurring level of 0.7% to higher levels required for nuclear reactors – about 4%-5%.

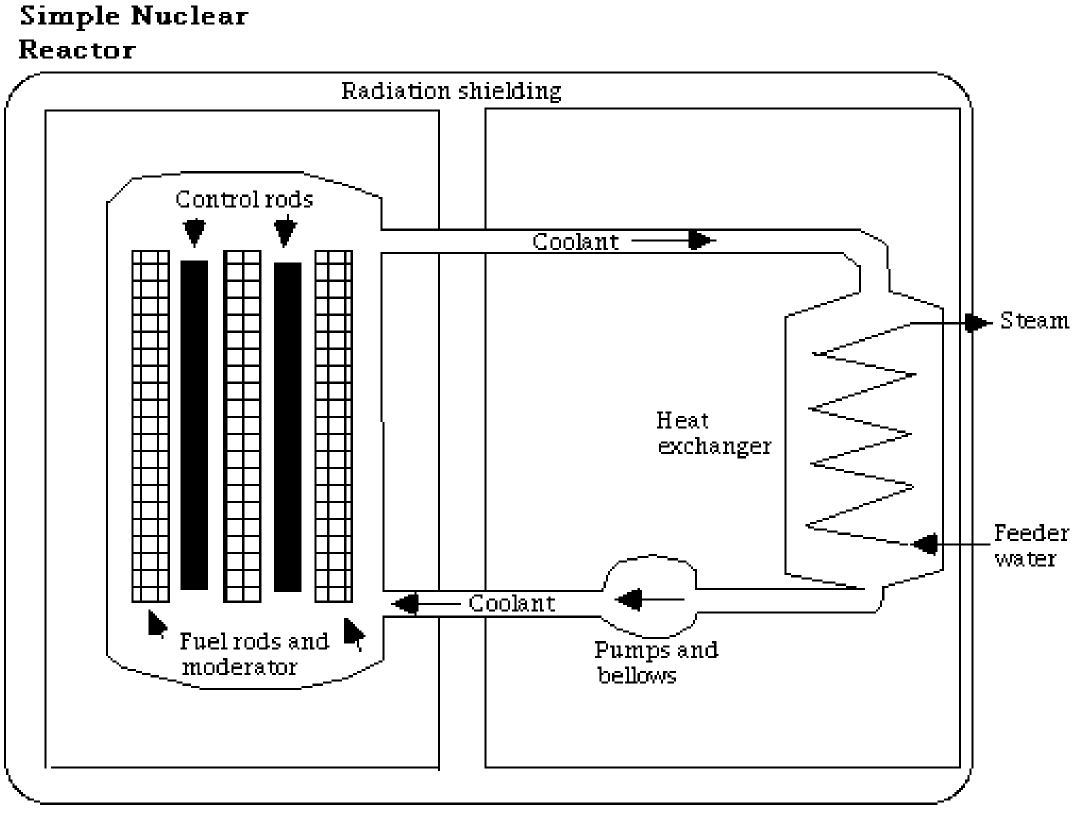
Fabrication

Enriched uranium is converted into uranium dioxide, formed into solid cylindrical pellets, sealed in metal fuel rods and bundled into fuel assemblies.

Power Production

Fuel assemblies are loaded into nuclear reactors where the U-235 fissions, producing heat and steam used to generate electricity.

Inside Containment Structure



- Coolant performs 2 functions
  - keeps reactor core from getting too hot
  - transfers heat which drives turbines

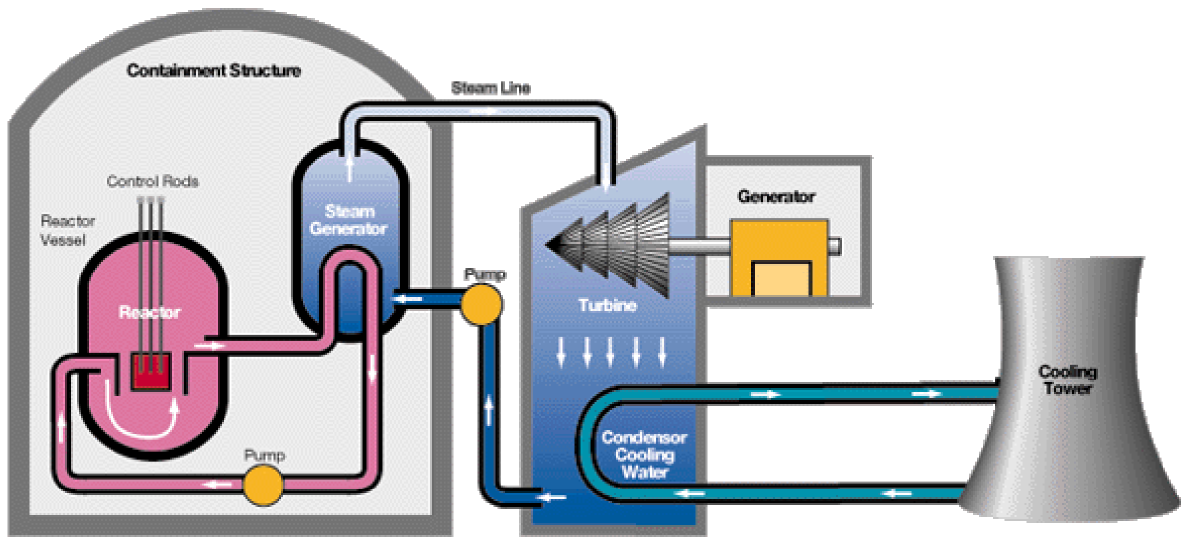
Water as Coolant

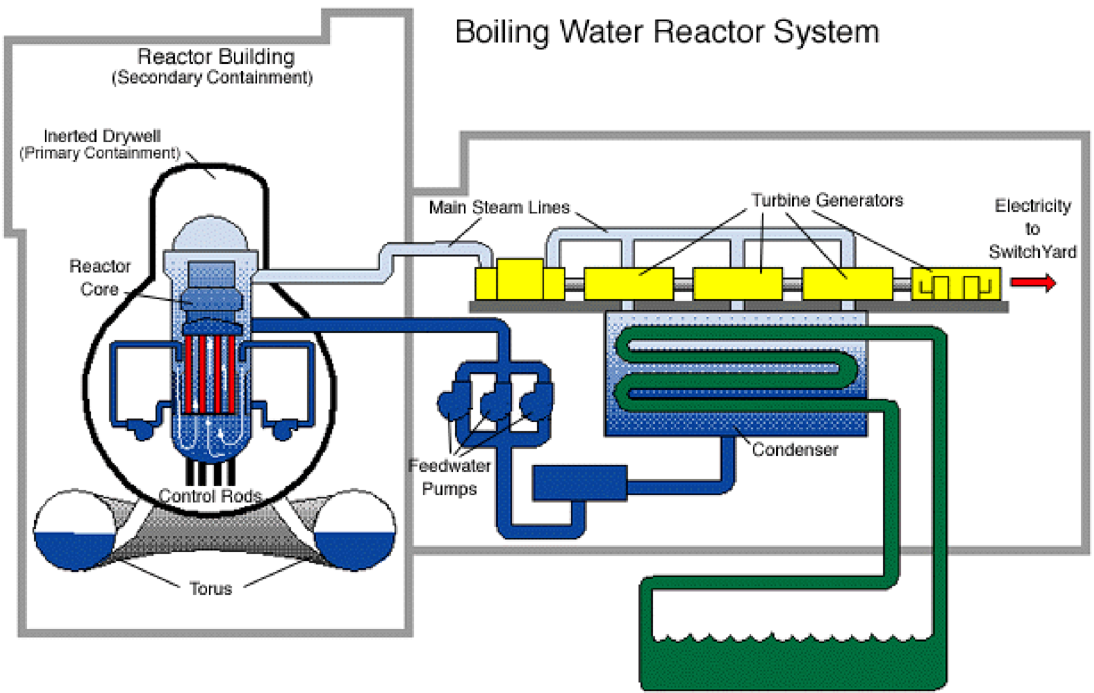
- Light Water Reactor (LWR)
  - uses ordinary water
  - needs enriched uranium fuel
  - common in U.S.
  - 80% of world's reactors
- Heavy Water Reactor (HWR)
  - uses D_2O
  - can use natural uranium
  - common in Canada and Great Britain
  - 10% of world's reactors

Water As Coolant

- Pressurized Water Reactors
  - uses a heat exchanger
  - keeps water that passes the reactor core in a closed loop
  - steam in turbines never touches fuel rods
- Boiling Water Reactors
  - no heat exchanger
  - water from reactor core goes to turbines
  - simpler design/greater contamination risk

PWR vs. BWR


Containment Structure
Steam Line
Control Rods
Reactor
Vessel
Reactor
Steam
Generator
Pump
Generator
Turbine
Pump
Condensor
Cooling
Water
Cooling
Tower


Boiling Water Reactor System
Reactor Building
(Secondary Containment)
Inerted Drywell
(Primary Containment)
Reactor
Core
Main Steam Lines
Turbine Generators
Electricity
to
SwitchYard
Feedwater
Pumps
Condenser
Control Rods
Torus

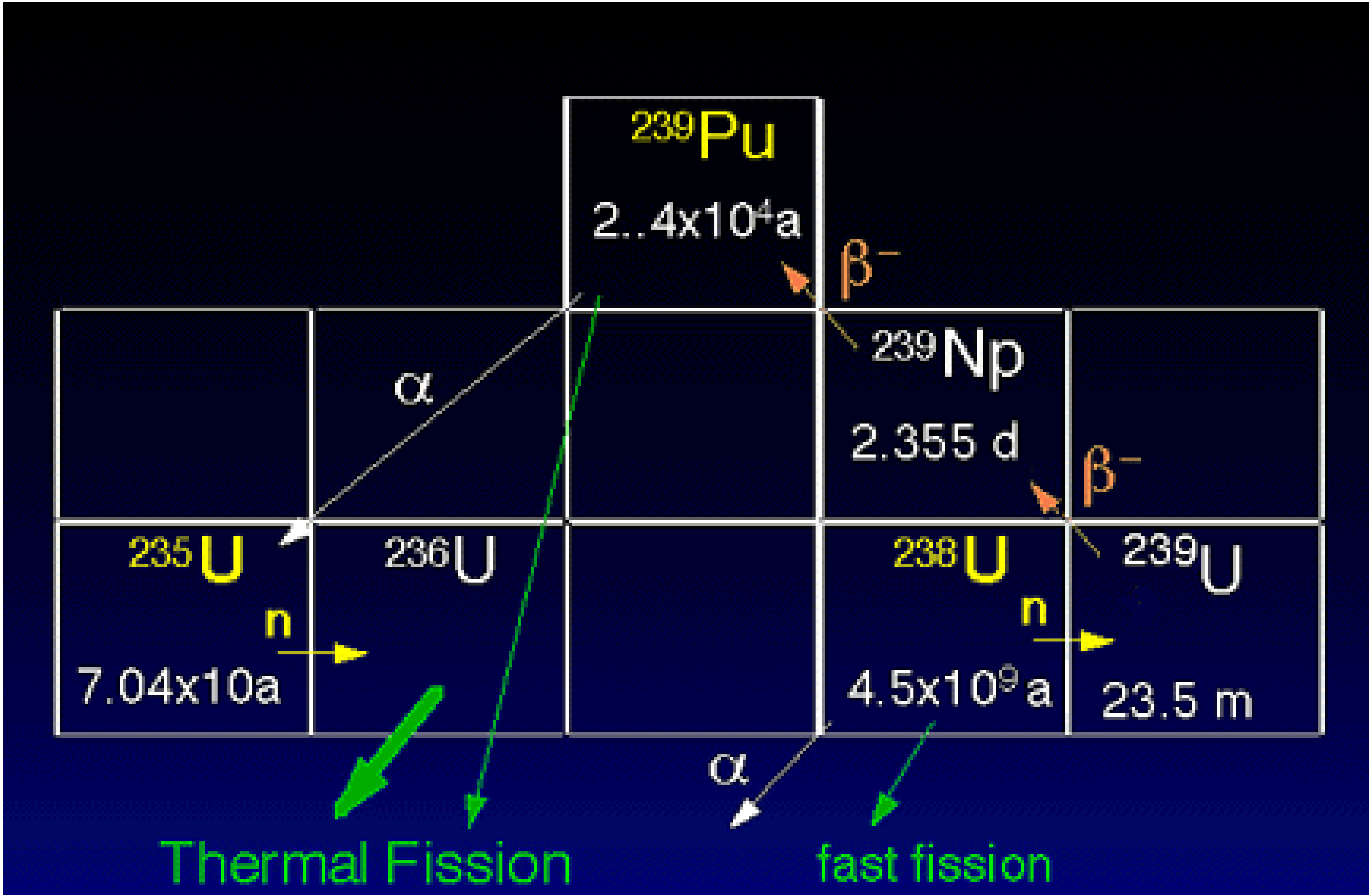
The Moderator

- Necessary to slow down neutrons
  - probability of causing a fission increased with slow moving neutrons
- Light water will capture some neutrons so enriched enriched fuel is needed
- Heavy water captures far fewer neutrons so don’t need enriched fuel

Breeder Reactors

- Generate more fissionable material than they consume
- Fuel U-238, U-235 & P-239
- No moderator is used
  - Fast neutrons captured by U-238
    - produces U-239
  - U-239 decays to fissile Pu-239
- Coolant is liquid sodium metal
- None in U.S.
  - France, Great Britain, Russia

Breeder Reactor Processes



Breeder Reactors

- Advantages
  - creates fissionable material by transforming U-238 into Pu-239
  - Fuel less costly

Breeder Reactors

- Disadvantages
  - no moderator
    - if something goes wrong, it happens quicker
  - liquid Na extremely corrosive and dangerous
  - Plutonium critical mass 50% < uranium
    - more widely used for weapons
    - more actively sought by terrorists
  - Fuel rods
    - require periodic reprocessing to remove contaminants resulting from nuclear reactions
      - cost consideration