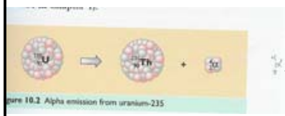
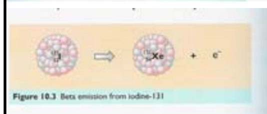
Main Types of Particles



# of protons + neutrons

Alpha particles (nucleus of $^{4}_{2}He$)

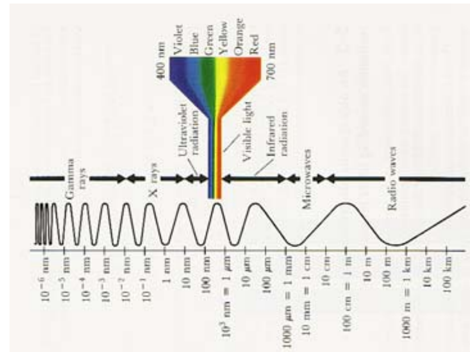
# of protons



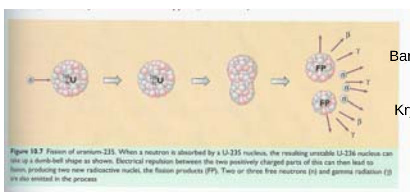
Beta particles (high speed electrons)

Gamma particles (similar to X-rays)

Electromagnetic Spectrum



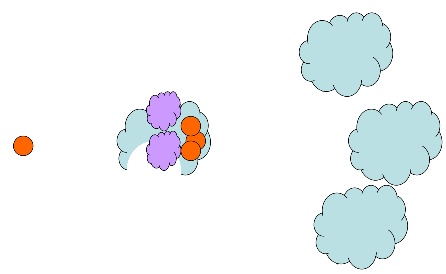
Fission



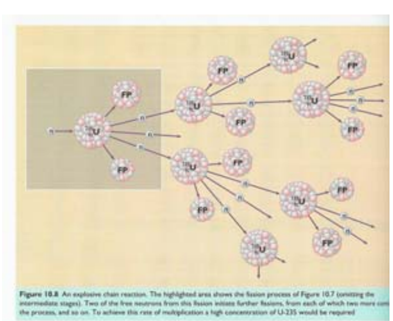
Barium

Krypton

Nuclear Fission



Chain Reaction



Half Lives and Activities

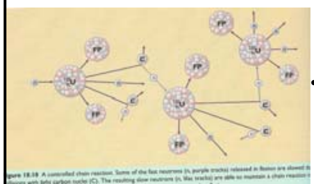
Table 10.1 Half-lives and activities

Isotope	U-238	U-235	Pu-239	Sr-90	I-131
type of particle[1]	α	α	α	β	β
half-life	4.5×10^9 years	7.0×10^8 years	24 000 years	28 years	8.1 days
activity of 1 g[2,3]	12 000 Bq	79 000 Bq	2300 MBq	5.3 TBq	4600 TBq
mass for 10 000 Bq[3]	0.81 g	0.13 g	4.3 μg	0.0019 μg	2.2 pg

1 γ-particles are also emitted in all cases except Sr-90.
2 This refers to one gram of the single isotope, and is the activity before it has had time to produce 'daughters' that would change the sample.
3 Notice the different units. 1 μg (microgram) is one millionth of a gram, and 1 pg (picogram) is one millionth of a microgram, or 10^{-12} g.

By the way, we still use Curies as the unit in the US.
1 Curie = 40 GBq (10^9 Bq) = 3.7e10 particles/second!

Effect of Moderator



- *Moderator*: material that slows down the neutrons in order to maintain the chain reaction
- Moderators:
  - Increase the fission rate
  - Rapidly reduce speed of neutrons without absorbing them
  - Are light atoms (like hydrogen, carbon, or heavy water)

Fission Probability vs Neutron Energy

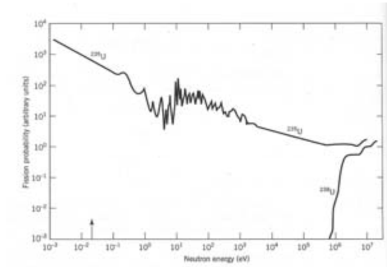
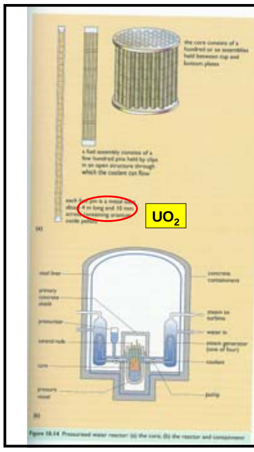


Figure 6.2 The fission probability for ^{235}U and ^{238}U as a function of neutron energy. The arrow at 0.025 eV indicates the energy of thermalized neutrons. For ^{238}U the fission probability becomes appreciable only above about 1 MeV neutron energy.

From Energy and the Environment, by Ristinen and Kraushaar

(#4) Safety Precautions

- Reactor construction
  - Strong Pressure vessel (air-tight)
  - Primary concrete shield
  - Steel liner
  - Concrete containment
- Coolant systems
  - Primary
  - Secondary
  - Tertiary
  - Quaternary…
- Fuel
  - Enriched very little
  - Well below critical mass
- Fission Control
  - Control rods absorb neutrons to keep reactor critical
  - Boron is incorporated into cooling fluids to absorb neutrons
  - (Moderator is not fission control, but fission enhancer!!!)



Pressurized Water Reactor (PWR)

- Common type (especially in US)
- Primary water is high pressure so it does not boil (like BYU heating plant)
- Pressurizer has heater and cooler in water with steam head
  - Remember this when discussing 3-Mile Island next time
- Uses regular (light) water, not deuterium or tritium

Pressurized Water Reactor (PWR)

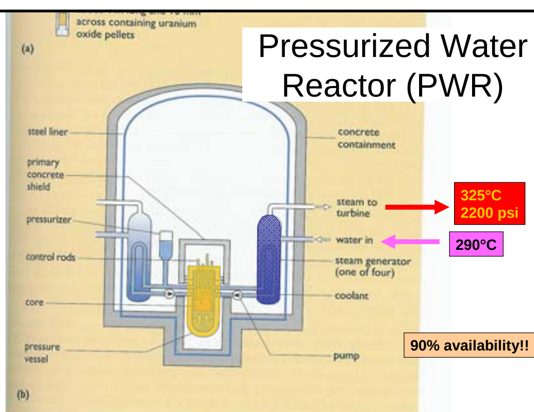
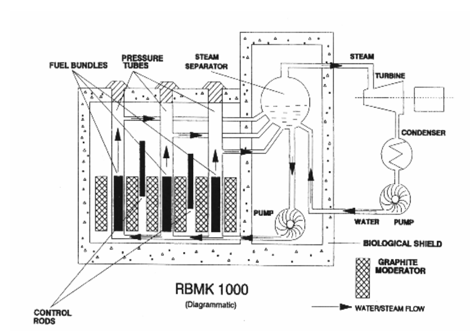


Figure 10.14 Pressurized water reactor: (a) the core; (b) the reactor and containment

RBMK is a Russian acronym translated roughly as "reactor cooled by water and moderated by graphite"



This same type was used at Chernobyl

CANDU Process

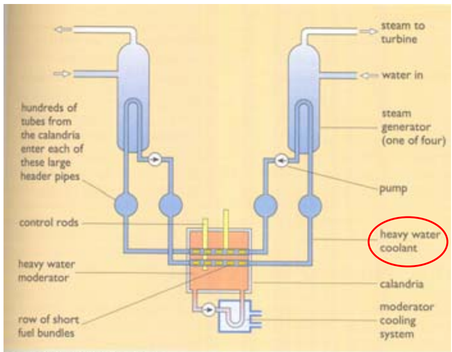


Figure 10.17 CANDU reactor

AGR

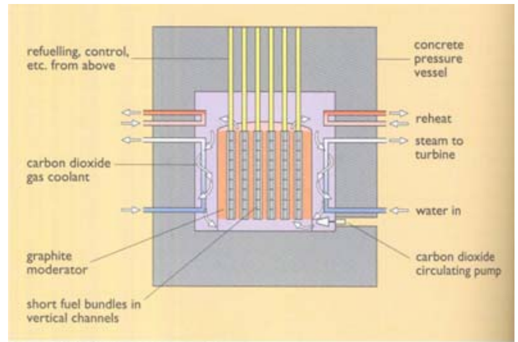


Figure 10.16 Advanced gas-cooled reactor

LMFBR
(Liquid metal fast breeder reactor)

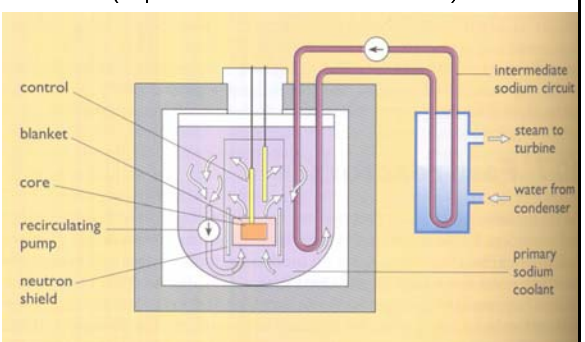


Figure 10.19 The main components of an LMFBR

Other Reactors

3-Mile Island

Table 10.3 Types of fission reactor

Reactor	Fuel	Moderator	Coolant
PWR	enriched uranium	light water	light water
BWR	enriched uranium	light water	light water/steam
Magnox	natural uranium	graphite	carbon dioxide gas
AGR	enriched uranium	graphite	carbon dioxide gas
CANDU	natural uranium	heavy water	heavy water
VVER	enriched uranium	light water	light water
RBMK	enriched uranium	graphite	light water/steam
LMFBR[1]	highly enriched uranium	none	liquid sodium

1 See Section 10.7 for details.

Chernobyl

Advantages

	PWR	BWR	RBMK	CANDU
On-Line Refueling			√	√
Capital Costs		√		
Worker Radiation Exposure	√			
Containment	√	√		√
Operating Costs	√	√		√

From http://www.nucleartourist.com/type/benefits.htm

(#6) Uranium Enrichment

- Gaseous Diffusion
  - Heavier isotope diffuses more slowly
- Centrifuge
  - Heavier isotopes are forced outwards
- Electromagnetic
  - Like mass-spec (very low thru-put, very high purity)
- Laser
  - Specially tuned laser preferentially ionizes atoms of preferred isotope that are then extracted electromagnetically

http://www.wordiq.com/definition/Isotope_separation

Products (1000 kg of spent fuel)

Table 10.4 Spent fuel from a thermal fission reactor. The table shows the main constituents of 1 tonne (1000 kg) of spent fuel removed from a reactor after 3 years. The quantities are approximate and will vary with the enrichment of the original fuel, the type of reactor and the mode of operation. These data might be typical for a PWR using fuel enriched to 3.5% U-235.

Content	Quantity / kg	Notes
U-235	7	Fission of U-235 will have contributed about two-thirds of the power output. Its concentration in the spent fuel is about the same as in natural uranium.
U-238	940	The original U-238 content will have been reduced by neutron absorption leading to plutonium and other actinides.
Plutonium	9	More than half the plutonium produced from U-238 will already have undergone fission, contributing about a third of the total power output.
Fission products	38	These lighter radioactive isotopes, mainly with half-lives from fractions of a second to a few years, contribute over 99% of the initial radioactivity of the spent fuel.
Actinides, U-236, etc.	6	The heavy radioactive isotopes, many with very long half-lives, contribute most of the radioactivity after a few hundred years.

Why throw this stuff away?

Additional Notes

0.7% U^{235}
99.3% U^{238} → (enrich for LWR) → 3% U^{235}, 97% U^{238} → LWR → ~1% U^{235}, ~1% Pu^{239}, 95% U^{238}, + fission products

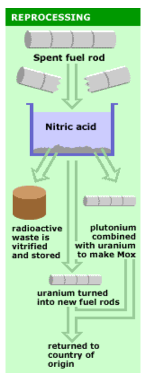
Tailings

- Could use heavy water with U^{238}

3% Pu^{239}, 97% U^{238} → Breeder → 4% Pu^{239}, 93% U^{238}, + fission products

(advanced fast neutron reactors)

Reprocessing



Advantages

- Greatly extends supply of uranium
  - From 50 yrs to 1000 yrs?
- Significantly reduces quantity of waste

Disadvantages

- Separating and storing large quantities of plutonium
  - Only 10 g needed to build bomb
  - Instructions on internet!
  - 10 g out of tons is easy to hide

U.S. position ---- No reprocessing (Jimmy Carter, 1978)
--- set example and world will follow (not all have followed, though)

Plasma-Generated Fusion

$${}^2_1H + {}^2_1H \to {}^1_1H + {}^3_1H$$

A. Make tritium from deuterium

$${}^2_1H + {}^3_1H \to {}^4_2He + n$$

B. Fusion of deuterium and tritium

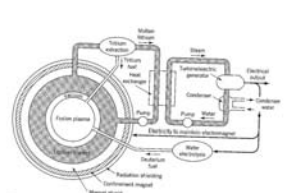


Figure 6.9 A D–T fusion power plant. The molten lithium is pumped through a heat exchanger that produces high-pressure steam to drive a turbine. The fusion plasma and lithium blanket regions are in the shape of a torus, a cross section of which is shown.

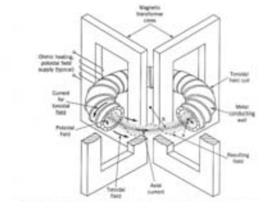


Figure 6.10 A Tokamak magnetic confinement system. A magnetic field confines the plasma within a torus.

From Energy and the Environment, by Ristinen and Kraushaar

Energy from Fusion

D – T reaction:

$${}^2_1H_1 + {}^3_1H_2 \to {}^4_2He_2 + n + 17.6\,MeV$$

D – D reaction:

$${}^2_1H_1 + {}^2_1H_1 \to {}^3_2He_1 + n + 3.2\,MeV$$

$${}^2_1H_1 + {}^2_1H_1 \to {}^3_1H_2 + {}^1_1H_0 + 4.0\,MeV$$

Sun reactions:

$${}^1_1H_0 + {}^1_1H_0 \to {}^2_1H_1 + \beta^+ + \nu + energy$$

$${}^1_1H_0 + {}^2_1H_1 \to {}^3_2He_1 + energy$$

$${}^3_2He_1 + {}^3_2He_1 \to {}^4_2He_1 + 2\,{}^1_1H_0$$

Net $(2a + 2b + c)$

$$4\,{}^1_1H_0 \to {}^4_2He_1 + 2\beta^+ + 2\nu + energy$$

β^+ = *positron*
ν = *neutrino*

Atomic mass

Number of neutrons

$${}^3_1H_2$$

Number of protons (atomic number)

Laser-Generated Fusion

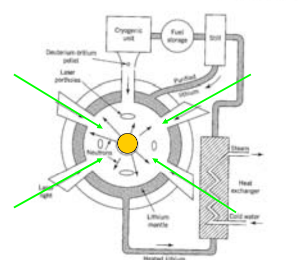


Figure 6.12 A cutaway view of a proposed laser fusion reactor. A microscopic deuterium–lithium pellet is injected into the reaction chamber several times per second. Precisely timed and sharpely focused pulsed laser beams of high intensity converge in the chamber, thereby creating the requisite conditions of temperature and density to initiate fusion. As in the magnetic confinement schemes, the resulting energetic neutrons are absorbed in a surrounding mantle of molten lithium, which is circulated to remove the heat energy. The tritium produced in the lithium mantle is separated out and incorporated into new D–T pellets.

From Energy and the Environment, by Ristinen and Kraushaar

Terminology/Units

- Light water
- Heavy Water
- Enrichment
- Critical Mass
- Half Life
- Activity
- Chain Reaction
- Plutonium
- MeV
- Curie
- Bq