PH20016 – Particles, nuclei & stars

I. Particle Physics

Conservation laws – Decays and reactions

Particle decay laws – Half life and mean lifetime

Unification of forces

Recent developments in particle physics (e.g. pentaquarks, neutrino oscillations)

II. The nucleus

Nucleon interactions and binding energy

Nuclear size and mass (isotopes and isobars)

Radioactive decay:

- beta-decay
  - electron and positron emission,
- K-capture
- alpha-decay
  - energetics and simplified tunnelling theory

The liquid drop model – Semi-empirical mass formula

The shell model

- Nuclear spin
- Excited states

III. Reactions, fission and fusion

Centre of Mass frame

Scattering

Spontaneous fission – Fission products

Induced fission – Chain reactions, delayed neutrons

Nuclear fusion reactions – Principles of fusion reactions

IV. The cosmic connection

Stellar evolution – Stellar nucleosynthesis – Stellar death: neutron stars, supernova, cosmic ray bursts

The Big Bang – Hubble's Law - Cosmic background radiation and ripples therein

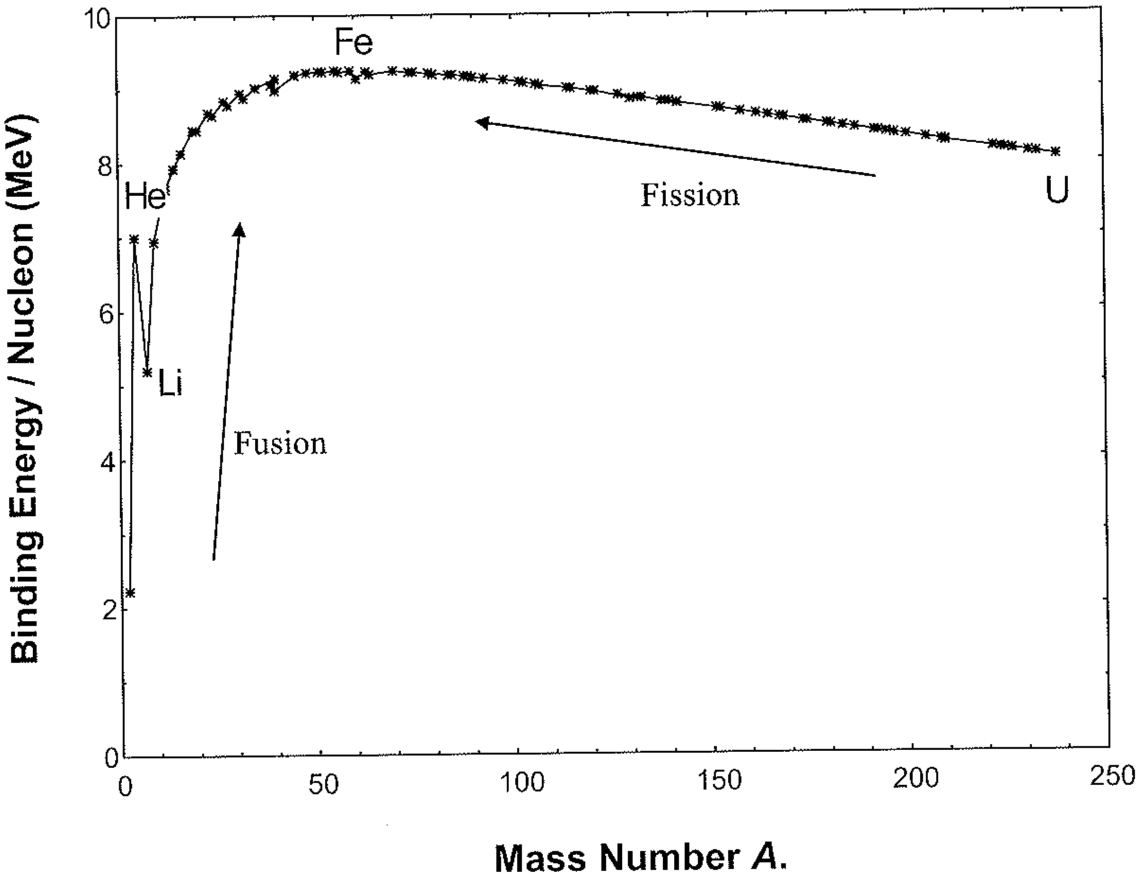
Separation of unified forces

Inflation theory

Formation of elementary particles – Cosmic nucleosynthesis

6. NUCLEAR POWER

6.1. Fission in practice



The binding energy per nucleon reaches a peak around A = 56

All atoms with A > 56 are likely to undergo fission:

$$^{A}_{Z}X \rightarrow {}^{B}_{Z_1}X + {}^{A-B}_{Z-Z_1}X$$

Binding energies: from semi-empirical mass formula

We can calculate the energy released:

Q = BE (products) – BE (reactants)

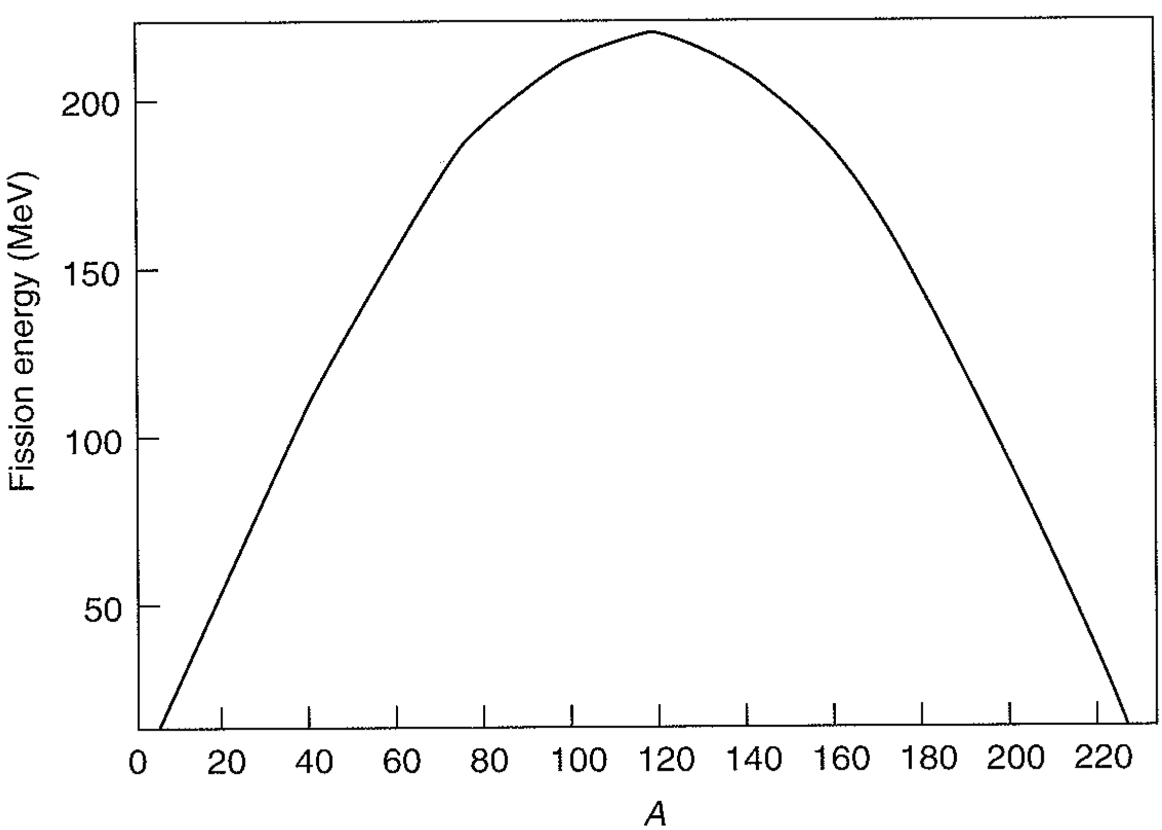
For example:

A = 236 (B.E. = 1.78 GeV)

Fission into 2 identical fragments:

A = 117 (total B.E. = 1.99 GeV)

Q = **210 MeV!**



Fission of ^{236}U as a function of A for <u>one</u> fragment

All atoms can undergo fission in several ways, e.g.

$$^{252}Cf \rightarrow {}^{112}_{46}Pd + {}^{138}_{52}Te + 2n$$

$$^{252}Cf \rightarrow {}^{101}_{42}Mo + {}^{148}_{56}Ba + 3n$$

$$^{252}Cf \rightarrow {}^{105}_{45}Rh + {}^{146}_{53}I + n$$

$$\ldots$$

Fission fragments carry away ~90% of the energy …

Neutrons carry around ~2% of the energy.

Induced fission (by neutrons):

$$n + {}^{235}U \rightarrow {}^{236}U + 6.46\ \mathrm{MeV} \quad (1)$$

$$n + {}^{238}U \rightarrow {}^{239}U + 4.78\ \mathrm{MeV} \quad (2)$$

Barrier height ~ 6.2 MeV $\Rightarrow$ only (1) produces fission
without QM tunnelling

Spontaneous fission creates more neutrons: chain reaction

6.2. Neutron dynamics

6.2.1. Neutron cross-sections

Neutrons can interact with nuclei by:

– **Elastic scattering**

KE conserved

Target recoil ⇒ neutron loses energy

– **Inelastic scattering**

Neutron loses KE

$$n + {}^{A}_{Z}X \rightarrow {}^{A}_{Z}X^{*} + n$$

– **Radiative capture**

Incident neutron absorbed, compound nucleus forms and rapidly decays to its ground state by gamma emission.

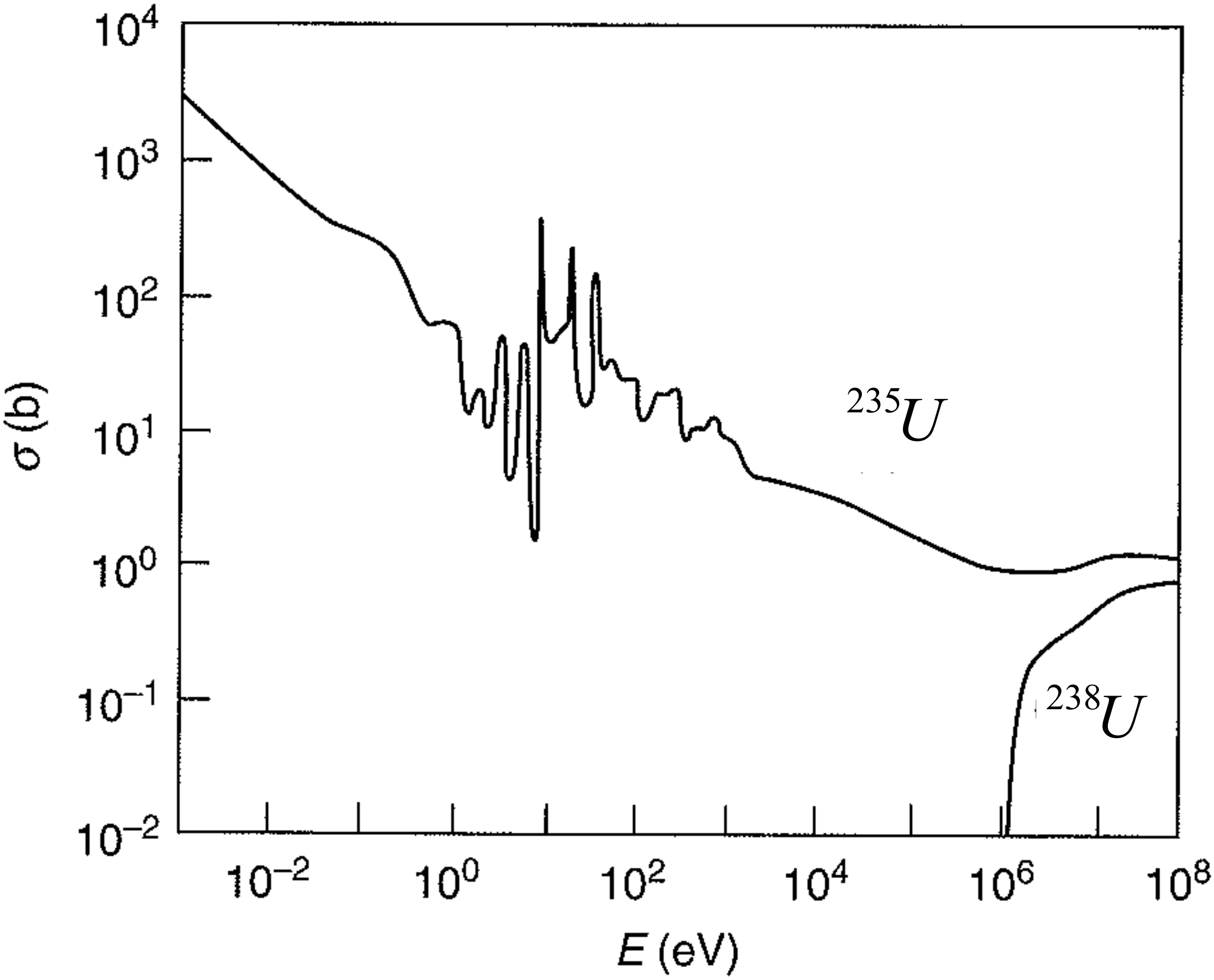
Resonances occur: cross section peaks corresponding to the discrete states or energy levels of the heavy nucleus

$$n + {}^{A}_{Z}X \rightarrow {}^{A+1}_{Z}X + \gamma$$

– **Fission**

Neutron leaves target at energy state above spontaneous fission barrier

Short time scale



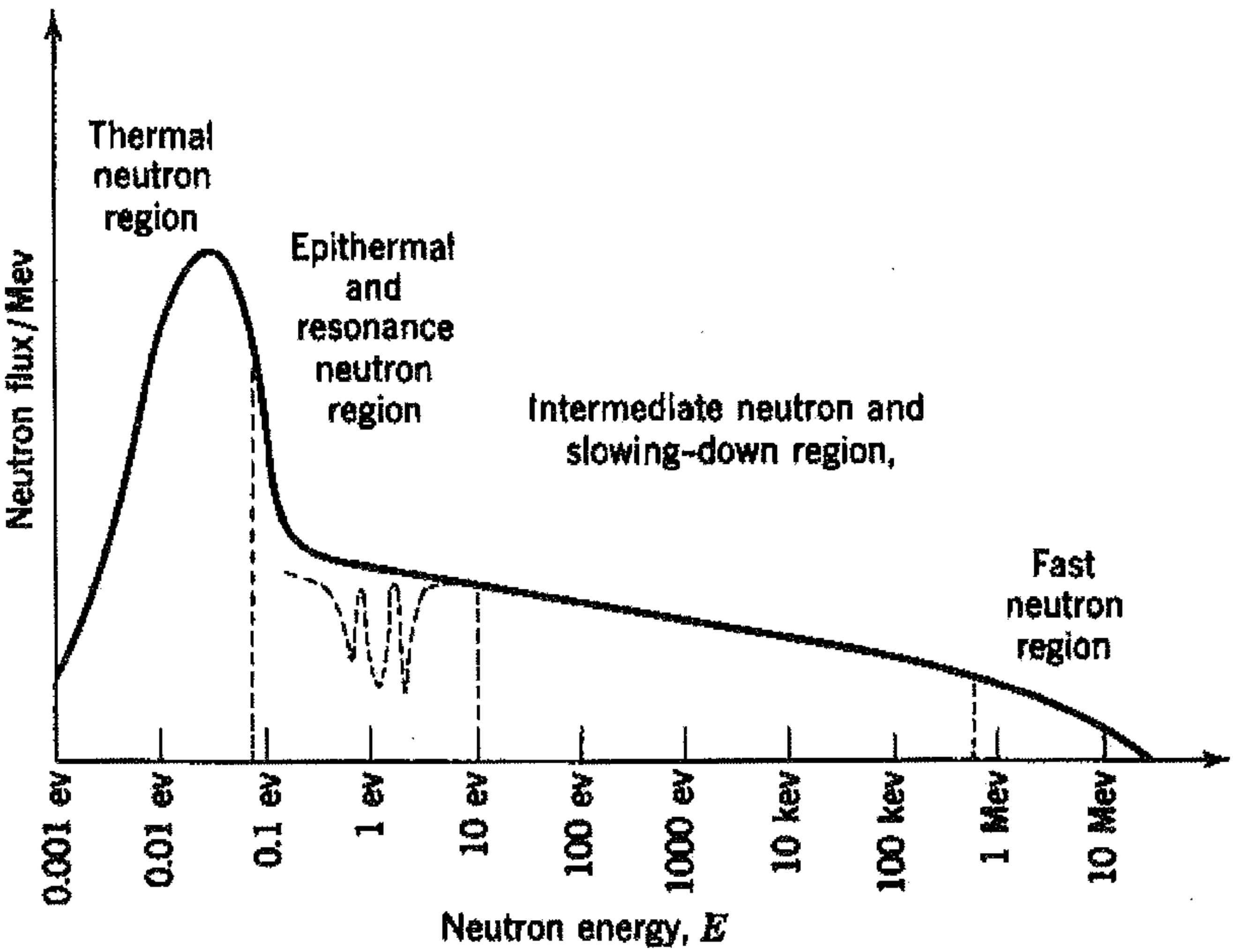
Neutron cross-sections will vary with energy

Neutron flux intensity attenuated through target:

$$I(x) = I_0 \, e^{-\frac{x}{l_0}}$$

where l_0 is the mean free path

Distribution of energies in a typical reactor:



These neutrons will interact with other target nuclei, e.g. in a ***moderator.*** The moderator material serves to slow down the fast neutrons to lower energies in the thermal regime where the cross section for inducing subsequent nuclear reactions is higher.

Elastic scattering between a neutron and a moderator:

Neutron: mass = 1 a.m.u, K.E. = E_0

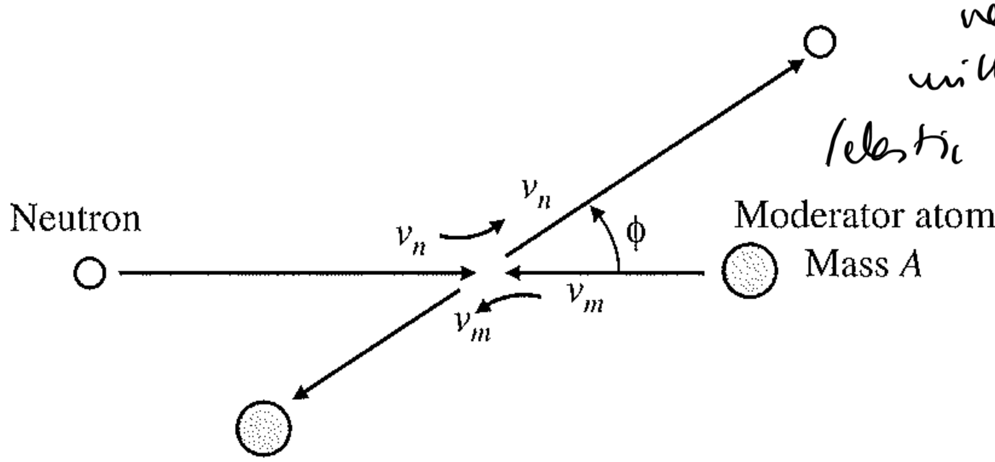
Moderator: mass = A a.m.u

neutron interacting with a nucleus

↓

neutrons will lose E (elastic or inelastic)

In the CM frame:



The final K.E. is:

$$E_1 = E_0 \frac{1 + A^2 + 2A\cos\phi}{(1+A)^2}$$

The energy loss is:

- minimum for grazing-angle collisions

- maximum for head-on collisions

The energy loss is minimum at grazing angle ($\phi = 0^o$)

$$E_1 = E_0 \frac{1 + A^2 + 2A}{(1+A)^2} = E_0$$

a not lost E at
$\varnothing = 0^\circ$

The energy loss is maximum for head-on collision ($\phi = 180^o$)

loss when
$\varnothing \neq 0^\circ$

$$E_1 = E_0 \frac{1 + A^2 - 2A}{(1+A)^2} = E_0 \frac{(1-A)^2}{(1+A)^2} = E_0\, \alpha$$

The energy lost by the neutron per scattering event varies with the scattering angle:

fractional E loss

$$0 < \left[\frac{\Delta E}{E_0}\right] < (1-\alpha), 0^\circ < \phi < 180^\circ$$

And: $(1-\alpha) = \dfrac{4A}{(1+A)^2}$

By integrating over a sphere centred on the scatterer, it is possible to calculate the average logarithmic energy decrement per collision δ

The average logarithmic decrement per collision equals:

$$\delta = 1 + \frac{(1-A)^2}{2A}\log\left(\frac{A-1}{A+1}\right)$$

For large A, $\delta \to 0$ } less slowing down power for bigger nuclei

This gives the mean energy reduction per event.

It does NOT give the likelihood of scattering.

For example: H (large δ but low σ)

Moderators with higher densities (even though smaller δ) can show better *Slowing Down Power*. E.g., graphite.

Moderator reduces neutron energies to thermal regime, where fission cross section is high.

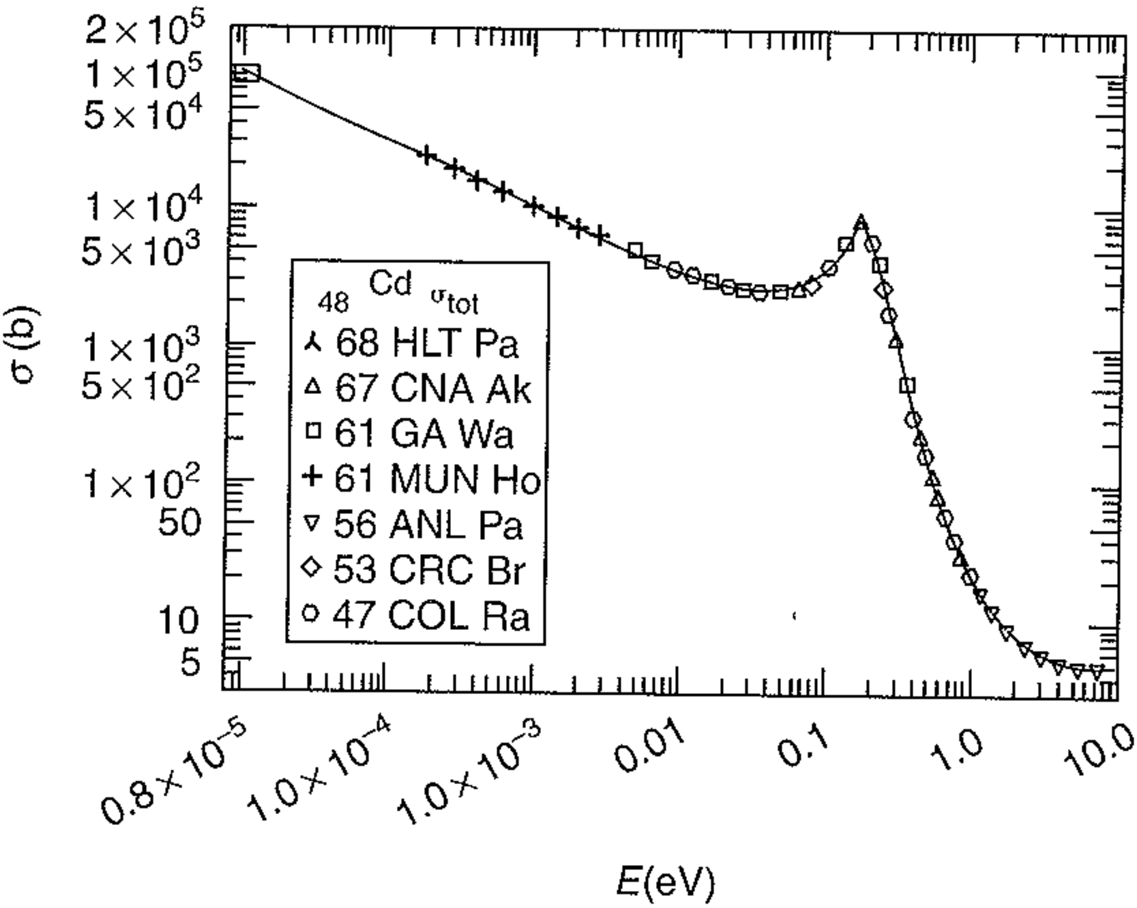
Considerations for good moderator material:
- Inexpensive and easily obtained
- Low radiative capture cross section (n,γ)
- Small A, to maximize energy transfer per scattering
- High density (increase react° rate)

scattering

MODERATOR: slowing down the neutrons (deuterium, hydrogen, graphite, ...) ... events

CONTROL RODS: absorption events: n's without inducing fission (cadmium, indium, silver)

Cadmium is often used in nuclear reactors:



Note the very high cross-sections, ideal to slow down neutrons when necessary

Number of neutrons available to induce fission regulated by adjusting position of Cadmium control rods.

lowering control rod into reservoir with fuel (Regulated delayed n's)

6.3. Critical Mass

All fission reactions produce neutrons.

In the case of ^{235}U fission, average of 2.5 neutrons

Let us define:

$$k = \frac{\mathrm{N(neutrons)\,produced\,at\,(n+1)^{th}\,stage\,of\,fission}}{\mathrm{N(neutrons)\,produced\,at\,n^{th}\,stage\,of\,fission}}$$

For $k = 1$, the process is *critical*

A sustained reaction can occur.
Ideal for a nuclear reactor.

For $k < 1$, the process is *sub-critical*

The reaction will die out. decline over time

For $k > 1$, the process is *supercritical*

The energy will grow very rapidly
(ideal for a bomb, not for a reactor)

Example: Uranium random walk !!

Typical density: $4.8 \times 10^{28}\ m^{-3}$

Average energy of fast neutron from fission: 2 MeV

From the plot of cross-sections before, we can see:
$\sigma \sim 7$ barns

Mean free path is therefore $l_0 \sim 3$ cm $\quad l_0 = \frac{1}{\rho \sigma}$

Probability of 18% of inducing another fission, releasing other neutrons. → scattering event

Probability of inducing fission after 1 collision = $p = 0.18$

After n collisions = $p\,(1-p)^{n-1}$

Mean number of collisions to induce fission is:

$$\bar{n} = \sum_{n=1}^{+\infty} n\, p\,(1-p)^{n-1}$$

(if the neutron does not escape …)

average distance travelled after N scattering events $= \sqrt{\langle dist^2 \rangle} = \sqrt{N}\, d_{\text{mean free}} = \sqrt{N}\, l_0$

from starting point

per

$\bar{n} \approx 6$ if $\rho = 0.18$ (from the cross-section)

A neutron will therefore travel at most ~ 7 cm before new fission event (and therefore creating more neutrons)

A sphere of 7 cm diameter is enough for critical mass

In practice, we need to account for the probability of each new neutron inducing fission.

The actual critical mass would be reached for a sphere of 9 cm (mass of about 50 kg)

Need to reduce the mass of fuel (e.g. uranium) to avoid super-critical state.

6.4. Neutron diffusion and leakage

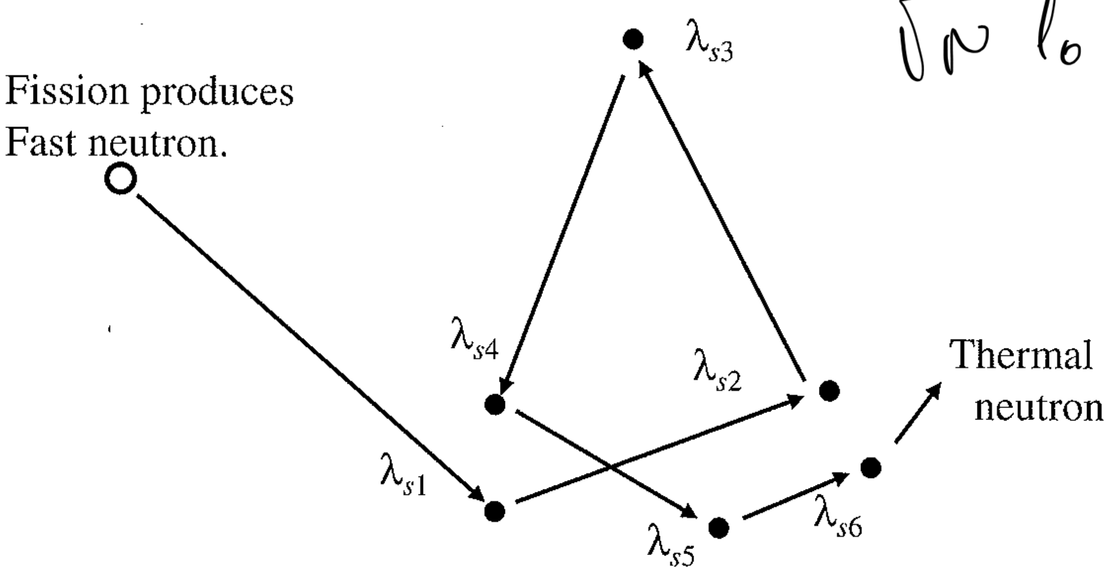
Neutron density at some point in the reactor will depend on the balance between:

- production (i.e. the slowing down at the energies considered);
- absorption;
- leakage (neutrons escape);

It is possible to demonstrate that, as expected, neutron density varies inversely with distance from the source.

Fast neutrons will slow down with collisions.

$\sqrt{n}\, l_0$



thermal losses -> changes in [illegible] sect° & mean free path

Diffusion and leakage are related to the geometry of the reactor and to the properties of the materials.

For example, if the reactor core is small, leakage is more probable.

Material properties: source will affect the production of neutrons at each fission stage. Moderator will affect the slowing down power. Fuel cladding and coolant will also play a role.

Super-critical state:

There is not enough neutron leakage from the core. Neutron levels rise inexorably unless control measures are taken to reduce neutron populations, i.e. insertion of control rods.

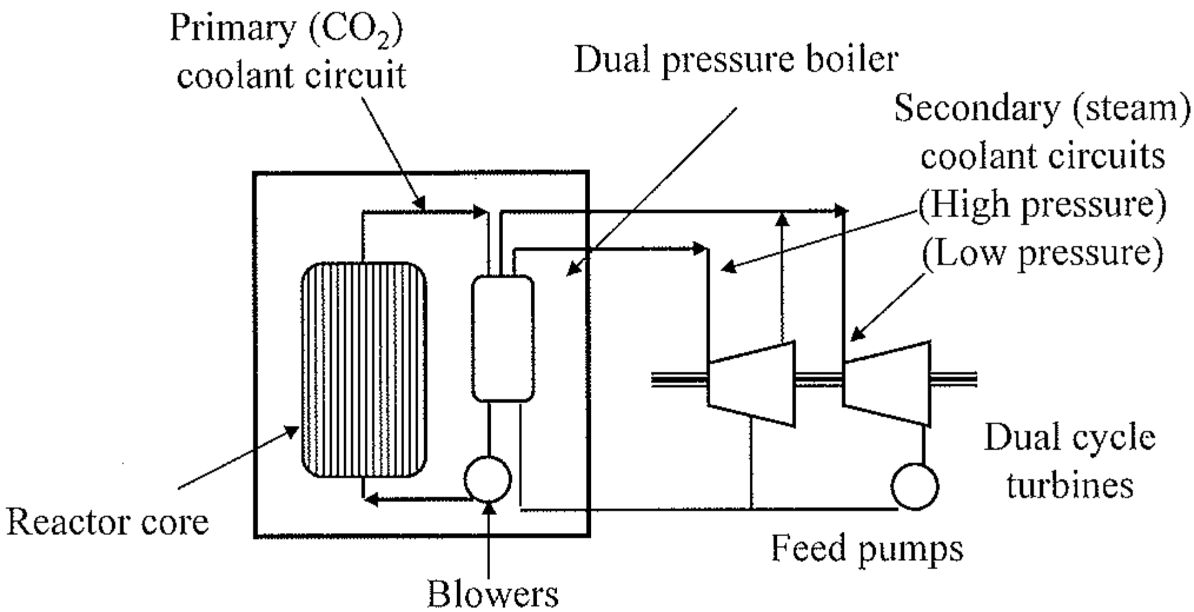
Sub-critical state:

Leakage is too large, and the neutron population will decay away, unless steps are taken to increase thermal neutron production.

Not examinable material

6.5. Example of reactor designs

Magnox gas-cooled reactor



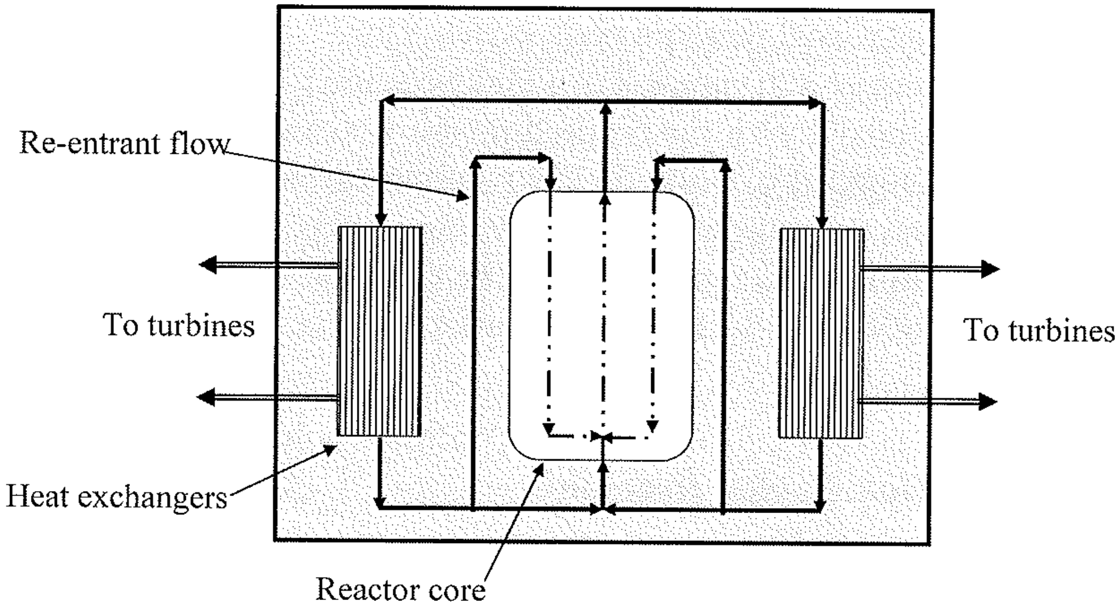
Calder Hall (UK), 1956. Decommissioned 2003.
25 built (22 in UK).

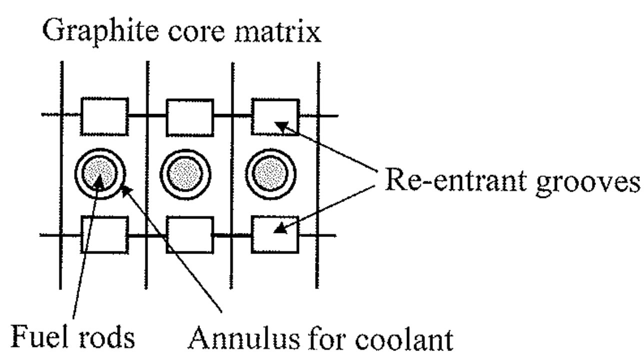
Graphite-moderated, CO_2-cooled
Natural Uranium fuel encased in Magnox (Mg-Al alloy)

CO_2 transfers heat to the boilers (410ºC, 280 MPa)

Not examinable material

Advanced Gas-Cooled Reactors





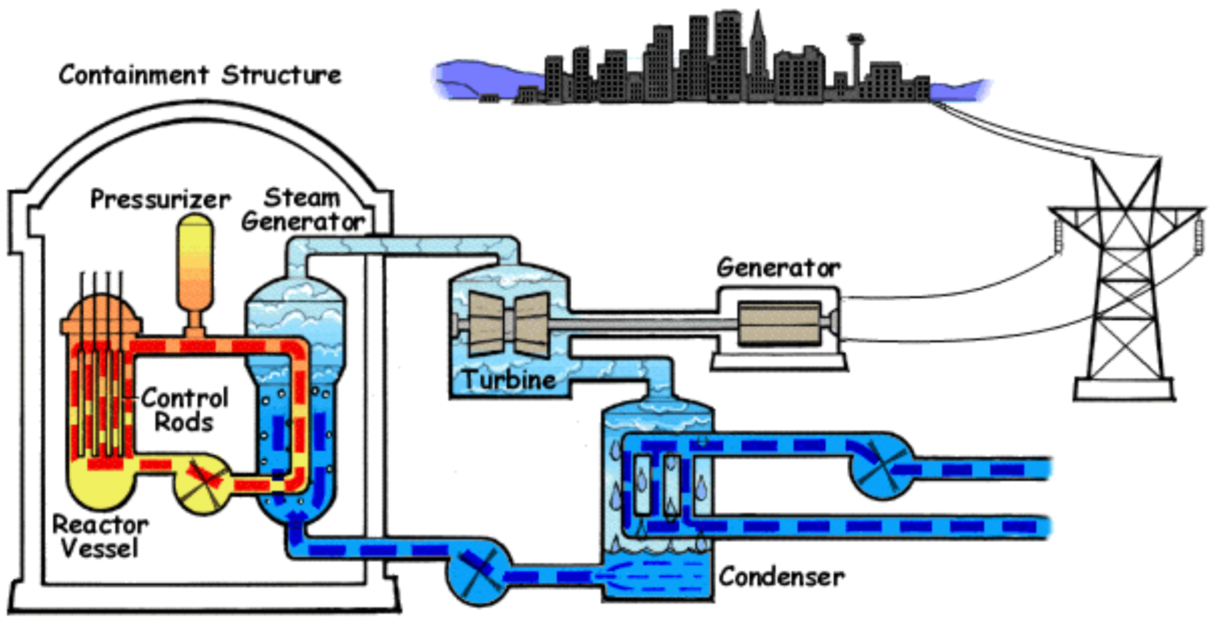
Ceramic UO_2 replaces natural Uranium
Stainless steel replaces Magnox

Fuel cans inserted in graphite sleeves, forming the core.

Reaches 650ºC and 400 MPa.

Not examinable material

Pressurized Water Reactors



Most widely used system around the world.
Uses light water (H_2O) as both coolant and moderator.
Enriched UO_2 clad in zircalloy (Zr-Sn-Fe-Ni alloy).

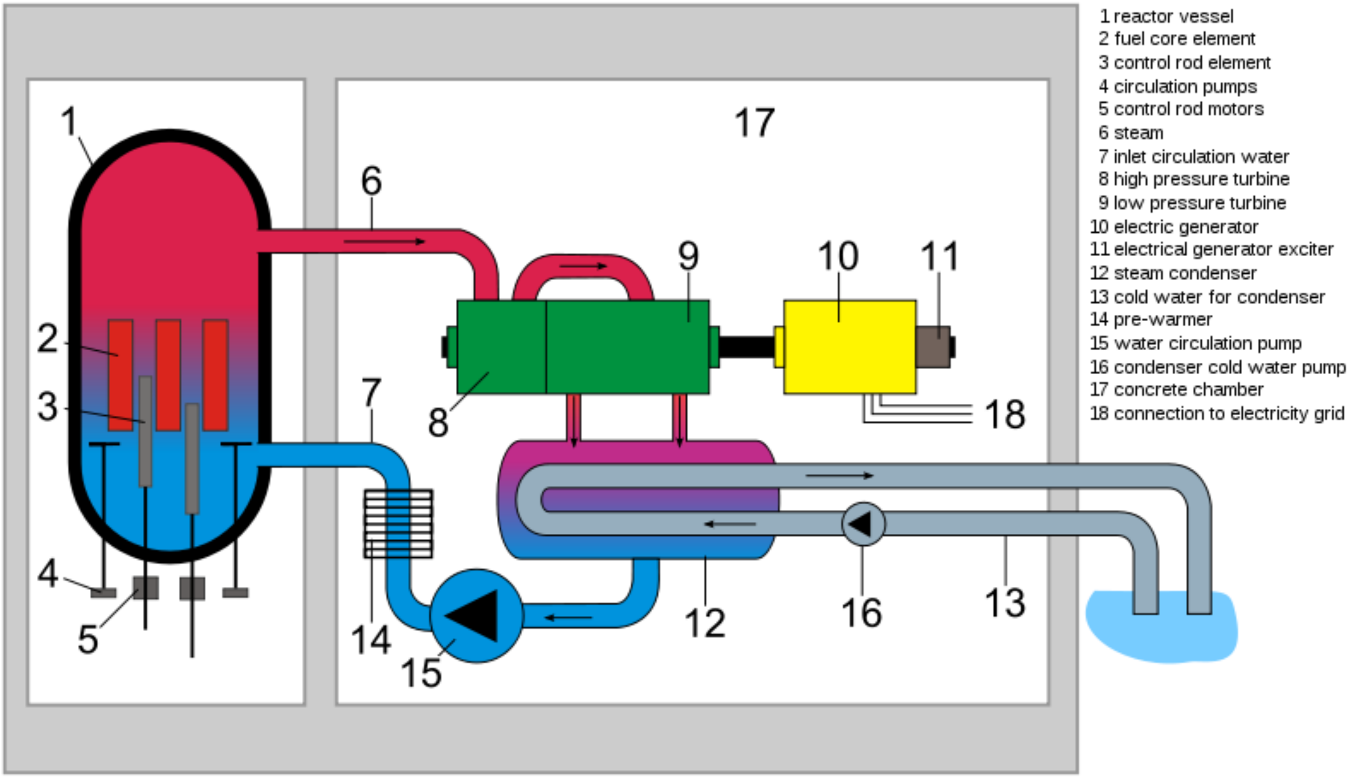
Pressurized cooling circuit avoids boiling (5-15 MPa, 300ºC)
Confines hazardous material within containment building <u>under normal operation.</u>
Loss of coolant means rapid overheating. Delayed neutrons would still create excess heat during shutdown.
First employed on USS Nautilus (1954)

Advanced Light Water Reactors

Uses “quench pools” as additional safety. Can flood reactor if necessary.

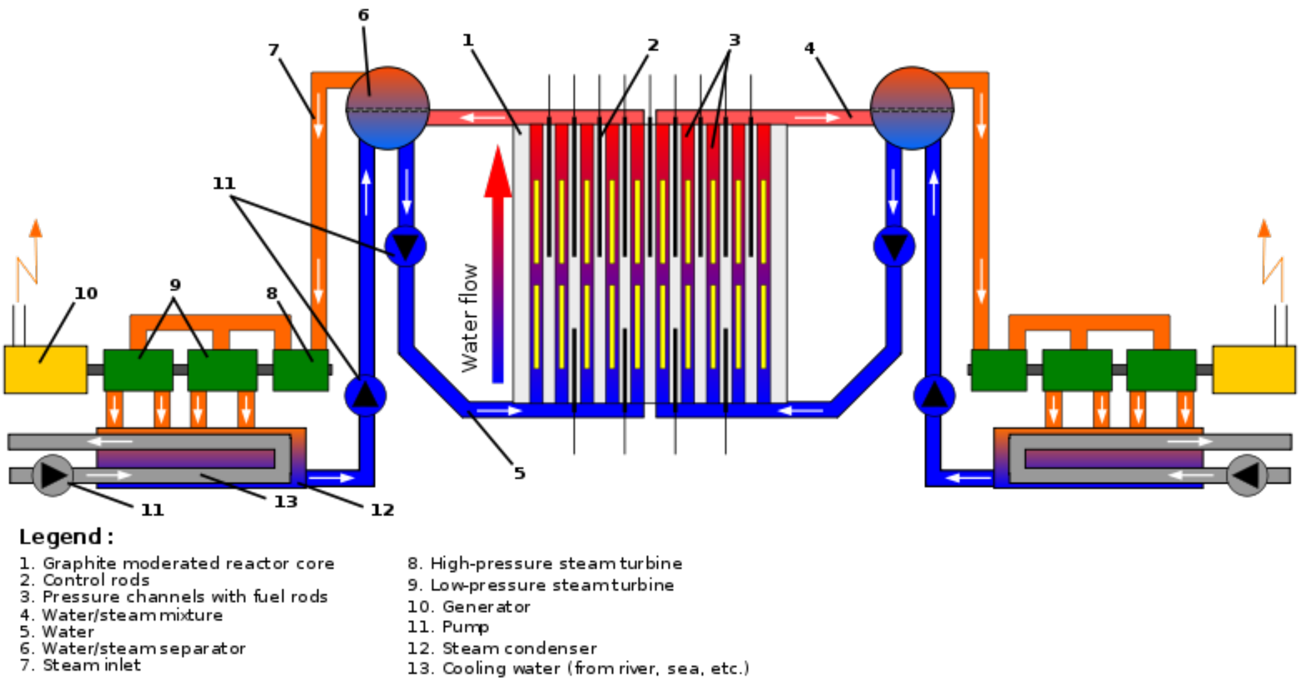
Not examinable material

Boiling Water Reactors



Alternative to the Pressurised Water Reactor.
Coolant/moderator water allowed to boil in the core.
First built 1960 (Dresden, USA).
Also built at: Fukushima-Daiichi, Japan.

RBMK Reactors



First installed: Leningrad (USSR), 1974.
Enriched UO_2 fuel encased in zirconium-niobium cans, arranged in vertical coolant channels surrounded by the graphite moderator.
Reactors typically arranged in pairs.
Chernobyl design

European Pressurised Water Reactors

First installed: Finland (2005).
Design for Hinckley Point C (Somerset)

T = 300°C, pressure 155 bar

Fuel: UO_2 fuel and/or MOX fuel

Coolant: soluble Boron acting as neutron absorber (use of variable concentrations)

Additional neutron absorbers (Gadolinium), in the form of burnable absorber-bearing fuel rods, are used to adjust the initial reactivity and power distribution.

In a Pressurized Water Reactor (PWR) like the EPR, ordinary water is utilized to remove the heat formed inside the reactor core by the nuclear fission phenomenon. This water also slows down (or moderates) neutrons (constituents of atom nuclei that are released in the nuclear fission process). Slowing down neutrons is necessary to keep the chain reaction going (neutrons have to be moderated to be able to break down the fissile atom nuclei).

The heat produced inside the reactor core is transferred to the turbine through the steam generators. From the reactor core coolant circuit (primary circuit) to the steam circuit used to feed the turbine (secondary circuit), only heat is transferred and there is no water exchange.

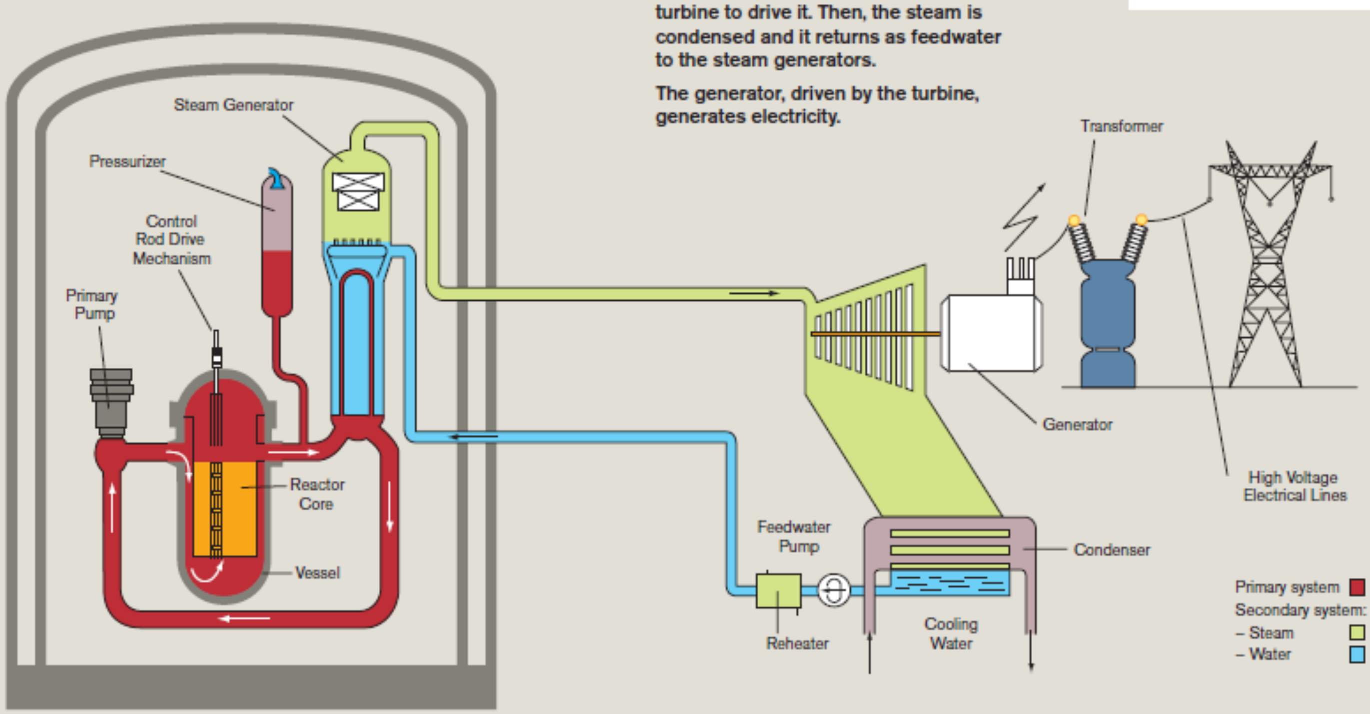
The primary water is pumped through the reactor core and the primary side of the steam generators, in four parallel closed loops, by electric motor-powered coolant pumps. Each loop is equipped with a steam generator and a coolant pump.

The reactor operating pressure and temperature are such that the cooling water does not evaporate and remains in the liquid state, which intensifies its cooling efficiency. A pressurizer controls the pressure; it is connected to one of the loops.

The feedwater entering the secondary side of the steam generators absorbs the heat transferred from the primary side and evaporates to produce saturated steam. The steam is dried in the steam generators then routed to the turbine to drive it. Then, the steam is condensed and it returns as feedwater to the steam generators.

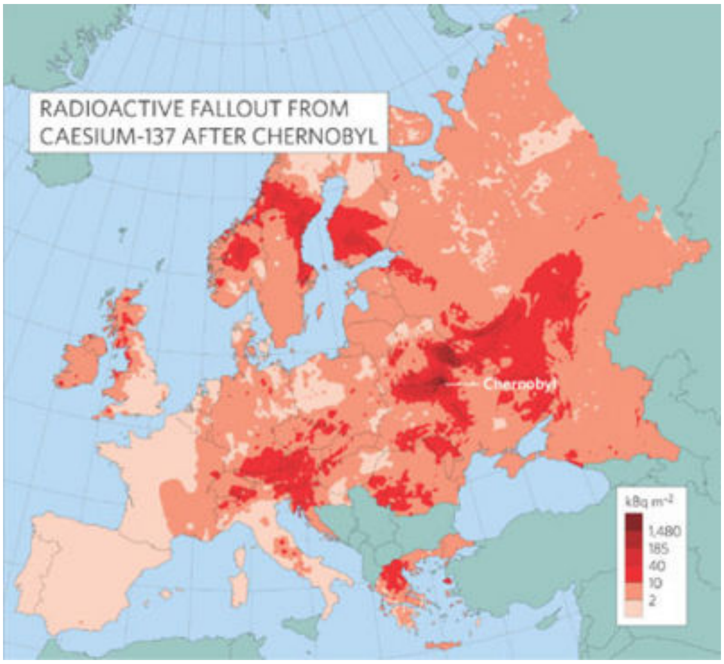
The generator, driven by the turbine, generates electricity.

The following chapte[…] detailed explanation [...] description and opera[…] nuclear power statio[…] the EPR reactor.



Not examinable material

6.6. Nuclear safety – Nuclear waste



Nuclear waste has long life-times (10^3-10^5 years)

Disposal site safety?

Waste reprocessing: expensive but transmutation an option.