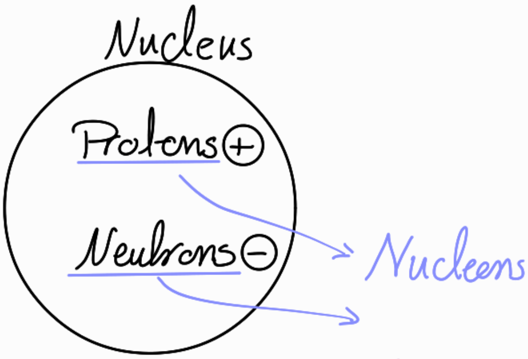
Nuclear Power

Involves changes in the nucleus

$${}^{A}_{Z}X$$

← Atomic mass = # of P + # of N

Atomic number = # P



Fusion and Fission

Fusion: energy is released by fusion of light-nuclei

A<56

Fission: energy is released by fission of heavy necleus

A>56

Binding energy

light speed in vaccum

$$B.E = \Delta m C^2$$

$$\Delta m = \underbrace{(m_P + m_N)}_{\text{mass of P \& N before nucleas formation}} - m_{Nucleas}$$

↪ = Atom mass − electrons mass

Radioactivity

- If the atomic number is >84, element has no stable isotopes so they decay which causes mass decrease
  ↪ α, β particles and γ radiation emitting

Example: $${}^{238}_{92}U \longrightarrow {}^{4}_{2}\alpha + {}^{234}_{90}Th$$

lost 2 protons & 2 neutrons
Also 2 e^- were emitted

It will attract two free electrons

Alpha particles $^{4}_{2}\alpha$

- Consists of two protons and two neutrons
- Its charge is +2
- Identical to helium atom $^{4}_{2}H$
- Highly ionizing and little penetrating ability

Beta particles $_{-1}\beta$

- High energy electrons
- has a negative charge -1

Gamma ray γ

- No charge (neutral)

It is an electromagnetic radiation of very short wavelength

- It represents excess energy emition
- Has high penetration abilities

Radioactivity decay

Number of atoms at time t

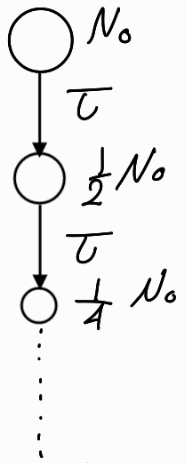
constant

$$N(t) = N_0 e^{-\lambda t}$$

Original number of atoms at t=0

- Half life time τ

$$t_{\frac{1}{2}} = \frac{0.693}{\lambda}$$



number of half lives

$$\text{Remaining fraction} = \left(\frac{1}{2}\right)^{n}$$

Artificial nuclear disintegration

$$\underbrace{^{235}U + {}^{1}n}_{\text{Bombardement}} \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + Q$$

$$\phantom{^{235}U + {}^{1}n \longrightarrow} {}^{137}_{56}Ba + {}^{97}_{36}Kr + 2\,{}^{1}_{0}n + Q$$

Energy released

- large quantity of energy is released with each fission
  ≈ 200 MeV
  ↪ Kinetic energy (Most) of neutrons and fission fragments + Small fraction as β & γ

- $E = \Delta m C^2$
  ↪ Energy released

Steady state chain reaction

- When each neutron produced by fission affects a successive fission of another nucleas

Example: $\boxed{\overbrace{{}^{235}_{92}U + {}^{1}_{0}n}^{m_1} \longrightarrow \overbrace{{}^{137}_{56}Ba + {}^{97}_{36}Kr + 2\,{}^{1}_{0}n}^{m_2} + Q}$ ← Typical fission reaction

$${}^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{137}_{56}Ba + {}^{97}_{36}Kr + 2\,{}^{1}_{0}n + Q$$

Note: $\boxed{m_1 > m_2}$

Fast neutrons

- when fission neutrons collide with another nucleus, they lose K.E but does not cause fission
- However, slow neutrons can cause fission

Fast neutrons ⟶ Moderator Nucleus
Elastic Collision ⟶ Slow neutrons
↪ Energy release

Neutron Stability methods :

1. Fission
2. Inelastic scattering : a process in which a $\overbrace{\text{neutron is ejected}}^{\text{Incident N}}$ for each neutron absorbed
3. Neutron absorption (resonance capture) : neutrons are lost
   Reaction: $^{1}_{0}n + ^{235}_{92}U \longrightarrow ^{236}_{92}U + \gamma + Q$

- Nuclear fuel produced in converter reactor is consumed in it

Reactions :

$$\text{Considered to be Conversion}\left\{\begin{array}{l} ^{1}_{0}n + ^{238}_{92}U \longrightarrow ^{239}_{92}U + \gamma + Q \\ ^{239}_{92}U \longrightarrow ^{239}_{93}Np + {}_{-1}\beta + Q \\ ^{239}_{93}Np \longrightarrow \underline{\underline{^{239}_{94}Pu}} + \beta + Q \\ ^{239}_{94}Pu \longrightarrow ^{235}_{92}U + ^{4}_{2}\alpha \end{array}\right.$$

↳ has a higher fission ability
Can be used for fueling reactors

↳ can reach ^{207}Pa in 11 steps with energy release

Conversion and breeding

Breeding: when the reactor produces more than one new fissionable nucleus for each fissioned nucleas

Conversion : when the production of a new fuel in quantity is less than the amount consumed

- Breading reaction

$$^{1}_{0}n + ^{232}_{90}Th \longrightarrow ^{233}_{90}Th + \gamma + Q$$

$$^{233}_{90}Th \longrightarrow ^{233}_{91}Pa + \beta + Q$$

$$^{233}_{91}Pa \longrightarrow ^{233}_{92}U + \beta + Q$$

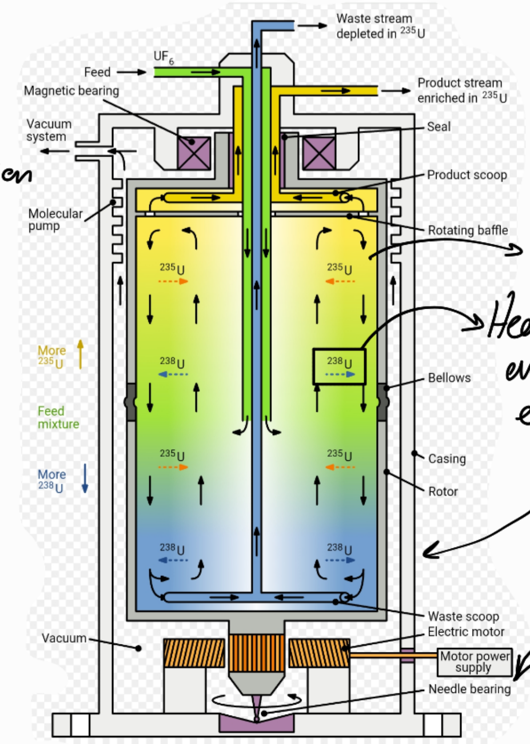
Uranium enrichement

- To enrich uranium, a process of isotopes separation is done (nonchemical)
- Separation methods:
  1- Gas separation in large centrifuges
  2- Gaseous diffusion
- Ore which contains 2.5 Kg of U_3O_8 per ton
  ↳ Contains uranium isotopes

- Centrifugation

$U_3O_8 \longrightarrow UF_6$

To get 2.5% concentration



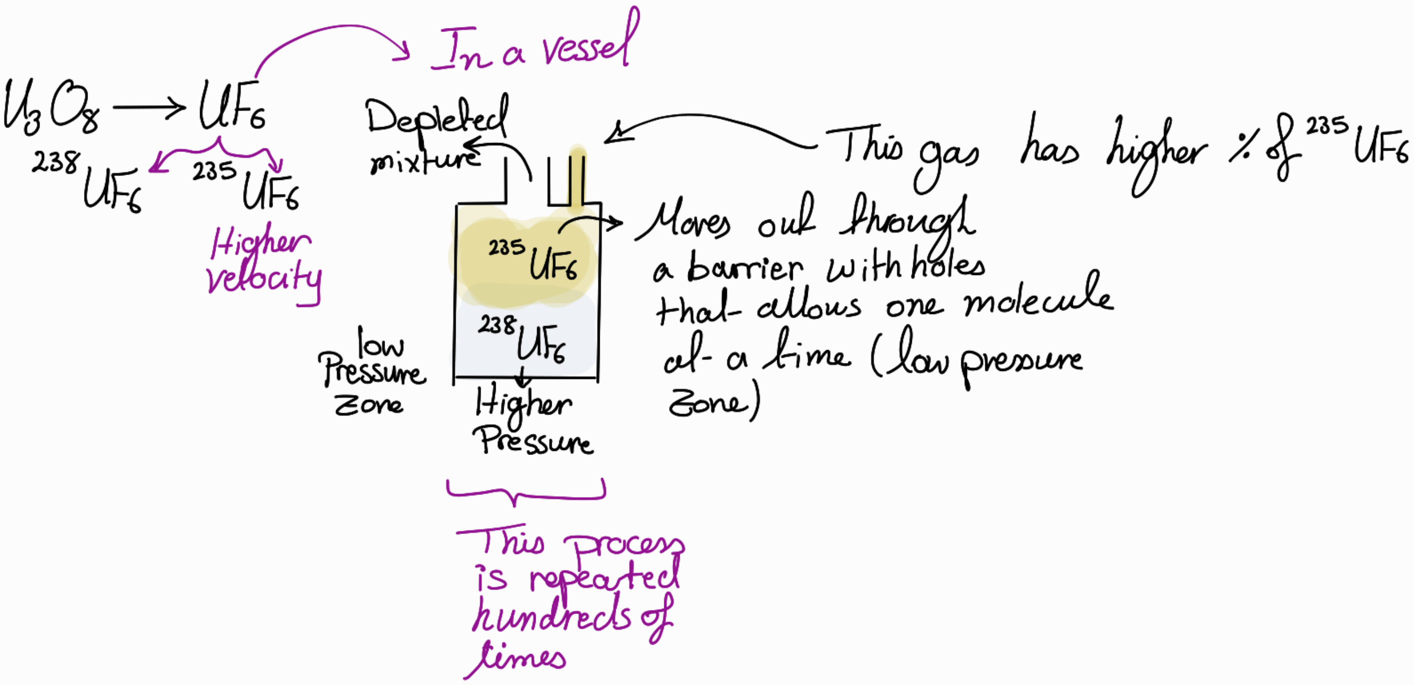
Lighter molecules gas

Heavier molecules are sent to the edge

Then goes down

Turns at a high speed

- Gaseous diffusion



This gas has higher % of $^{235}UF_6$

Moves out through a barrier with holes that allows one molecule at a time (low pressure Zone)

This process is repeated hundreds of times

- The enriched UF_6 is chemically processed into uranium dioxide UO_2
  ↳ refined and compacted into fuel pellets
  Diameter ≈ 8mm

Reactor Design

- Reactors can be:
  1. Fast reactors: e^- energy > 1000 eV
  2. Intermediate reactors: $0.05 < e^-$ energy < 1000 eV
  3. Thermal reactors: e^- energy < 0.05
     ↳ Uses a moderator to reduce energy to lower than 0.05
       - has little capability for absorbing neutrons
       - has low atomic weight
       - Examples: Hydrogen introduced as Heavy water / Graphite / Helium
         moderator and reflector

- Microscopic cross section

- It is the probability that a particular interaction between a nucleus and a moving particle will occur. (σ)
- Unit is barn $= 1\times10^{-24}\ cm^{-2}$
- $\sigma_t = \overset{\sigma_a}{\boxed{\sigma_c + \sigma_f}} + \sigma_s \leftarrow$ scatter cross section σ_a: absorption cross sectional area

capture cross section
Area of absorption without fission

fission cross section
Area for neutron to strike and cause fission

scatter cross section
Area that scatters or deflect a striking neutron

Total Microscopic cross section

$\Sigma = N\sigma$

↳ number of nuclei per cm³ $\Rightarrow N = \#$ of moles/cm³ × Avogadro number

$$= \frac{\rho}{\text{Molecular weight}} \times 6.023\times10^{23}\ \frac{\text{atom}}{1\ \text{g}\cdot\text{mole}}$$

$\lambda = \frac{1}{\Sigma}$

↳ Mean free path

- Criticality

- It represents the maintainance of the fission chain reaction at a Constant rate
- Classification of reactors based on criticality:
  1. Supercritical : fission rate is increasing
  2. Subcritical : fission rate is decreasing

- Reflector

- It is placed around the reactor core to return neutrons escaping from the core
- Made of: Low atomic weight → For thermal reactors
  High atomic weight → For Fast reactors

- The reactor should be shielded to prevent harmful α, β and γ radiations

  caught in reactor structure

  intercepts with the neutron by large masses of concrete placed around the reactor vessel

Reactor Control

- Fissioning rate is proportional to the quantity of fissionable material in the core and the neutron density

  Power level is controlled by

- Number of neutrons emitted per fission in a critical reactor is 2.5

$$ {}^{1}_{0}n + {}^{235}U \longrightarrow x + y + Q + \underline{2.5} $$

→ 1 for the next fission

↳ 1.5 is excess neutron

- To control the reactor:
  - A constant neutron production must remain constant unless the power output of the reactor is needed to change

- Effective neutron multiplication factor

$$ K_{eff} = \frac{\text{neutron production}}{\text{neutron leakage} + \text{neutron absorption}} \begin{cases} > 1 & \text{Supercritical reactor} \\ = 1 & \text{Constant power level} \\ < 1 & \text{subcritical reactor} \end{cases} $$

- It is the ratio of neutron population in each generation to the population in the previous generation

- Reactivity ρ

$$\rho = \frac{K_{eff} - 1}{K_{eff}}$$

- Nuetron life time τ^*

It is defined as the average time between successive neutron generations or the mean time that elapses between the production of neutron by fission and the subsequent fission effective by these neutrons or loss of neutrons from the reaction

- Neutron density

n : # of N existing in a unit volume

$$n = n_0 e^{\tau} \quad \tau \rightarrow \frac{\rho}{\tau^*}\tau$$

τ^*: Nuetron life time

n_0: neutron density at $\tau = 0$

$$\frac{n}{n_0} = \frac{P}{P_0}$$

- Production can be altered by changing the neutron absorption or neutron leakage

Leakage → Cannot be controlled

Absorption → Achieved by altering the quantity of neutron absorbing material in the reactor

- Control rods are composed of a substance that has a high thermal cross section for absorption.
- These are moved singly or in groups

Note: reactors (in practice) are designed larger than their critical size (Why? in slide 49)

Reactor power

- The highest fission rate in the reactor core occurs at the geometric center of the composite structure
- Energy release rate:

$$\dot{q}_v = E_f \Sigma_f \emptyset C_{fn}$$

Effective Microscopic fission cross section $[cm^{-1}]$

neutrons flux $[neutrons/s.cm^2]$

specific energy release rate $[MeV/s.cm^2]$

Energy per reaction $[MeV/fission] = 180\,eV$

$$\Sigma_f = \sigma_f N_{ff} \quad [Nuclei/cm^3]$$

$[cm^2]$

عد الانوية القابلة للانشطار

$$\Sigma = \left(\frac{\rho}{M.W} \times A.N\right) \cdot \sigma$$

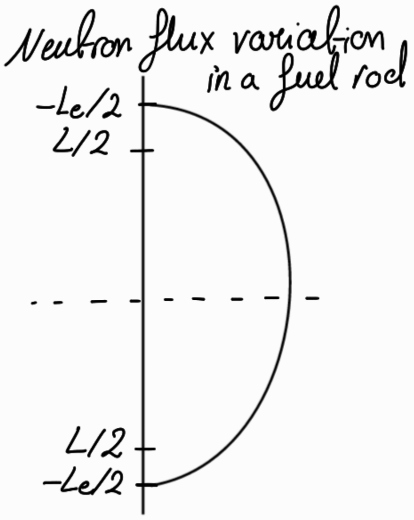
atom/1gmole

$C_{fn} \simeq 1$ or 1.08 for water reactors

$N_{ff} = 2.372 f \times 10^{22}$ ^{235}U nuclei/cm³ for UO_2 fuel

Heat generated in the fuel rod

- Neutron flux longitudinal variation in neutron flux can be aproximated by a function of z



$$q_t = \frac{2}{\pi} \dot{q}_{v,o} A_t L$$

Length of rod

transfers area of rod

Thermal energy of the fuel rod

specific energy release at the fuel rod center

Heat generated in the reactor core

$$q_t = K n A_t L \dot{q}_{v,o}$$

number of fuel rods in the reactor core

Specific energy release rate at the geometric center

height of the reactor core = Active length of fuel rods

Heat Generation rate

characteristics of the reactor

Transerse area of a single fuel rod

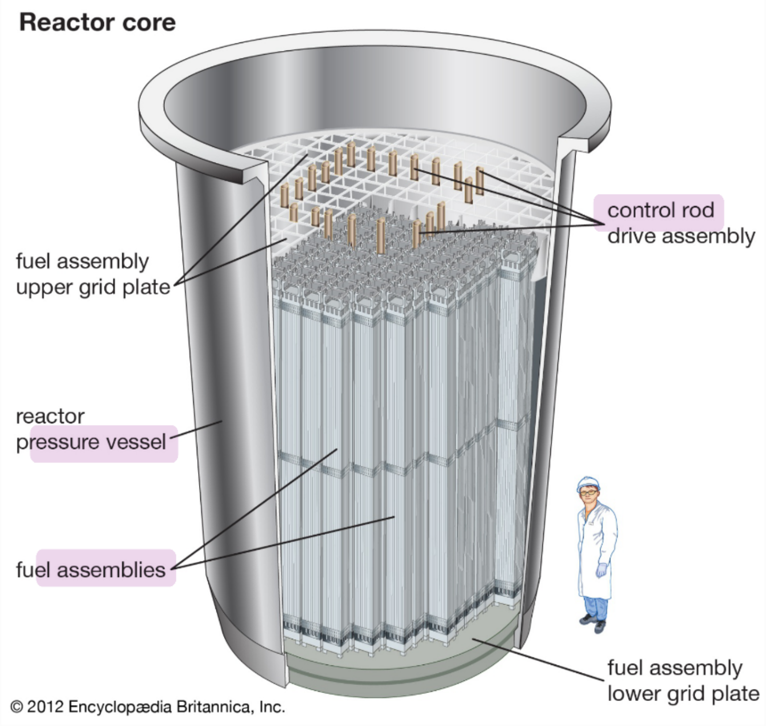
Note: q_t is the power generated in fuel & cladding

Reactor core construction (Back to slide 60)

- Fuel: Small cylindrical UO_2 fuel pellets are encased in the thin walled tubes to form fuel rods

— A fuel assembly consists of a square array of 200-300 fuel rods
↳ 200-250 fuel assembly in a reactor

- Stainless Steel or zirconium are used for structure:
  1. To endure high T
  2. To resist corrosion



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- A coolant enters the core (liquid or gas) to transfer heat from the core (coolant characterestics in slide 62
- Control rods are made with neutron absorbing material. They are used to control the rate of the reaction by inserting or removing it

- Pressure vessel is a steel vessel containing the reactor core and moderator/coolant

- Containment: the structure around the reactor. It is used to protect it from outside intrusion and to prevent radiation

— Made of concrete and steel structure

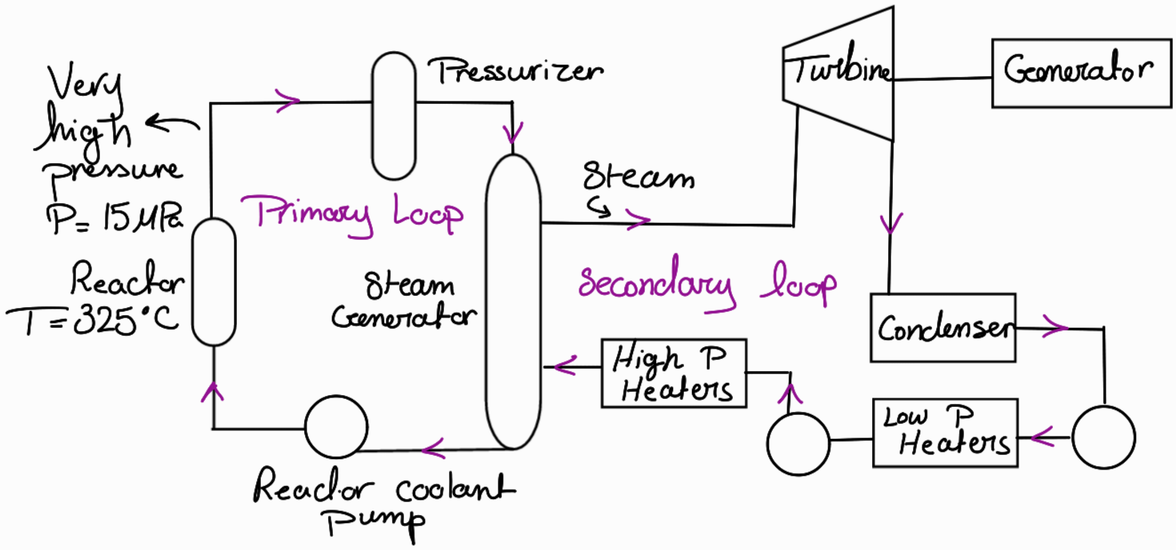
Classification of Reactors

Based on

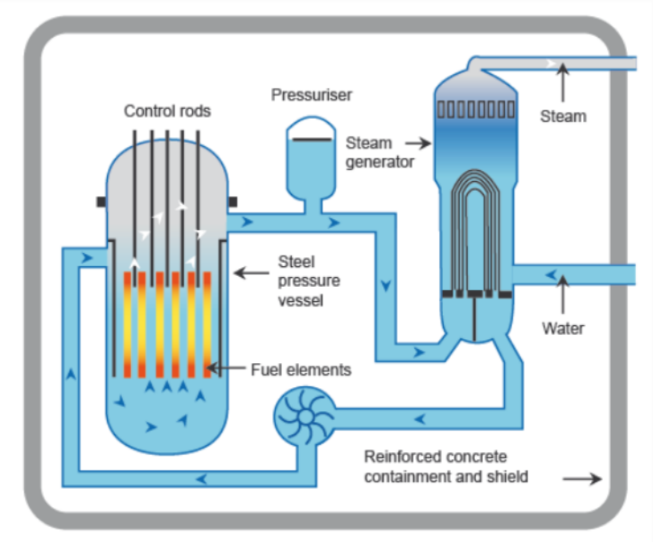
- Type of reaction
  - Radioactive decay such as: radioisotope Thermoelectric generators
  - Nuclear fission
    - Thermal reactors
    - Fast-neutron reactors
  - Nuclear fusion
- Moderator
  - Graphite moderator
  - Water moderator
    - Heavy Water
    - Light-Water (Also used as coolant)
  - Light element moderator
    - Molten salt reactors (lithium or beryllium)
    - Liquid metal cooled reactors (BeO and coolant is a mix of Lead and Bismuth)
  - Organically moderated reactors (uses biphenyl & terphenyl as moderator & coolant)
- Coolant
  - Water cooled
    - PWR
    - BWR
  - Liquid metal cooled (Fast-reactors)
    - Sodium cooled
    - Lead cooled
  - Molten salt cooled reactors (mixture of fluoride salts such as FLiBe)
  - Gas cooled reactors (Helium or CO_2 or N_2)

Pressurized water reactor

- Moderator & Coolant: Light water
  Water in circulated the Primary loop to prevent boiling

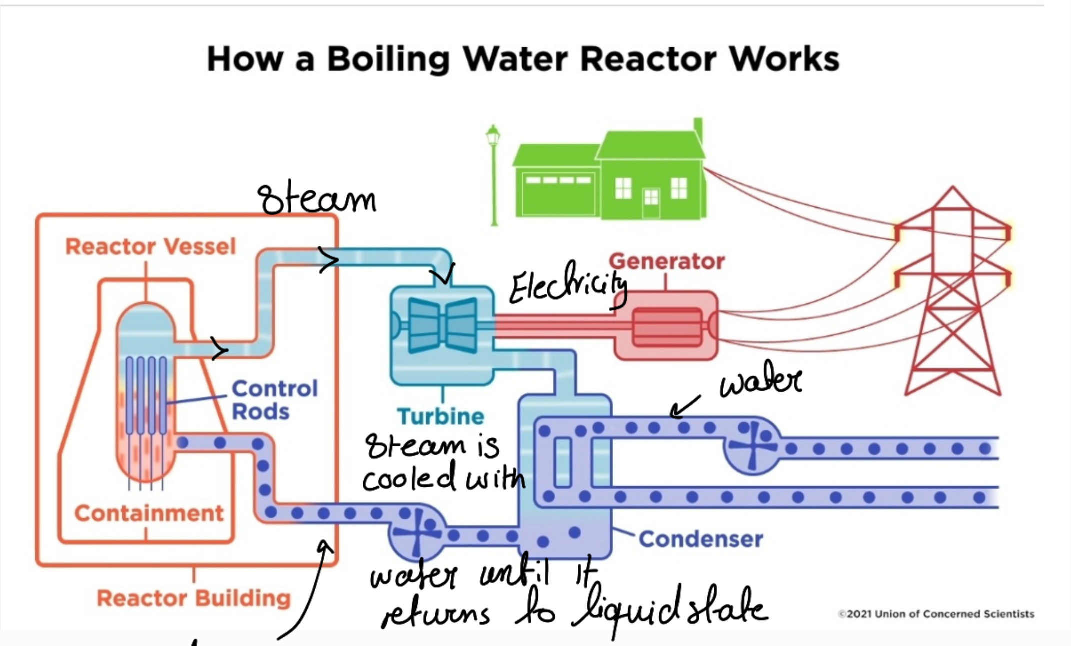


- The Pressurizer maintains the pressure of the coolant within the prescribed limits
- Fuel is UO_2 enriched / 200-300 fuel rods / fuel assembly / 150-250 fuel assemblies



Boiling Water Reactor

- Moderator & Coolant : Light or ordinary Water
  Fuel: UO_2 enriched
- Pressure = 7 MPa to allow water boiling within the core
  → when water boils, Its abilities as a moderator are reduced,


How a Boiling Water Reactor Works

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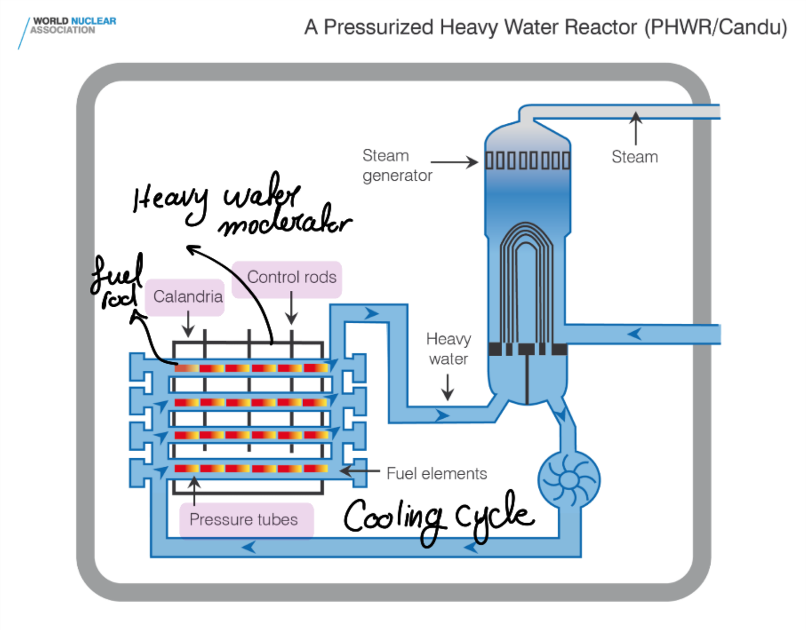
Cooled steam
(water) is pumped back
to the core

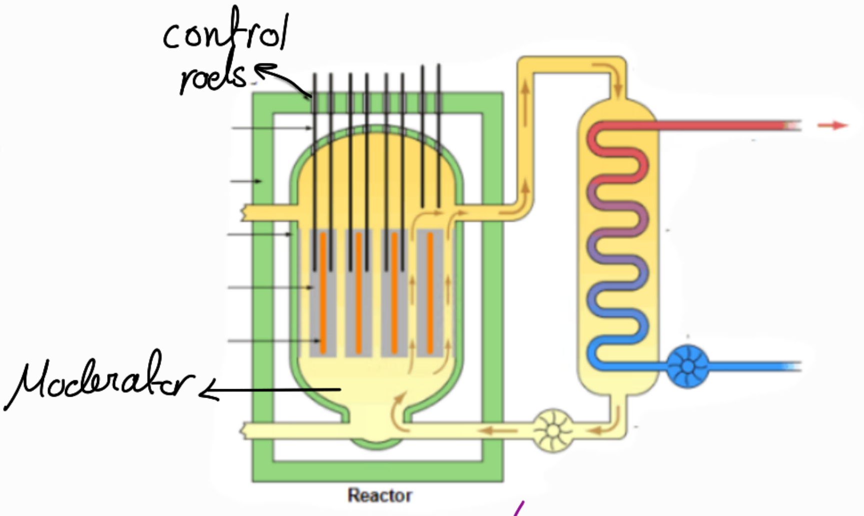
Pressurised heavy water reactor

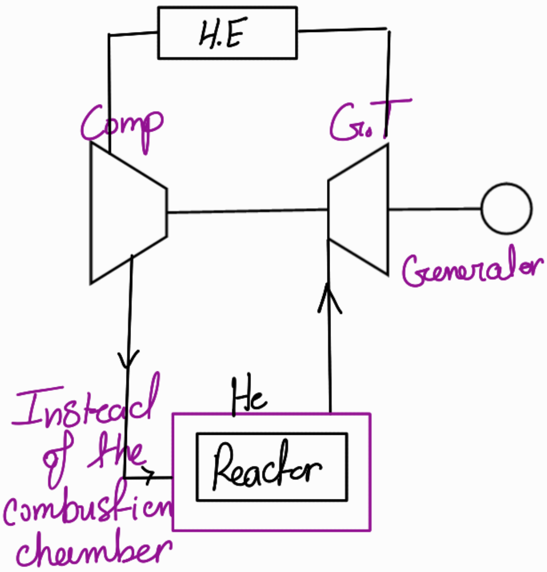
- Fuel: natural uranium (0.7% ^{235}U) Oxide
- Moderator: needs to be more efficient. e.g: Heavy water
- Cooler: heavy water or light water
- Pressure tubes: horizontal tubes that form fuel channels


A Pressurized Heavy Water Reactor (PHWR/Candu)

Advanced Gas-cooled reactor (AGR)

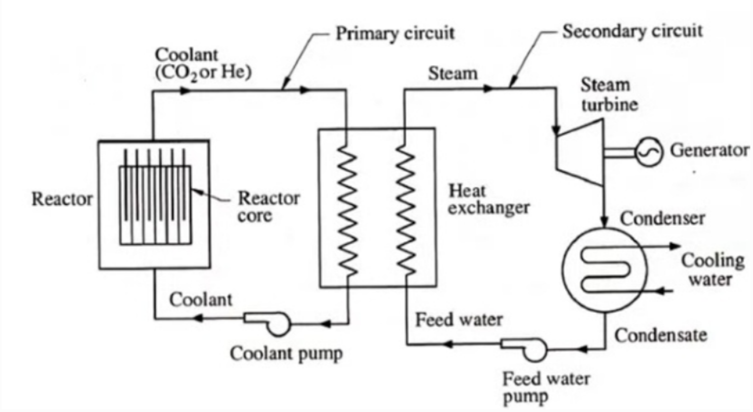
- Moderator: graphite
- Coolant: carbon dioxide
- Fuel: uranium oxide pellets enriched (2.5-3.5%) in stainless steel tubes
- Works on high Temperatures since no liquids exist
- It can be coupled to a gas turbine with He as a Working fluid





AGR coupled with a gas turbine

schematic



AGR coupled with a steam Turbine

Fast neutron reactors (FNR)

- Does not have a moderator since Fast neutrons are used
- Fuel: ^{238}U converted to Fissionable plutonium(^{239}Pu) mixed with UO_2 (15% enrichement needed)
- High Temperature (540°) and pressure (24 MPa)

(Back to Slide 9c)

Liquid Metal Fast breeder reactor

- Uses fast neutrons for fission so No moderator needed
- Produces more fuel than it consumes (breeds fuel) since they produce fissionable fuel
- Coolant: liquid metal (low density and high atomic weight needed
  - Sodium cooled: prevents corrosion / explodes with H_2O / becomes radio-active producing gamma rays

- Lead Cooled : Excellent radiation shielding / Fewer neutrons are lost in coolant / Does not become radioactive / Toxic and not easy to dispose

Nuclear fusion

- Nuclear reaction in which two atoms nuclei collides at a very high speed and form a new nucleus

Reactions:

$$^1_1H + ^1_1H \longrightarrow ^2_2He + \nu$$
$$^2_1H + ^2_1H \longrightarrow ^3_2He + n + \gamma$$
$$^2_1H + ^3_1H \longrightarrow ^4_2He + n$$

- Star burning results from fusion of H atoms

$$H + H \longrightarrow \underset{\text{Deutrium}}{D} + \beta^+ + \underset{\text{neutrino}}{\nu}$$

- $\underbrace{\text{Energy barrier should be overcome}}_{\text{overcoming repulsion forces}}$ for fusion to occur

- Fusion approaches:
  - Magnetic confinement : magnetic field is used to hold particles & energy of a hot plasma in place
  - Inertial confinement : a small pellet of solid hydrogen fuel is hit on all sides by many laser beam until It reaches fusion temperature