Energy Conversion ME 531

Nuclear Power

Afif Hasan
Mechanical & Mechatronics Engineering

Outline

- Nuclear energy
- Radioactivity
- Fission reactions
- Fuel preparation
- Reactor design
- Reactor power
- Nuclear reactors

Nuclear Energy versus Chemical Energy

- Chemical energy, such as a combustion reaction, deals with electrons in the outer shells of atoms, while nucleus remains unchanged.
- Nuclear reaction involves a change in the nucleus of atoms.
- Chemical reaction for example $C + O_2 \rightarrow CO_2$. releases 4.0eV per carbon atom, while a fission nuclear reaction releases about 200MeV per fission.

Nucleus

- The nucleus contains:

  Protons with a positive charge and 1.00727 amu.

  Neutron, neutral charge and 1.008665 amu.
- In symbols $^{1}_{1}P$ proton

  $^{1}_{0}n$ neutron
- In general use the notation $_{Z}^{A}X$

  Where; A: atomic mass number in amu and equals number of protons + neutron.

  Z: atomic number, and equals number of protons.

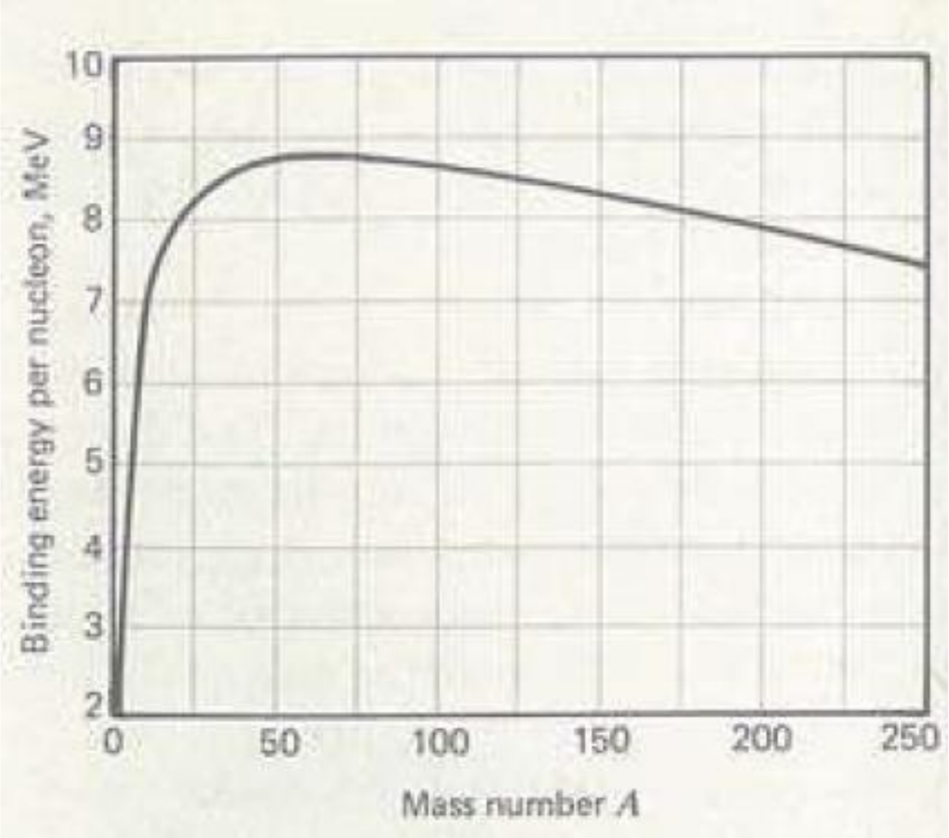
e.g. $^{238}_{92}U$ A = 238 = number of (protons + neutrons)

Z = 92 = number of protons

Neutrons = 238 – 92 = 146.

Binding Energy

- Protons and neutrons in the nucleus are held together by the binding energy.
- The binding energy per nucleon is a function of the mass number, *see Fig. 9.1 p.306 Sorenson*, the higher the binding the more stable in the atom.
- ''Fe'' has the greatest binding energy per nucleon and is the most stable B.E = 8.7857 MeV/nucleon.
- Nuclear transformation is toward iron from both sides.



Binding Energy

- Binding energy: is energy released in the formation of a nucleus or energy required to decompose the nucleus into the constituent nucleons.
- Binding energy per nucleus or per nucleon

Computing binding energy

- B.E can be computed using Einstein formula of mass energy equivalent, B.E = ΔmC^2.
- Where: Δm = (mass of proton + mass of neutrons in the nuclei) – (mass of nucleus).
- mass of nucleus = mass of atom – mass of elements

  C^2 = (light speed)^2 = 931 MeV/amu.

Proton	$^{1}_{1}P$	1.007277amu
Neutron	$^{1}_{o}n$	1.008665amu
Electron	e	0.000549amu
Alpha particle	$^{4}_{2}\alpha$	4.001505amu

Example- Binding Energy

Calculate the B.E for ^4_2He given mass of helium atom = 4.00260atm.

Mass of nucleus = 4.002603 – 2x0.00549 = 4.001505 amu

Mass of proton + mass of neutrons = (2)(1.007277) + (2)(1.008665) = 4.031884amu

Δm = 4.031884 – 4.001505 = 0.03037 amu

per nucleon Δm/nucleon = 0.03037/4 = 0.007595

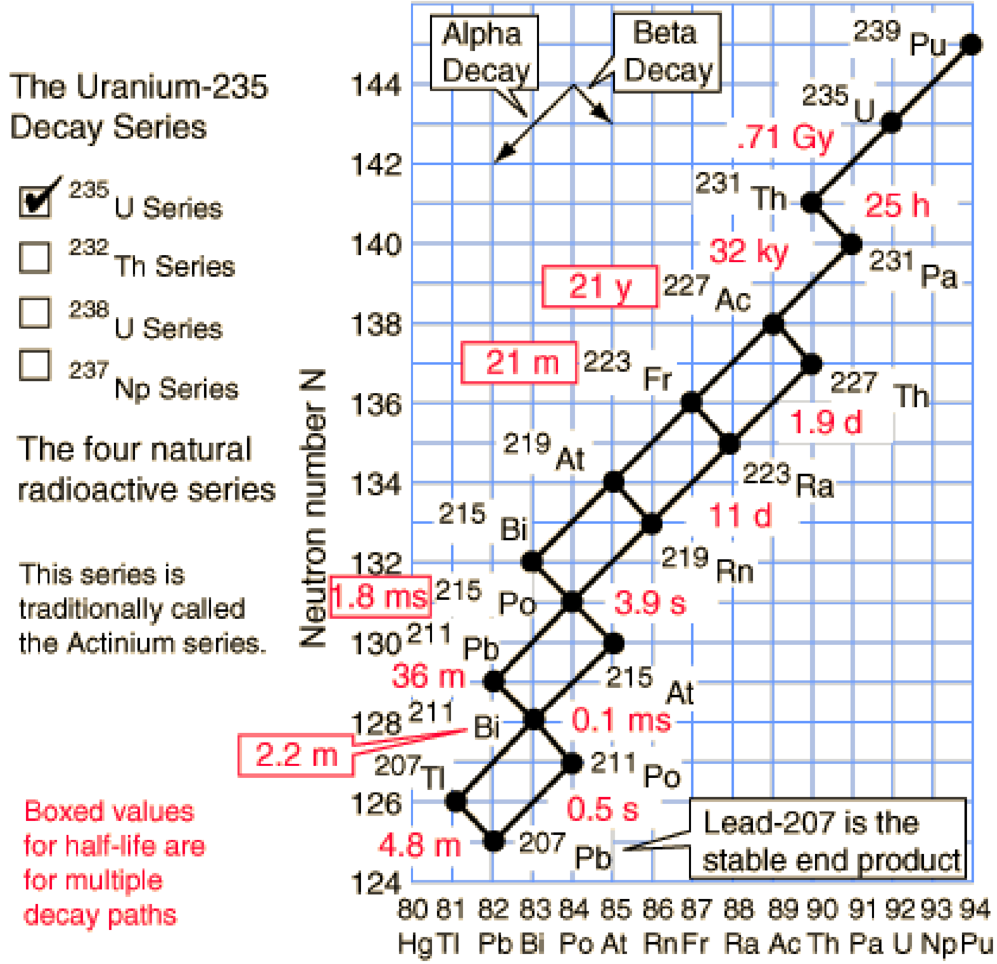
Then:

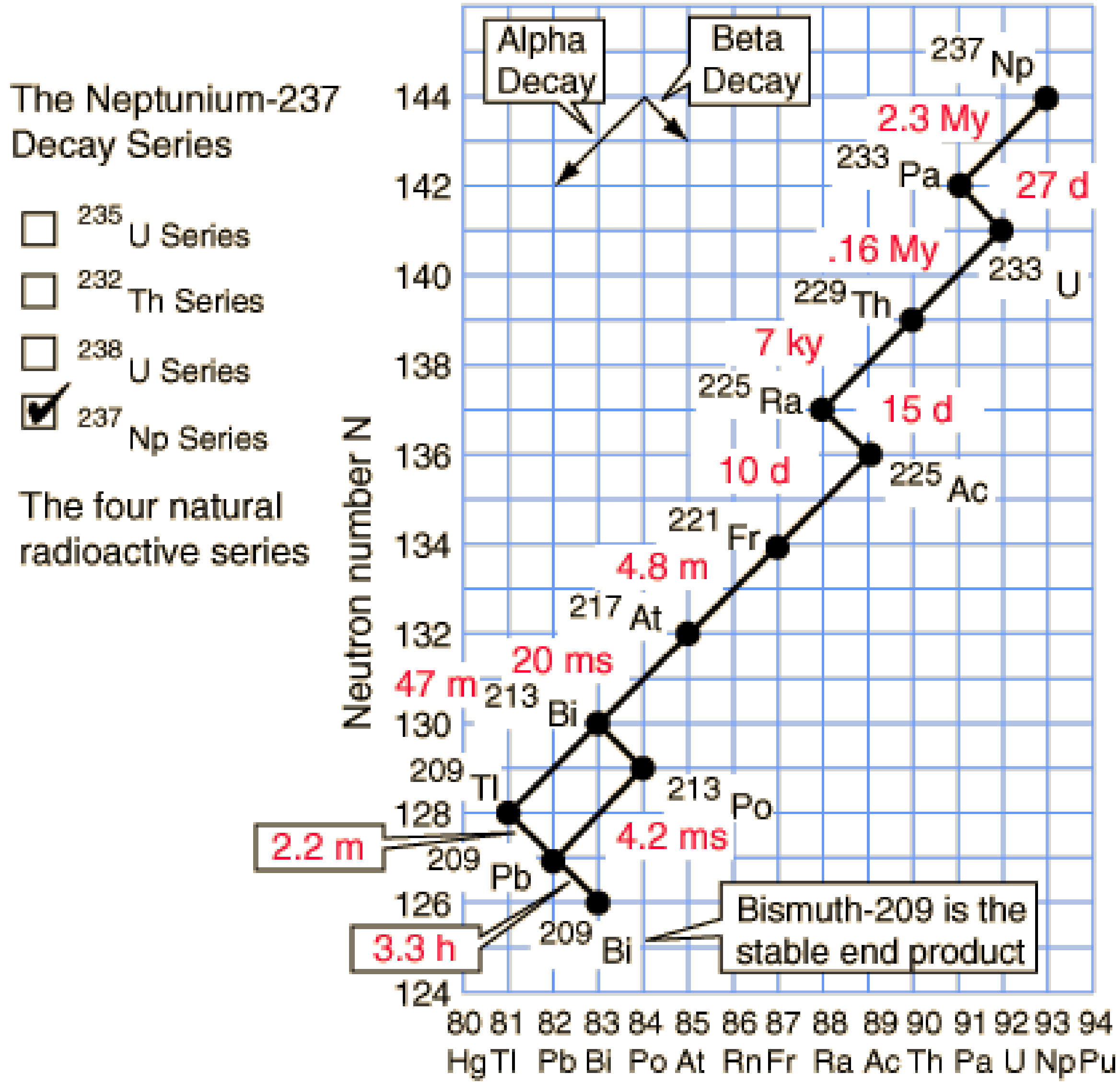
$$\Delta E = \Delta mC^2 = 0.007595 x 931 = 7.071 \text{ MeV/nucleon}$$

Note that 1eV = $1.602x10^{-19}$J

Radioactivity

- Elements of atomic number above 84 have no stable isotopes because of this instability they decay to more stable ones, and in doing this they emit alpha particles, Beta particles and gamma radiation.




The Neptunium-237 Decay Series
235 U Series
232 Th Series
238 U Series
237 Np Series
The four natural radioactive series
Alpha Decay
Beta Decay
Neutron number N
144
142
140
138
136
134
132
130
128
126
124
237 Np
2.3 My
233 Pa
27 d
.16 My
233 U
229 Th
7 ky
225 Ra
15 d
10 d
225 Ac
221 Fr
4.8 m
217 At
20 ms
47 m
213 Bi
209 Tl
213 Po
2.2 m
4.2 ms
209 Pb
3.3 h
209 Bi
Bismuth-209 is the stable end product
80 81 82 83 84 85 86 87 88 89 90 91 92 93 94
Hg Tl Pb Bi Po At Rn Fr Ra Ac Th Pa U Np Pu

Alpha particles

- Alpha particles: it is identical to helium nucleus $^{4}_{2}He$ then $^{4}_{2}\alpha$ the alpha particle consists of two protons and 2 neutrons.
- Its charge is positive +2
- Speed: high speed about 0.1C and KE = 4.6MeV
- Penetration: highly ionizing, with little penetration ability ≈ few cm, in air.

Example:

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

Beta particle

- <u>Beta particle</u>: it is a high energy electrons.
  - Symbol $_{-1}\beta$
  - Charge: negative charge –1
  - Speed ≈ 1C
  - Source: neutron → electron + Proton

    The electron becomes β

Example:

$$^{234}_{90}Th \rightarrow {}^{234}_{91}Pa + \beta$$

- Emission of alpha and beta particles effects a decrease in mass and a transformation of element to another element of different chemical characteristic.

Gamma ray

- Gamma ray: very short wave, electromagnetic radiation
  - Symbol γ
  - Charge: no charge, neutral
  - Speed ≈ 1C
  - High penetration ability.
- Following emission of α and β the nucleus still in an excited state and in order to reach ground state, it emits excess energy in form of gamma rays.

Example

$$^{60}_{27}Co \rightarrow ^{60}_{28}Ni + _{-1}\beta + \gamma$$

Radioactivity decay

Radioactive decay rate $dN/dt = -\lambda N$

By integration $N(t) = N_o e^{-\lambda t}$

Where: N_o: is original number of atoms (at t=0)

λ: proportionality constant.

N: number of atoms at time t

Half-life time, τ: is the time for population of a radioactive species to fall to one-half of its initial value.

$N(t)/N_o = \exp(-\lambda t_{1/2})$

$\ln(N/N_o) = -\lambda t = \ln(1/2)$

$t_{1/2} = \tau = -\ln(1/2)/\lambda = 0.693/\lambda$

After n half-lives the fraction remaining is $(1/2)^n$

e.g. : τ = 5hours, after 20hours or 20/5 = 4 half-live

The remaining fraction = $(1/2)^4 = 0.0625$

Artificial Nuclear Disintegration

- Bombardment of some isotopes with neutron produces unstable nucleus which fission into two stable nucleus and assortment of particles; α, β, and neutrons.

<u>Example of fission induced reaction:</u>

i) $^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{137}_{56}Ba + {}^{97}_{36}Kr + 2{}_{o}^{1}n + Q$

ii) $^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{140}_{54}Xe + {}^{94}_{38}Sr + 2{}_{o}^{1}n + Q$

iii) $^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{141}_{56}Ba + {}^{92}_{36} + 3{}^{1}_{o}n + Q$

Uranium 235 fission products 1,2, or 3 neutrons per fission and on the average 2.47 neutrons per fission,

$$^{235}_{92}U + {}^{1}_{0}n \rightarrow \begin{cases} {}^{141}_{56}Ba + {}^{92}_{36} + 3{}^{1}_{o}n + Q \\ {}^{137}_{56}Ba + {}^{97}_{36}Kr + 2{}_{o}^{1}n + Q \end{cases}$$

TABLE 9.2 Neutrons Produced in Thermal Neutron Fission

Nucleus	*Average Number of Neutrons Produced per Fission*	
Uranium 235	2.47	(2.43)
Plutonium 239	2.91	(2.90)
Uranium 233	2.55	(2.51)

Energy released

- A large quantity of energy ≈ 200MeV is released with each fission,
- Most energy exists as kinetic energy of the fission fragments and neutrons.
- Small fraction of energy is emitted as β and γ radiation.
- Released energy is equivalent to the mass decrease, since mass of fission products is less than the combined masses of original nucleus and neutrons.

  $E = \Delta m C^2$

Steady state chain reaction

- A steady state chain reaction can be sustained if for each fission a product neutron affects in turn a successive fission of another nucleus

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

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

Fast neutrons

- Neutrons ejected by fission are fast with speed ≈ 1600 Km/s (K.E ≈ 2MeV) when they collide with another nucleus they just lose K.E but will not cause fission.
- Meanwhile slow neutrons K.E ≈ (1/40)eV can cause fission of $^{235}_{92}U$ ($^{238}_{92}U$).
- Fast neutrons are slowed down by colliding with nucleus of moderator where they lose energy and become slow ones.

Neutron process

When a neutron enters a nucleus it becomes unstable and gains stability through:

- Fission.
- Inelastic scattering it ejects one neutron for each absorbed one.
- Neutron absorption or resonance capture, where nucleus emits a particle and energy

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U + \gamma + Q$$

$$^{238}_{92}U + ^{1}_{0}n \longrightarrow ^{239}_{92}U + \gamma + Q$$

$$^{239}_{92}U \longrightarrow ^{239}_{93}N_p + _{-1}\beta + Q$$

$$^{239}_{93}N_p \longrightarrow ^{239}_{94}Pu + _{-1}\beta + Q$$

$$^{239}_{94}Pu \longrightarrow ^{235}_{92}U + ^{4}_{2}\alpha$$

TABLE 9.3 Neutron Balance in a Natural Uranium Reactor

		Product Neutrons (Fast)
Disposition of 1000 fast neutrons		
Resonance capture by ^{235}U and ^{238}U	100	
Leakage from the reactor	192	
Fission of ^{235}U	4	10
Fission of ^{238}U	4	10
Transformation by the moderator to slow neutrons	700	
	1000	
Disposition of 700 slow neutrons		
Fission of ^{235}U	382	955
Fission of plutonium	10	25
Captured by fission products	23	
Captured by reactor materials	2	
Resonance capture by ^{235}U and ^{238}U	208	
Leakage from reactor	75	
	700	1000

Conversion

Conversion: when the production of new nuclear fuel in amount less than consumed.

The new fissionable fuel produced in converter reactor is consumed in the same reactor.

Uranium 238 and Thorium 232 both can be used for conversion and breeding by reducing neutron leakage.

$$^{238}_{92}U \longrightarrow {}^{239}_{94}Pu$$

$$^{238}_{92}U + {}^{1}_{0}n \longrightarrow {}^{239}_{92}U + \gamma + Q$$

$$^{239}_{92}U \longrightarrow {}^{239}_{93}N_p + {}_{-1}\beta + Q$$

$$^{239}_{93}N_p \longrightarrow {}^{239}_{94}Pu + {}_{-1}\beta + Q$$

$$^{239}_{94}Pu \longrightarrow {}^{235}_{92}U + {}^{4}_{2}\alpha$$

Breeding

When reactor produces more than one new fissionable nucleus that fissional.

$^{232}_{90}Th + ^{1}_{o}n \rightarrow ^{233}_{90}Th + \gamma + Q$

$^{233}_{90}Th \rightarrow ^{233}_{91}Pa + _{-1}\beta + \nu + Q$ ν neutrino has no mass

$^{233}_{91}Pa \rightarrow ^{233}_{92}U + _{-1}\beta + \nu + Q$ $^{233}_{92}U$ is a nuclear fuel

Neutron emitted will bombard a thorium blanket placed around the core of the reactor, this thorium will yield 1.02 $^{233}_{92}U$ atom for each consumed atom.

Example: $^{235}_{92}U$ used as a fuel surrounded by a blanket of $^{238}_{92}U$, the reactor is designed such that for every atom fission about 1.2 atoms of $^{239}_{94}Pu$ is created, hence breeding is achieved using the fast produced neutrons from fuel fission to produce another fuel from non-fuel element by neutron absorption ($^{238}_{92}U \rightarrow ^{239}_{94}Pu$).

Uranium enrichment

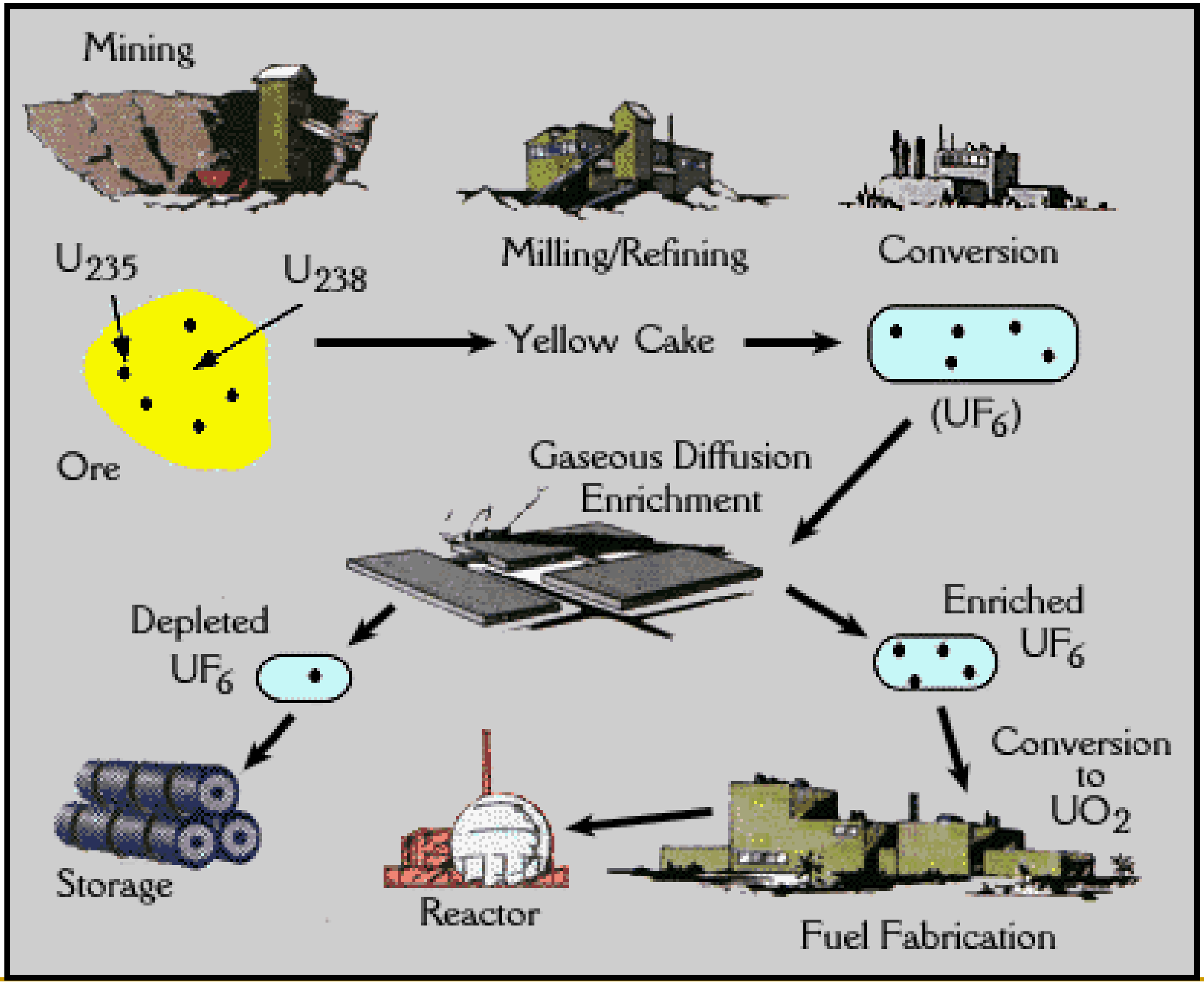
- Ore: common mineral containing uranium is Uran.
- It contains Uranium oxides U_3O_8 and it consists of about 2.5Kg U_3O_8 /ton of ore.
- Ore is mined and U_3O_8 is extracted as yellow cake that consists 70-90% U_3O_8.
- Now U_3O_8 contains Uranium isotopes as shown in the table

^{235}U	**0.72%**
^{238}U	99.27%
^{234}U	0.006%

Uranium Enrichment

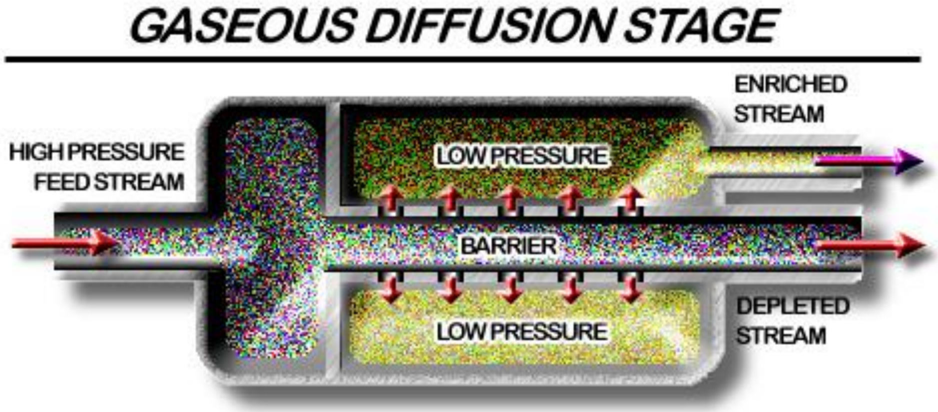
- Reactor fuel should contain 2-5% $^{235}_{92}U$, hence enrichment is needed to up grade 0.72% to 2-5% ^{235}U in the fuel.
- Uranium oxide in yellow cake is converted into uranium hexafloride ($U_3O_8 \rightarrow UF_6$) which is a gas.
- Two methods are used to enrich or separate $^{235}UF_6$, $^{238}UF_6$:
  - Gas separation in large high-speed centrifuges, in stages of development.
  - Gaseous diffusion, being used commercially.

Uranium Enrichment



Gaseous diffusion

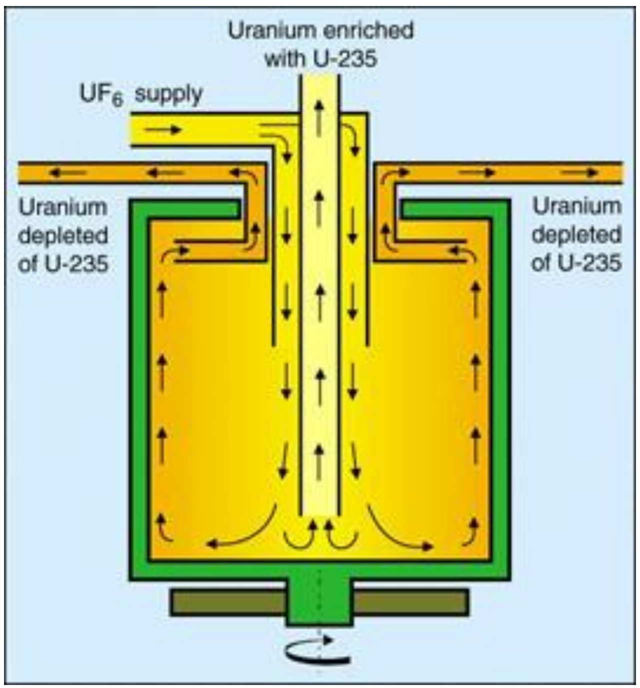
- Using special membrane, which allows for molecules to pass through, as $^{235}UF_6$ is lighter than $^{238}UF_6$ it passes more.
- Pressure difference is applied across membrane using compressor.
- Process is repeated in various stages till required enrichment is attained.

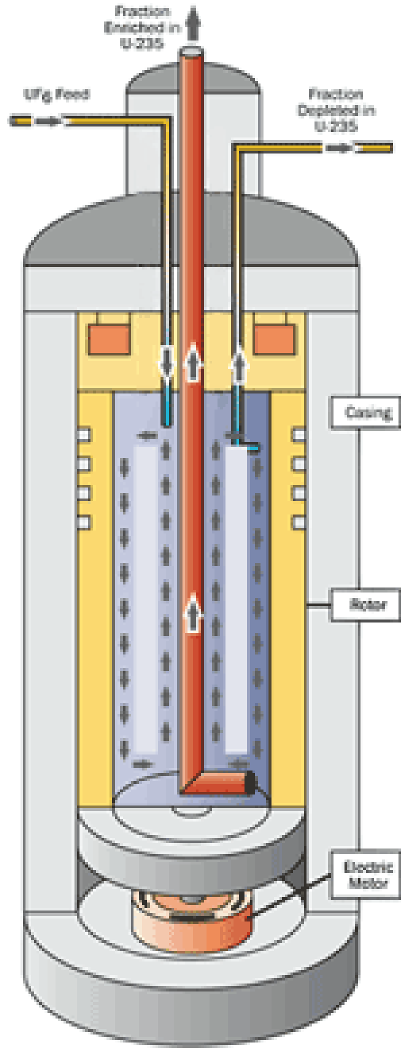


Centrifugation

- Gaseous UF_6 is introduced into a cylinder turning at very high speed in a vacuum in an air-tight chamber.
- Under the effect of the centrifugal force, the heavier molecules are sent to the edge of the tube.
- The gas enriched in the lighter uranium-235 isotope in the center of the tube rises. The gas richer in heavier uranium-238 descends.
- The enriched and depleted products are recovered at the 2 ends of the tube, the top and bottom.

Centrifugation





Fuel pellets & rods

Fuel Pellets:

- After enrichment UF_6 is converted into UO_2 by chemical reactions.
- UO_2 is refined and compacted under high pressure to pellets of size = 8mm in diameter and a similar length.

Fuel rods:

- Fuel pellets are placed in a thin-walled tube 1cm O.D fabricated from Zirconium alloy cladding.
- Tube of the fuel is welded from bottom then filled with pellets and helium gas, then welded at the second end, proving plenum at the top of the tube collected fission gases.

Aspects of Reactor Design

- Reactors in general are classified in accordance with neutron velocities that are prescribed for effecting fission.
  - Fast reactor: fast neutrons cause fission with K.E above 1000eV and usually about 2MeV.
  - Intermediate reactors: fission is caused by neutrons with K.E between 0.05 and 1000eV, those reactors are in experimental stages and they require high enrichment.
  - Thermal reactor: fission is caused by slow or thermal neutrons with K.E below 0.05eV.

Moderator

- Moderator: effective reduction of neutrons velocity to that below 0.05eV as required in thermal reactor is achieved by elastic collision with nucleus of moderator.
- Characteristics of good moderators:
  - Little capacity for absorbing neutrons.
  - Low atomic weight, in order to reduce velocity by elastic collisions over short distance and in few collisions.

Moderator

Example of moderators:

- Hydrogen is highly effective moderator, but it absorbs neutrons and produce deuterium and gamma rays. Hydrogen may be used in compounds such as H_2O.
- Heavy water: good moderator, but expensive.
- Graphite good moderator, but weak in structure.
- Helium in gas phase, but large distance between atoms.

Microscopic cross section

- Microscopic cross section describes the probability of a particular interaction between a nucleus and a moving particle.
- The symbol for microscopic cross section, σ, and the units is barn (1barn = $10^{-24}cm^2$).
- For a specific reaction σ is the effective area prescribed by the stationary nucleus to the approaching particle. Large σ means reaction is more likely to occur, σ depends on type of reaction and energy of incident particle.

Microscopic cross section

The total σ_t equals:

$\sigma_t = \sigma_c + \sigma_f + \sigma_s$

where: σ_c : capture cross sectional, a measure of area for absorption without fission.

σ_f : fission cross sectional area presented for a neutron to strike and cause fission.

σ_s : scatter cross sectional area presented that will scatter or deflect a striking neutron.

Also $\sigma_a = \sigma_c + \sigma_f$; σ_a absorption cross sectional for fission and capture without fission.

Microscopic cross sectional Σ

Σ is given as : $\Sigma = N\sigma$

Where: N is the number of nuclei per cm^3.

It is calculate as:

$N = (\text{no. of moles}/cm^3)(\text{Avogadro number})$

$N = (\rho/M.Wt)(6.023 * 10^{23} \text{atom}/1\text{gmole})$

Mean free path $\lambda = 1/\Sigma$

For a compound Σ=summation of Σ for each element

e.g. $\Sigma_{H2O} = \Sigma_{2H} + \Sigma_o$

$= (\rho/M.wt)(6.023*10^{23})(2\sigma_H| + \sigma_o)$

Criticality of Reactor

a) Reactor is critical if the fission chain reaction is being maintained at constant rate.
b) Super critical if the fission rate is increasing.
c) Subcritical if the fission rate is decreasing, then chain reaction is not maintained, eventually it shuts down.

Fission rate is proportional to quantity of fissionable material and to the average neutron density.
Since the quantity of fuel decreasing very slowly, the fission rate is controlled by neutron density.

Reflector

- In order to return many of neutrons that escape from the core a reflector is needed.
- Characteristics of reflector:
  - Material of low atomic weight for thermal reactor in order to reduce velocity of neutrons.
  - High atomic weight for fast reactor to reflect neutrons that have velocity by collision.

Shielding

- Reactor must be adequately shielded in order to trap the harmful radiation of α, β and γ .
- α and β are caught in reactor structure, while
- γ and thermal neutron travel larger distance and have to be shielded against using masses of concrete a steel and lead.

Reactor control

- Reactor need to be controlled to regulate thermal output power and protect reactor from failure.
- Fission rate determine the out power and the fission rate is determined mainly by neutron density.
- At steady state when reactor is critical on the average 2.5 neutrons are emitted per fission one is absorbed to case the next fission and 1.5 neutrons leak or get absorbed.

Reactor control

- Neutron production must remain constant except for a short period when reactor power output is changing.
- To increase the reactor power the neutron fission rate must be increase to high level, and as soon as the prescribed output is attained the neutron multiplication rate is reduce to zero.

Effective neutron multiplication factor

- K_{eff} is the ratio of neutron population in each generation to the population in the proceeding (previous) generation.
- Reactively, ρ is the ratio of excess of the effective multiplication factor, K_{eff} to the effective multiplication factor.

$\rho = (K_{eff} - 1)/K_{eff}$

$K_{eff} = 1.0 \rightarrow \rho = 0$ constant power level.

$K_{eff} < 1.0 \rightarrow \rho < 0$ reactor subcritical, chain reaction is not sustained and will die down.

$K_{eff} > 1.0 \rightarrow \rho > 0$ reaction is supercritical and reaction rate increases indefinitely

Neutron lifetime, τ

- Is the average time between successive neutron generation ,or
- the mean time that elapses between production of neutron by fission and the subsequent fission effective by these neutrons or loss of neutrons from the reaction.

Neutron density

- The time rate of change of neutron density is given as:

  $dn/dt = n\rho/\tau^{*} \rightarrow$

- integrating $\ln(n/n_o) = \rho t/\tau^{*}$ or

  $n = n_o \exp(\rho t/\tau^{*}) = n_o \exp(z)$.

n: number of neutron per unit volume, neutron density.

n_o: neutron density at time = 0 initially.

t: time.

τ^{*}: neutron life time.

ρ: reactivity.

Example 9.1

A reactor is operating at a low power of 1 W. The reactor then becomes supercritical with $k_{eff} = 1.0015$. The average neutron lifetime is 0.0001 s, a value that is applicable to prompt neutrons. Determine the reactor power level at the end of 1 s.

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

$$= \frac{1.0015 - 1}{1.0015} = 0.0014978$$

$$z = \frac{\rho}{\tau^*}\tau$$

$$= \frac{0.0014978}{0.0001}1 = 14.978$$

$$\frac{n}{n_0} = e^z = e^{14.978}$$

$$= 3.198 \times 10^6$$

Example 9.2

- Calculate the time required for reactor power to double. Given keff=1.002 for time constants 0.0001, 0.1

$$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}}$$

$$= \frac{1.002 - 1}{1.002} = 0.0019960$$

$$\frac{n}{n_0} = 2 = e^z \qquad z = 0.69315$$

(a) $\tau^* = 0.0001$ s

$$\tau = \frac{z\tau^*}{\rho}$$

$$= \frac{0.69315 \times 0.0001}{0.0019960} = 0.0347 \text{ s}$$

(b) $\tau^* = 0.1$ s

$$\tau = \frac{z\tau^*}{\rho}$$

$$= \frac{0.69315 \times 0.1}{0.0019960} = 34.73 \text{ s}$$

Example 9.3

Calculate the time required for the reactor power to double if only prompt neutrons participate in the reaction. $k_{eff} = 1.0076$; $\tau^* = 0.0001$ s.

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

$$= \frac{1.0076 - 1}{1.0076} = 0.0075427$$

$$\frac{n}{n_0} = 2 = e^z \qquad z = 0.69315$$

$$\tau = \frac{z\tau^*}{\rho}$$

$$= \frac{0.69315 \times 0.0001}{0.0075427} = 0.00919 \text{ s}$$

Neutron control

- Neutron production can be altered by changing either neutron absorption or leakage.
- Regulating neutron absorption is achieved by altering the quantity of neutron absorbing material present in the reactor. Control rods are used for such purpose.
- Control rods are composed of a substance that has a high thermal cross section for absorption. e.g.: Boron, and Cadmium.
- Control rods are moved in the reactor to appropriable position.

Neutron control

- In practice reactors are designed for excess reactivity:
  - Because of the absorption of neutrons by some of the fission products.
  - To compensate for fuel consumption.
  - For possible errors in design.
  - To provide for operation flexibility.

Reactor Power

Specific energy : release rate of nuclear reactor

$q_v = E_f \Sigma_f \Phi$

where q_v : specific energy release rate MeV/s.cm^3

E_f : energy per reaction , MeV/ fission

Σ_f : effective macroscopic cross section for fission , cm^{-1}

Φ : neutron flux , neutron / cm^3.s.

But $\Sigma_f = \sigma_f N_{ff}$

Where N_{ff} density of fissionable fuel , nuclei/ cm^3

$q_v = \sigma_f N_{ff} E_f \Phi c_{fn}$

since σ_f accounts for fission by thermal neutrons a constant.

c_{fn} is added to account for fission by fast neutrons , c_{fn} depends on type of reactor and fuel , for e.g in pressuring water reactors $c_{fn} = 1.08$.

Reactor Power

for UO_2 fuel N_{ff} is given as $N_{ff} = 2.3272 * 10^{22}\ f\ {}^{235}U$ nuclei / cm^3
where f is enrichment of ${}^{235}U$ by mass fraction.

Example 9.4 p.320 Sorensen

Determine for a light-water-moderated uranium reactor the specific energy release rate for the following conditions.

$$\phi = 10^{13} \text{ neutrons/s·cm}^2$$
$$f = 0.035$$
$$\sigma_f = 577 \text{ barns} = 577 \times 10^{-24} \text{ cm}^2$$

From Eq. 9.25,

$$N_{ff} = 2.372f \times 10^{22}$$
$$= 0.035 \times 2.372 \times 10^{22}$$
$$= 8.302 \times 10^{20} \text{ nuclei/cm}^3$$

From Eq. 9.24a,

$$\dot{q}_v = E_f \sigma_f N_{ff} \phi C_{fn}$$
$$= 180(577 \times 10^{-24})(8.302 \times 10^{20})10^{13} \times 1.08$$
$$= 9.312 \times 10^{14} \text{ MeV/s·cm}^3$$

Since 1 MeV = 1.602×10^{-13} J,

$$\dot{q}_v = (9.312 \times 10^{14})(1.602 \times 10^{-13})$$
$$= 149.2 \text{ W/cm}^3$$

Heat in the fuel rods

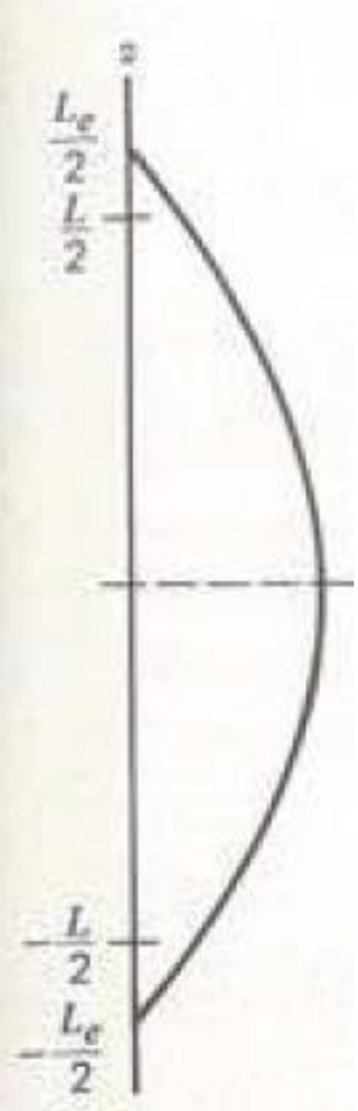
$$\dot{q}_{v,z} = \dot{q}_{v,c} \cos \frac{\pi z}{L_e} \qquad (9.26)$$

where

$\dot{q}_{v,c}$ = the specific energy release rate at the center point of the rod

$\dot{q}_{v,z}$ = the specific energy release rate at a distance z from the center point

$$\dot{q} = \frac{2}{\pi} \dot{q}_{v,c} A_f L$$



Example 9.5

The diameter of the pellets in a fuel rod is 10 mm. The length of the rod is 380 cm. At the center of the rod, $\dot{q}_{v,c} = 149\ \text{W/cm}^3$. (See Example 9.4.) Determine the thermal power for the fuel rod.

Applying Eq. 9.28,

$$\dot{q} = \frac{2}{\pi}\dot{q}_{v,c}A_f L$$

$$= \frac{2}{\pi} \times 149 \times \frac{\pi}{4} \times 380$$

$$= 28{,}310\ \text{W}$$

Heat generated in reactor core

Heat in core is computed as: $q_t = Kq_{v,co}(nA_tL)$

Where: $q_{v,co}$: specific energy released at geometric center of reactor core.

n: number of rods.

A_t: transfers area of rod.

L: length of rod.

K: characteristic constant of reactor

Example 9.6

Fuel rod data for a power reactor are: diameter = 10.92 mm, length = 365.76 cm, number = 42,640. The maximum specific energy release rate is 0.61667 kW/cm^3. K = 0.3685. Power generated in the fuel and cladding is 97.3 percent of the total reactor power. Determine the reactor thermal power.

$$A_t = 0.9369 \text{ cm}^2$$

$$\begin{aligned} \dot{q}_t &= KnA_tL\dot{q}_{v,co} \\ &= 0.3685 \times 42640 \times 0.9369 \\ &\quad \times 365.76(0.61667 \times 10^{-3}) \\ &= 3320 \text{ MW(t)} \end{aligned}$$

Note: MW(t) = thermal power, MW.

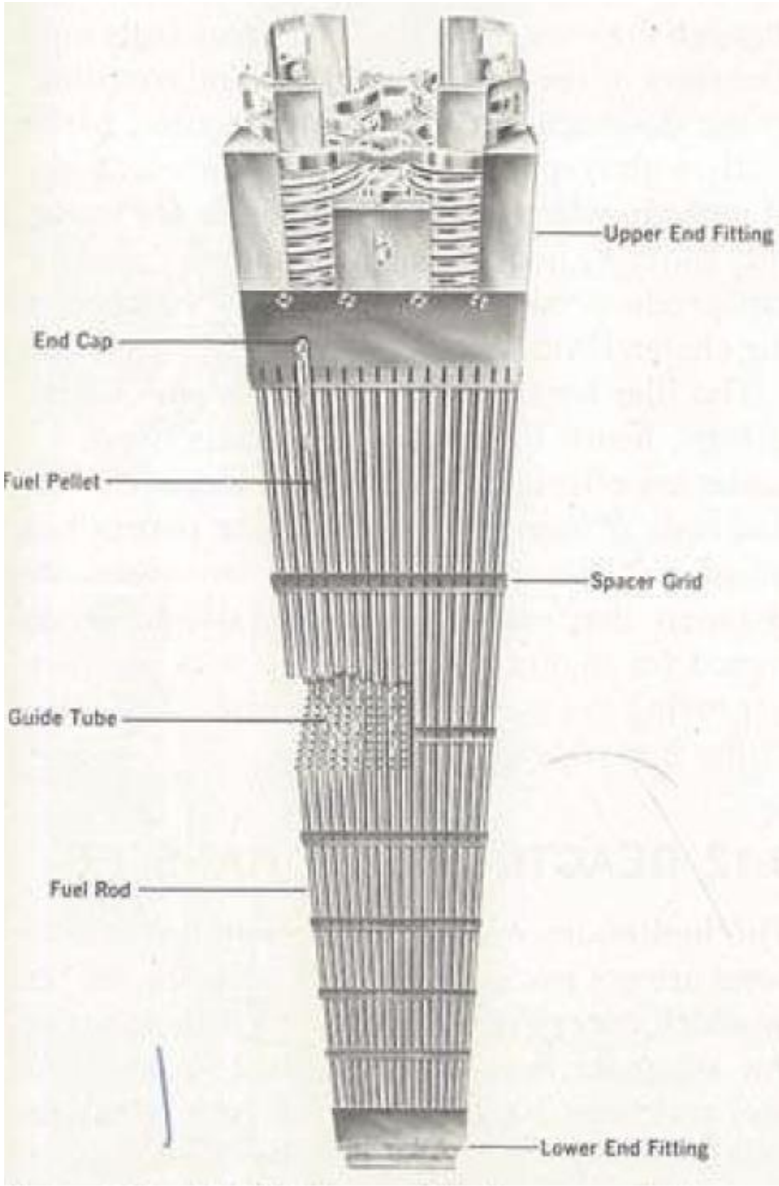
$$\begin{aligned} \text{Total reactor power} &= \frac{3320}{0.973} \\ &= 3413 \text{ MW(t)} \end{aligned}$$

Reactor Core

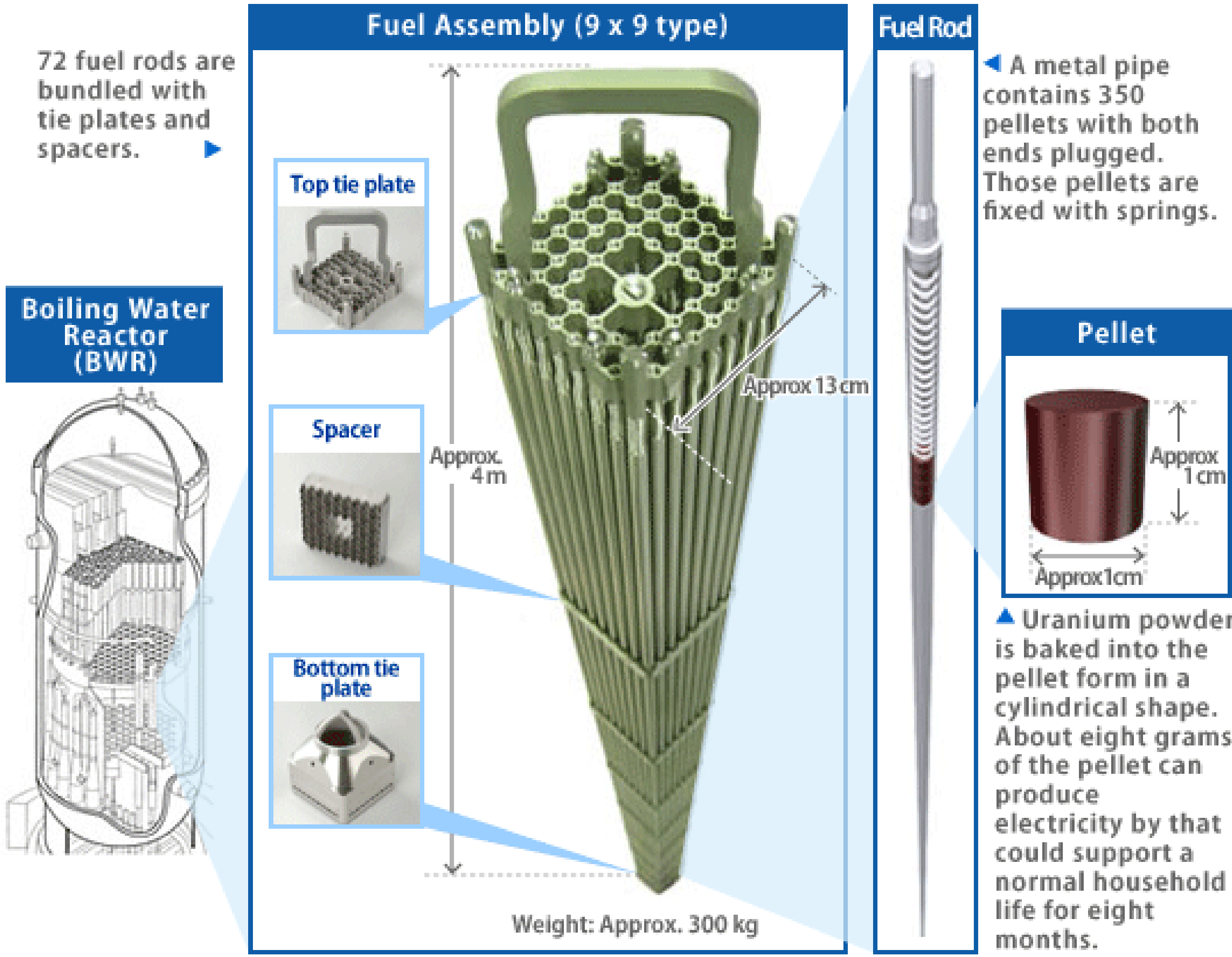
- The reactor core consists of the fuel rods, control rods, moderator, cooling medium, and the structure all above material.
- Assembly:

The core contains a square array typical 20x20 cm, containing 200-300 fuel rods. Space is left in the core for movement of control rods also holes are provided for cooling circulation. Stainless steel or zirconium are used for structure, since they resist corrosion, endure high temperature and radiation with low neutron absorption

Fuel assembly



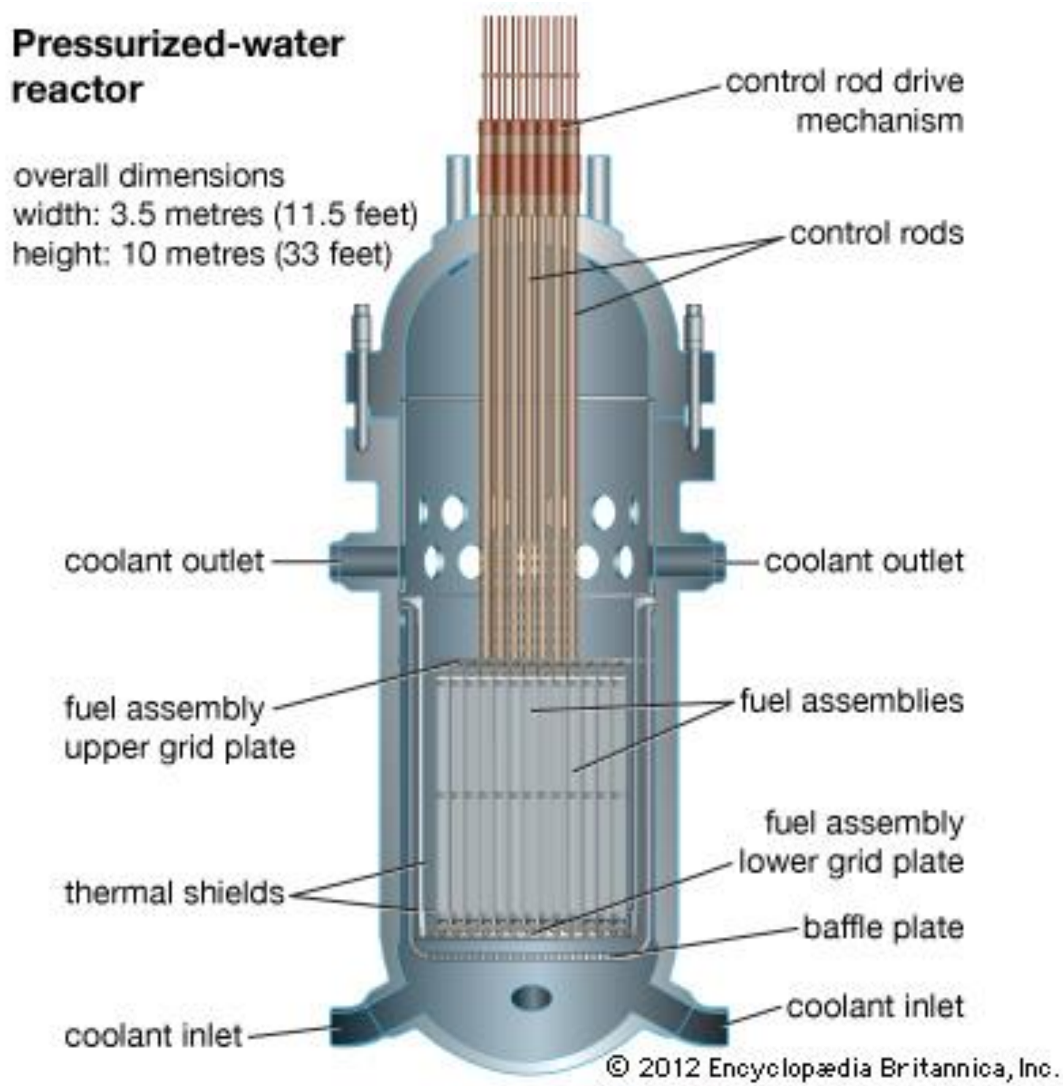
Fuel rods and assembly



Reactor components

- **Fuel:** Usually pellets of uranium oxide (UO2) arranged in tubes to form fuel rods. The rods are arranged into fuel assemblies in the reactor core.
- **Moderator:** This is material in the core which slows down the neutrons released from fission so that they cause more fission. It is usually water, but may be heavy water or graphite.
- **Control rods:** These are made with neutron-absorbing material such as cadmium, hafnium or boron, and are inserted or withdrawn from the core to control the rate of reaction, or to halt it
- **Coolant:** A liquid or gas circulating through the core so as to transfer the heat from it.
- **Pressure vessel or pressure tubes:** Usually a robust steel vessel containing the reactor core and moderator/coolant, but it may be a series of tubes holding the fuel and conveying the coolant through the moderator.

Reactor core



Reactor coolant

Coolant: material must satisfy :

1. Purity as impurities can become radioactive.
2. Corrosion must not be corrosive.
3. Leakage should not be easy in leakage.
4. Heat transfer has a good heat transfer characteristic.

Examples of coolant:

Gas ,e.g helium

Liquid , e.g water

Liquid metals , sodium.

See Fig 9.3 P.323 Sorensen for core structure.

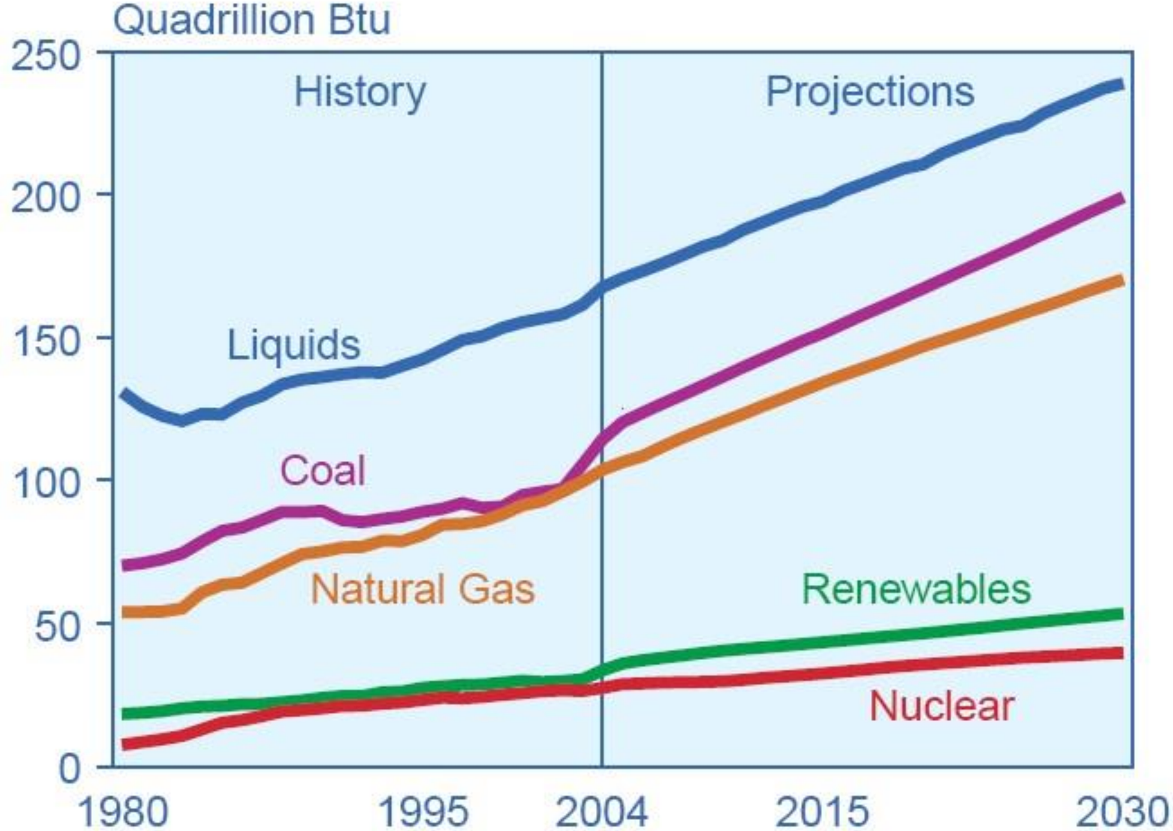
Reactor components

- **Steam generator:** (not in BWR) Part of the cooling system where the primary coolant bringing heat from the reactor is used to make steam for the turbine
- **Containment:** The structure around the reactor core which is designed to protect it from outside intrusion and to protect those outside from the effects of radiation in case of any malfunction inside. It is typically a metre-thick concrete and steel structure.
-

Nuclear energy contribution

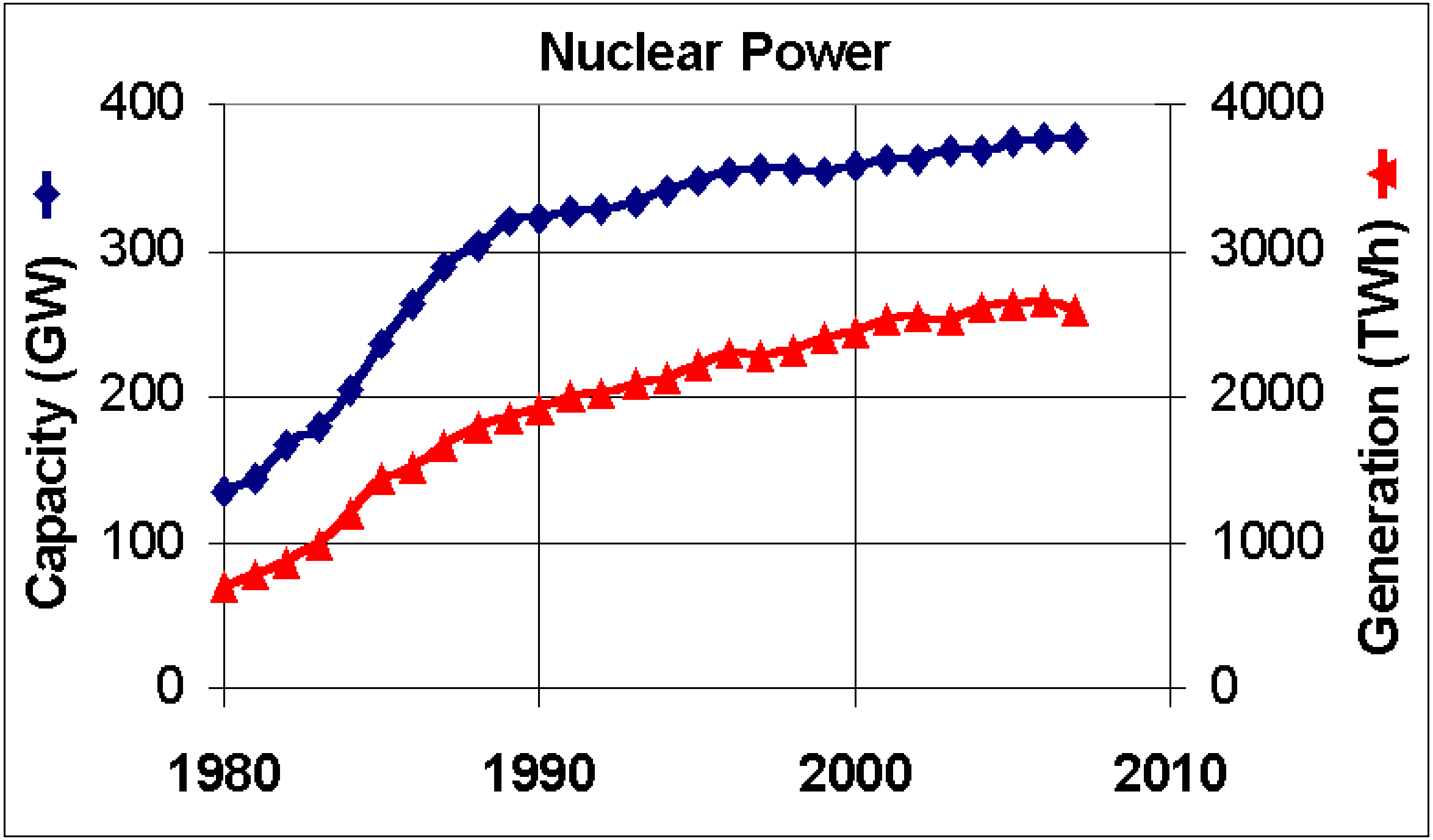
- Over 16% of the world's electricity is produced from nuclear energy, more than from all sources worldwide in 1960.
- The United States produces the most nuclear energy, with nuclear power providing 19% of the electricity it consumes.
- France produces the highest percentage of its electrical energy from nuclear reactors 78% as of 2006.
- In the European Union as a whole, nuclear energy provides 30% of the electricity.

Figure 4. World Marketed Energy Use by Fuel Type, 1980-2030



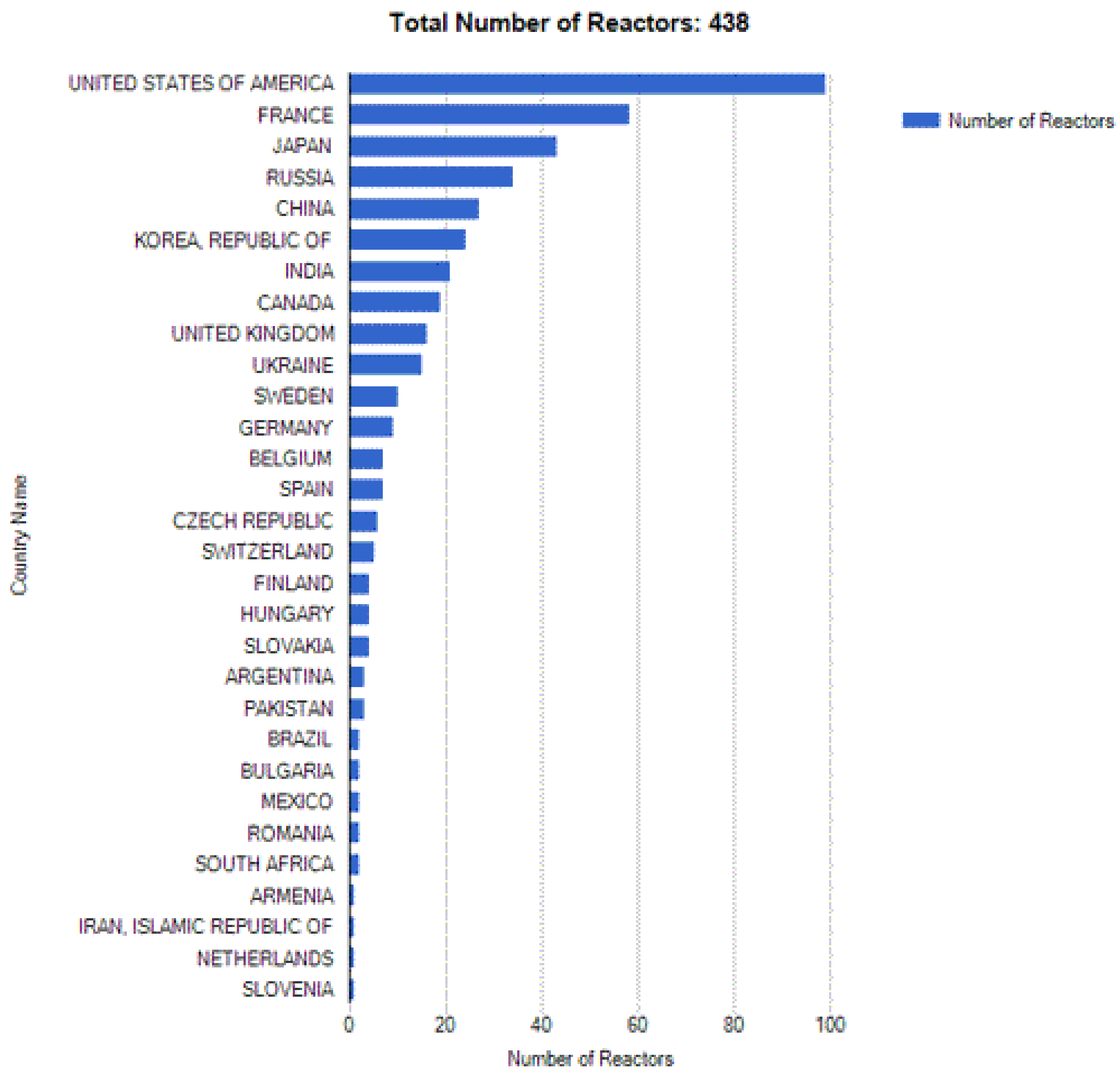
Sources: **History:** Energy Information Administration (EIA), *International Energy Annual 2004* (May-July 2006), web site www.eia.doe.gov/iea. **Projections:** EIA, System for the Analysis of Global Energy Markets (2007).

Nuclear power capacity



Commercial nuclear reactors

Reactor type	Main Countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised Water Reactor (PWR)	US, France, Japan, Russia, China	265	251.6	enriched UO_2	water	water
Boiling Water Reactor (BWR)	US, Japan, Sweden	94	86.4	enriched UO_2	water	water
Pressurised Heavy Water Reactor 'CANDU' (PHWR)	Canada	44	24.3	natural UO_2	heavy water	heavy water
Gas-cooled Reactor (AGR & Magnox)	UK	18	10.8	natural U (metal), enriched UO_2	CO_2	graphite
Light Water Graphite Reactor (RBMK)	Russia	12	12.3	enriched UO_2	water	graphite
Fast Neutron Reactor (FBR)	Japan, France, Russia	4	1.0	PuO_2 and UO_2	liquid sodium	none
Other	Russia	4	0.05	enriched UO_2	water	graphite
	TOTAL	441	386.5			



Number of reactors in operation, worldwide, 2015-06-01 (IAEA 2015)

Classification by type of reaction

- Nuclear fission. Most reactors, and all commercial ones, are based on nuclear fission.
  - Thermal reactors use slowed or thermal neutrons. Almost all current reactors are of this type.
  - Fast neutron reactors use fast neutrons to cause fission in their fuel. They do not have a neutron moderator
- Nuclear fusion. Fusion power is an experimental technology, generally with hydrogen as fuel.
- Radioactive decay. Examples include radioisotope thermoelectric generators.

Classification by moderator material

- Graphite moderated reactors
- Water moderated reactors
  - Heavy water reactors
  - Light water moderated reactors (LWRs). Light water reactors use ordinary water to moderate and cool the reactors.
- Light element moderated reactors. These reactors are moderated by lithium or beryllium.
  - Molten salt reactors (MSRs) are moderated by a light elements such as lithium or beryllium, which are constituents of the coolant/fuel matrix salts LiF and BeF2.
  - Liquid metal cooled reactors, such as one whose coolant is a mixture of Lead and Bismuth, may use BeO as a moderator.
- Organically moderated reactors (OMR) use biphenyl and terphenyl as moderator and coolant.

Classification by coolant

- Water cooled reactor.
  - Pressurized water reactor (PWR)
  - Boiling water reactor (BWR)
- Liquid metal cooled reactor. Since water is a moderator, it cannot be used as a coolant in a fast reactor .
  - Sodium-cooled fast reactor
  - Lead-cooled fast reactor
- Gas cooled reactors are cooled by a circulating inert gas, often helium in high-temperature designs, others use carbon dioxide or Nitrogen.
- Molten Salt cooled Reactors (MSRs) are cooled by circulating a molten salt, typically a eutectic mixture of fluoride salts, such as FLiBe .

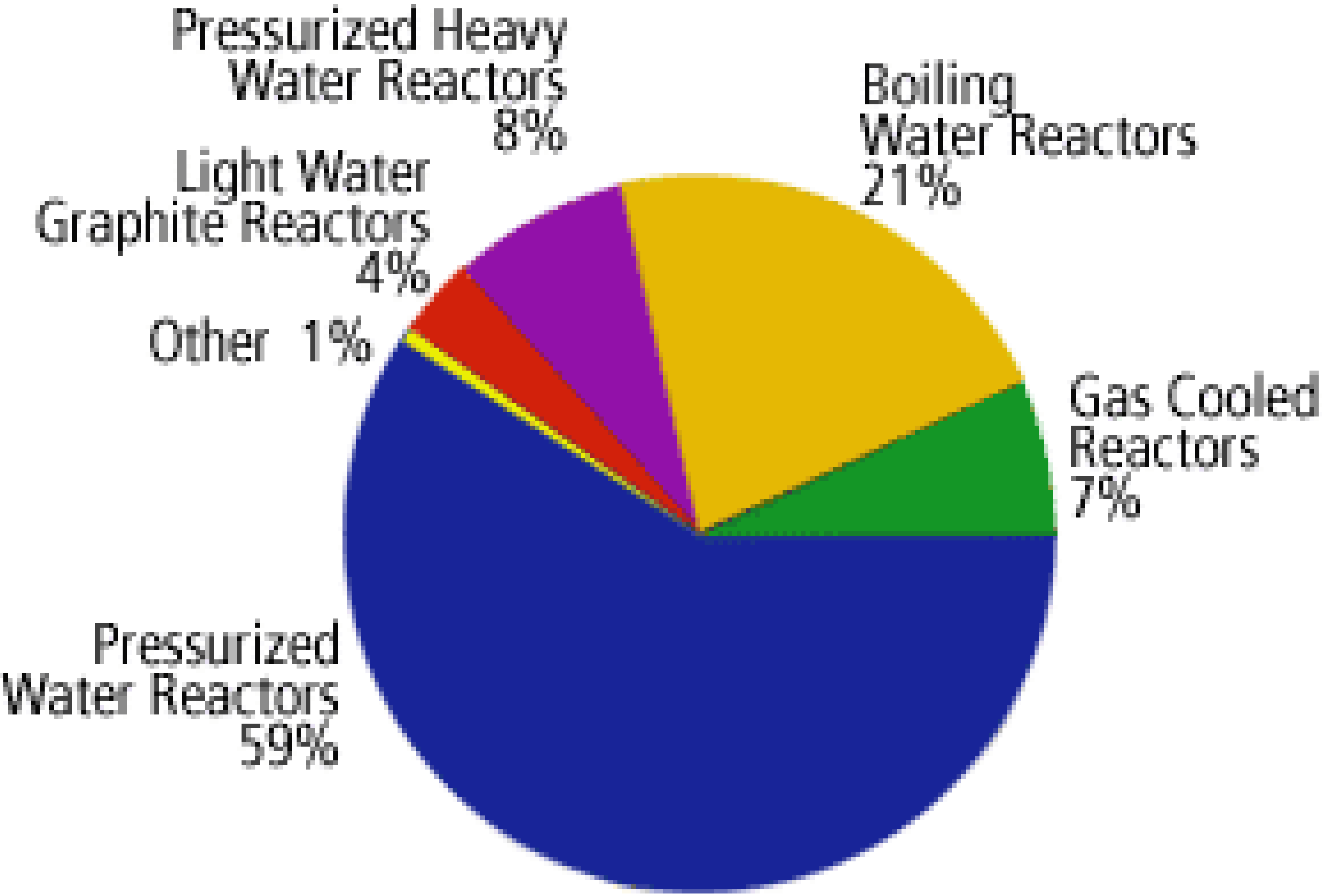
Reactor usage

- Electricity
  - Nuclear power plants
- Propulsion
  - Nuclear marine propulsion
  - Various proposed forms of rocket propulsion
- Other uses of heat
  - Desalination
  - Heat for domestic and industrial heating
  - Hydrogen production for use in a hydrogen economy

Type of nuclear power reactors

- Light water reactors
- Pressurized Water Reactor PWR
- Boiling Water Reactor BWR
- Heavy Water Reactor
- Gas Cooled Reactors
- Fast Breeding reactors

Reactor Types in Use Worldwide, January 2003



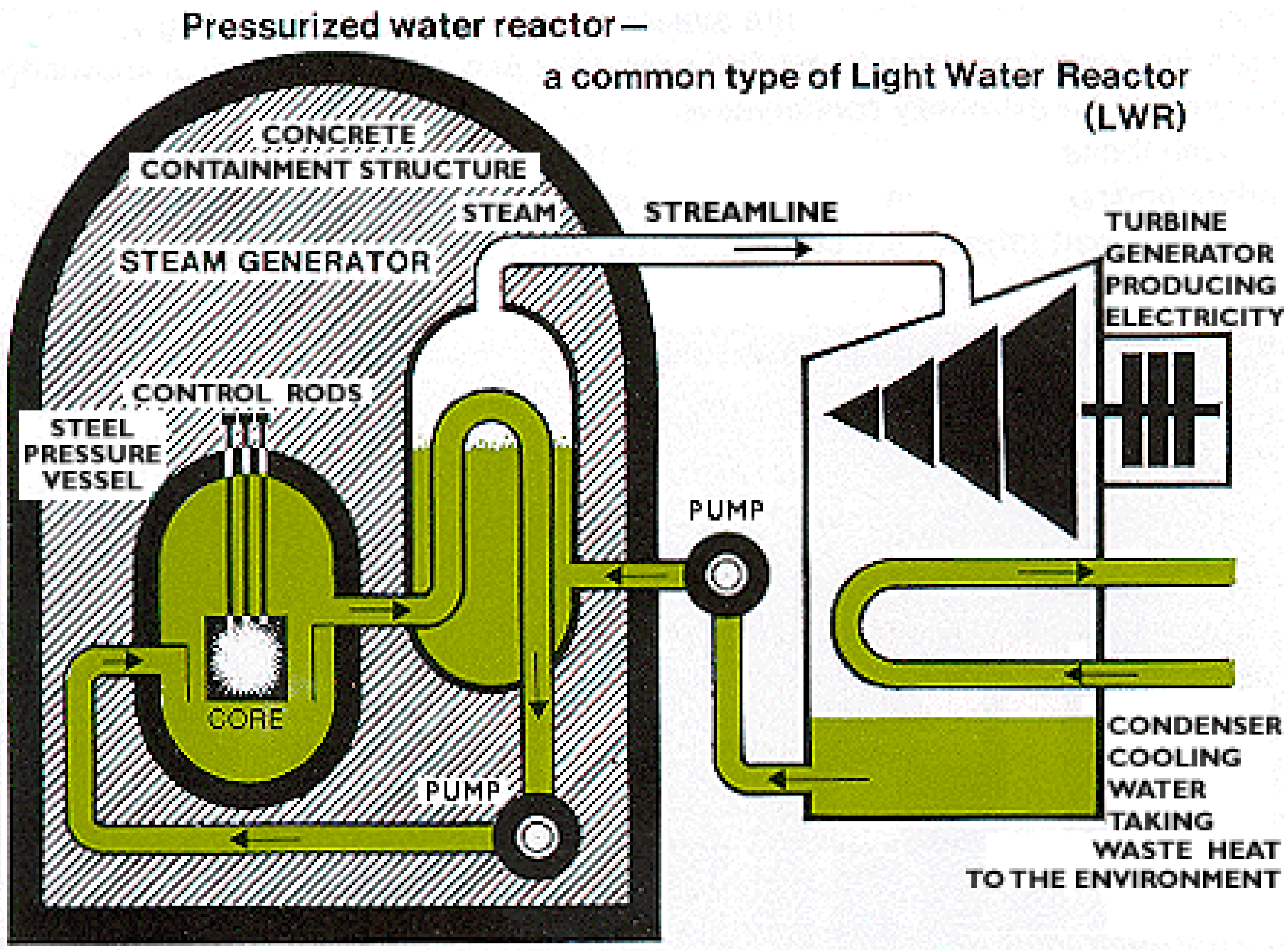
Pressurized Water Reactor PWR

- This is the most common type, with over 230 in use for power generation.
- PWRs use ordinary water as both coolant and moderator.
- The design is distinguished by having a primary cooling circuit which flows through the core of the reactor under very high pressure to prevent water boiling, and a secondary circuit in which steam is generated to drive the turbine.
- A PWR has fuel assemblies of 200-300 rods each, arranged vertically in the core, 150-250 fuel assemblies in the core. Fuel UO_2 enriched.

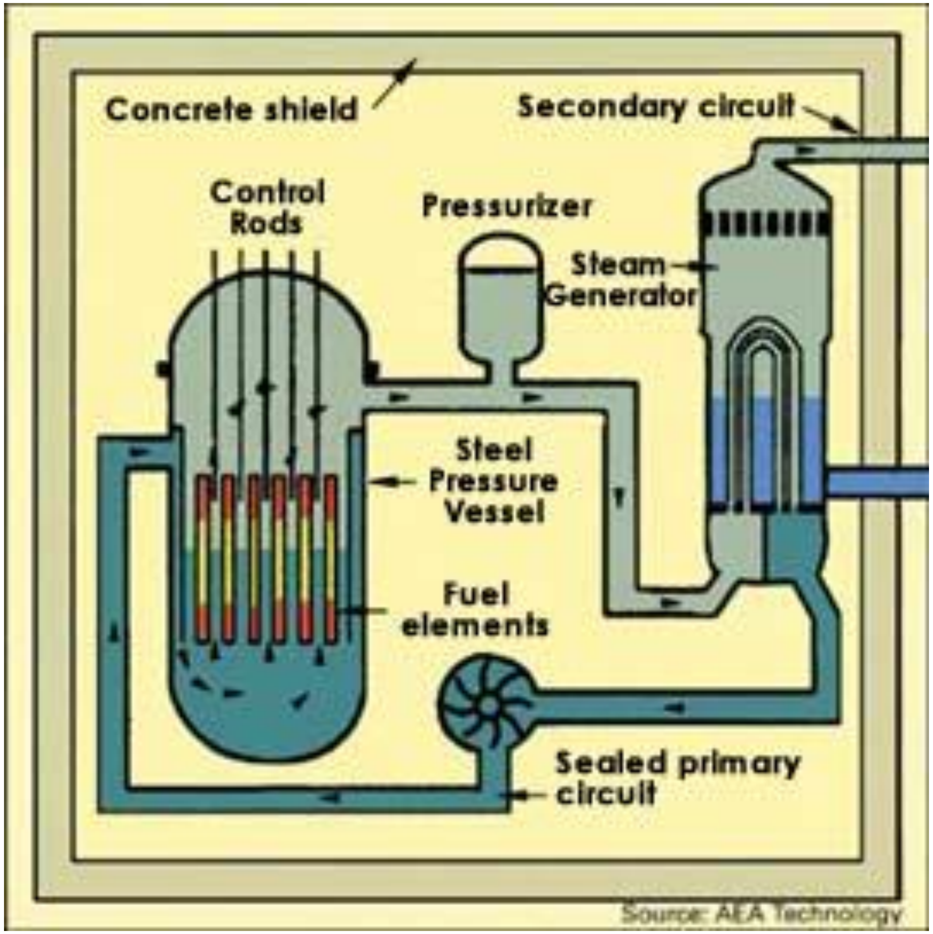
Pressurized Water Reactor PWR

- Water in the reactor core reaches about 325°C, hence it must be kept under about 150 times atmospheric pressure (15 MPa) to prevent it boiling.
- In the primary cooling circuit the water is also the moderator, and if any of it turned to steam the fission reaction would slow down, why?
- The secondary circuit is under less pressure and the water here boils in the heat exchangers which are thus steam generators. The steam drives the turbine to produce electricity, and is then condensed and returned to the heat exchangers in contact with the primary circuit.

Pressurized Water Reactor PWR



PWR



Concrete shield
Secondary circuit
Control Rods
Pressurizer
Steam Generator
Steel Pressure Vessel
Fuel elements
Sealed primary circuit
Source: AEA Technology

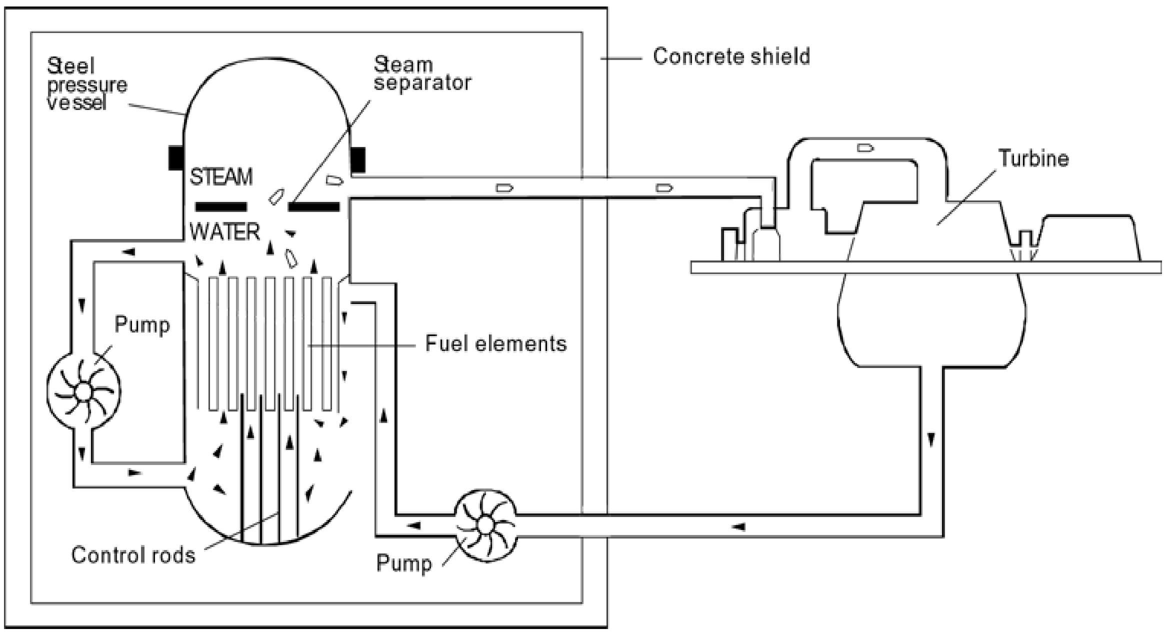
Boiling Water Reactor (BWR)

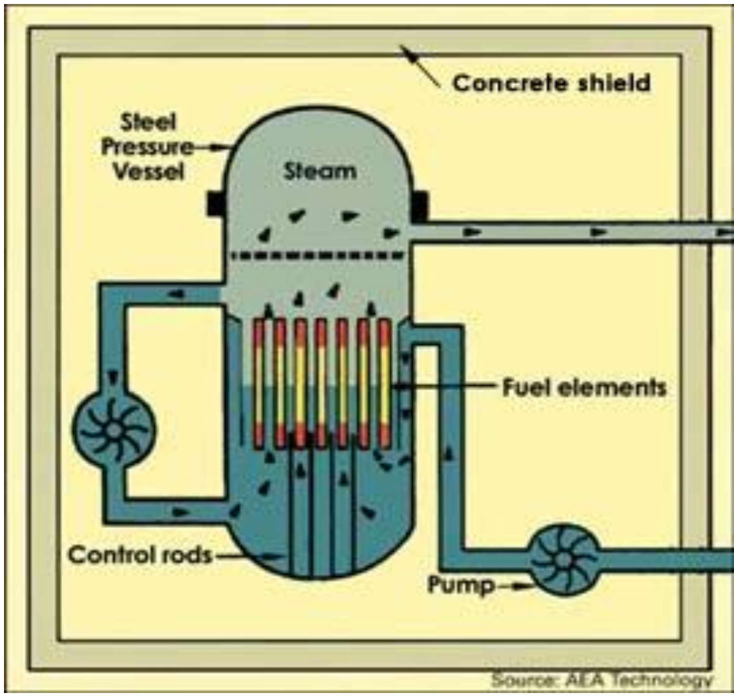
- There is only a single circuit. Eliminate heat exchanger between two loops (reactor loop and steam cycle loop). Reactor can operate at lower temperature.
- Water is moderator and coolant.
- Water is at lower pressure (about 75 times atmospheric pressure) so that it boils in the core at about 285°C.
- The steam passes through drier plates (steam separators) above the core and then directly to the turbines.

BWR

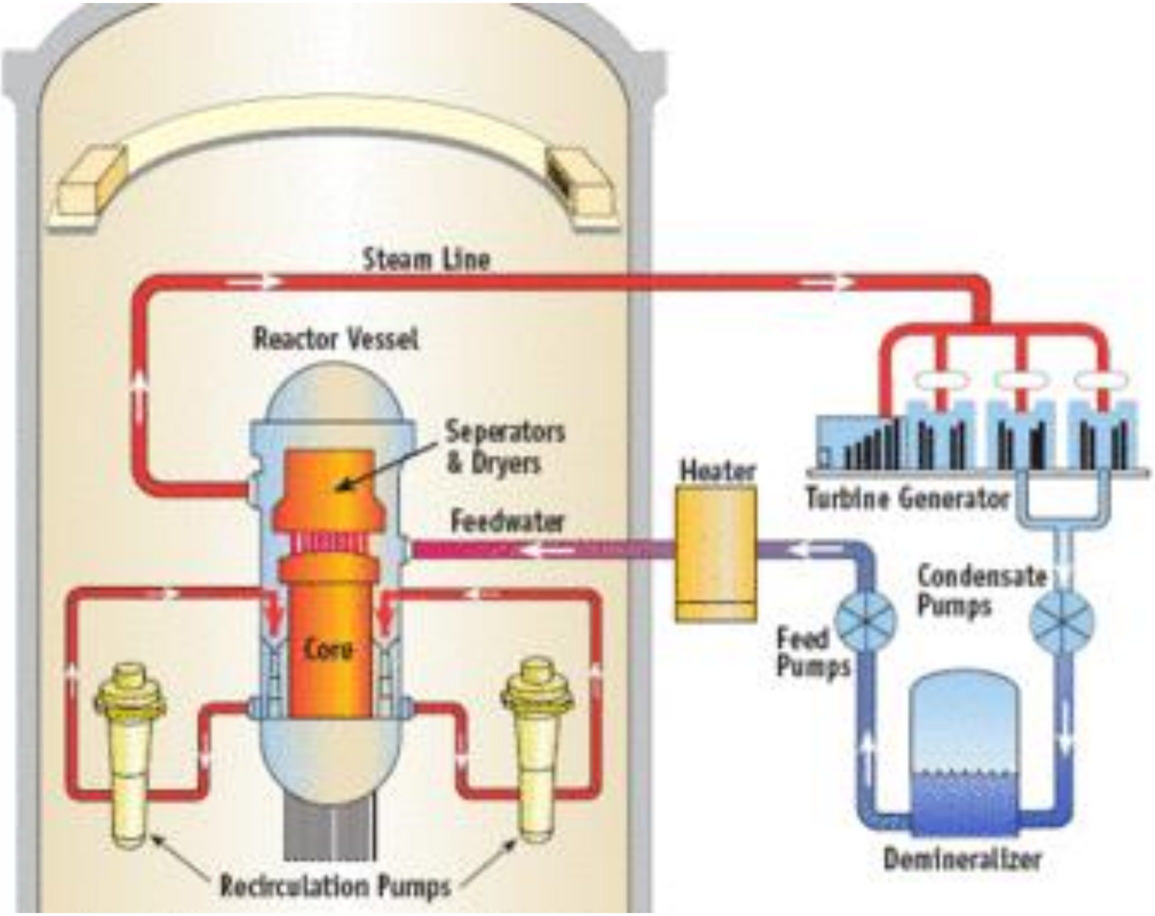
- Since the water around the core of a reactor is always contaminated with traces of radionuclides, it means that the turbine must be shielded.
- A BWR fuel assembly comprises 90-100 fuel rods, and there are up to 750 assemblies in a reactor core.
- The secondary control system involves restricting water flow through the core so that more steam in the top part reduces moderation (Self regulation).
- Problem for steam superheating.

Boiling Water Reactor (BWR)





BWR


Steam Line
Reactor Vessel
Seperators
& Dryers
Feedwater
Core
Recirculation Pumps
Heater
Turbine Generator
Condensate
Pumps
Feed
Pumps
Demineralizer

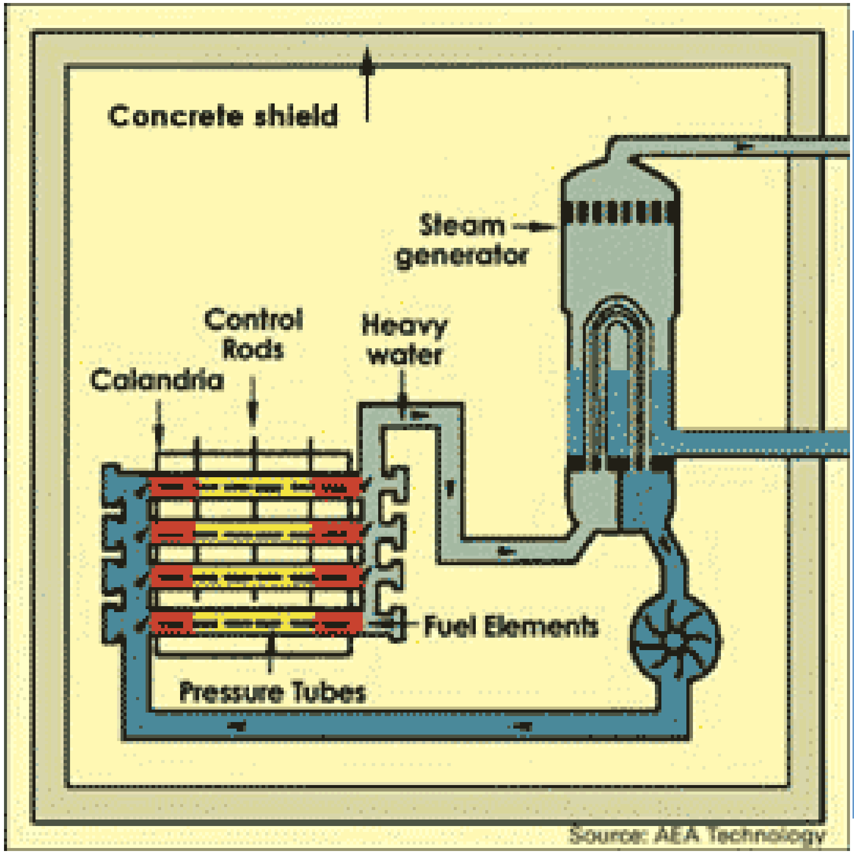
Pressurised Heavy Water Reactor (PHWR or CANDU)

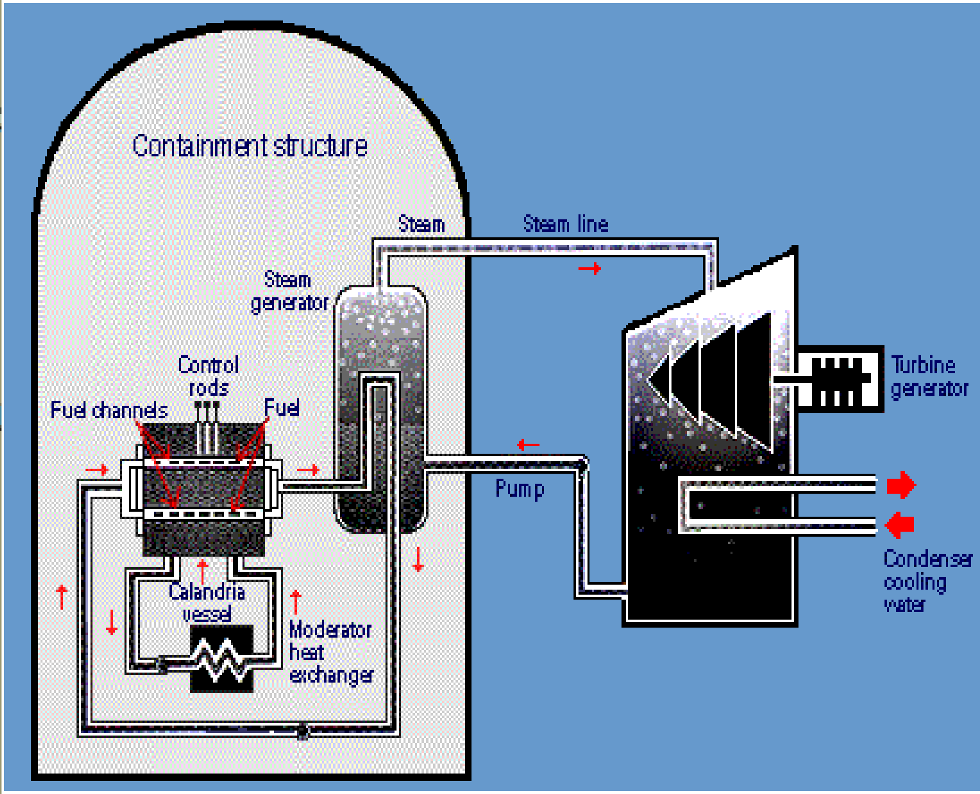
- The PHWR reactor design has been developed since the 1950s in Canada as the CANDU, and more recently also in India.
- It uses natural uranium (0.7% U-235) oxide as fuel, hence needs a more efficient moderator
- Heavy water (D_2O) is used as moderator.
- The moderator is in a large tank/ pipes
- penetrated by several hundred horizontal pressure tubes which form channels for the fuel,

Heavy Water Reactor

- Cooled by a flow of heavy water under high pressure in the primary cooling circuit, reaching 290°C. Some designs use light water for cooling.
- A CANDU fuel assembly consists of a bundle of 37 half meter long fuel rods (ceramic fuel pellets in zircaloy tubes) plus a support structure, with 12 bundles lying end to end in a fuel channel.
- Control rods penetrate the calandria vertically.

Heavy Water Reactor





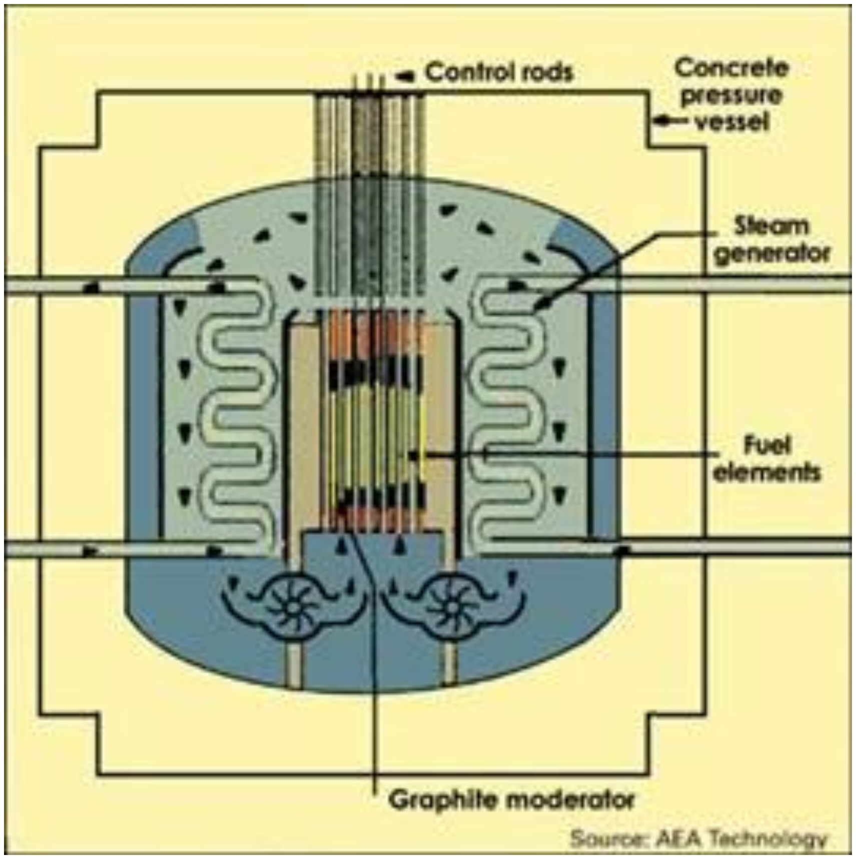
Advanced Gas-cooled Reactor (AGR)

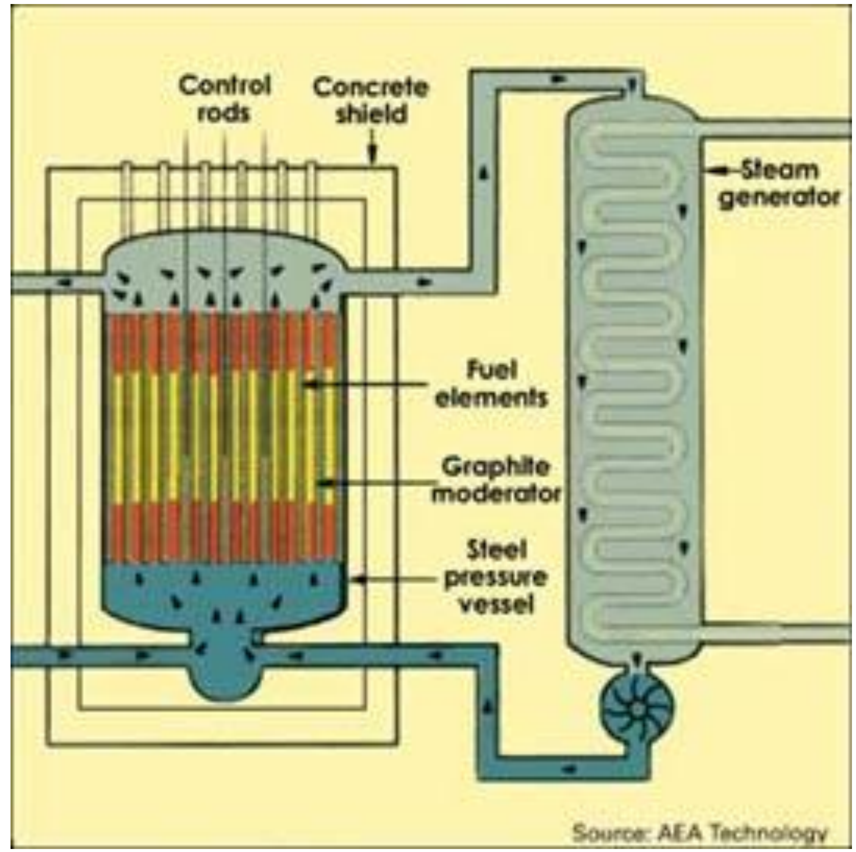
- Uses graphite moderator and carbon dioxide as coolant.
- The fuel is uranium oxide pellets, enriched to 2.5-3.5%, in stainless steel tubes.
- The carbon dioxide circulates through the core, reaching 650 °C and then past steam generator tubes outside it, but still inside the concrete and steel pressure vessel.
- Control rods penetrate the moderator and a secondary shutdown system involves injecting nitrogen to the coolant.

AGR

- The AGR was developed from the Magnox reactor, also graphite moderated and CO_2 cooled.
- Higher temperatures since no liquid boiling, hence higher thermal efficiency up to 39%.
- Coupling to a gas turbine using helium as working fluid, the reactor replaces the combustion chamber.

Gas-cooled Reactor





Fast neutron reactors (FNR)

- Some reactors (only one in commercial service) do not have a moderator and utilize fast neutrons.
- Generating power from plutonium while making more of it from the U-238 isotope in or around the fuel.
- fuel UO_2 and PuO_2 mixture, enrichment of 15 % is needed because of high parasitic capture of neutrons.
- While they get more than 60 times as much energy from the original uranium compared with the normal reactors, they are expensive to build.
- Higher temperature and pressure of steam since no moderating liquid is used. It can generate steam at 540 ^{o}C and 24 MPa.

FNR designs for near- to mid-term deployment

Reactor	type, coolant	Power thermal/elect	Fuel (future)	country	notes
PRISM	Demonstration, pool, sodium	840/311	metal	USA	From 2020s
Astrid	Demonstration, pool, sodium	1500/600	oxide	France, with Japan	From 2024
Allegro	Experimental, loop?, gas	50-100 MWt	oxide	France	About 2025
MYRRHA	Experimental, Pb-Bi	57/-	oxide?	Belgium, with China	Early 2020s
ALFRED	Prototype, lead	300/120	oxide	Romania, with Italy & EU	From 2025
BN-1200	Commercial, pool, sodium	2900/1220	oxide, nitride	Russia	From mid-2020s
BREST-300	Demonstration, loop, lead	700/300	nitride	Russia	From 2020
SVBR-100	Demonstration, pool, Pb-Bi	280/100	oxide (variety)	Russia	From 2019
MBIR	Experimental, loop, sodium (Pb-Bi, gas)	100-150 MWt	oxide	Russia	From 2020
CDFR-1000	Demonstration, pool, sodium	/1000	oxide	China	From 2023
CDFBR-1200	Commercial, pool, sodium	/1200	metal	China	From 2028
PGSFR	Prototype, pool, sodium	/150	metal	South Korea	From 2028
JSFR	Demonstration, loop, sodium	/500	oxide	Japan	From 2025?
TWR	Prototype, sodium	/600	metal	China, with USA	From 2023?

Liquid Metal Fast Breeder Reactor (LMFBR)

- This is a reactor design that is cooled by liquid metal,
- Use fast neutrons for fission, hence un-moderated.
- Produces more fuel than it consumes. They are said to "breed" fuel, because they produce fissionable fuel during operation because of neutron capture.
- Doubling time for fuel is 12 -20 years (time required to double the amount of original fuel).
- Coolant must be of low density and high atomic weight to avoid moderation of neutrons.
- These reactors come in two types (according to the coolant):
  - Sodium cooled
  - Lead cooled
-

Sodium cooled

- Most LMFBRs are of this type. The sodium is relatively easy to obtain and work with, and it also manages to actually prevent corrosion on the various reactor parts immersed in it.
- Sodium explodes violently when exposed to water, so care must be taken, but such explosions wouldn't be vastly more violent than (for example) a leak of superheated fluid from other reactors.
- Sodium becomes radioactive producing gamma rays.

Lead cooled

- Using lead as the liquid metal provides excellent radiation shielding, and allows for operation at very high temperatures.
- Also, lead is (mostly) transparent to neutrons, so fewer neutrons are lost in the coolant, and the coolant does not become radioactive.
- Unlike sodium, lead is mostly inert, so there is less risk of explosion or accident,
- but such large quantities of lead may be problematic from toxicology and disposal points of view.

Nuclear fusion

- **nuclear fusion** is a nuclear reaction in which two or more atomic nuclei come very close and then collide at a very high speed and join to form a new nucleus.
- Fusion reactions;

$$ {}^{1}_{1}H + {}^{1}_{1}H \rightarrow {}^{2}_{2}He \qquad (2) $$

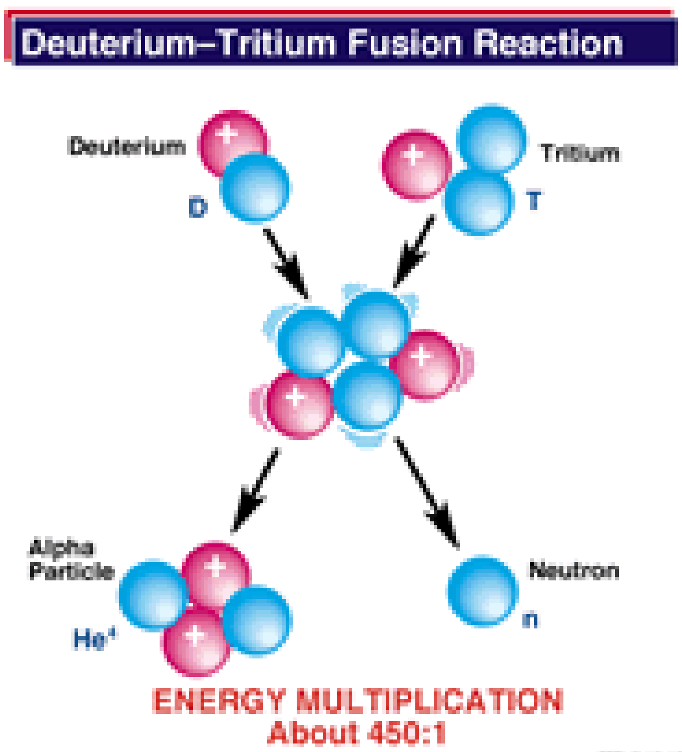
$$ {}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + n \qquad (3) $$

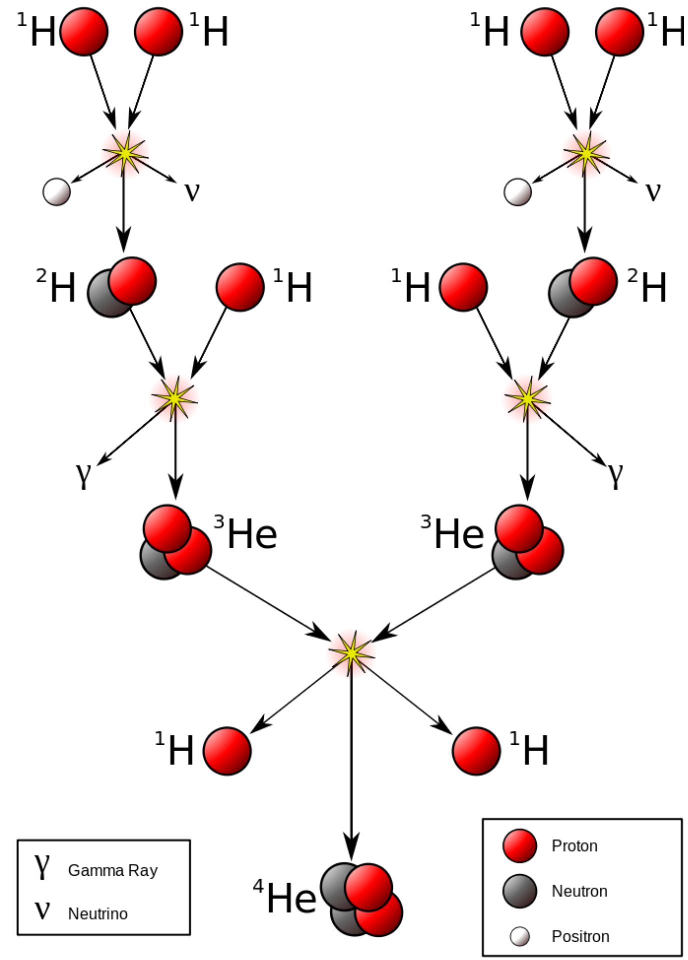
$$ {}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + n \qquad (5) $$

Fusion reactions of light elements power the stars

The reaction, that which initiates star burning, involves the fusion of two hydrogen nuclei to form deuterium (the H-H fusion reaction):

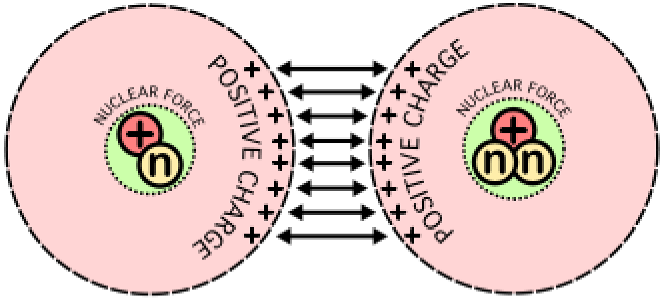
$H + H \rightarrow D + \beta^+ + \nu$,





Requirements

- energy barrier of electrostatic forces must be overcome before fusion can occur.
- If two nuclei can be brought close enough together, however, the electrostatic repulsion can be overcome by the attractive nuclear force, which is stronger at close distances.



Confinement

- Practical efforts to harness fusion energy involve two basic approaches to containing a high-temperature plasma of elements that undergo nuclear fusion reactions: magnetic confinement and inertial confinement.
- In magnetic confinement the particles and energy of a hot plasma are held in place using magnetic fields.
- The trajectories of fast-moving electrically charged particles are bent in a magnetic field. Plasma physicists have devised very complex arrangements of magnets, so that the electrons and ions are kept within a finite volume.

Inertial confinement fusion

- In inertial confinement, a small pellet of solid hydrogen fuel is hit on all sides by many laser beams. This compresses the pellet, and heats it to a fusion temperature.
- **Inertial confinement fusion** a fuel mass is compressed rapidly to densities 1,000 to 10,000 times greater than normal by generating a pressure as high as 10^{17} pascals (10^{12} atmospheres) for periods as short as a nanosecond (10^{-9} second).

Fusion outlook

- Although fusion energy will not be available in the near future, it seems worthwhile to continue research into it, (1) because fuel is effectively unlimited, and (2) because there is almost no problem of radioactive waste.

End of nuclear energy