Unit-II Nuclear Energy: Fundamental forces in the universe, Quantum mechanics relevant for nuclear physics, Nuclear forces, energy scales and structure, Nuclear binding energy systematics, reactions and decays, Nuclear fusion, Nuclear fission and fission reactor physics, Nuclear fission reactor design, safety, operation and fuel cycles

Fundamental Forces

Watch me!

Physicists have identified four fundamental forces that account for the account all phenomena in the universe.*

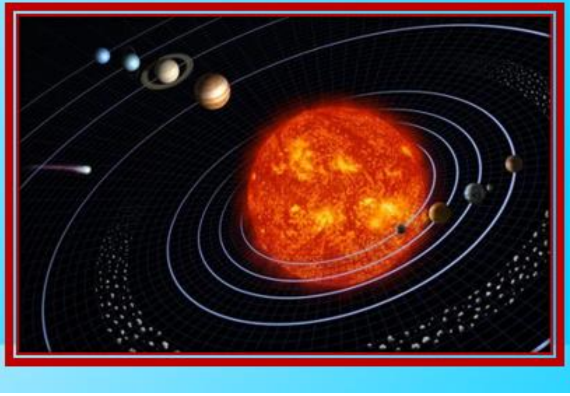
* Many scientists believe that these four forces are different aspects of ONE fundamental force – this is the search for the Unified Theory

Force	Strength	Distance of action	Description
Strong nuclear	Very strong!	Very, very Short	Holds the nucleus together
Weak nuclear	Very weak	Short	Arise during radioactive decay
Electromagnetic	Very weak	Infinite – but decreases with the square of distance	Attraction / repulsion of charged particles
Gravitational	Very, very, very weak	Infinite – but decreases with the square of distance	Attraction between matter

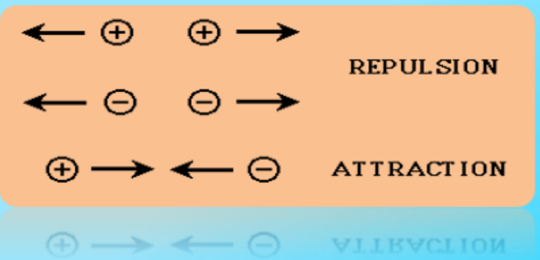
With the exception of gravity, ***all*** the forces we studied up to now are due, on a molecular level, to interactions between the electrons of objects – that is, they are caused by the electromagnetic force

1. Gravitational Force : The gravitational force is the force of mutual attraction between any two objects by virtue of their masses. It is a universal force. Every object experiences this force due to every other object in the universe.

All objects on the earth experience the force of gravity due to the earth. Gravity governs the motion of the moon and artificial satellites around the earth, motion of the earth and planets around the sun.



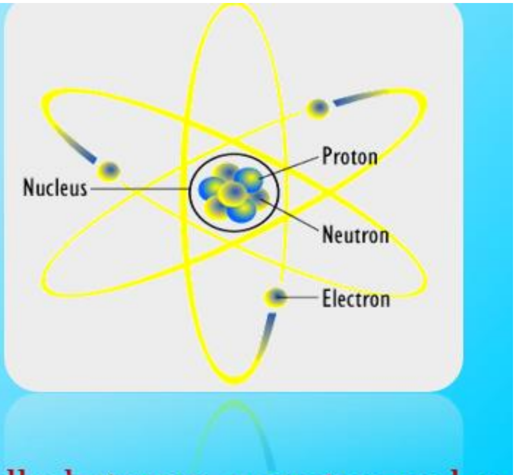
2.Electromagnetic Force: Electromagnetic force is the force between charged particles. When charges are at rest, the force is given by Coulomb's law : attractive for unlike charges and repulsive for like charges.



Charges in motion produce magnetic effects and a magnetic field gives rise to a force on a moving charge. Electromagnetic force acts over large distances and does not need any intervening medium.

Electromagnetic force can be attractive or repulsive.

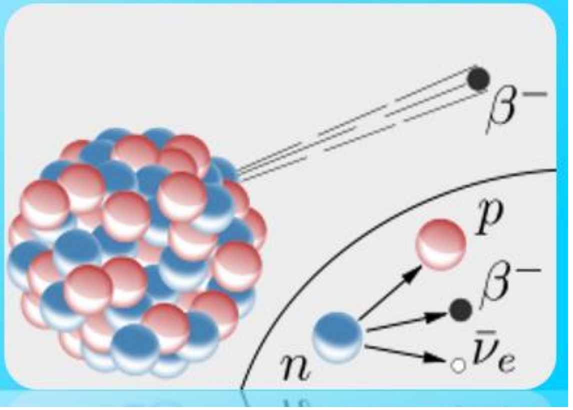
3. Strong Nuclear Force: The strong nuclear force binds protons and neutrons in a nucleus. The strong nuclear force is the strongest of all fundamental forces, about 100 times the electromagnetic force in strength.

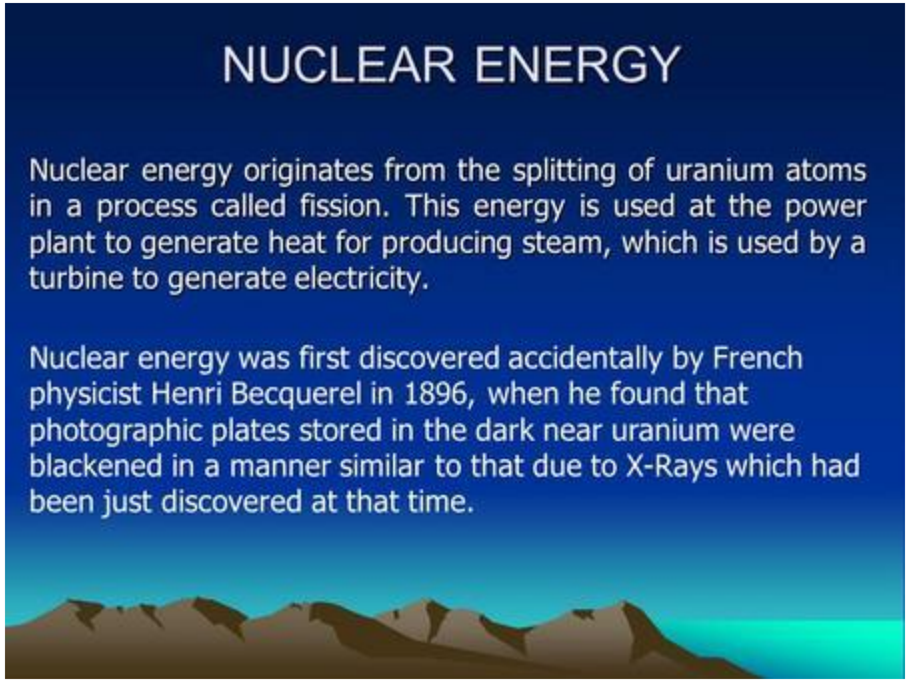


It is charge-independent and acts equally between a proton and a proton, a neutron and a neutron, and a proton and a neutron. Its range is, extremely small, of about nuclear dimensions (10^{-15}m). It is responsible for the stability of nuclei.

4.Weak Nuclear Force : The weak nuclear force appears only in certain nuclear processes such as the β-decay of a nucleus. In β-decay, the nucleus emits an electron and an uncharged particle called neutrino.

The weak nuclear force is not as weak as the gravitational force, but much weaker than the strong nuclear and electromagnetic forces. The range of weak nuclear force is exceedingly small, of the order of 10^{-16} m.





NUCLEAR ENERGY

Nuclear energy originates from the splitting of uranium atoms in a process called fission. This energy is used at the power plant to generate heat for producing steam, which is used by a turbine to generate electricity.

Nuclear energy was first discovered accidentally by French physicist Henri Becquerel in 1896, when he found that photographic plates stored in the dark near uranium were blackened in a manner similar to that due to X-Rays which had been just discovered at that time.

- **One major form of energy**
- **it is trapped inside each atom**
- **it makes up about 17 percent of the world's electricity.**
- **Some country depend on nuclear energy more than other energy**
- **There are now more than 400 nuclear power plants around the world.**

THE NUCLEAR FORCE

➢The force that binds together protons and neutrons inside the nucleus is called the **Nuclear Force.**

➢Some characteristics of the nuclear force are:

1.It does not depend on charge.

2.It is very short range.

3.It is much stronger than the electric force.

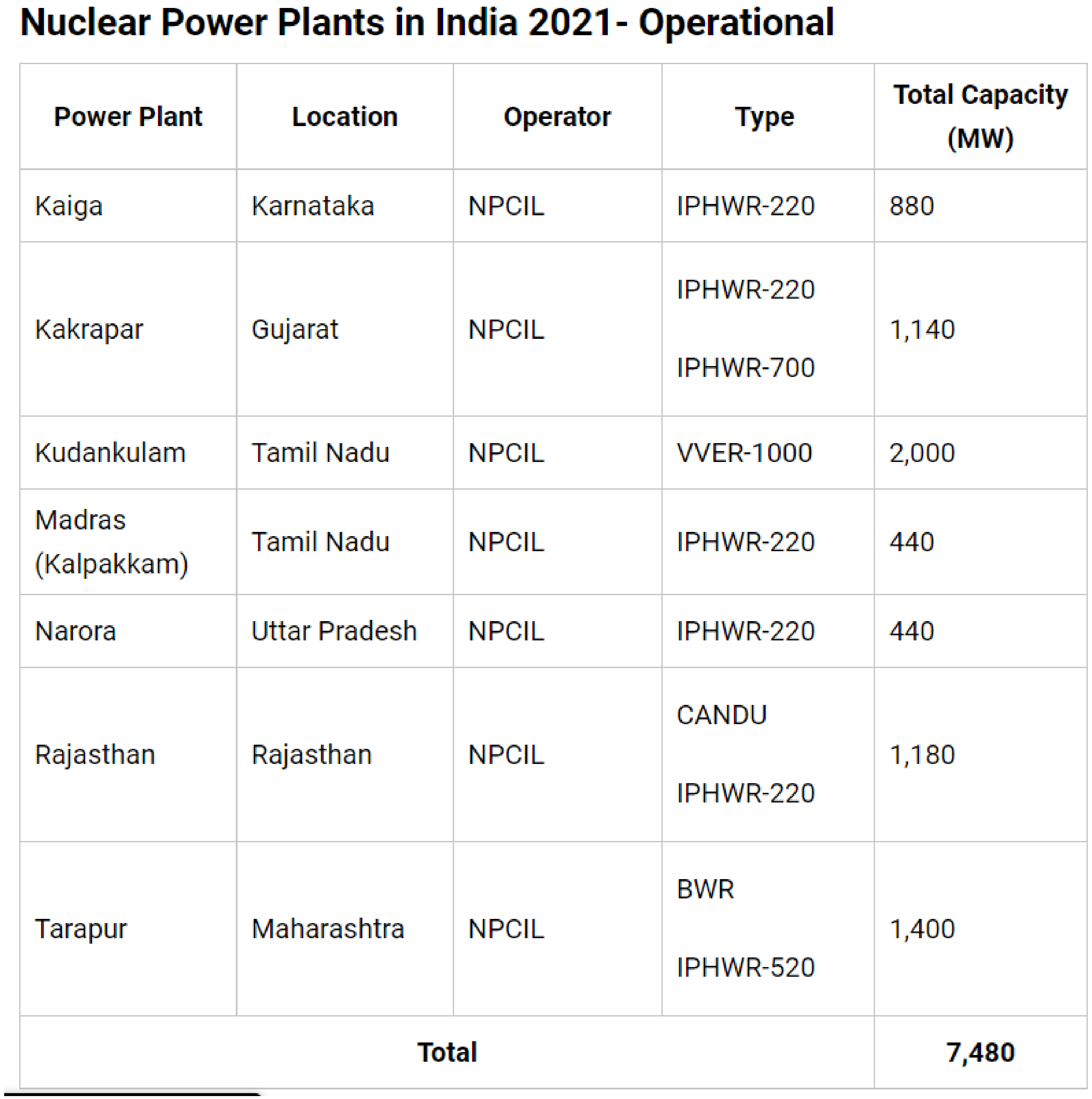
4.It is saturated force .

5.It favours formation of pairs of nucleons with opposite spins.

Nuclear power in India

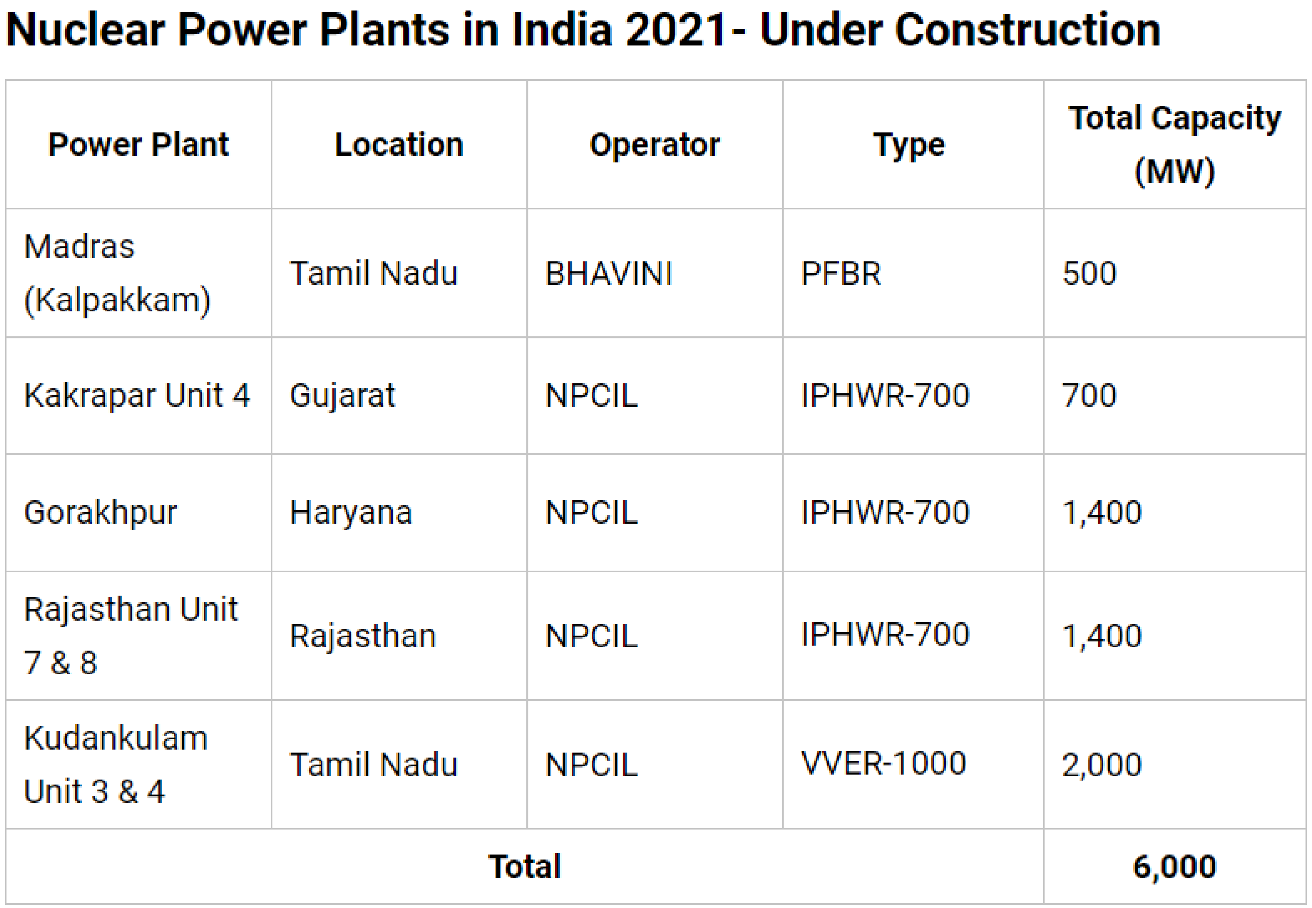
- Nuclear Power is the fifth-largest source of generating electricity in India after coal, gas, wind power and hydroelectricity. At present, India has 22 operating nuclear reactors with an installed capacity of 6,780 MW in 7 nuclear power plants.

- Asia's first nuclear reactor is the Apsara Research Reactor situated in Mumbai. The domestic uranium reserve in India is small and the country is dependent on uranium imports from other countries to provide fuel to its nuclear power industry. Since the 1990s, Russia has been a major supplier of nuclear fuel to India.



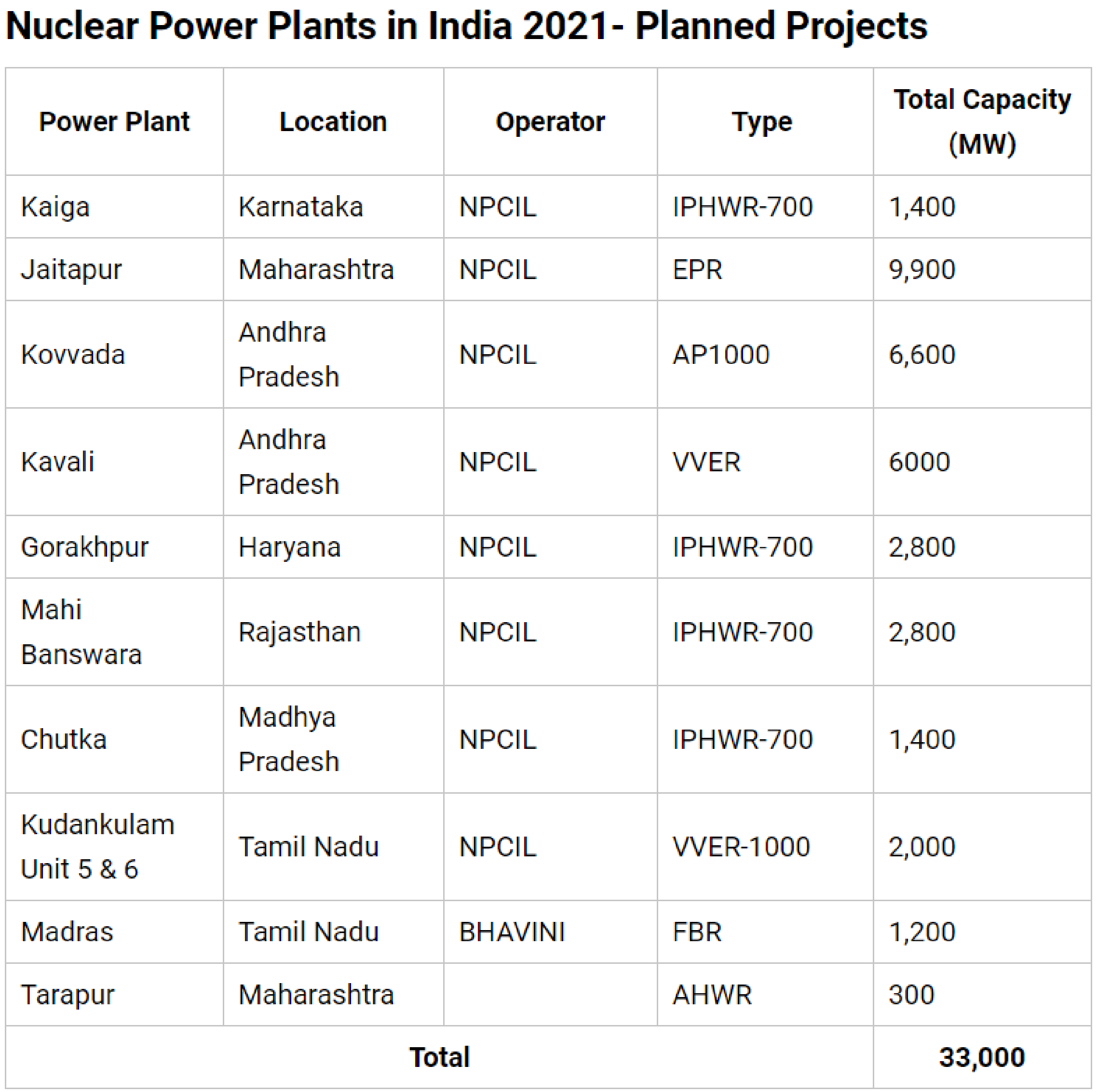
Nuclear Power Plants in India 2021- Operational

Power Plant	Location	Operator	Type	Total Capacity (MW)
Kaiga	Karnataka	NPCIL	IPHWR-220	880
Kakrapar	Gujarat	NPCIL	IPHWR-220 IPHWR-700	1,140
Kudankulam	Tamil Nadu	NPCIL	VVER-1000	2,000
Madras (Kalpakkam)	Tamil Nadu	NPCIL	IPHWR-220	440
Narora	Uttar Pradesh	NPCIL	IPHWR-220	440
Rajasthan	Rajasthan	NPCIL	CANDU IPHWR-220	1,180
Tarapur	Maharashtra	NPCIL	BWR IPHWR-520	1,400
Total				**7,480**



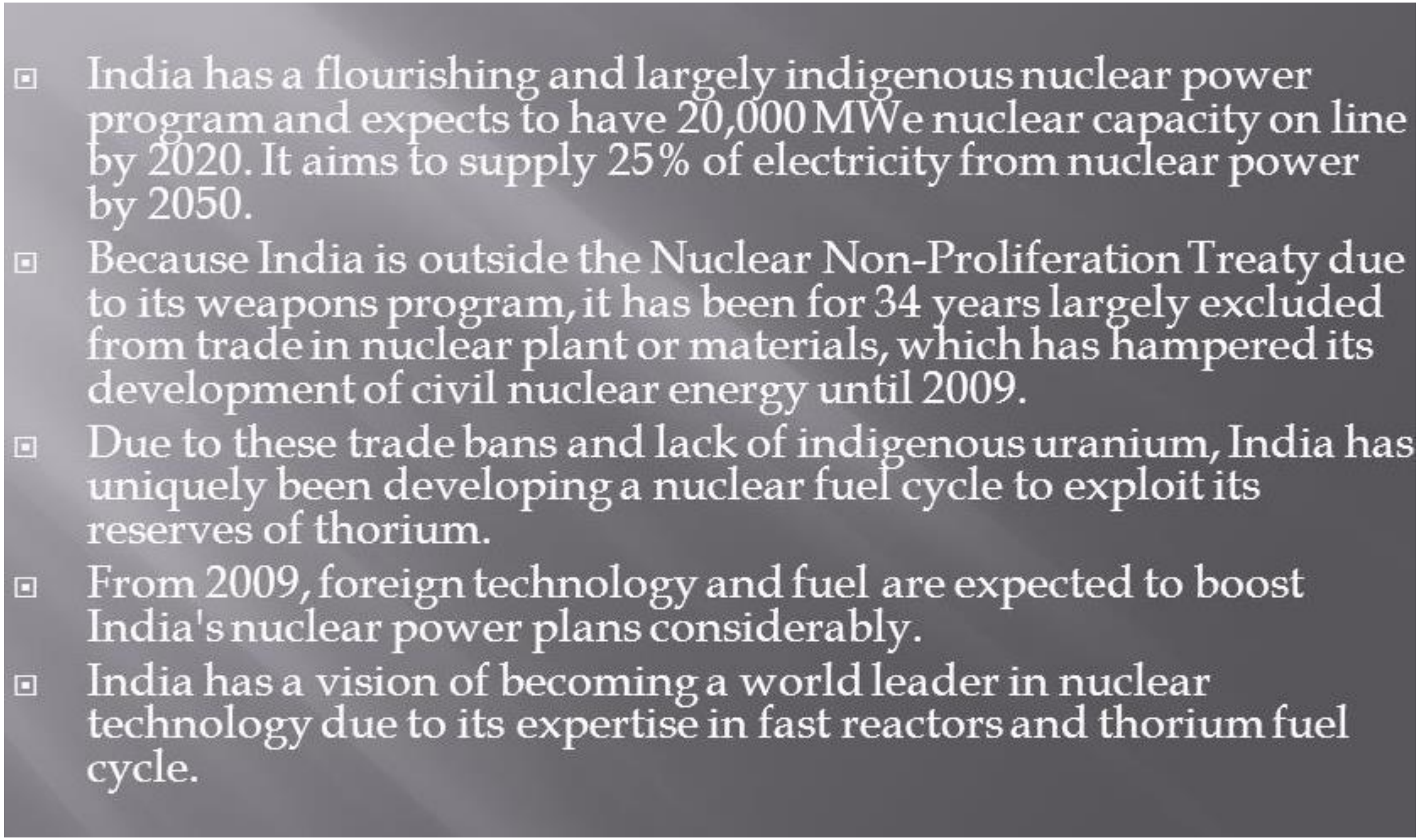
Nuclear Power Plants in India 2021- Under Construction

Power Plant	Location	Operator	Type	Total Capacity (MW)
Madras (Kalpakkam)	Tamil Nadu	BHAVINI	PFBR	500
Kakrapar Unit 4	Gujarat	NPCIL	IPHWR-700	700
Gorakhpur	Haryana	NPCIL	IPHWR-700	1,400
Rajasthan Unit 7 & 8	Rajasthan	NPCIL	IPHWR-700	1,400
Kudankulam Unit 3 & 4	Tamil Nadu	NPCIL	VVER-1000	2,000
Total				**6,000**



Nuclear Power Plants in India 2021- Planned Projects

Power Plant	Location	Operator	Type	Total Capacity (MW)
Kaiga	Karnataka	NPCIL	IPHWR-700	1,400
Jaitapur	Maharashtra	NPCIL	EPR	9,900
Kovvada	Andhra Pradesh	NPCIL	AP1000	6,600
Kavali	Andhra Pradesh	NPCIL	VVER	6000
Gorakhpur	Haryana	NPCIL	IPHWR-700	2,800
Mahi Banswara	Rajasthan	NPCIL	IPHWR-700	2,800
Chutka	Madhya Pradesh	NPCIL	IPHWR-700	1,400
Kudankulam Unit 5 & 6	Tamil Nadu	NPCIL	VVER-1000	2,000
Madras	Tamil Nadu	BHAVINI	FBR	1,200
Tarapur	Maharashtra		AHWR	300
Total				**33,000**



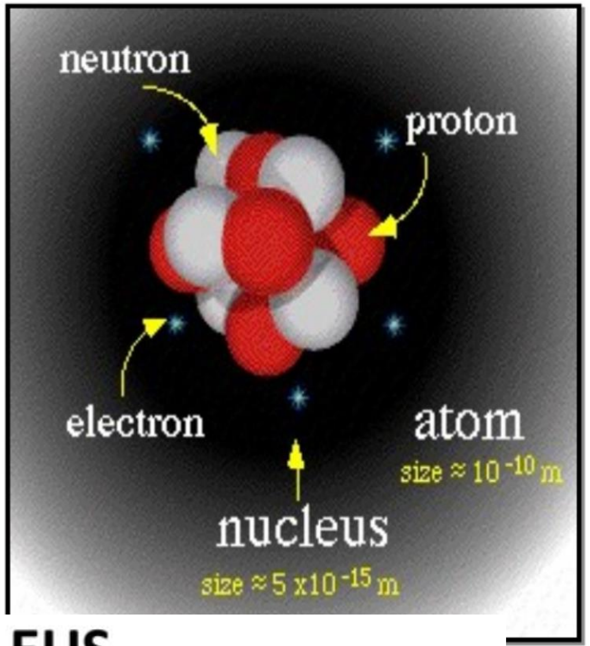
- India has a flourishing and largely indigenous nuclear power program and expects to have 20,000 MWe nuclear capacity on line by 2020. It aims to supply 25% of electricity from nuclear power by 2050.
- Because India is outside the Nuclear Non-Proliferation Treaty due to its weapons program, it has been for 34 years largely excluded from trade in nuclear plant or materials, which has hampered its development of civil nuclear energy until 2009.
- Due to these trade bans and lack of indigenous uranium, India has uniquely been developing a nuclear fuel cycle to exploit its reserves of thorium.
- From 2009, foreign technology and fuel are expected to boost India's nuclear power plans considerably.
- India has a vision of becoming a world leader in nuclear technology due to its expertise in fast reactors and thorium fuel cycle.

- Nuclear physics is the field of physics that studies the building blocks and interactions of atomic nuclei.
- It includes the study of,

1. The general properties of nucleus.
2. The particles contained in the nucleus.
3. The interaction between these particles.
4. Radio activity and nuclear reactions.
5. Practical applications of nuclear phenomena.

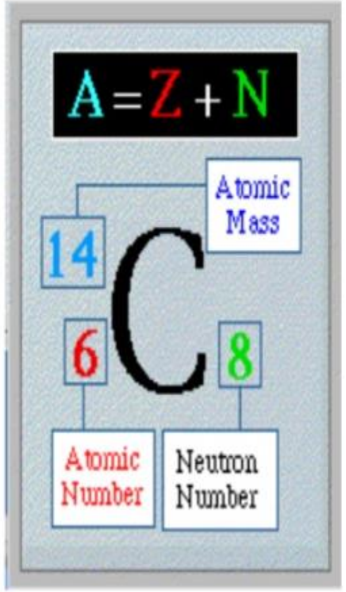
NUCLEUS

- Every atom contains a centre, an extremely dense, positively charged nucleus.
- The nucleus is made of protons and neutrons.
- Protons have positive electric charge.
- Neutrons have no electrical charge.



NUCLEUS

- <u>MASS NUMBER**(A)**:</u> total number of nucleon.A=Z(protons)+N(neutrons).
- <u>ATOMIC NUMBER(**Z**):</u> number of protons.
- <u>NEUTRON NUMBER N</u>: number of neutrons.
- <u>RADIUS</u>: $\mathbf{r=r_0A^{1/3}}$, $r_0=1.25x10^{-15}$ m.
- <u>MASS</u> **<u>M=AU</u>**,$u=1.66\times10^{-}27$kg



THE NUCLEAR FORCE

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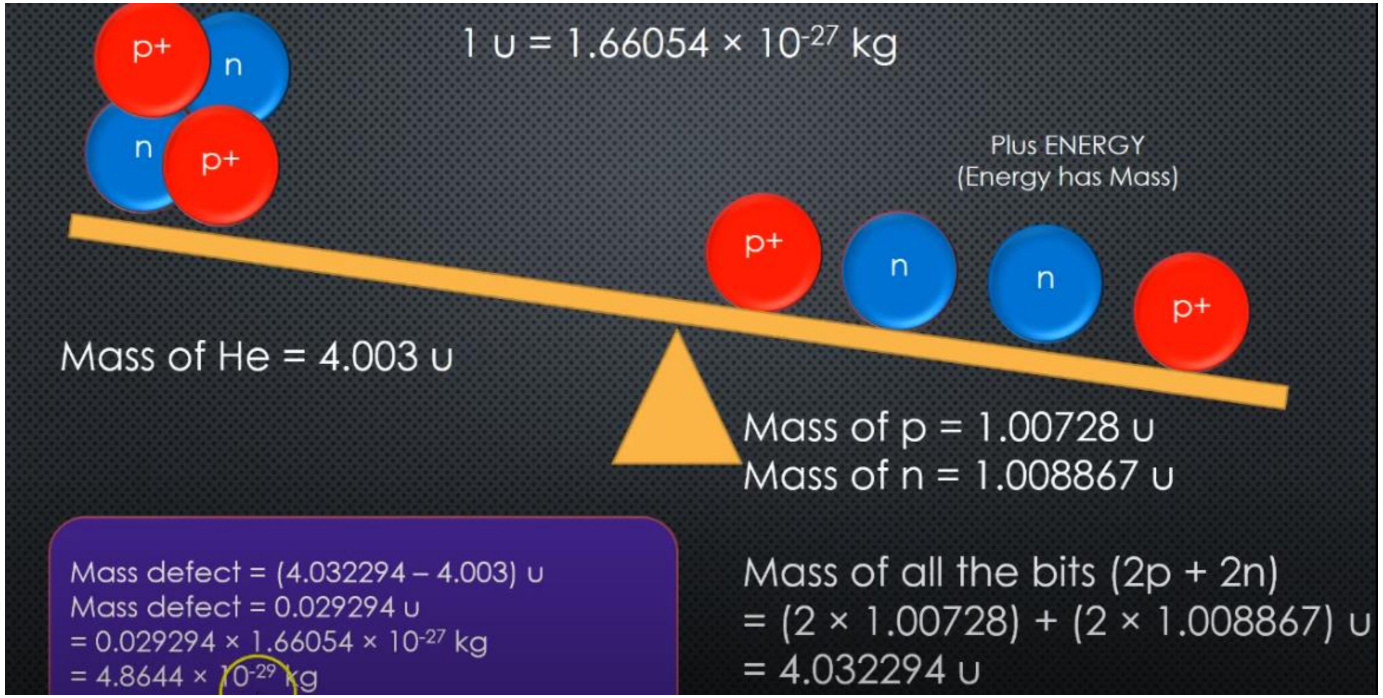
NUCLEAR BINDING ENERGY

Nuclear binding energy is the energy required to split a nucleus of an atom into its component parts: protons and neutrons.



1 u = 1.66054×10^{-27} kg

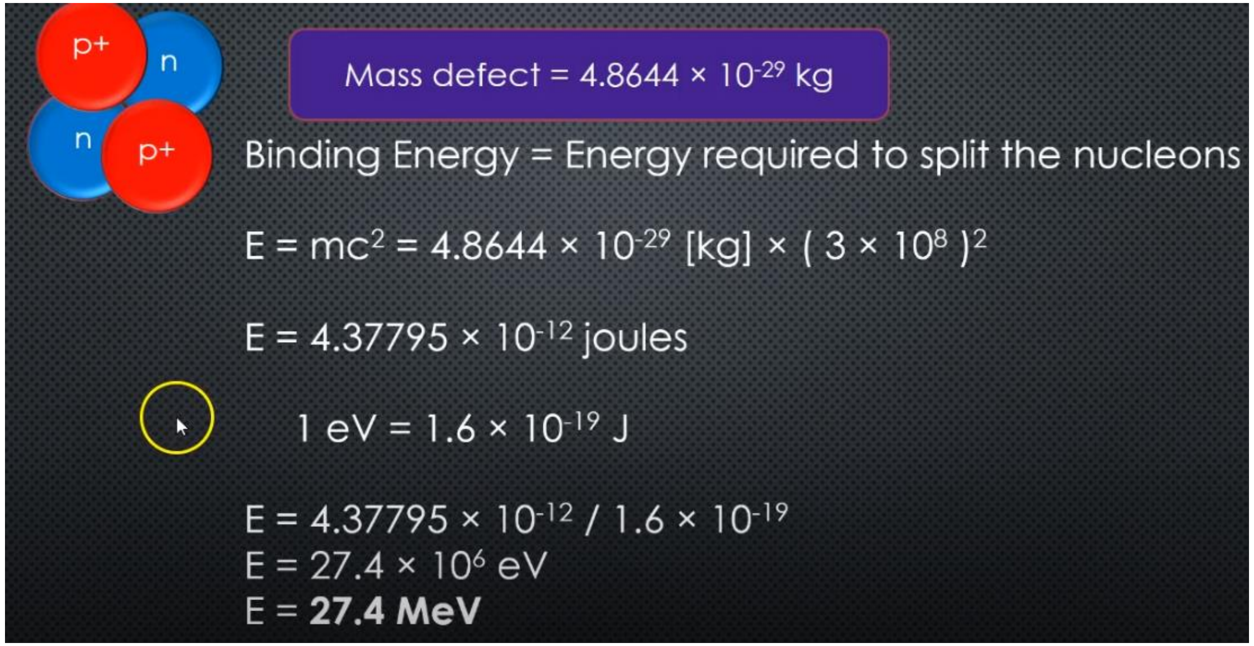
Plus ENERGY
(Energy has Mass)

Mass of He = 4.003 u

Mass of p = 1.00728 u
Mass of n = 1.008867 u

Mass defect = (4.032294 – 4.003) u
Mass defect = 0.029294 u
= $0.029294 \times 1.66054 \times 10^{-27}$ kg
= 4.8644×10^{-29} kg

Mass of all the bits (2p + 2n)
= (2 × 1.00728) + (2 × 1.008867) u
= 4.032294 u



Mass defect = 4.8644×10^{-29} kg

Binding Energy = Energy required to split the nucleons

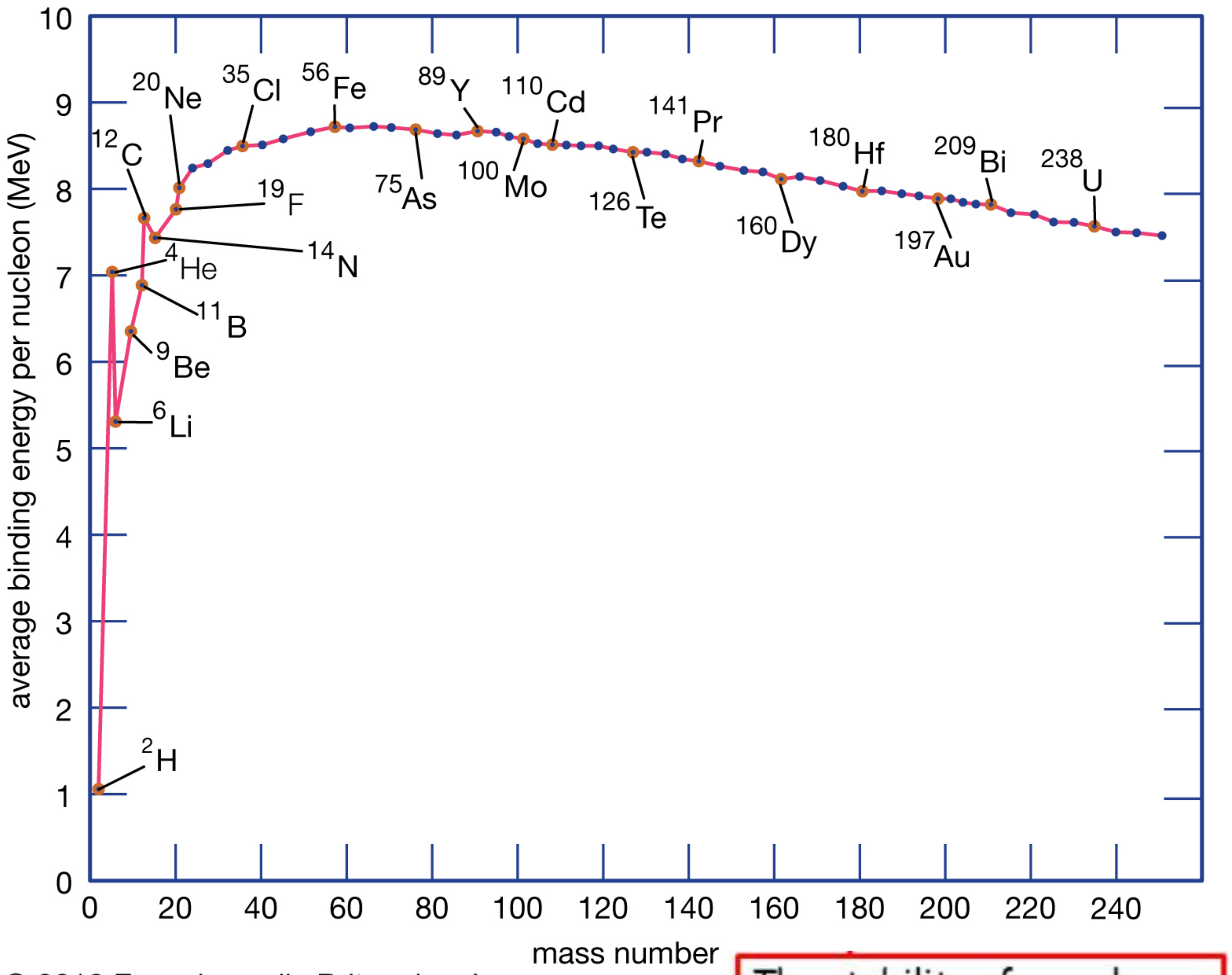
$E = mc^2 = 4.8644 \times 10^{-29}$ [kg] × $(3 \times 10^{8})^2$

$E = 4.37795 \times 10^{-12}$ joules

1 eV = 1.6×10^{-19} J

$E = 4.37795 \times 10^{-12} / 1.6 \times 10^{-19}$
$E = 27.4 \times 10^{6}$ eV
E = **27.4 MeV**

Binding energy per nucleon = 27.4 / 4 = 6.8 MeV



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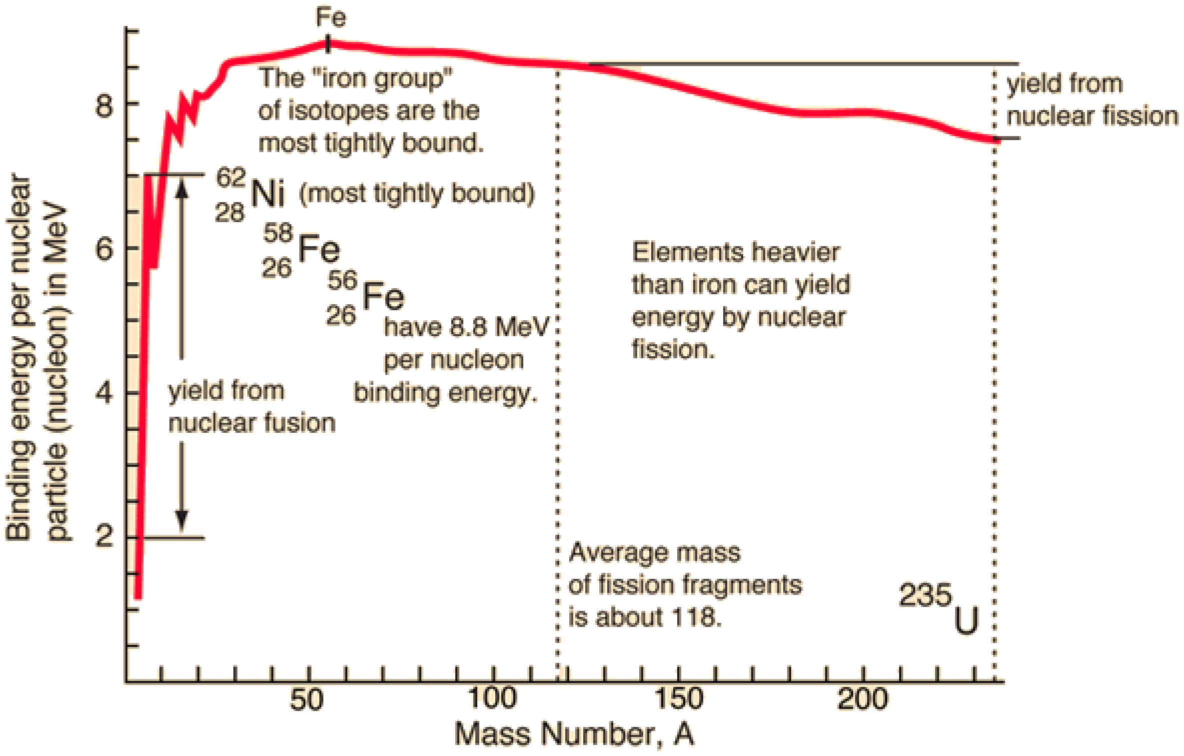
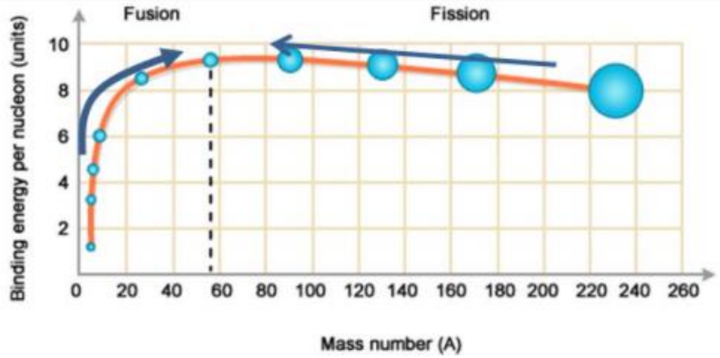
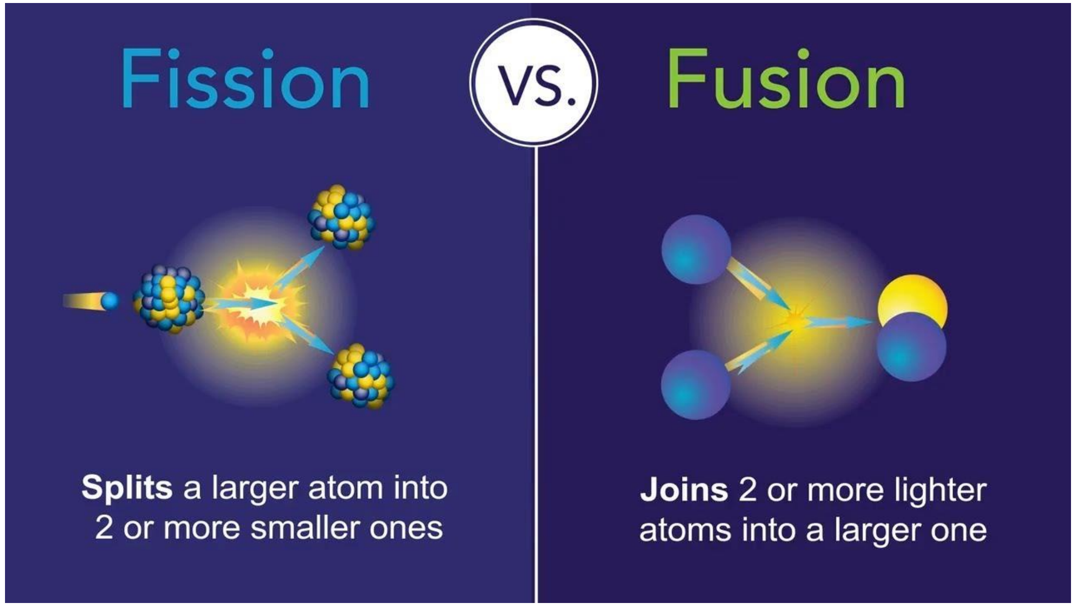
The stability of a nucleus depends on its binding energy per nucleon. **Iron** has the greatest stability because it has the largest binding energy per nucleon – lots of energy is required to separate its nucleons.





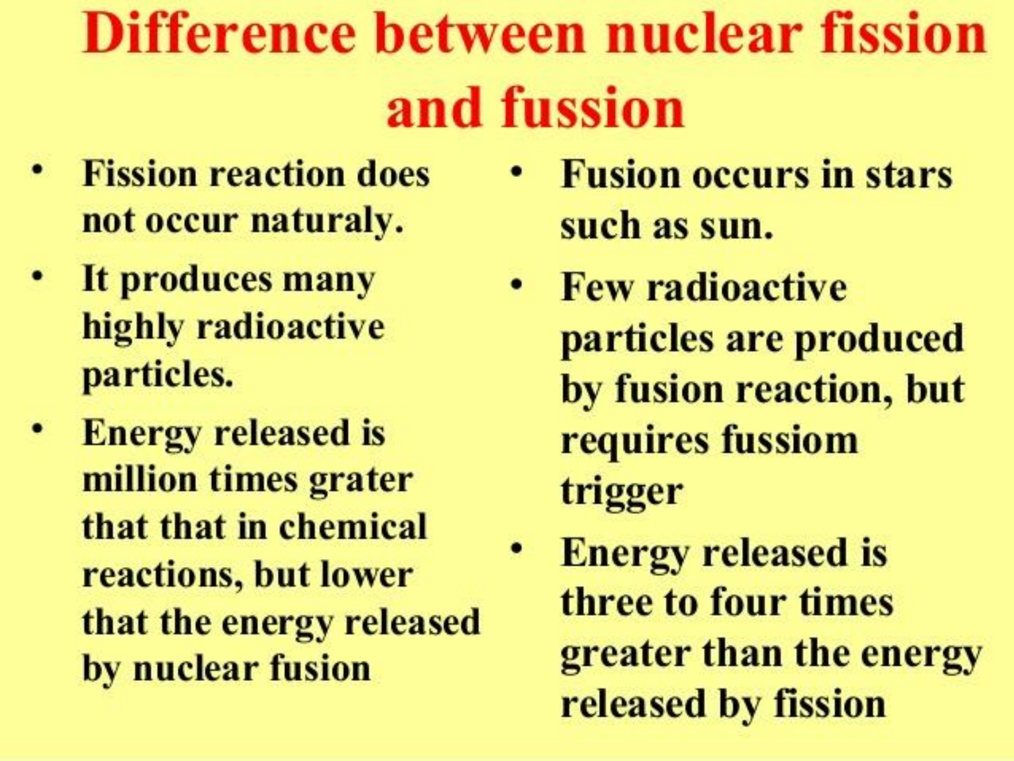
Nuclear fission and nuclear fusion both **release energy** because **both processes increase the binding energy per nucleon** of the particles involved.

Nuclear reaction change in the identity or characteristics of an atomic nucleus, induced by bombarding it with an energetic particle.



Splits a larger atom into 2 or more smaller ones

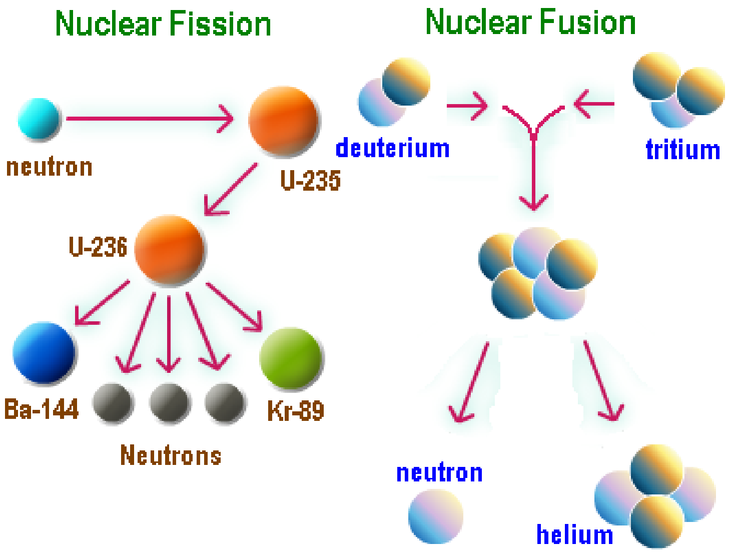
Joins 2 or more lighter atoms into a larger one

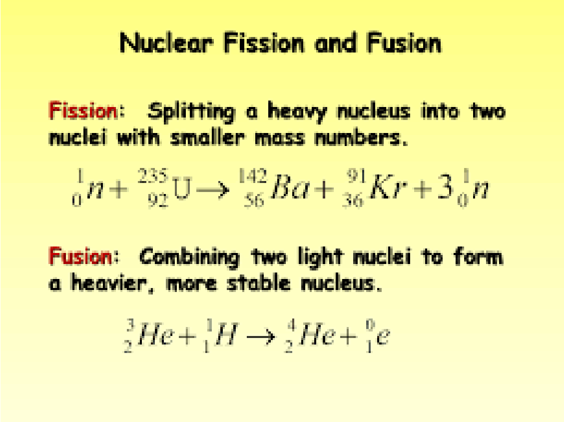


Difference between nuclear fission and fusion

- Fission reaction does not occur naturaly.
- It produces many highly radioactive particles.
- Energy released is million times grater that that in chemical reactions, but lower that the energy released by nuclear fusion

- Fusion occurs in stars such as sun.
- Few radioactive particles are produced by fusion reaction, but requires fussion trigger
- Energy released is three to four times greater than the energy released by fission





Nuclear Fission and Fusion

Fission: Splitting a heavy nucleus into two nuclei with smaller mass numbers.

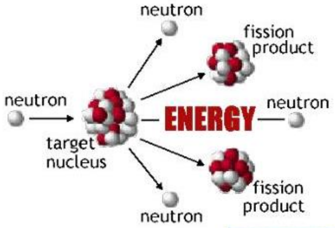
$$^{1}_{0}n + ^{235}_{92}\mathrm{U} \rightarrow ^{142}_{56}Ba + ^{91}_{36}Kr + 3\,^{1}_{0}n$$

Fusion: Combining two light nuclei to form a heavier, more stable nucleus.

$$^{3}_{2}He + ^{1}_{1}H \rightarrow ^{4}_{2}He + ^{0}_{1}e$$

What is Nuclear Fuel?

Nuclear fuel is an energy source that results from the splitting of atoms.



Advantages:
1)Helps generate electricity
2)Low fuel costs (Uranium – 235)
3)Water vapor is the only emission

Problems:
1) Cause thermal pollution of waterways.
2) Difficult to safely dispose of nuclear (radioactive) wastes .

SOURCE OF FUEL

- Uranium is the primary fuel for nuclear reactor.

- Uranium is a naturally-occurring element in the Earth's crust.

- Traces of it occur almost everywhere, although mining takes place in locations where it is naturally concentrated.

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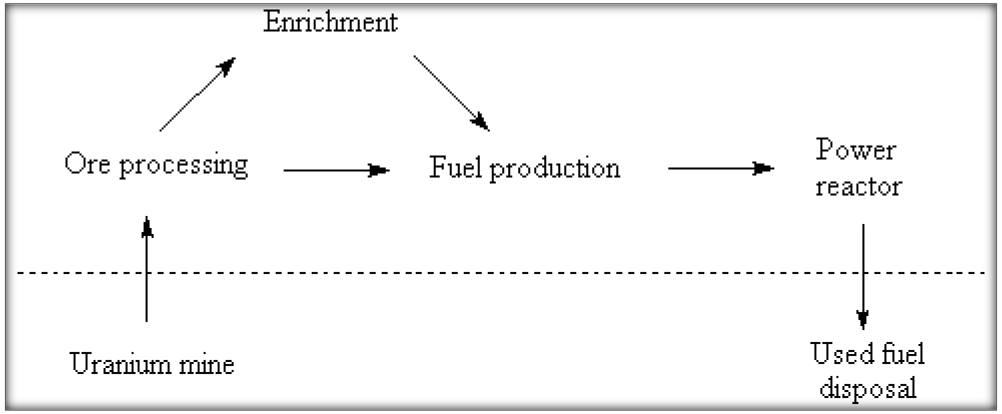
- Uranium mines operate in some twenty countries, though about half of world production comes from just ten mines in six countries, in Canada, Australia, Niger, Kazakhstan, Russia and Namibia.

Nuclear Fuel Cycle

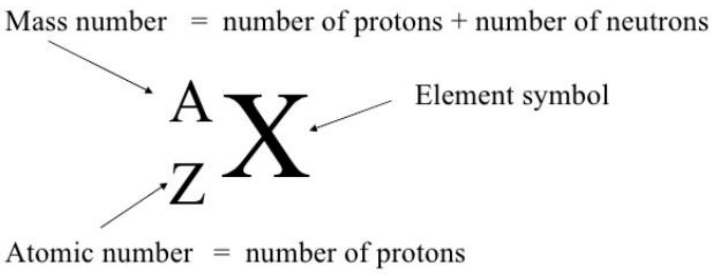
- It is the progression of nuclear fuel through a series of stages.
- Nuclear fuel may be Uranium-235, Plutonium-239 etc.
- Front end : consists of mining of fuel, chemical purification, conversion to appropriate form and fuel rod fabrication.
- Back end : consists of steps to safely manage, contain, and either reprocess (closed cycle) or dispose(open cycle) spent nuclear fuel.



Uranium-235 is used as a fuel in different concentrations. Some reactors, such as the CANDU reactor, can use natural uranium with uranium-235 concentrations of only 0.7%, while other reactors require the uranium to be slightly enriched to levels of 3% to 5%.

Plutonium-239 is produced and used in reactors (specifically fast breeder reactors) that contain significant amounts of uranium-238. It can also be recycled and used as a fuel in thermal reactors. Current research is being done to investigate how thorium-232 can be used as a fuel.

Isotope Symbol Review



Mass number = number of protons + number of neutrons

$^{A}_{Z}X$

Element symbol

Atomic number = number of protons

A = number of protons + number of neutrons

Z = number of protons

A – Z = number of neutrons

*****Number of neutrons = Mass Number – Atomic Number*****

Fill in the chart for each isotope

$^{235}_{92}U$

A	235
Z	92
Number of protons	92
Number of neutrons	143

$^{238}_{92}U$

A	238
Z	92
Number of protons	92
Number of neutrons	146

Isotopes of any particular element contain the **same** number of protons, but **different** numbers of neutrons.

- Most of the isotopes which occur naturally are stable.
- A few naturally occurring isotopes and all of the man-made isotopes are unstable.
- Unstable isotopes can become stable by releasing different types of particles.
- This process is called radioactive decay and the elements which undergo this process are called radioisotopes.
- The products of this decay are called **daughter isotopes**

Radioactive Decay

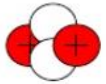
Radioactive decay results in the emission of either:

- an alpha particle (α),
- a negative beta particle (electron) (β^-),
- a positive beta particle (positron) (β^+),
- or a gamma ray (γ).

In a nuclear reaction the MASS and ATOMIC NUMBER must be the SAME on both sides of the equations

Alpha Decay

An alpha particle is identical to that of a helium nucleus.



It contains two protons and two neutrons.

$$ {}^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He $$

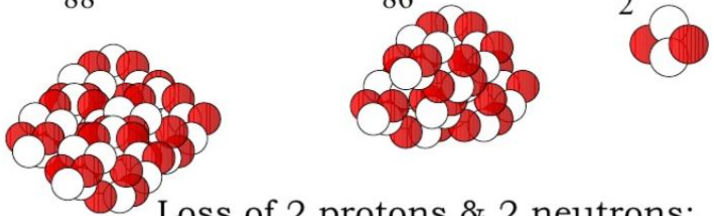
unstable atom

more stable atom

alpha particle

Alpha Decay

$$ {}^{226}_{88}Ra \longrightarrow {}^{222}_{86}Rn + {}^{4}_{2}He $$

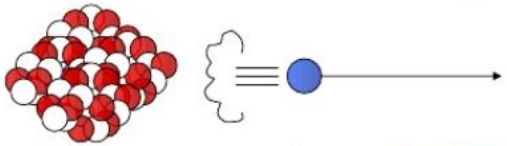


Loss of 2 protons & 2 neutrons:
Atomic # decreases by 2
Mass # decreases by 4

$$ {}^{234}_{92}U \longrightarrow {}^{230}_{90}Th + {}^{4}_{2}He $$

Beta Emission

A beta particle is a fast moving electron which is emitted from the nucleus of an atom undergoing radioactive decay.



Beta emission occurs when a **neutron changes into a proton and an electron**.

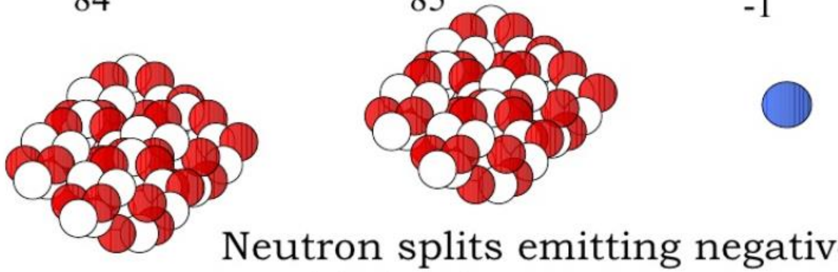
$$ {}^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e $$

proton stays in nucleus

beta particle (electron)

Beta Emission

$$ {}^{218}_{84}Po \longrightarrow {}^{218}_{85}At \; - \; {}^{0}_{-1}e $$



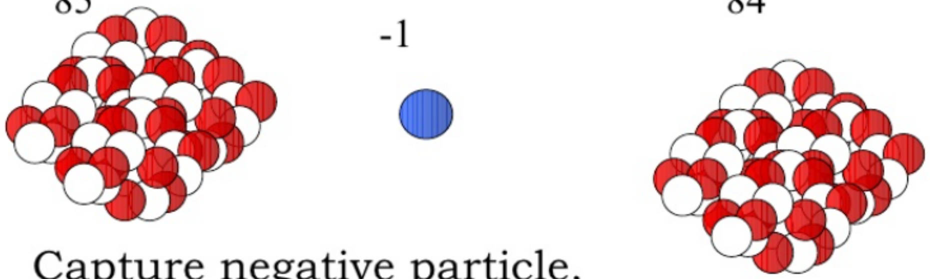
Neutron splits emitting negative particle leaving a proton.

- •Atomic # increases by 1
- •Mass # stays the same (electrons have no mass)

$$ {}^{234}_{90}Th \longrightarrow {}^{234}_{91}Pa + {}^{0}_{-1}e $$

Electron Capture

$$^{218}_{85}\text{At} + ^{0}_{-1}\text{e} \longrightarrow ^{218}_{84}\text{Po}$$

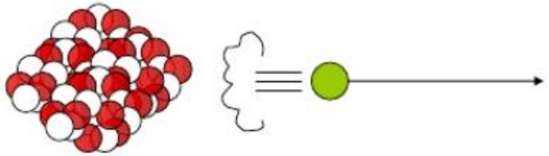


Capture negative particle, forming a neutron from a proton

- Atomic # decreases by 1
- Mass # stays the same
  (electrons have no mass)

Positron Emission

A positron is like an electron but it has a positive charge.



During positron emission a **proton changes into a neutron** and the excess positive charge is emitted.

$$^{A}_{Z}X \longrightarrow \underset{\substack{\uparrow \\ \text{mass stays} \\ \text{in nucleus}}}{^{A}_{Z-1}Y} + \underset{\substack{\uparrow \\ \text{positron}}}{^{0}_{+1}e}$$

Gamma Decay

- When atoms decay by emitting α or β particles to form a new atom, the nuclei of the new atom formed may still have too much energy to be completely stable. These atoms will emit gamma rays to release that energy.
- Gamma rays are high energy radiation
- Gamma rays are not charged particles like α and β particles.
- There is **no** change in mass or atomic number

$$^{A}_{Z}X \longrightarrow ^{A}_{Z}X + ^{0}_{0}\gamma$$

Summary

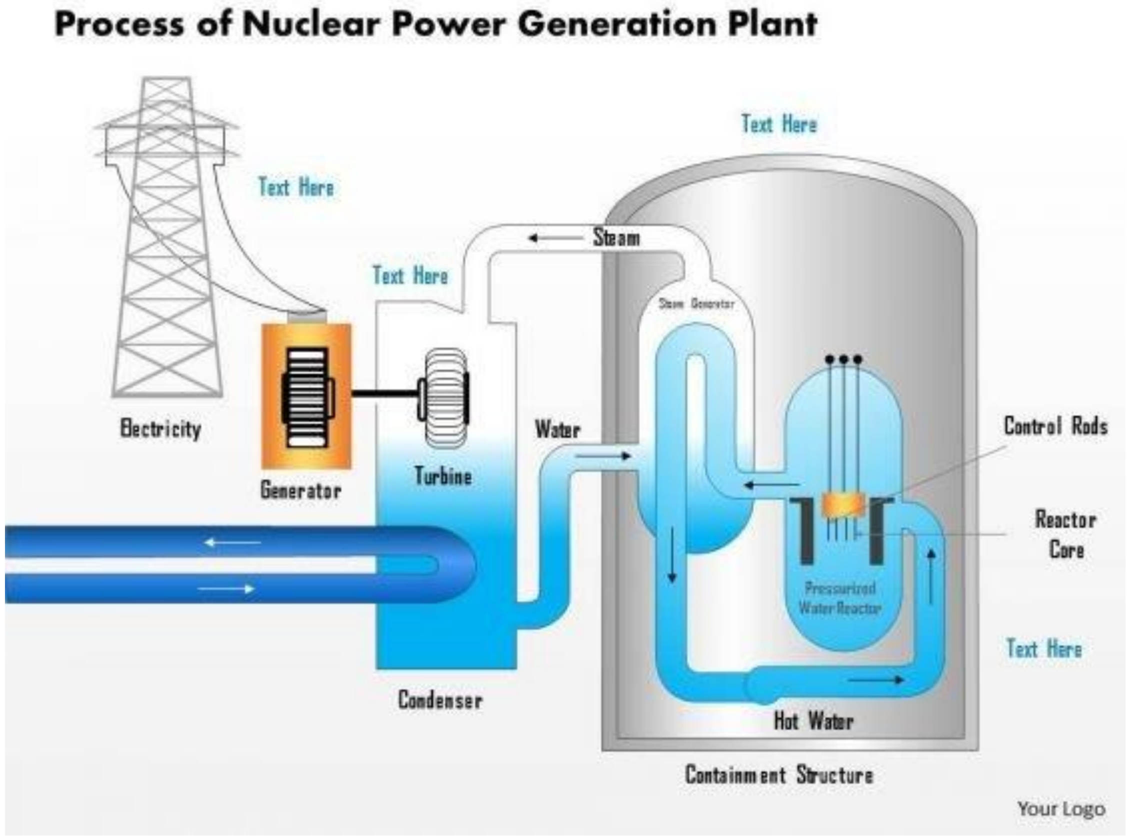
Reaction	What happens?	Mass #	Atomic #
Alpha Decay α	Lose Helium Nucleus	**-4**	**-2**
Beta Decay β^-	Lose electron from nucleus (neutron turns into proton)	**No change**	**+1**
Electron Capture	Gain electron in nucleus (proton turns into neutron)	**No change**	**-1**
Positron Emission β^+	Lose positron (proton turns into neutron)	**No change**	**-1**
Gammy Decay γ	Emit high energy gamma ray	**No change**	**No change**

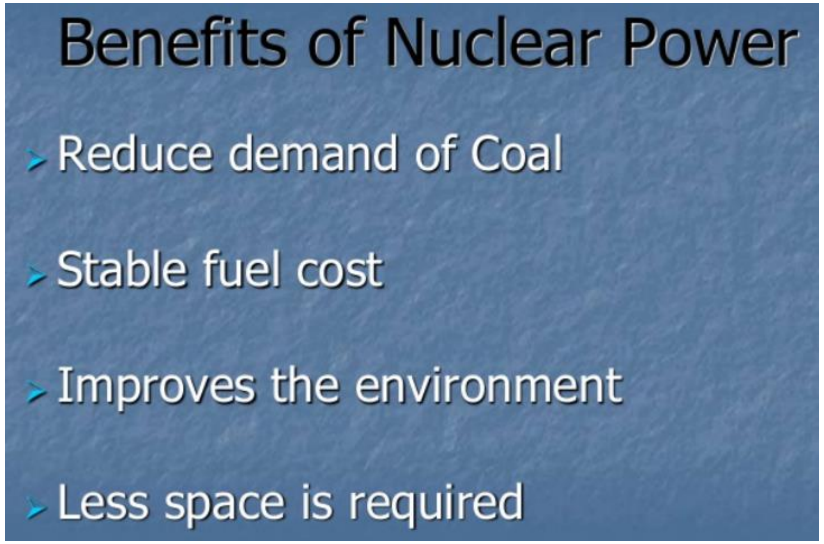
Nuclear Stability

- The strong nuclear force holds all nuclei together
  - Otherwise protons would repel each other
  - Neutrons space out protons and make nucleus stable
- Not all isotopes are radioactive
- Only **unstable** nuclei decay
- In smaller atoms stable isotopes have **equal** numbers of protons and neutrons
- In larger atoms stable isotopes will have **more** neutrons than protons
- Too many or too few neutrons makes the nucleus unstable

Introduction to Nuclear Power

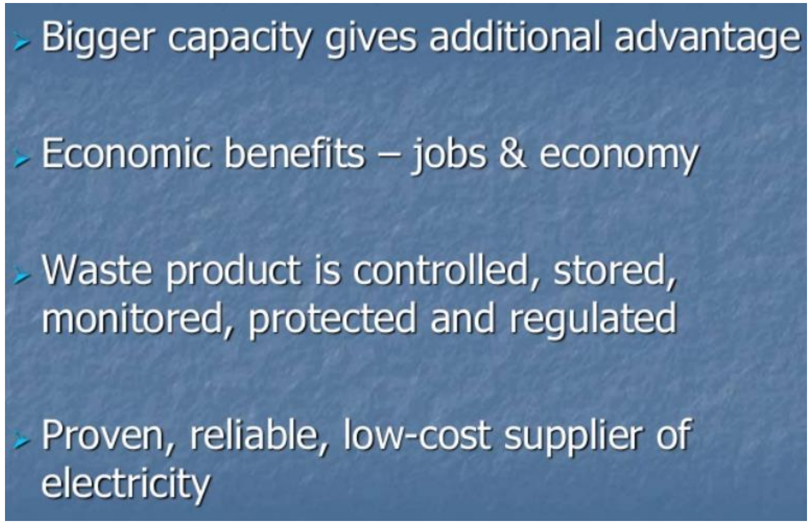
- It is the use of Nuclear Fission reactions to Generate Power
- Nuclear energy is the world's largest source of emission-free energy
- Most efficient Power Source per Unit Area
- Used in 31 Countries (approx 441 reactors)[1]
- Accounts for about 16% of all electricity generated world wide (approx 351 Gigawatts)





Benefits of Nuclear Power

- Reduce demand of Coal
- Stable fuel cost
- Improves the environment
- Less space is required

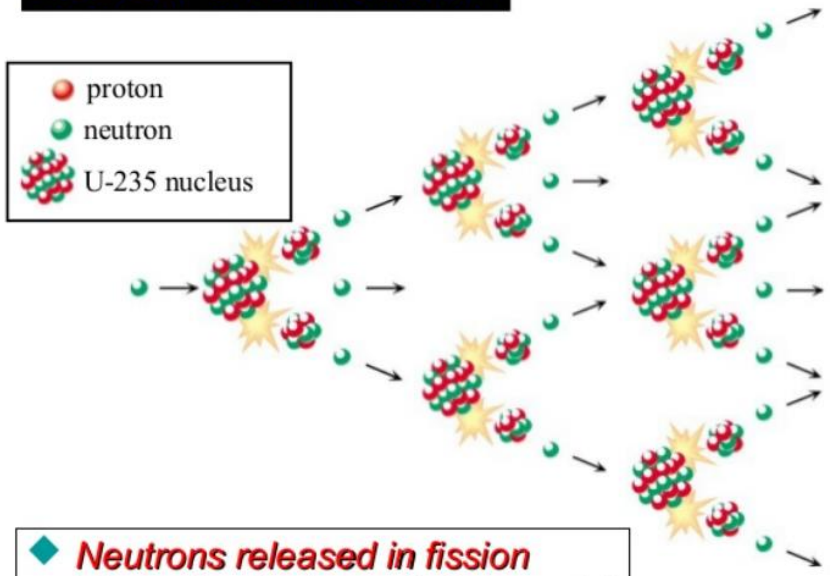


- Bigger capacity gives additional advantage
- Economic benefits – jobs & economy
- Waste product is controlled, stored, monitored, protected and regulated
- Proven, reliable, low-cost supplier of electricity

❑ Working principle :

- ❖ A nuclear power plant works in a similar way as a thermal power plant. The difference between the two is in the fuel they use to heat the water in the boiler(steam generator).
- ❖ Inside a nuclear power station, energy is released by nuclear fission in the core of the reactor.
- ❖ 1 kg of Uranium U^{235} can produce as much energy as the burning of 4500 tonnes of high grade variety of coal or 2000 tonnes of oil.

Nuclear chain reaction

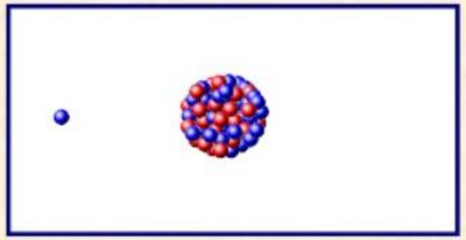


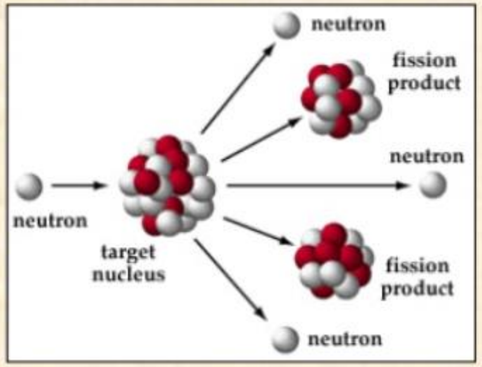
◆ ***Neutrons released in fission***
trigger the fissions of other nuclei

❑ Chain Reaction…

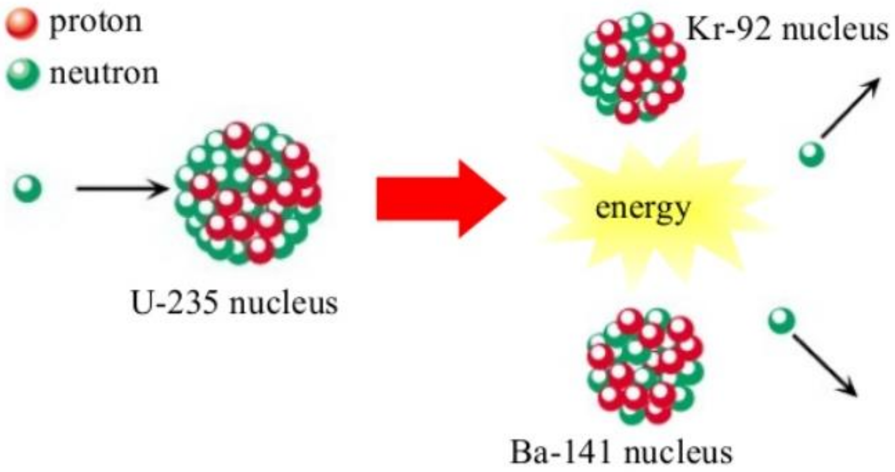
- ➢ Uranium exists as an isotope in the form of U^{235} which is unstable.
- ➢ When the nucleus of an atom of Uranium is split, the neutrons released hit other atoms and split them in turn. More energy is released each time another atom splits. This is called a chain reaction.

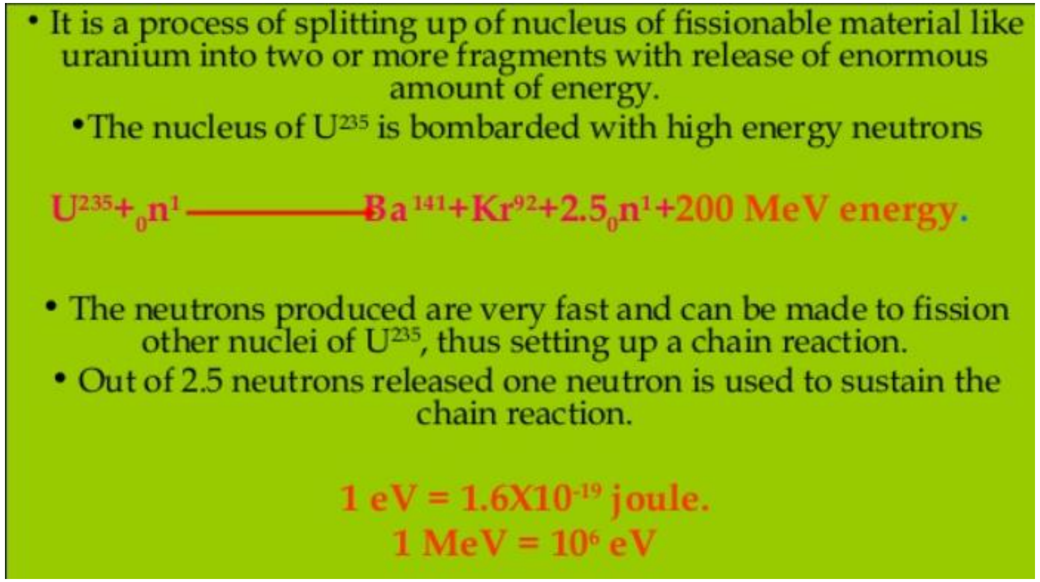
❑ Nuclear fission:





- **Nuclear fission**: **heavy nuclei split into two smaller parts** in order to become more stable



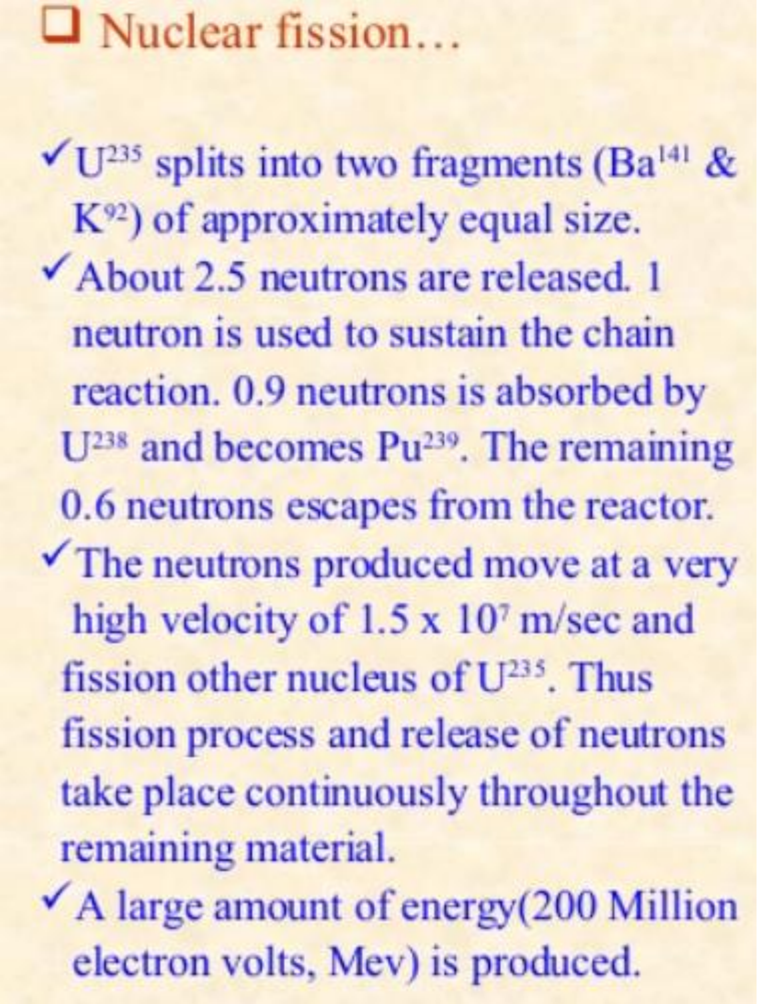


- It is a process of splitting up of nucleus of fissionable material like uranium into two or more fragments with release of enormous amount of energy.
- The nucleus of U^{235} is bombarded with high energy neutrons

$$U^{235}+{}_0n^1 \longrightarrow Ba^{141}+Kr^{92}+2.5\,{}_0n^1+200\text{ MeV energy.}$$

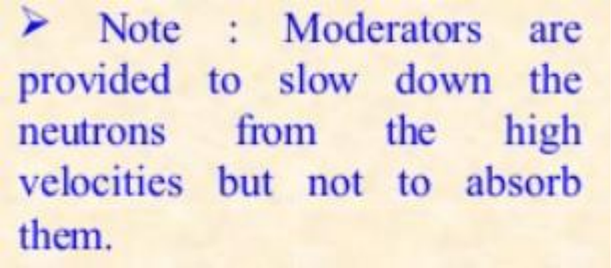
- The neutrons produced are very fast and can be made to fission other nuclei of U^{235}, thus setting up a chain reaction.
- Out of 2.5 neutrons released one neutron is used to sustain the chain reaction.

1 eV = $1.6\text{X}10^{-19}$ joule.
1 MeV = 10^6 eV

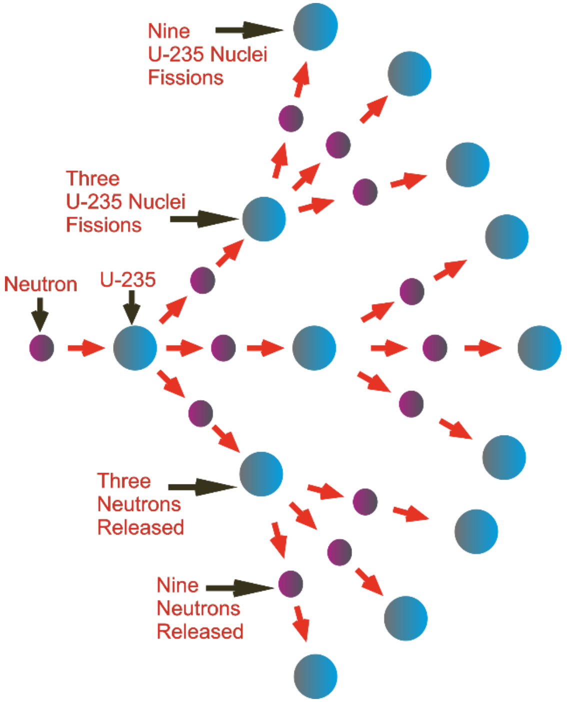


☐ Nuclear fission…

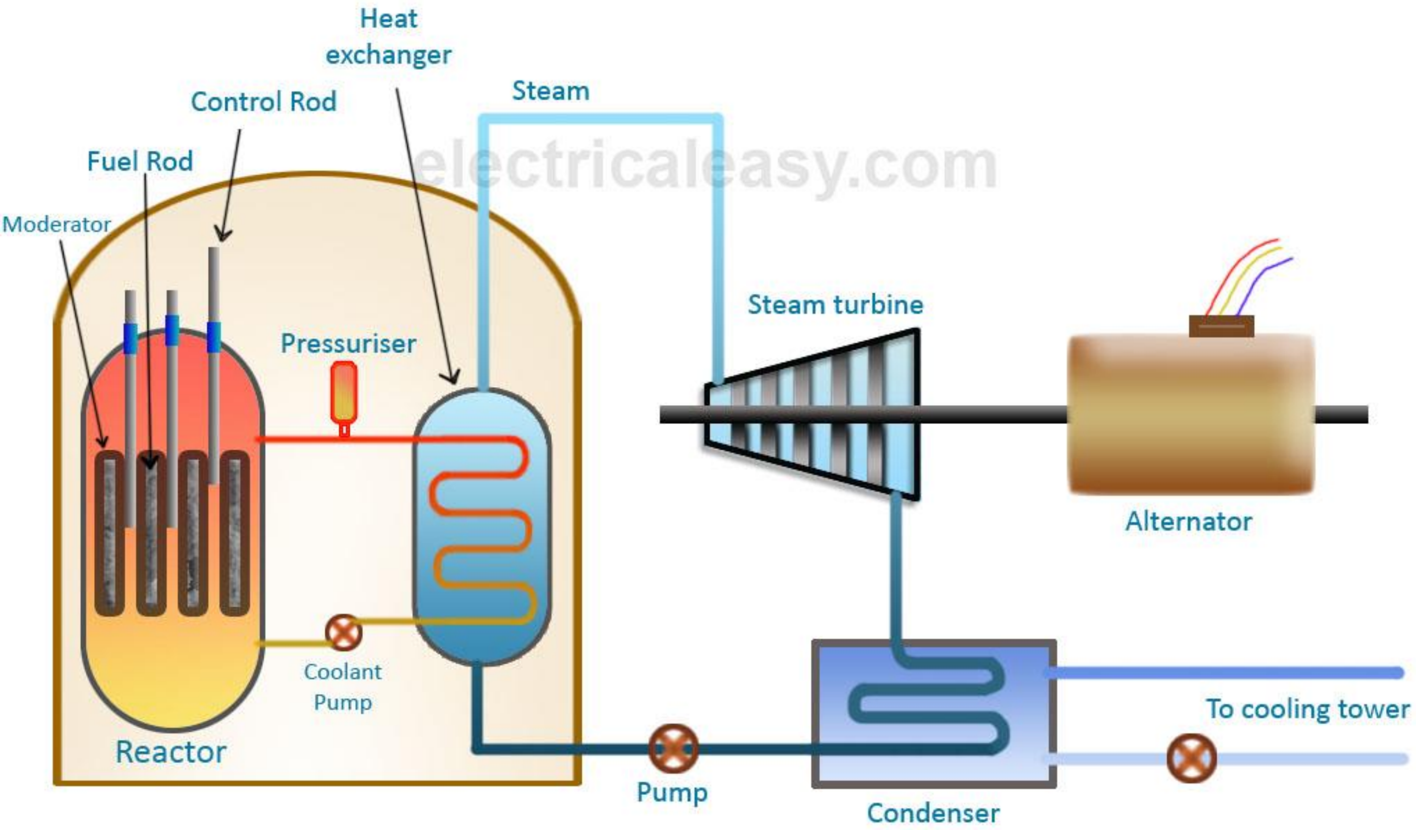
- ✓ U^{235} splits into two fragments (Ba^{141} & K^{92}) of approximately equal size.
- ✓ About 2.5 neutrons are released. 1 neutron is used to sustain the chain reaction. 0.9 neutrons is absorbed by U^{238} and becomes Pu^{239}. The remaining 0.6 neutrons escapes from the reactor.
- ✓ The neutrons produced move at a very high velocity of 1.5×10^7 m/sec and fission other nucleus of U^{235}. Thus fission process and release of neutrons take place continuously throughout the remaining material.
- ✓ A large amount of energy(200 Million electron volts, Mev) is produced.

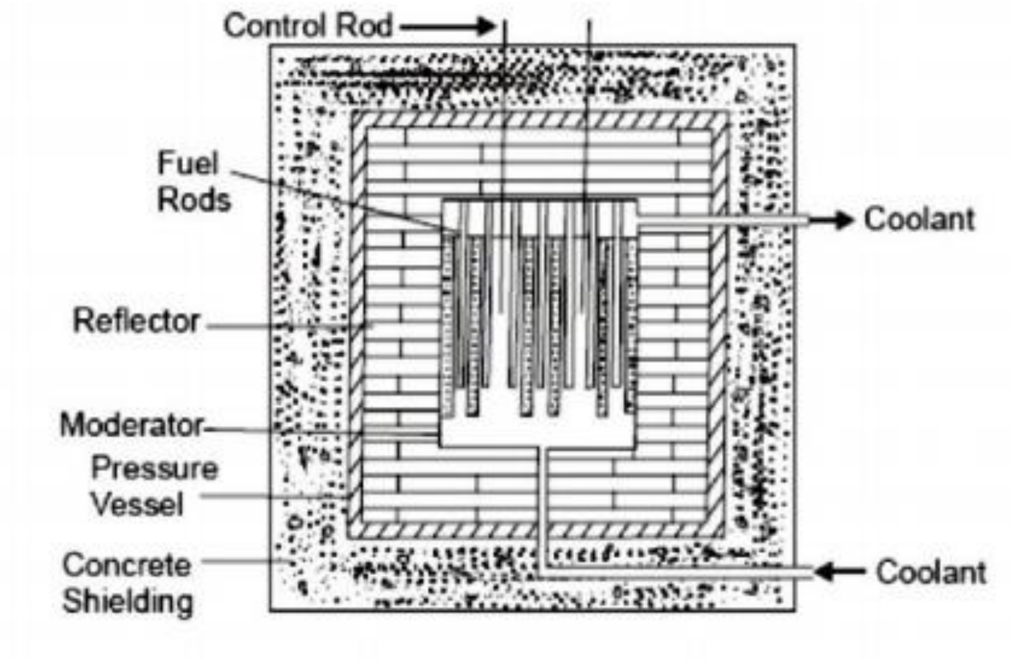


➢ Note : Moderators are provided to slow down the neutrons from the high velocities but not to absorb them.



Parts of nuclear power plant





Nuclear reactor

1. Reactor Core

It consists of fuel elements, control rods, coolant, moderator and pressure vessels. Cores generally have shapes of right circular cylinders with diameters ranging from .5 to 15 metres. Fuel rods made of uranium rods clod in thin sheath of stainless steel, zirconium or aluminium.

2. Reflector-

It is placed round the core, to reflect back some of the neutrons that leak out from core surface.

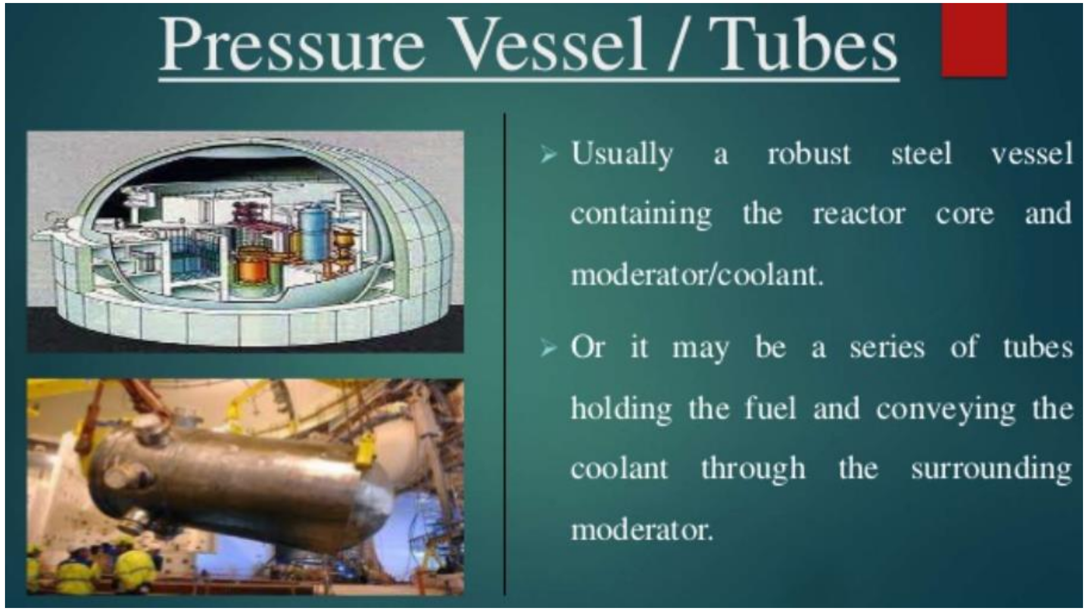
3. Control Rods

- It is made up of heavy mass element.It simply absorb the neutrons so that it can either maintain or stop a reaction.

Examples-Cadmium,lead etc.

It has following purposes-

1. For starting the reactor.
2. For maintaining at that level.
3. For shutting the reactor down under normal or emergency conditions.

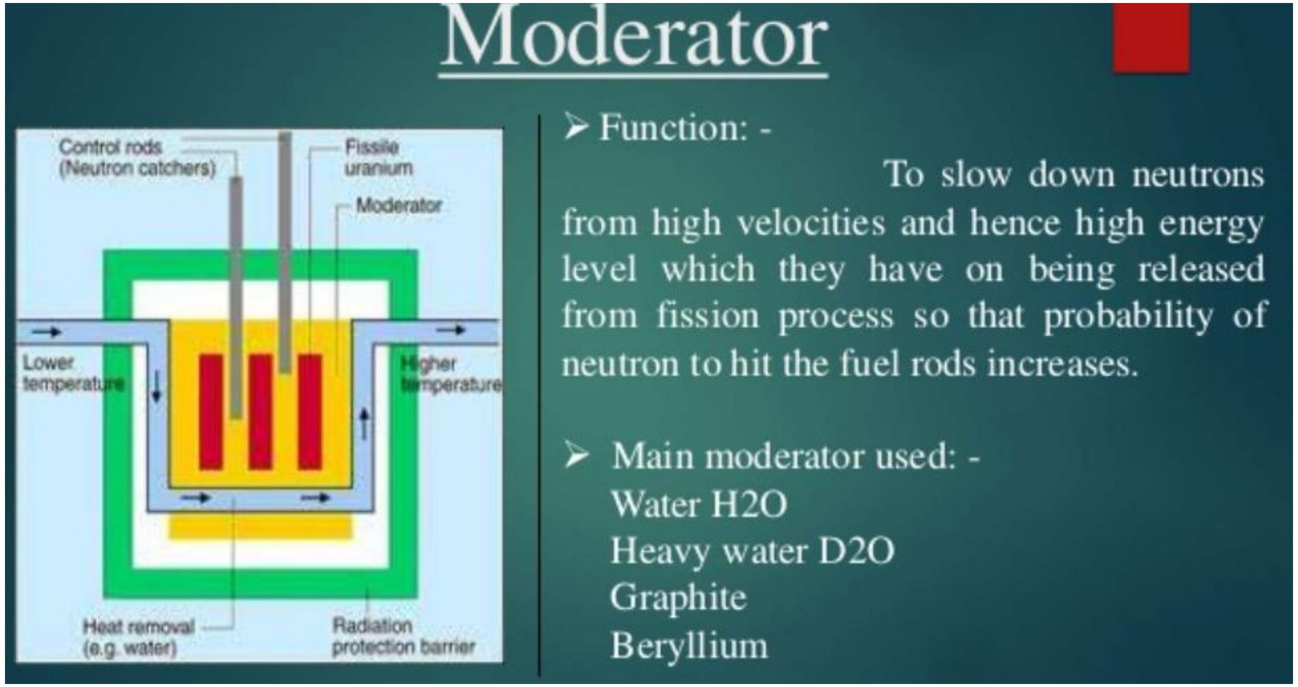


Pressure Vessel / Tubes

- Usually a robust steel vessel containing the reactor core and moderator/coolant.
- Or it may be a series of tubes holding the fuel and conveying the coolant through the surrounding moderator.

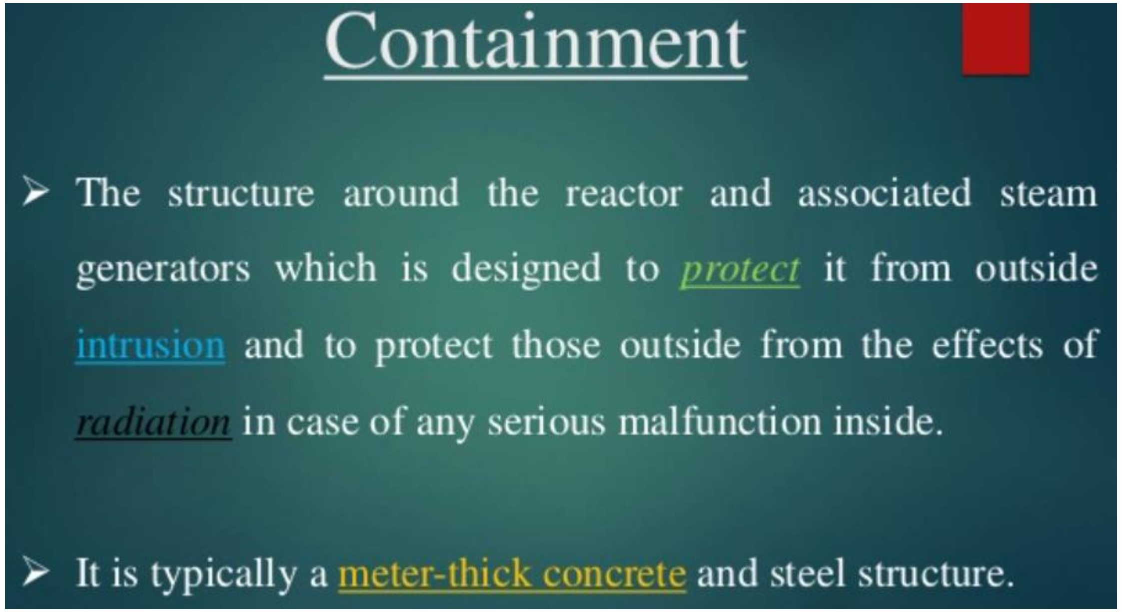
Fuel

- Uranium-235 is the basic fuel.
- Usually pellets of uranium oxide (UO_2) are arranged in tubes to form *fuel rods*.



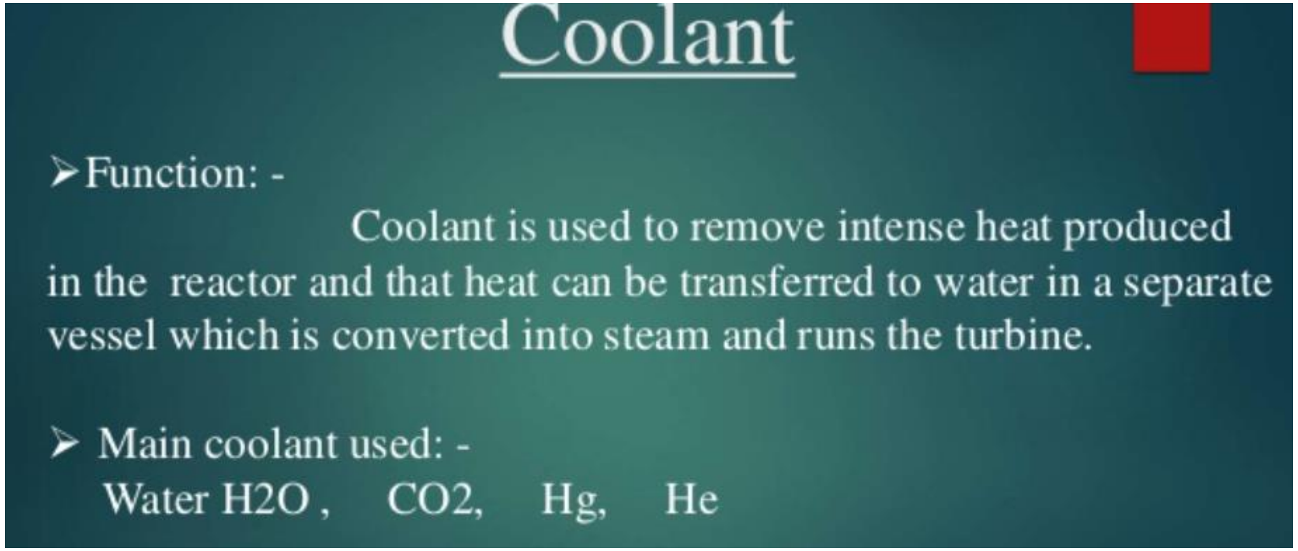
Moderator

- Function: -
  To slow down neutrons from high velocities and hence high energy level which they have on being released from fission process so that probability of neutron to hit the fuel rods increases.
- Main moderator used: -
  Water H2O
  Heavy water D2O
  Graphite
  Beryllium



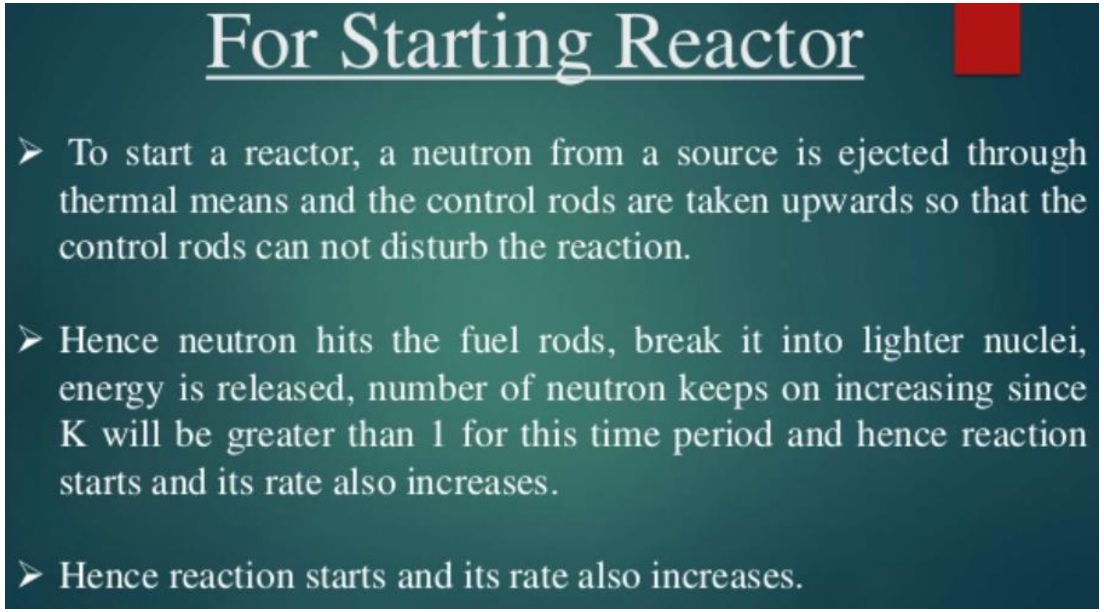
Containment

- The structure around the reactor and associated steam generators which is designed to *protect* it from outside intrusion and to protect those outside from the effects of *radiation* in case of any serious malfunction inside.
- It is typically a meter-thick concrete and steel structure.



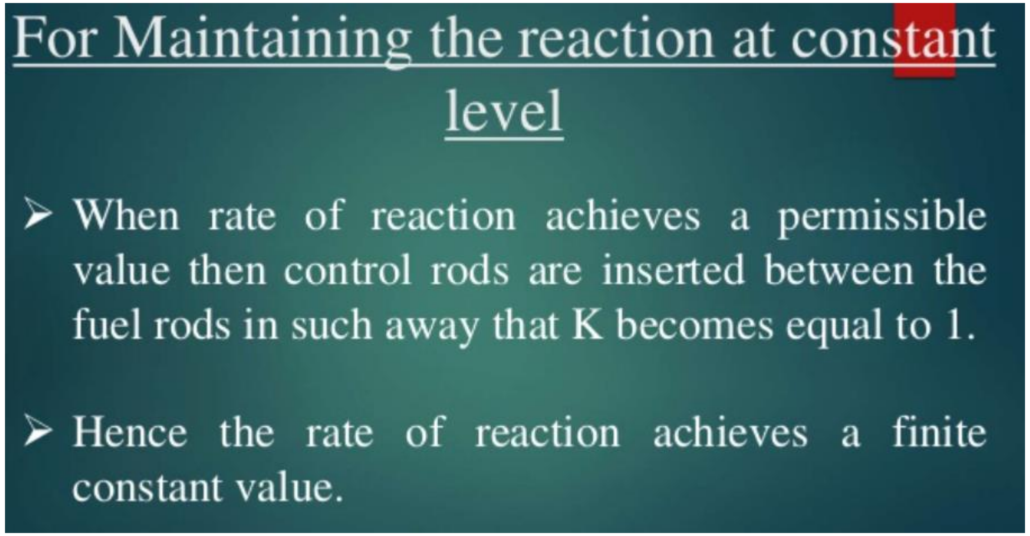
Coolant

- Function: -
  Coolant is used to remove intense heat produced in the reactor and that heat can be transferred to water in a separate vessel which is converted into steam and runs the turbine.
- Main coolant used: -
  Water H2O , CO2, Hg, He



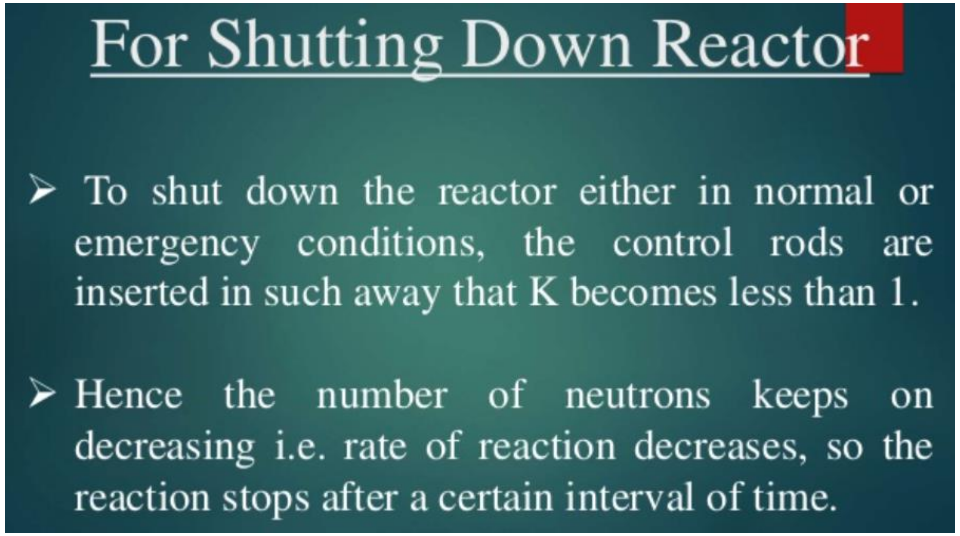
For Starting Reactor

- To start a reactor, a neutron from a source is ejected through thermal means and the control rods are taken upwards so that the control rods can not disturb the reaction.
- Hence neutron hits the fuel rods, break it into lighter nuclei, energy is released, number of neutron keeps on increasing since K will be greater than 1 for this time period and hence reaction starts and its rate also increases.
- Hence reaction starts and its rate also increases.



For Maintaining the reaction at constant level

- When rate of reaction achieves a permissible value then control rods are inserted between the fuel rods in such away that K becomes equal to 1.
- Hence the rate of reaction achieves a finite constant value.



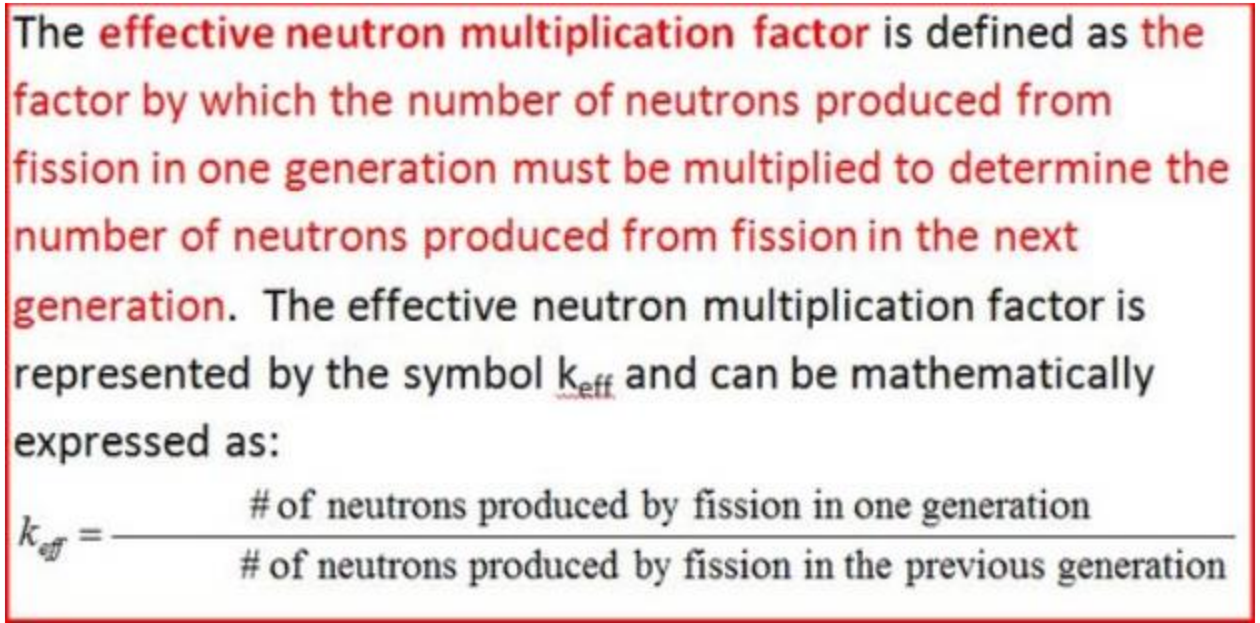
For Shutting Down Reactor

- To shut down the reactor either in normal or emergency conditions, the control rods are inserted in such away that K becomes less than 1.
- Hence the number of neutrons keeps on decreasing i.e. rate of reaction decreases, so the reaction stops after a certain interval of time.

1. Define Neutron Generation Time

A neutron generation is described as the absorption of a neutron which causes fission to the absorption of the neutrons from that fission. The time associated with this is known as the neutron generation time. By comparing the number of neutrons produced from fission in one generation to the number of neutrons produced from fission in the next generation, an indication of the rate of change in neutron population is obtained.

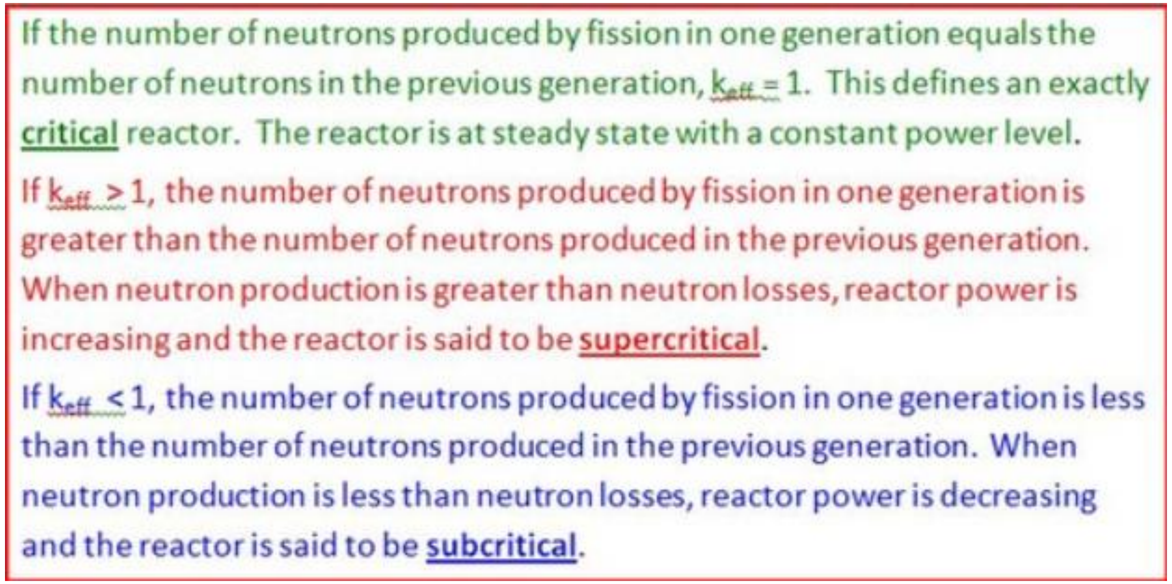
2. Define effective multiplication factor and discuss its relationship to the state of the reactor.



The effective neutron multiplication factor is defined as the factor by which the number of neutrons produced from fission in one generation must be multiplied to determine the number of neutrons produced from fission in the next generation. The effective neutron multiplication factor is represented by the symbol k_{eff} and can be mathematically expressed as:

$$k_{eff} = \frac{\#\text{ of neutrons produced by fission in one generation}}{\#\text{ of neutrons produced by fission in the previous generation}}$$

3. Define critical, subcritical and super critical with respect to the reactor and in terms of the effective neutron multiplication factor.



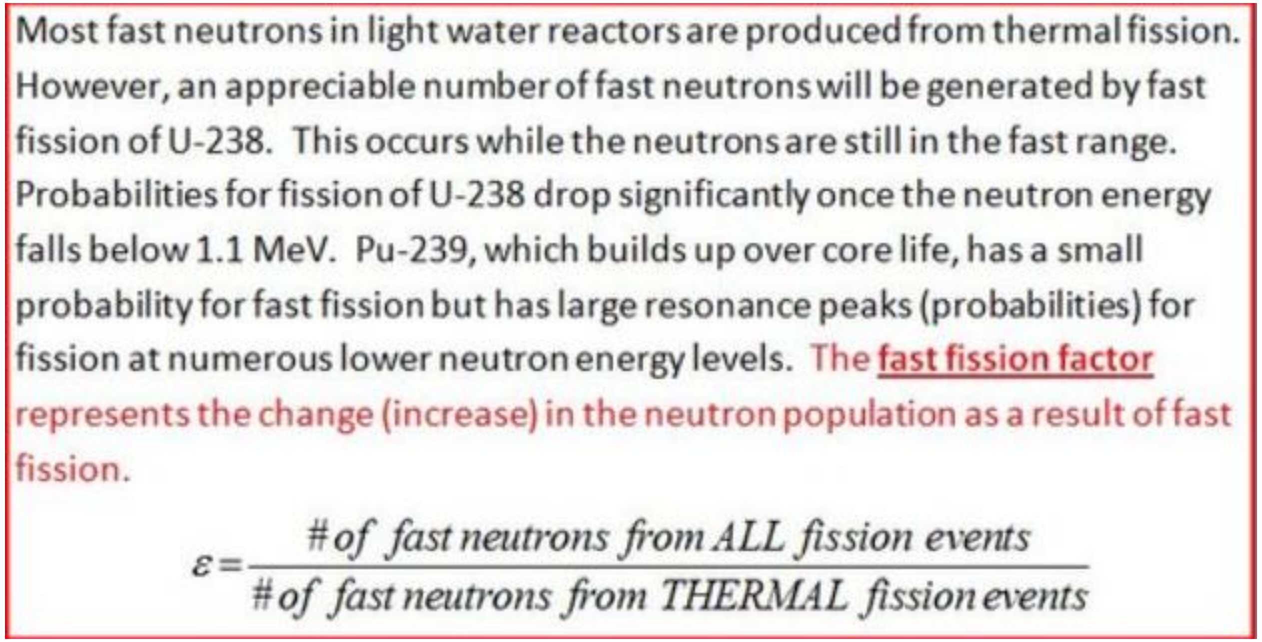
If the number of neutrons produced by fission in one generation equals the number of neutrons in the previous generation, $k_{eff} = 1$. This defines an exactly **critical** reactor. The reactor is at steady state with a constant power level.

If $k_{eff} > 1$, the number of neutrons produced by fission in one generation is greater than the number of neutrons produced in the previous generation. When neutron production is greater than neutron losses, reactor power is increasing and the reactor is said to be **supercritical**.

If $k_{eff} < 1$, the number of neutrons produced by fission in one generation is less than the number of neutrons produced in the previous generation. When neutron production is less than neutron losses, reactor power is decreasing and the reactor is said to be **subcritical**.

4. Describe the Neutron Life Cycle using the following terms:

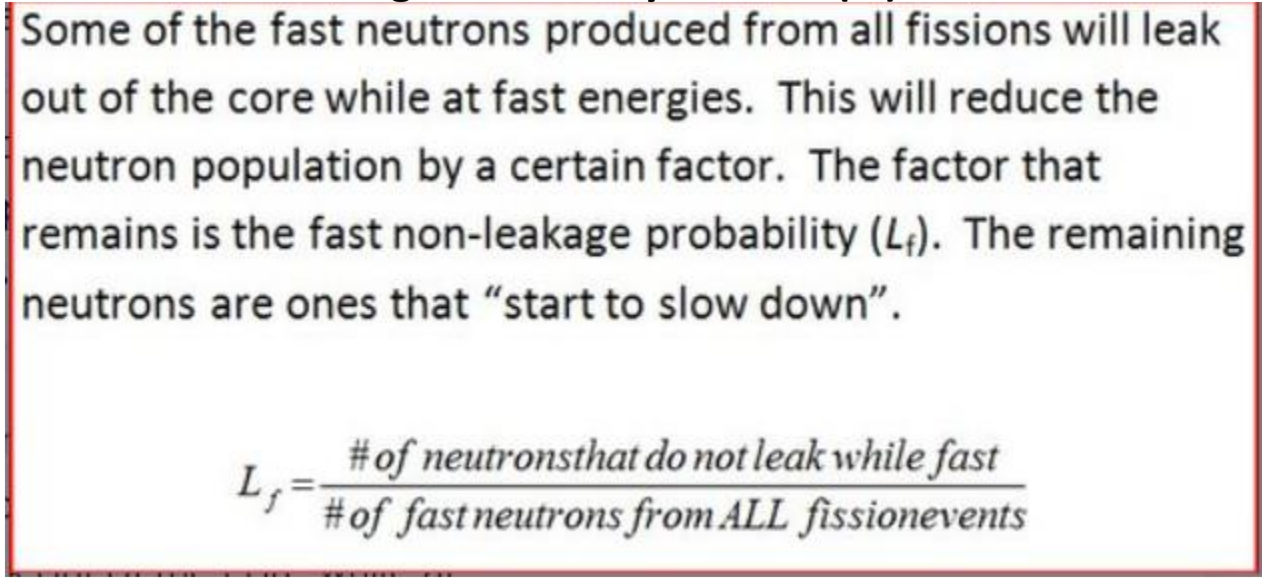
4A: Fast Fission Factor - ()



Most fast neutrons in light water reactors are produced from thermal fission. However, an appreciable number of fast neutrons will be generated by fast fission of U-238. This occurs while the neutrons are still in the fast range. Probabilities for fission of U-238 drop significantly once the neutron energy falls below 1.1 MeV. Pu-239, which builds up over core life, has a small probability for fast fission but has large resonance peaks (probabilities) for fission at numerous lower neutron energy levels. The **fast fission factor** represents the change (increase) in the neutron population as a result of fast fission.

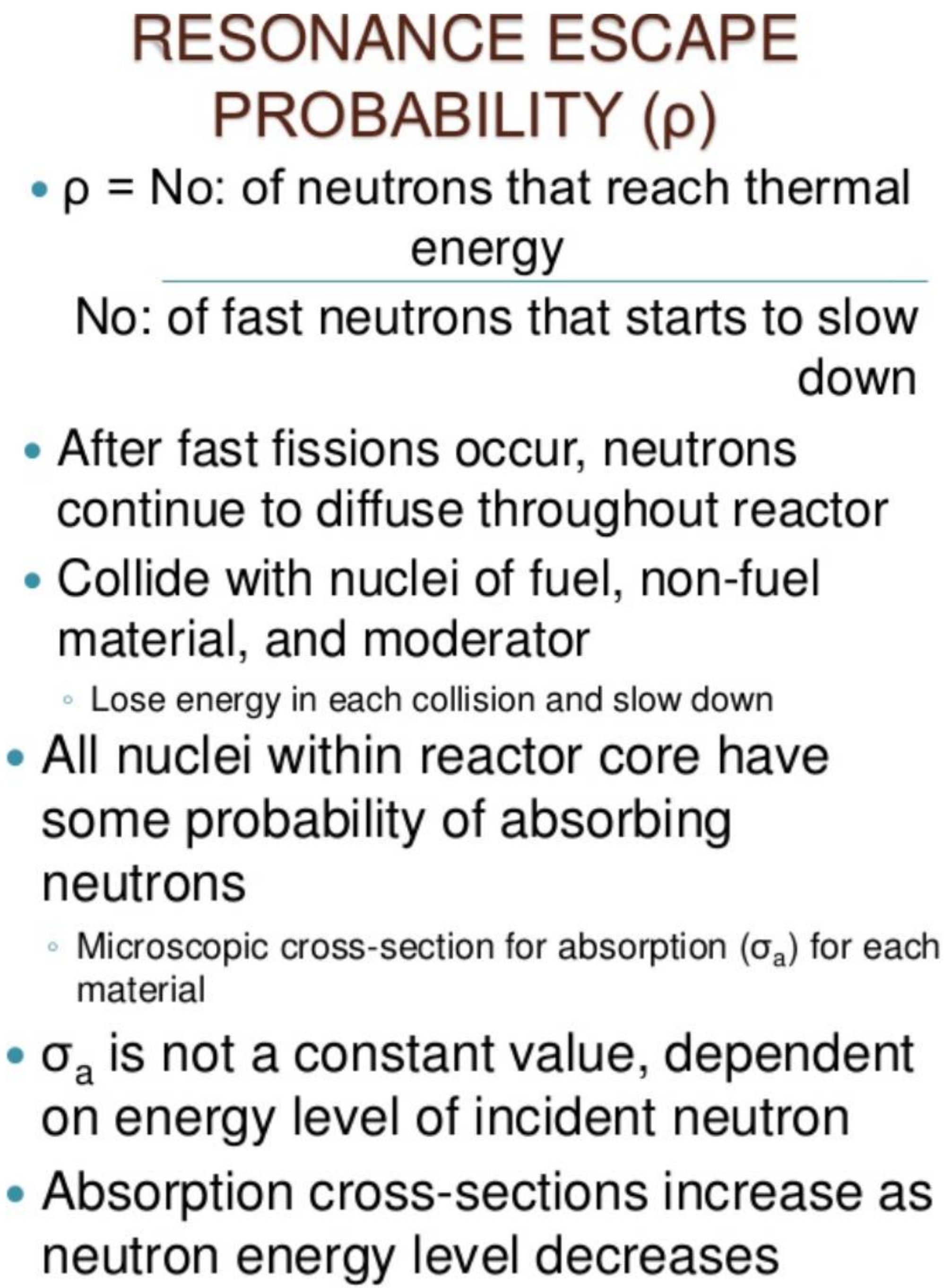
$$\varepsilon = \frac{\#of\ fast\ neutrons\ from\ ALL\ fission\ events}{\#of\ fast\ neutrons\ from\ THERMAL\ fission\ events}$$

4B: Fast Non-Leakage Probability Factor - (Lf)



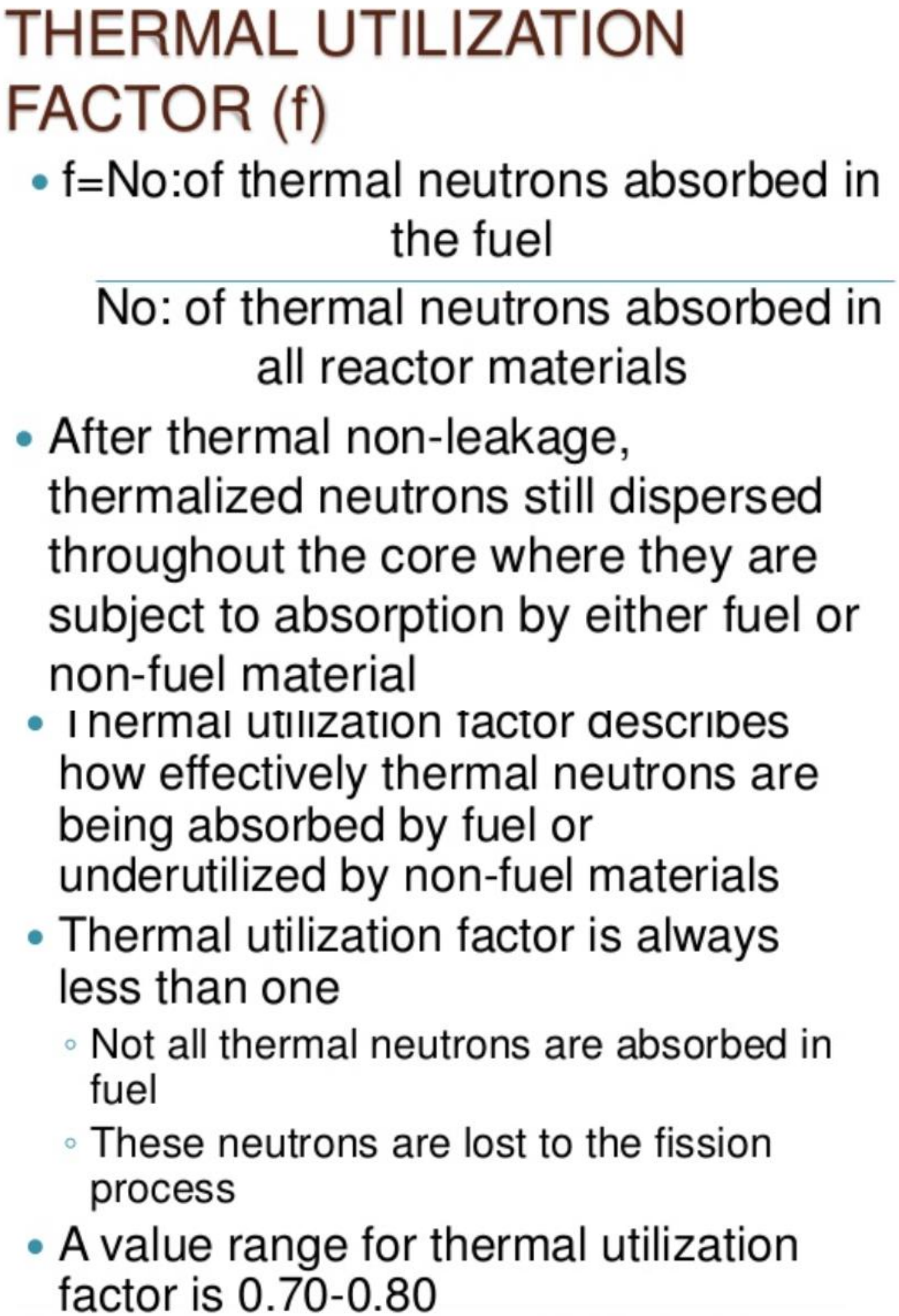
Some of the fast neutrons produced from all fissions will leak out of the core while at fast energies. This will reduce the neutron population by a certain factor. The factor that remains is the fast non-leakage probability (L_f). The remaining neutrons are ones that "start to slow down".

$$L_f = \frac{\#of\ neutronsthat\ do\ not\ leak\ while\ fast}{\#of\ fastneutrons\ from\ ALL\ fissionevents}$$



RESONANCE ESCAPE PROBABILITY (ρ)

- ρ = No: of neutrons that reach thermal energy / No: of fast neutrons that starts to slow down
- After fast fissions occur, neutrons continue to diffuse throughout reactor
- Collide with nuclei of fuel, non-fuel material, and moderator
  - Lose energy in each collision and slow down
- All nuclei within reactor core have some probability of absorbing neutrons
  - Microscopic cross-section for absorption (σ_a) for each material
- σ_a is not a constant value, dependent on energy level of incident neutron
- Absorption cross-sections increase as neutron energy level decreases



THERMAL UTILIZATION FACTOR (f)

- f=No:of thermal neutrons absorbed in the fuel / No: of thermal neutrons absorbed in all reactor materials
- After thermal non-leakage, thermalized neutrons still dispersed throughout the core where they are subject to absorption by either fuel or non-fuel material
- Thermal utilization factor describes how effectively thermal neutrons are being absorbed by fuel or underutilized by non-fuel materials
- Thermal utilization factor is always less than one
  - Not all thermal neutrons are absorbed in fuel
  - These neutrons are lost to the fission process
- A value range for thermal utilization factor is 0.70-0.80

REPRODUCTION FACTOR (η)

- η= No: of fast neutrons neutrons produced by thermal fission

  No: of thermal neutrons absorbed in the fuel

- Most neutrons absorbed in fuel cause fission, but some do not
- Reproduction factor represents net gain in neutron population
- Value range of 1.65-2.0

Formula:

Mass per atom of U^{235} $= \frac{At.weight\ of\ U^{235}}{Avogadro\ number}$

$= \frac{235}{6.02 \times 10^{26}}$

Where Avogadro Number = 6.023×10^{23}

1 ev = 1.6 X 10^{-12} erg

1 Mev = 1.6 X 10^{-6} erg

1 Joule/sec = 10^{7} erg/sec

1 watt = Joule/sec

fission rate = P/E

Where, P = Power

E = Energy realeased

Example: 1

Calculate the number of fission in uranium per second required to produce 2 kw power if energy released per fission is 200 Mev.

Here ,

P= Power = 2 kw

E = Energy released per fission = 200 Mev = 200 × 10^{6}

= 200 X10^{6} X1.6 X10^{-12} ergs

= 3.2 × 10^{-4} ergs

[1 ev =1×10^{-12} energy]

P = 2kw = 2000 watts = 2000 joules/sec

= 2000 × 10^{7} ergs/sec = 2 × 10^{10} ergs/sec

N = Number of fission per/ sec

= P/E

= (2×10^{10}) / 3.2 X10^{-4}

= 6.25 X 10^{-3} (answer).

Example: 2

Calculate the fusion rate of U^{235} for producing power of one watt if 200 Mev if energy is released per fusion of U^{235}.

Solution: Here given that,

P = Power = 1watt

E = Energy released per fusion of U^{235} nucleus

= 200 Mev

= 200 × 10^{6} ev

= 200 × 10^{6} 1.6× 10^{-12} ergs [1 ev = 1.6 10^{-12} ergs]

= 3.2 ×10^{-4} ergs

Fission rate of producing one watt of power = P/E

= (1 X 10^{7}) / (3.2 X 10^{-4})

= 3.1 x 10^{10} fusion/sec (answer)

Example: 3

A railway engine is driven by atomic power at an efficiency of 40% and develops an average power of 1600 kw during 8 hours run from one station to another. Determine how much U^{238} would be consumed on the run if each atom on fission releases 200 Mev.

Solution:

Output = 1600 kw

Efficiency η = 0.4

η = output / Input

input = 1600 /0.4

input = 4000 kw = 40 X 10^{6} watts

E = Energy released per fission = 200 Mev = 200 × 10^{6} ev

= 200 × 10^{6} 1.6× 10^{-12} ergs

[1 ev = 1.6 10^{-12} ergs]

= 3.2 ×10^{-4} ergs

t = Time = 8 hours = 8 × 3600 seconds

Input nuclear energy required for 8 hours = Input × t

= 4×10^{6}×8×3600 j

=115.2×10^{9}j

= 115.2×10^{16} ergs

Number of U^{235} atoms required for 8 hour run

= 115.2 X 10^{9}/ E

= (115.2 X 10^{9}) / (3.2 X 10^{-11})

= 36 X 10^{20}

Weight of 6.023 X 10^{23} Uranium = 235 gm

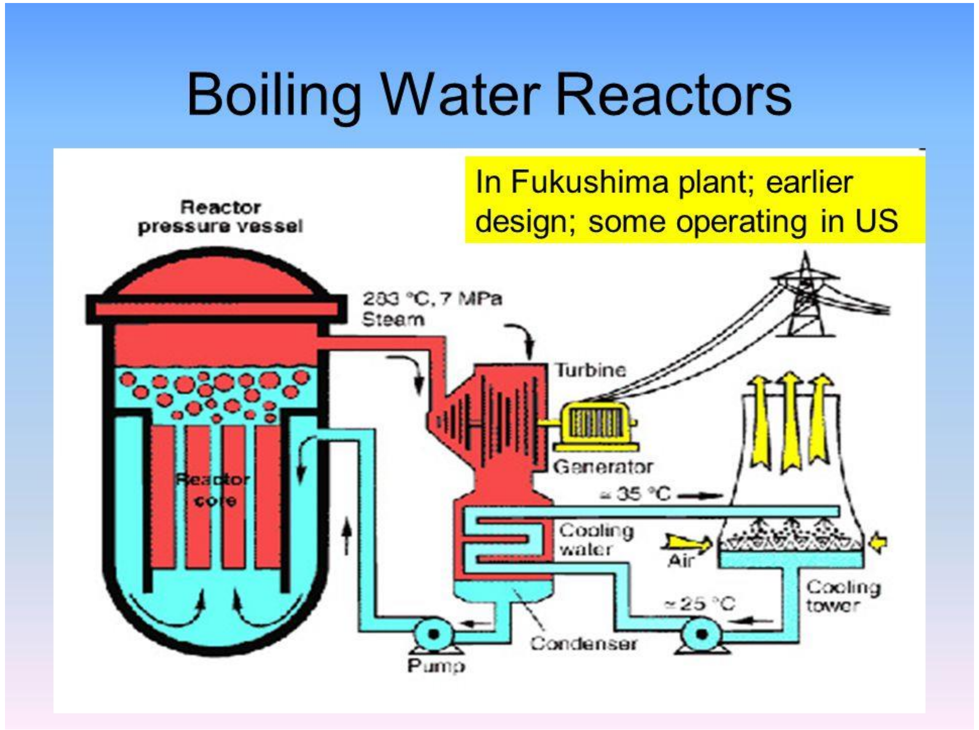
Weight of 1 Uranium = 235/ 6.023 X 10^{23}

Weight of 36 X 10^{20} Uranium $= \frac{235\ X\ 36\ X\ 10^{20}}{6.023\ X 10^{23}}$

= 1.4 gm (Ans)

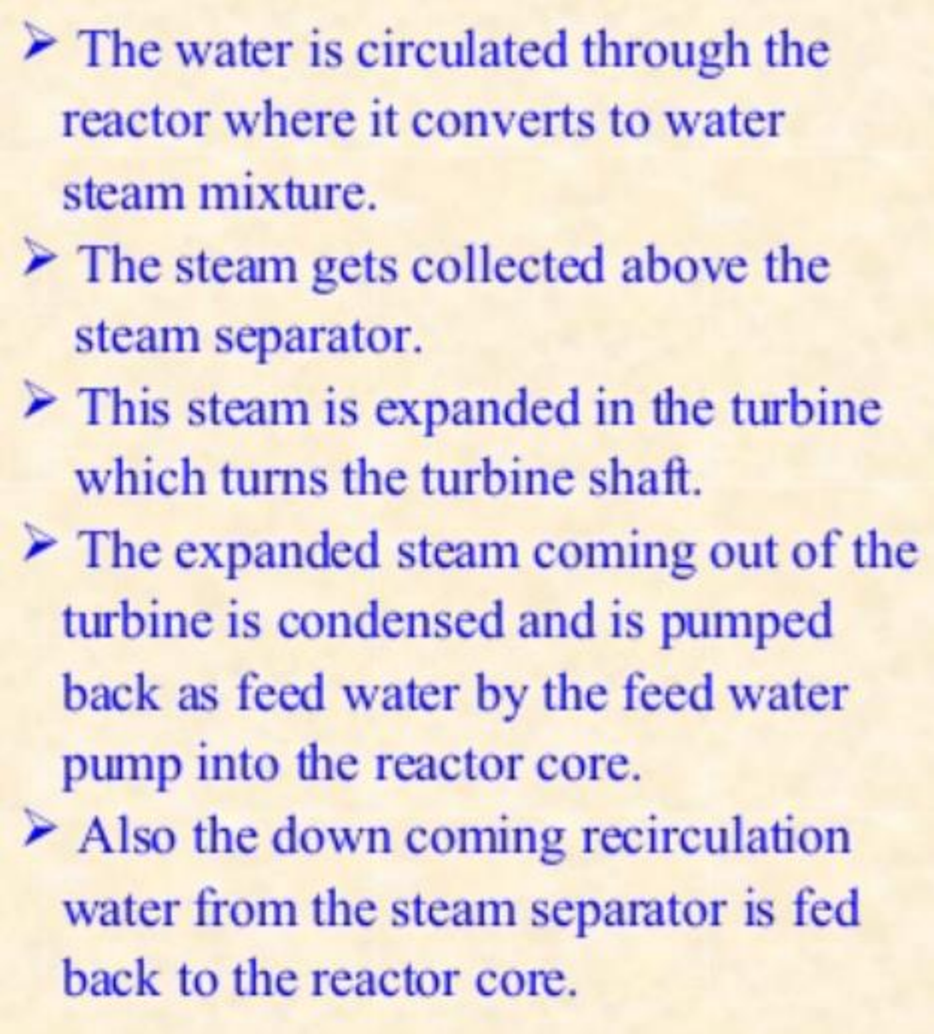
Types of Nuclear Reactors

1. BWR-Boiling Water Reactor
2. PWR-Pressurized Water Reactor
3. PHWR-Pressurised Heavy Water Reactor
4. GCR-Gas Cooled Reactor
5. AGR-Advanced Gas-Cooled Reactor
6. LGR-Light Water Cooled - Graphite Moderated Reactor



Boiling Water Reactors

In Fukushima plant; earlier design; some operating in US



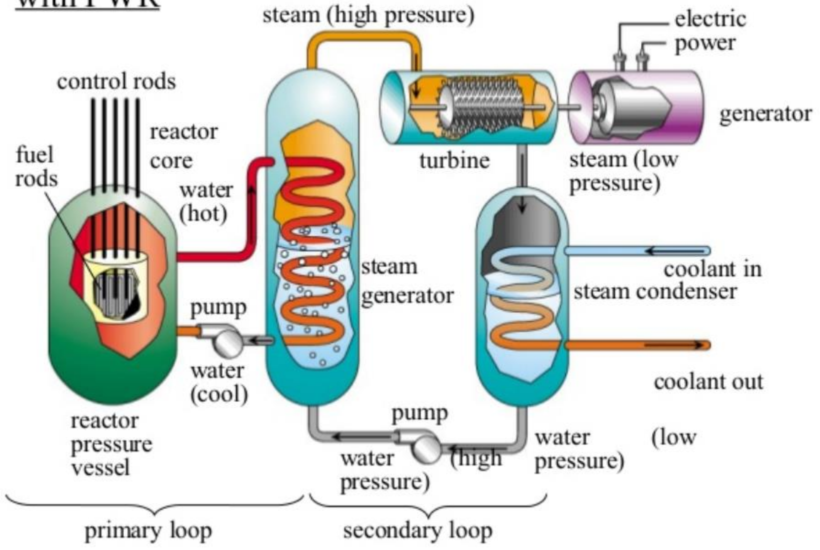
- ➢ The water is circulated through the reactor where it converts to water steam mixture.
- ➢ The steam gets collected above the steam separator.
- ➢ This steam is expanded in the turbine which turns the turbine shaft.
- ➢ The expanded steam coming out of the turbine is condensed and is pumped back as feed water by the feed water pump into the reactor core.
- ➢ Also the down coming recirculation water from the steam separator is fed back to the reactor core.

BWR Advantages:

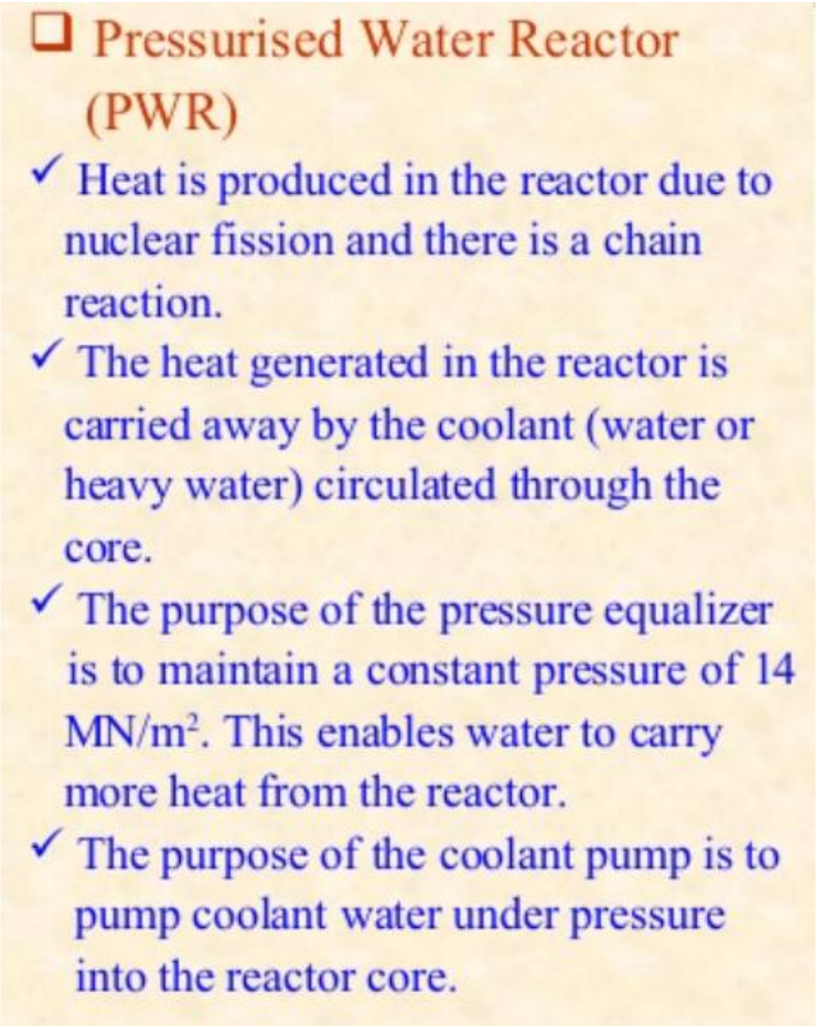
- Direct cycle, no secondary loop
- Less mass flow rate since coolant water is permitted to absorb latent heat and sensible heat.
- Can operate at lower pressure ~ 900 psi {not zero/ atmospheric pressure since
  1. high temp required to drive turbines
  2. high pressure prevents wall dryout}
- Lower pressure mean thinner pressure vessel and less expensive components.

BWR Disadvantages:

- Radioactive coolant throughout engine room
- Shielding and containment larger
- Lower power density – need larger core and PV then PWR



Schematic diagram of a nuclear power plant with PWR



☐ Pressurised Water Reactor (PWR)

- ✓ Heat is produced in the reactor due to nuclear fission and there is a chain reaction.
- ✓ The heat generated in the reactor is carried away by the coolant (water or heavy water) circulated through the core.
- ✓ The purpose of the pressure equalizer is to maintain a constant pressure of 14 MN/m^2. This enables water to carry more heat from the reactor.
- ✓ The purpose of the coolant pump is to pump coolant water under pressure into the reactor core.

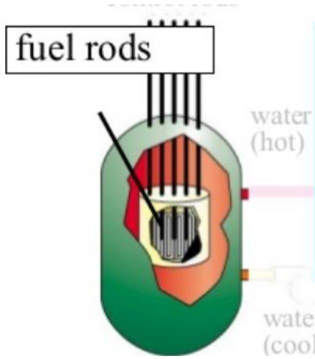
✓ The steam generator is a heat exchanger where the heat from the coolant is transferred on to the water that circulates through the steam generator. As the water passes through the steam generator it gets converted into steam.

✓ The steam produced in the steam generator is sent to the turbine. The turbine blades rotate.

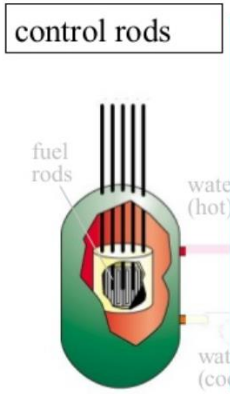
✓ The turbine shaft is coupled to a generator and electricity is produced.

✓ After the steam performing the work on the turbine blades by expansion, it comes out of the turbine as wet steam. This is converted back into water by circulating

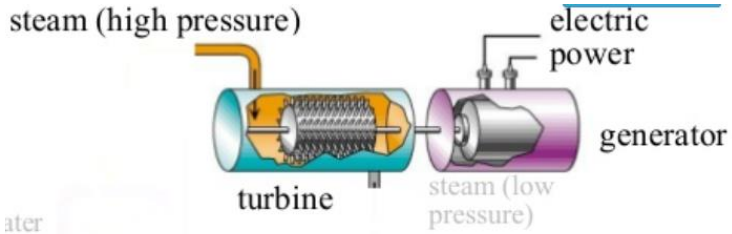
✓ The feed pump pumps back the condensed water into the steam generator.



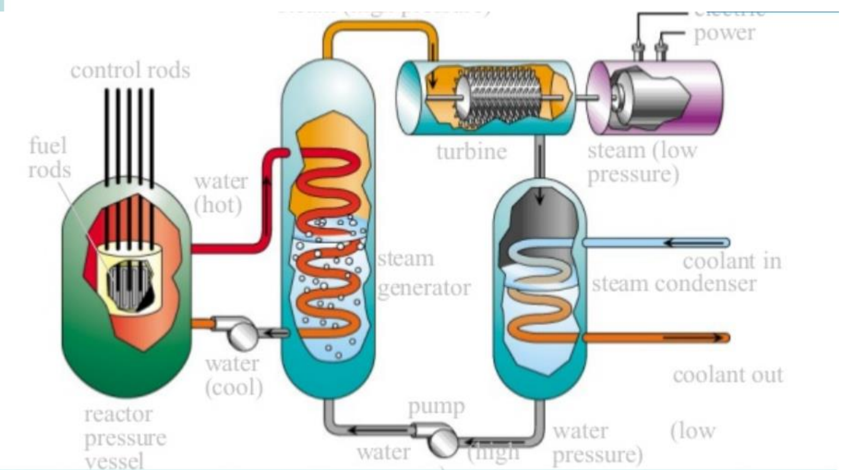
- They contain the nuclear fuel: uranium (U-235)
- They are surrounded by a **moderator (water or graphite)** to ***slow down the neutrons released.***



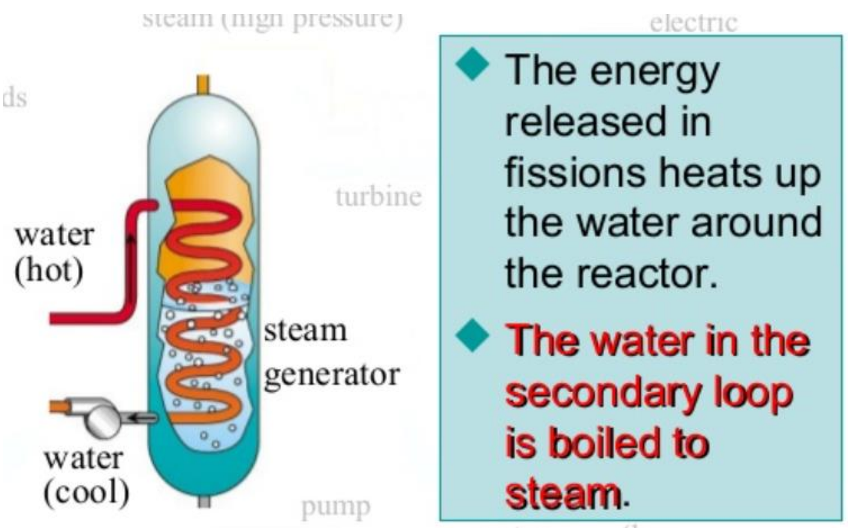
- They control the rate of reaction by moving in and out of the reactor.
  - Move in: rate of reaction ↓
  - Move out: rate of reaction ↑
  - All are moved in: the reactor is shut down
- They are made of boron or cadmium that can ***absorb neutrons.***



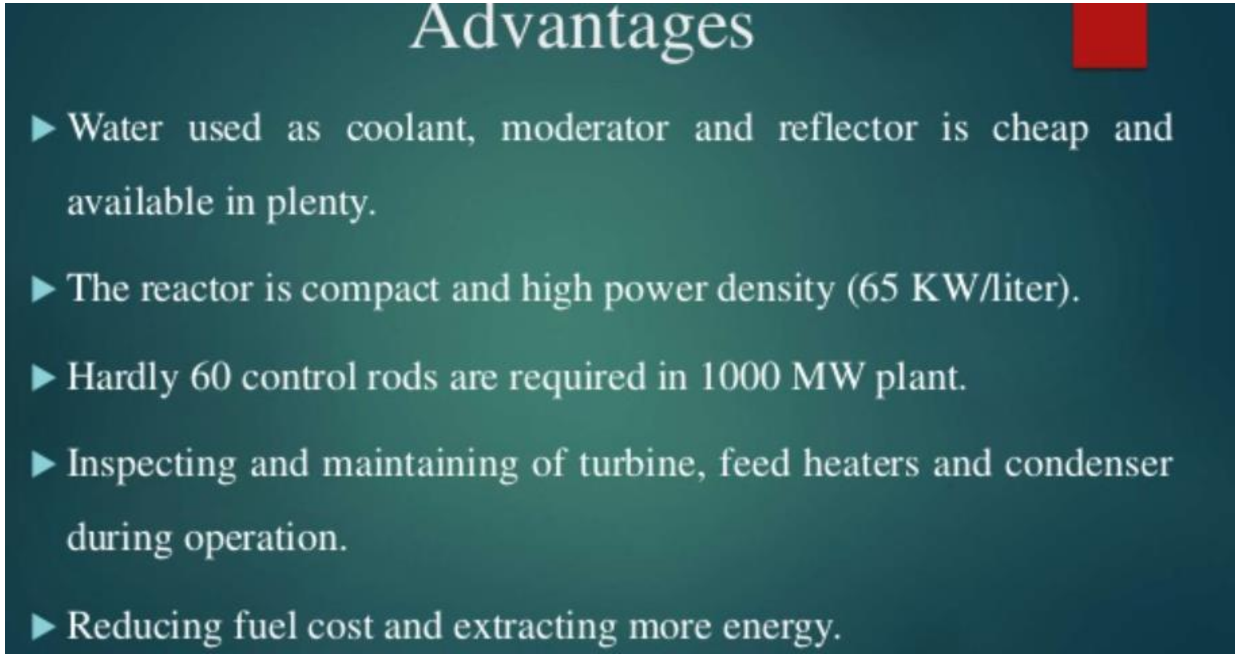
- **The steam drives a turbine, which turns the generator.**
- Electricity is produced by the generator.



- ***Two separate water systems*** are used to avoid radioactive substances to reach the turbine.

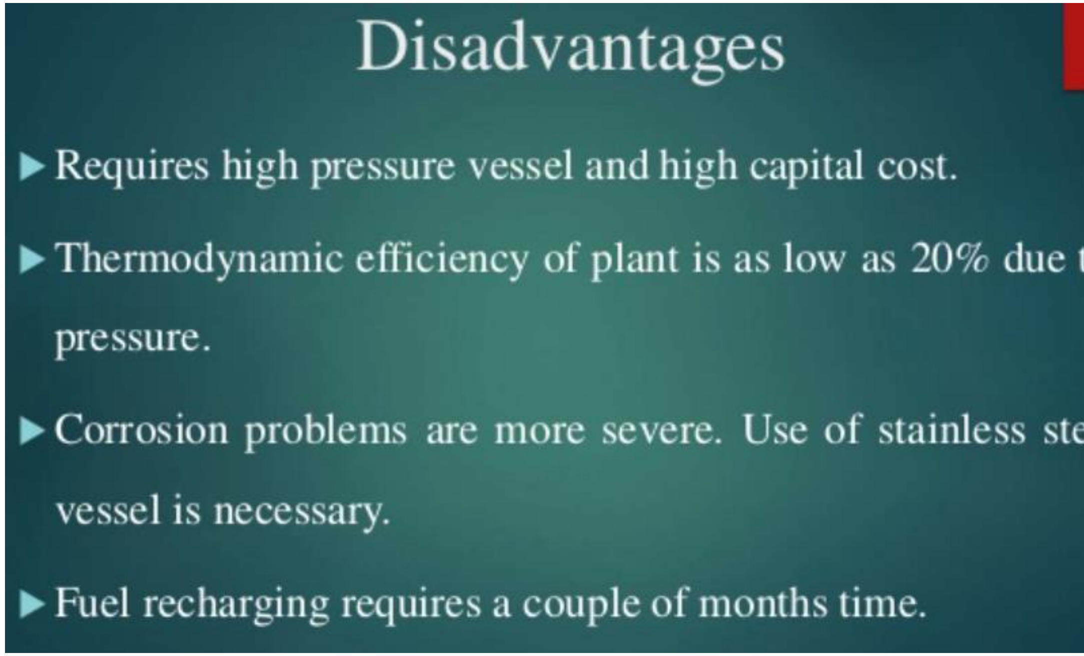


- The energy released in fissions heats up the water around the reactor.
- **The water in the secondary loop is boiled to steam.**



Advantages

- Water used as coolant, moderator and reflector is cheap and available in plenty.
- The reactor is compact and high power density (65 KW/liter).
- Hardly 60 control rods are required in 1000 MW plant.
- Inspecting and maintaining of turbine, feed heaters and condenser during operation.
- Reducing fuel cost and extracting more energy.



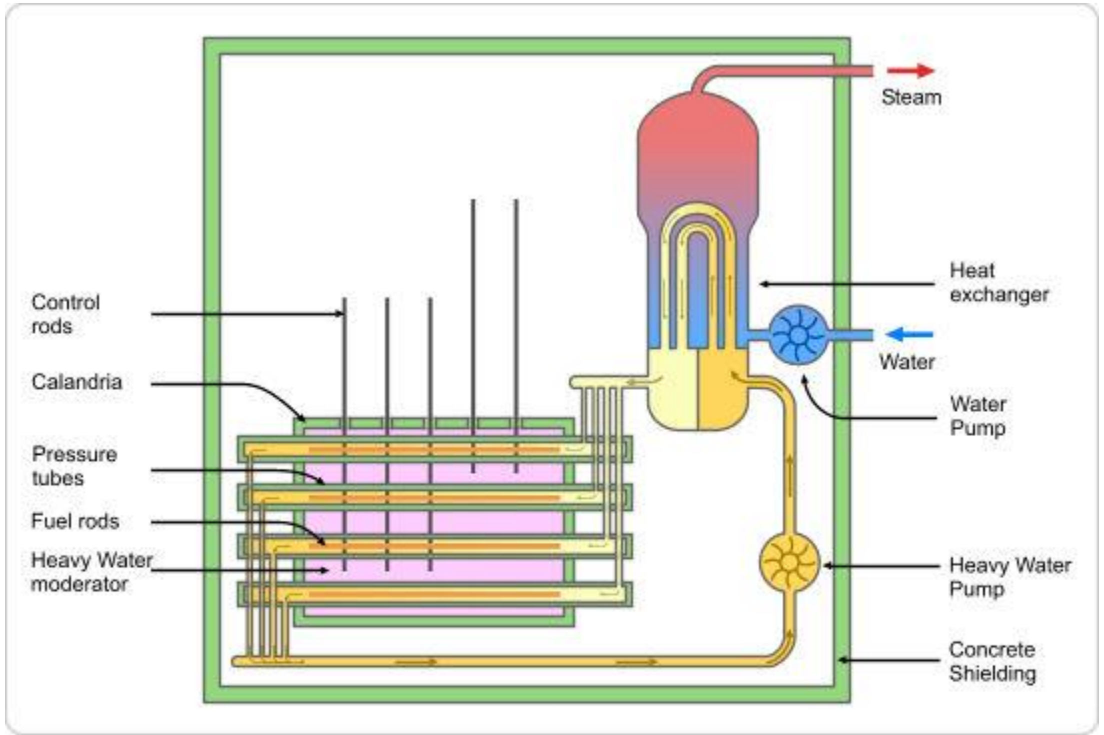
Disadvantages

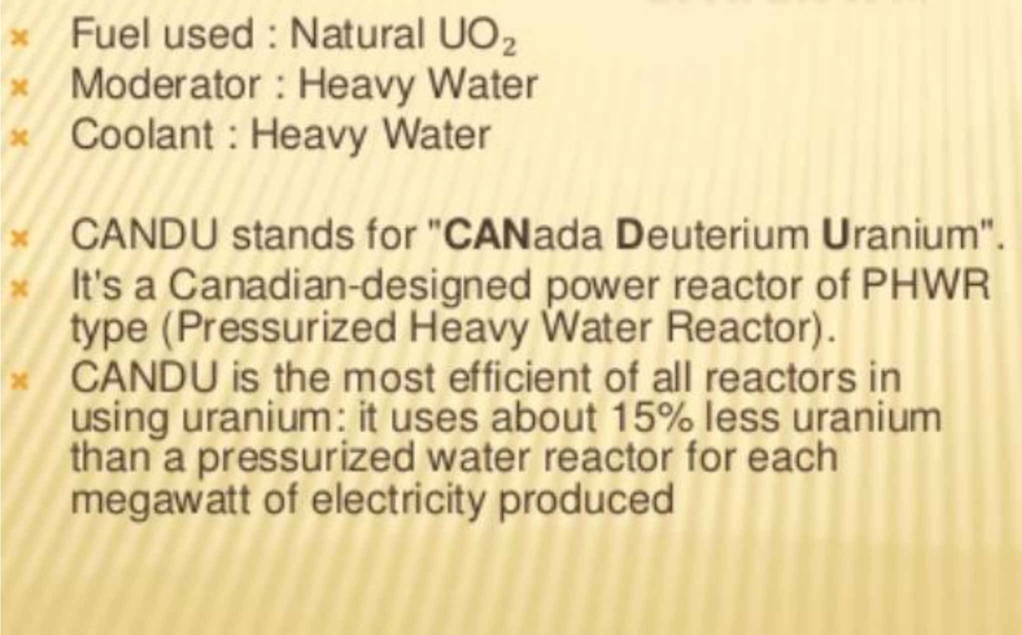
- Requires high pressure vessel and high capital cost.
- Thermodynamic efficiency of plant is as low as 20% due t pressure.
- Corrosion problems are more severe. Use of stainless ste vessel is necessary.
- Fuel recharging requires a couple of months time.

Relative Advantages & Disadvantages of PWR vs. BWR

	BWR	PWR
Thermodynamic Cycle	Single loop (turbine steam directly from reactor) - lower capital cost	Two loops - higher capital cost
	Lower pressure (7 MPa) decreases capital cost	Higher pressure (15 MPa) increases capital cost
Power Density (kW/liter)	Low power density due to boiling moderator	High power density
	Better power distribution	Must use zone loading to flatten power distribution
Major Equipment	Larger pressure vessel (due to low power density)	Smaller pressure vessel
	Thinner vessel walls (lower pressure)	Thicker vessel walls (higher pressure)
	Steam separators	Steam generator, pressurizer
Control	Control by rods and burnable poison	Control by rods, burnable poison, and chemical shim
	Use jet pumps to load follow	Natural ability to load follow
Core Design	Larger fuel pins, smaller burnup	Smaller diameter fuel pins, larger burnup
Materials Problems	Lower temperatures	Higher temperatures
	Little control over coolant purity	Good control over coolant purity

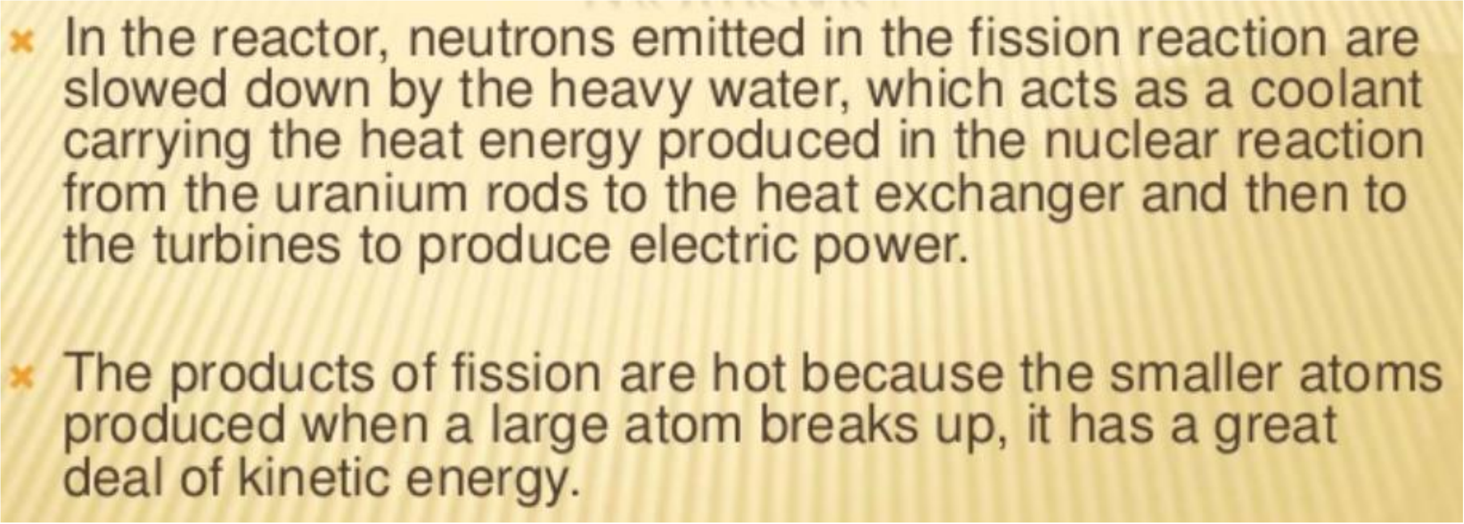
Pressurized Heavy Water Reactor (PHWR)
“CANDU”





- Fuel used : Natural UO_2
- Moderator : Heavy Water
- Coolant : Heavy Water

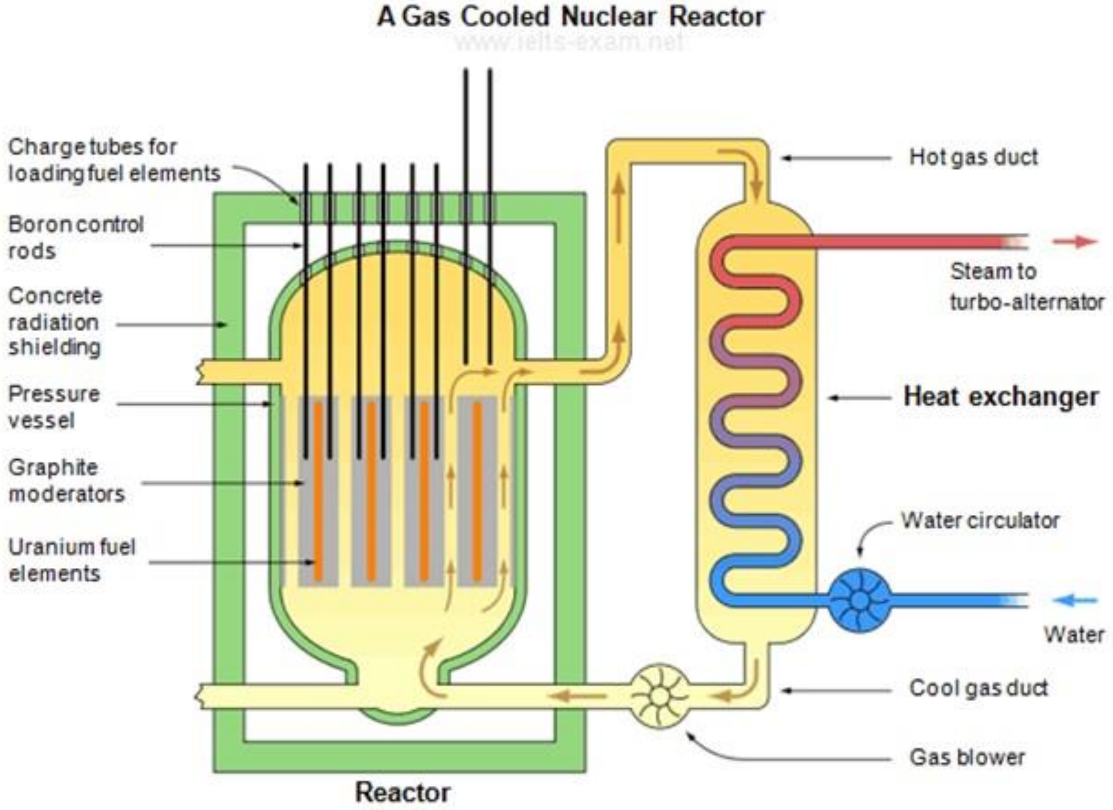
- CANDU stands for "**CAN**ada **D**euterium **U**ranium".
- It's a Canadian-designed power reactor of PHWR type (Pressurized Heavy Water Reactor).
- CANDU is the most efficient of all reactors in using uranium: it uses about 15% less uranium than a pressurized water reactor for each megawatt of electricity produced



- In the reactor, neutrons emitted in the fission reaction are slowed down by the heavy water, which acts as a coolant carrying the heat energy produced in the nuclear reaction from the uranium rods to the heat exchanger and then to the turbines to produce electric power.

- The products of fission are hot because the smaller atoms produced when a large atom breaks up, it has a great deal of kinetic energy.

Gas cooled nuclear reactor



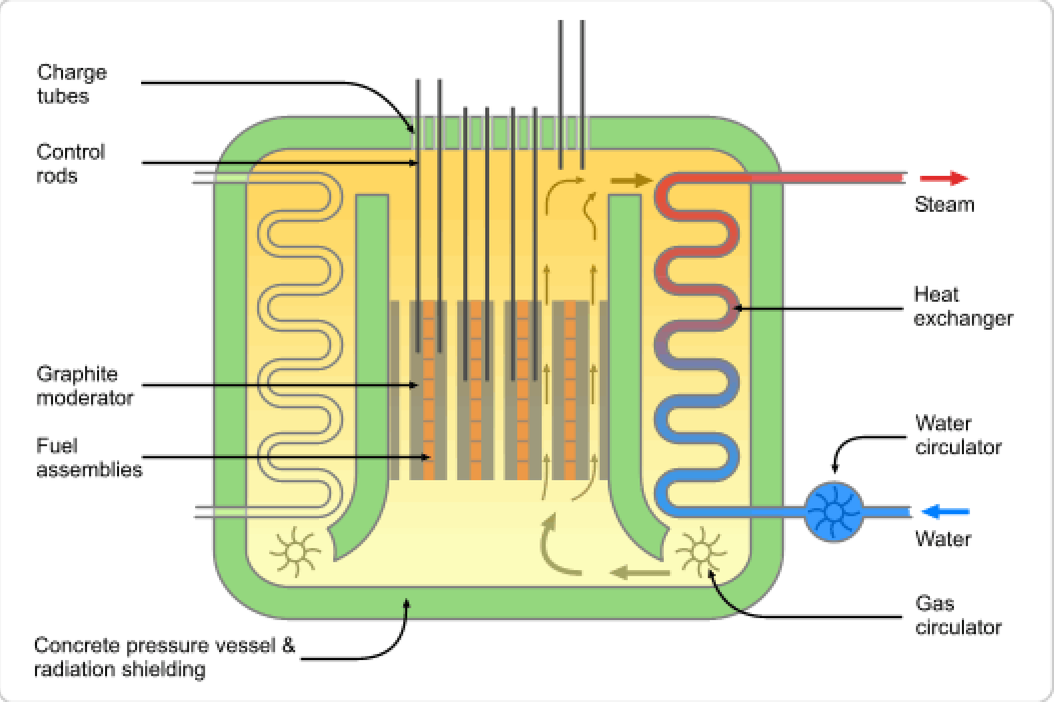
- Gas Cooled Reactor is also termed as Magnox reactor as the magnesium alloy is used to encase the fuel, natural uranium metal.

- These reactors are generally graphite moderated and CO_2 cooled. The whole assembly is cooled by blowing carbon dioxide gas past the fuel cans, which are specially designed to enhance heat transfer. The hot gas then converts water to steam in a steam generator.

- They can have a high thermal efficiency compared with PWRs due to higher operating temperatures.

AGR-Advanced Gas-Cooled Reactor

- To improve the cost effectiveness of the gas cooled reactor, it was necessary to go to higher temperatures to achieve higher thermal efficiencies and higher power densities to reduce capital costs.
- This entailed increases in cooling gas pressure and changing from Magnox to stainless steel cladding and from uranium metal to uranium dioxide fuel. This in turn led to the need for an increase in the proportion of U^{235} in the fuel.
- The resulting design is known as the AGR-Advanced Gas-Cooled Reactor

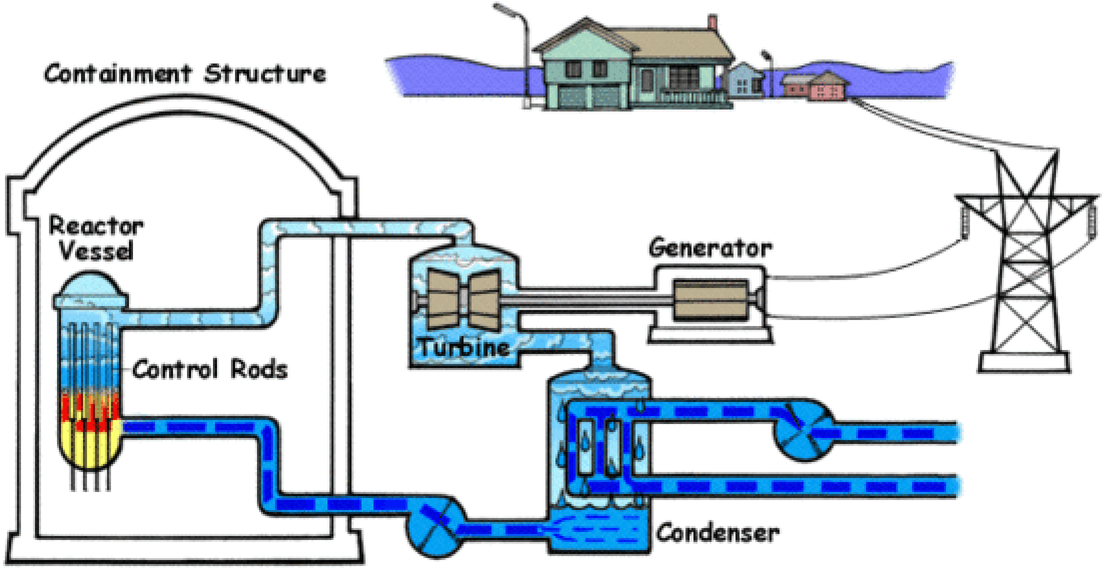


LGR-Light Water Cooled - Graphite Moderated Reactor

- In this type of reactor heat is removed from the fuel by pumping water under pressure up through the channels where it is allowed to boil, steam generated here drives electrical turbo-generators.

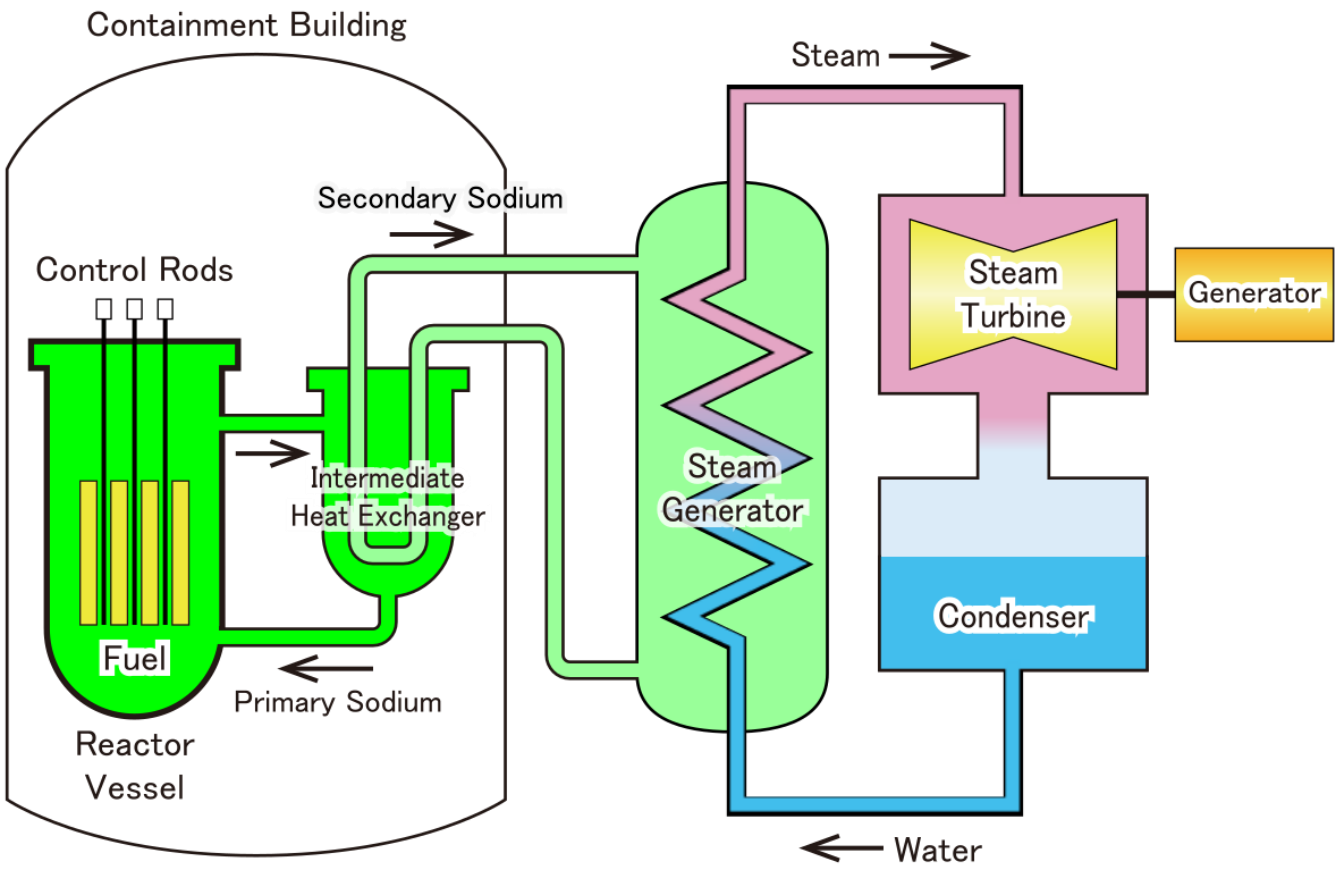
- Many of the major components, including pumps and steam drums, are located within a concrete shield to protect operators against the radioactivity of the steam.

- The design of this type of reactor is known as the RBMK Reactor.



Fast neutron reactor (FNR)/FBR

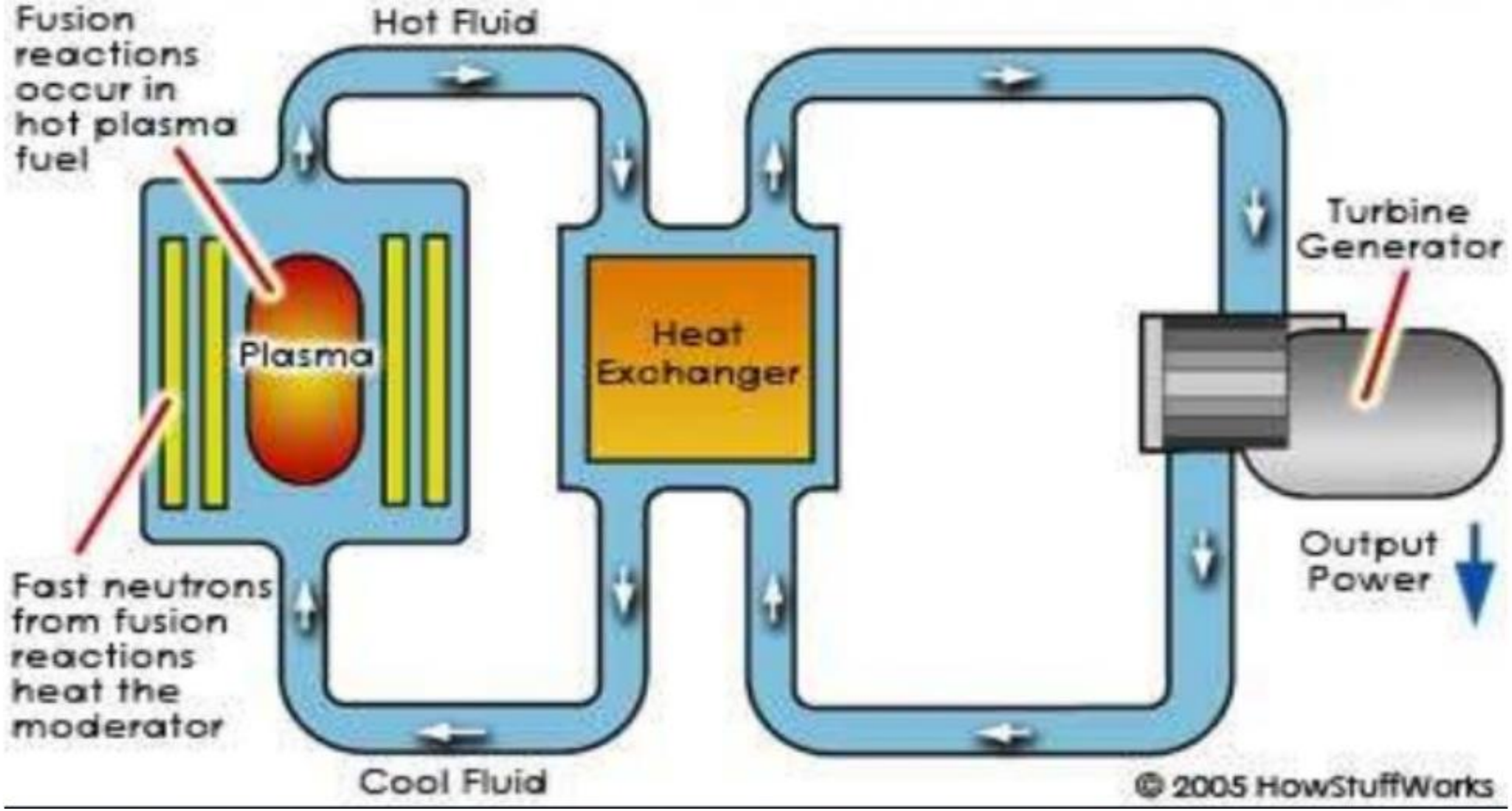
Some reactors do not have a moderator and utilise fast neutrons, generating power from plutonium while making more of it from the U-238 isotope in or around the fuel. While they get more than 60 times as much energy from the original uranium compared with normal reactors, they are expensive to build. Further development of them is likely in the next decade, and the main designs expected to be built in two decades are FNRs. If they are configured to produce more fissile material (plutonium) than they consume they are called fast breeder reactors (FBR).



Nuclear power plants in commercial operation or operable

Reactor type	Main countries	Number	GWe	Fuel	Coolant	Moderator
Pressurised water reactor (PWR)	USA, France, Japan, Russia, China, South Korea	302	287.0	enriched UO_2	water	water
Boiling water reactor (BWR)	USA, Japan, Sweden	63	64.1	enriched UO_2	water	water
Pressurised heavy water reactor (PHWR)	Canada, India	49	24.5	natural UO_2	heavy water	heavy water
Advanced gas-cooled reactor (AGR)	UK	14	7.7	natural U (metal), enriched UO_2	CO_2	graphite
Light water graphite reactor (LWGR)	Russia	12	8.4	enriched UO_2	water	graphite
Fast neutron reactor (FBR)	Russia	2	1.4	PuO_2 and UO_2	liquid sodium	none
TOTAL		442	393			

A Fusion Reactor



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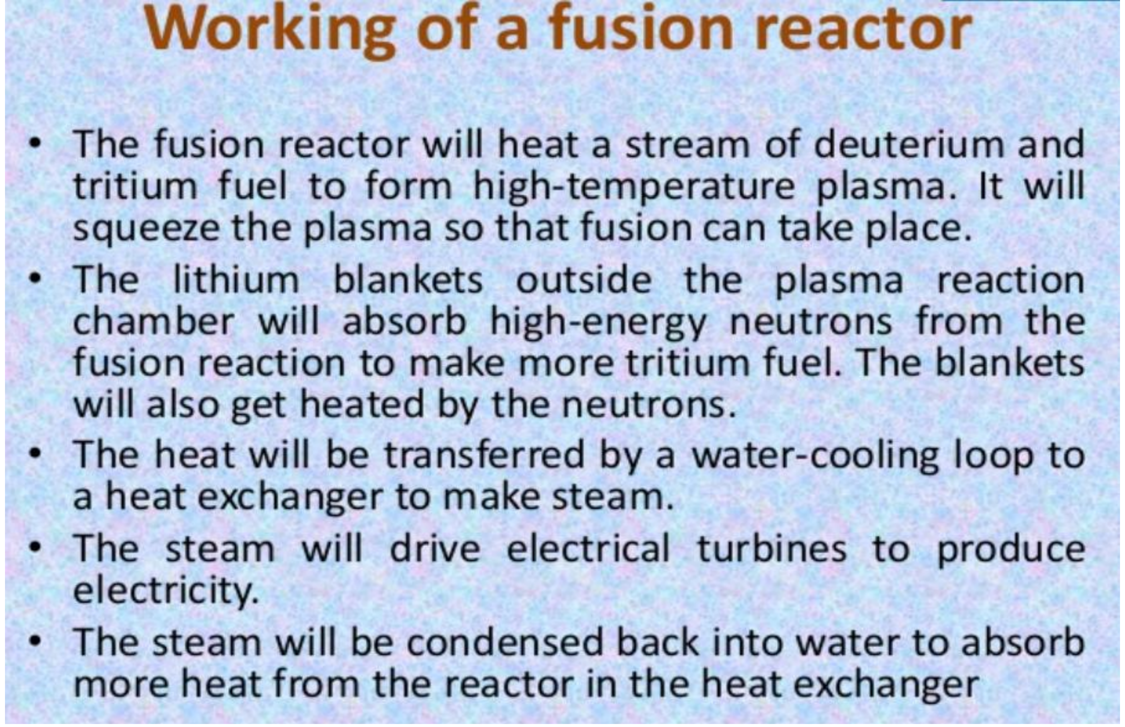
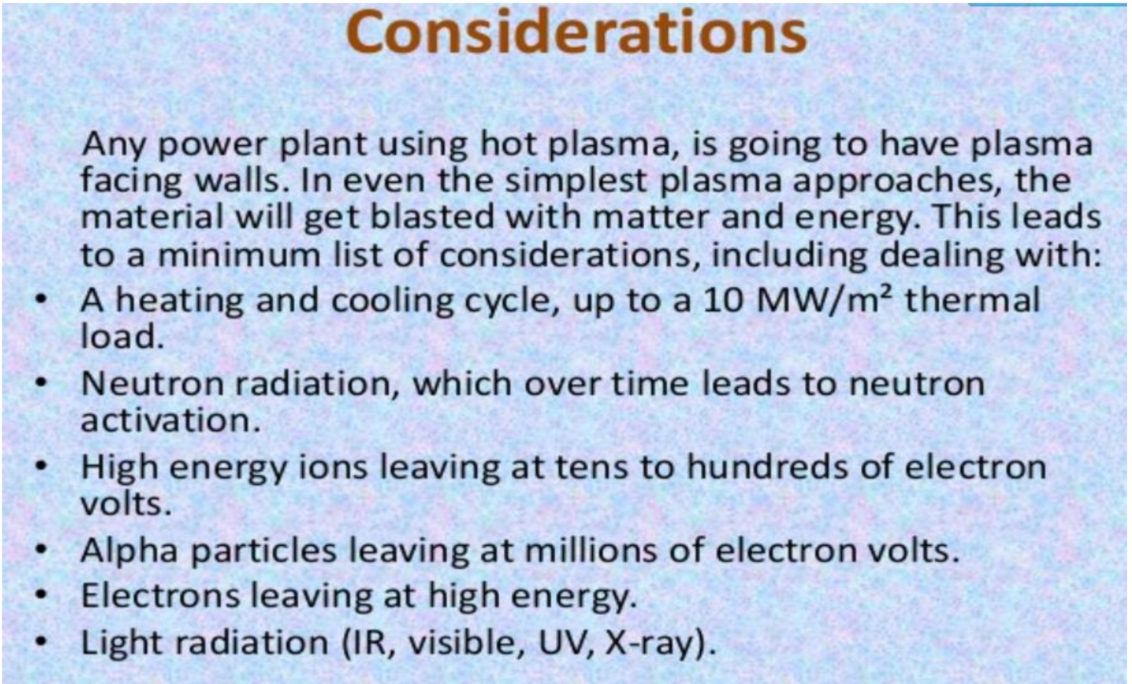


Working of a fusion reactor

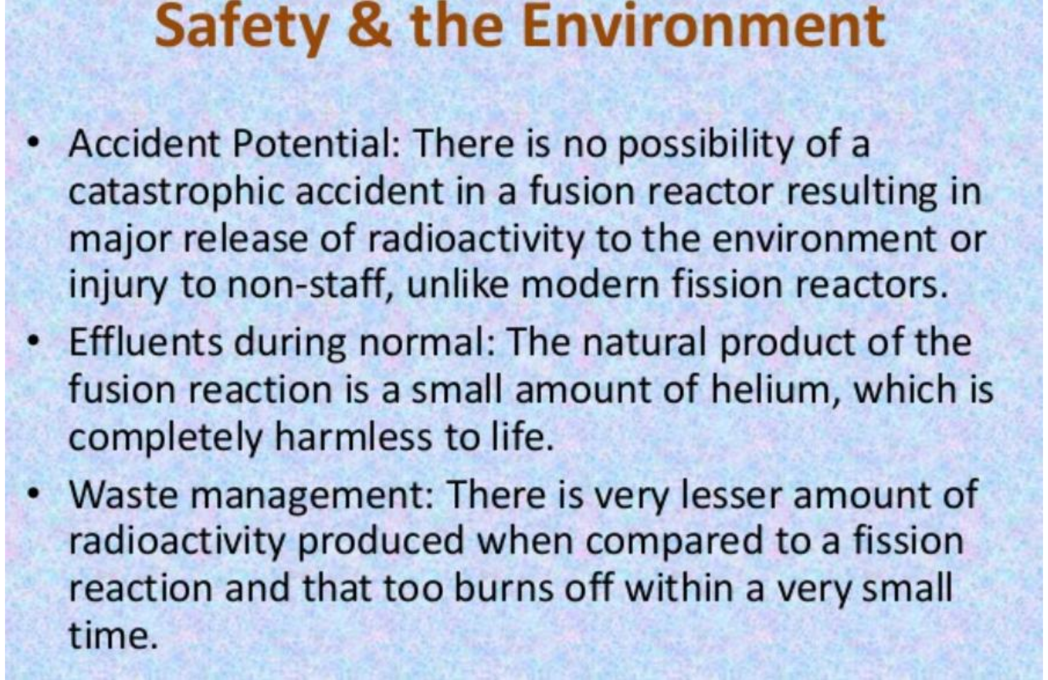
- The fusion reactor will heat a stream of deuterium and tritium fuel to form high-temperature plasma. It will squeeze the plasma so that fusion can take place.
- The lithium blankets outside the plasma reaction chamber will absorb high-energy neutrons from the fusion reaction to make more tritium fuel. The blankets will also get heated by the neutrons.
- The heat will be transferred by a water-cooling loop to a heat exchanger to make steam.
- The steam will drive electrical turbines to produce electricity.
- The steam will be condensed back into water to absorb more heat from the reactor in the heat exchanger



Considerations

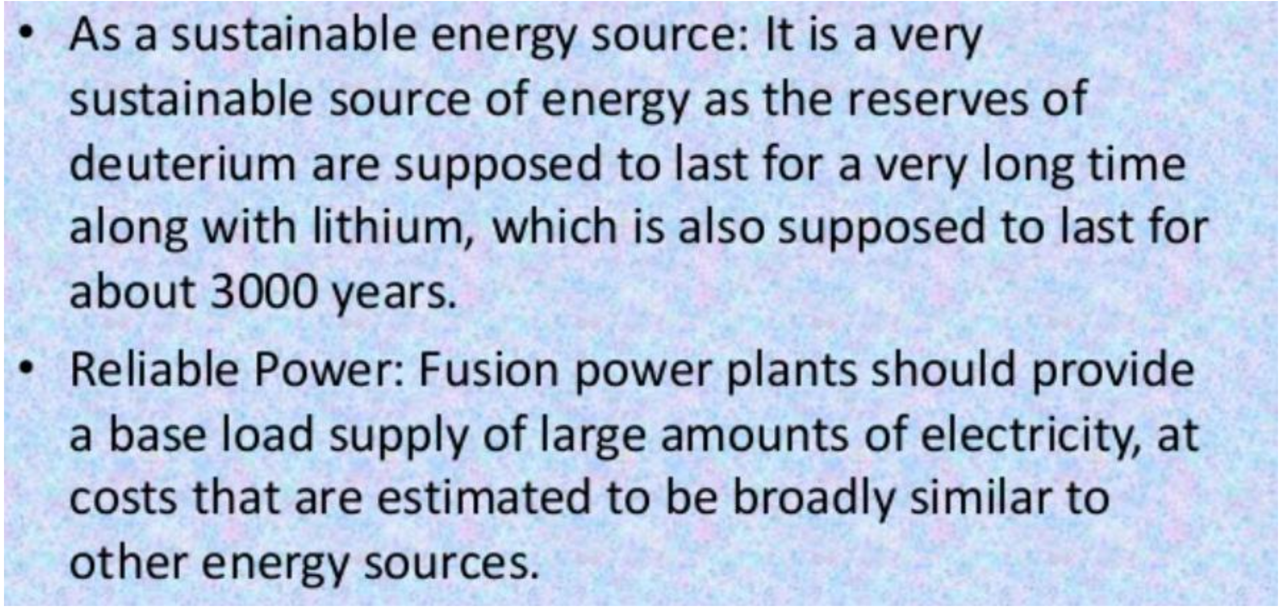
Any power plant using hot plasma, is going to have plasma facing walls. In even the simplest plasma approaches, the material will get blasted with matter and energy. This leads to a minimum list of considerations, including dealing with:

- A heating and cooling cycle, up to a 10 MW/m² thermal load.
- Neutron radiation, which over time leads to neutron activation.
- High energy ions leaving at tens to hundreds of electron volts.
- Alpha particles leaving at millions of electron volts.
- Electrons leaving at high energy.
- Light radiation (IR, visible, UV, X-ray).

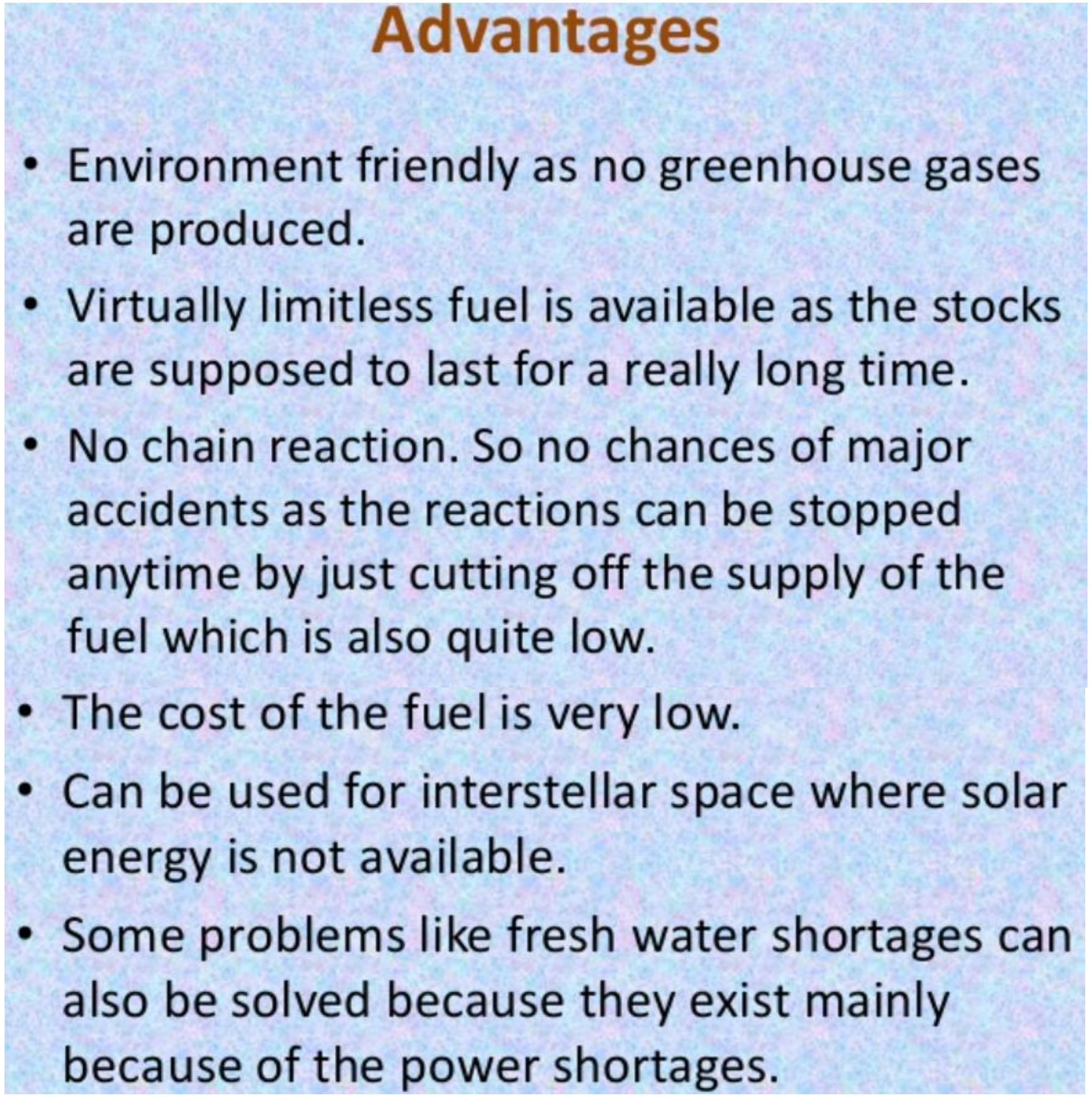


Safety & the Environment

- Accident Potential: There is no possibility of a catastrophic accident in a fusion reactor resulting in major release of radioactivity to the environment or injury to non-staff, unlike modern fission reactors.
- Effluents during normal: The natural product of the fusion reaction is a small amount of helium, which is completely harmless to life.
- Waste management: There is very lesser amount of radioactivity produced when compared to a fission reaction and that too burns off within a very small time.

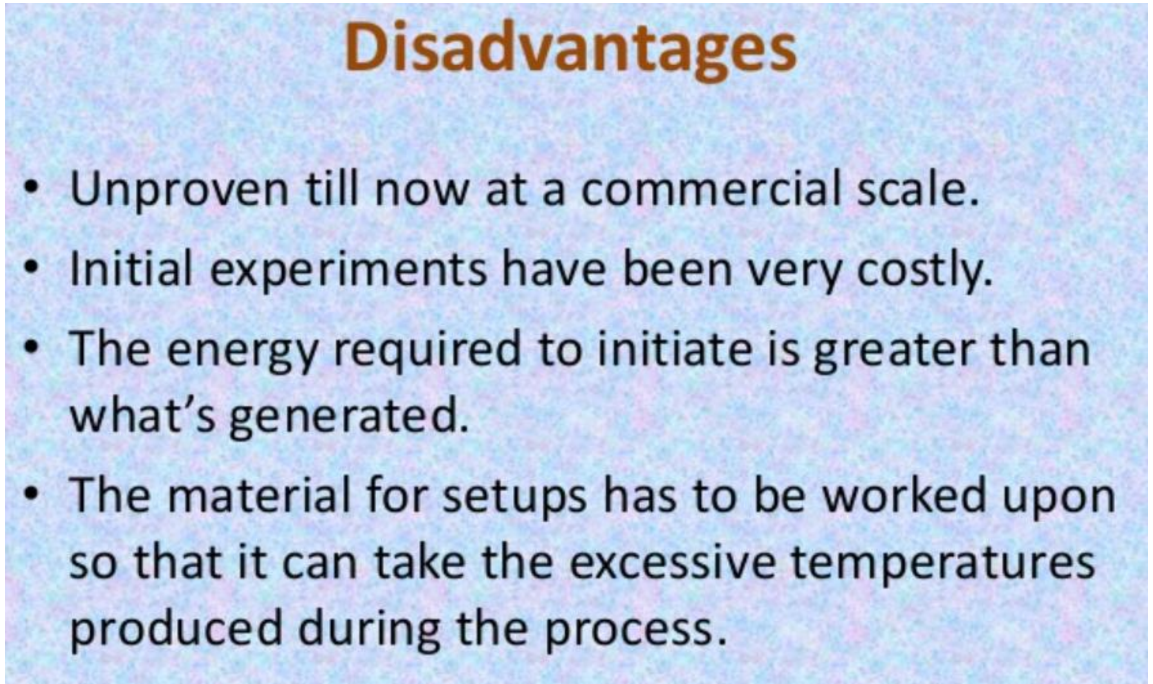


- As a sustainable energy source: It is a very sustainable source of energy as the reserves of deuterium are supposed to last for a very long time along with lithium, which is also supposed to last for about 3000 years.
- Reliable Power: Fusion power plants should provide a base load supply of large amounts of electricity, at costs that are estimated to be broadly similar to other energy sources.



Advantages

- Environment friendly as no greenhouse gases are produced.
- Virtually limitless fuel is available as the stocks are supposed to last for a really long time.
- No chain reaction. So no chances of major accidents as the reactions can be stopped anytime by just cutting off the supply of the fuel which is also quite low.
- The cost of the fuel is very low.
- Can be used for interstellar space where solar energy is not available.
- Some problems like fresh water shortages can also be solved because they exist mainly because of the power shortages.



Disadvantages

- Unproven till now at a commercial scale.
- Initial experiments have been very costly.
- The energy required to initiate is greater than what's generated.
- The material for setups has to be worked upon so that it can take the excessive temperatures produced during the process.

Main Sources of Radioactive Contamination

Three main sources of radioactive contamination are:

- **Fission** of nuclei or nuclear **fuels**
- The **effect** of **neutron fluxes** *(number of neutrons travelling through a unit area in unit time)* on the **heat** carried in the primary cooling system and on the ambient air.
- **Damage** of **shell** of fuel elements

All the above can cause health hazards to workers, communing and natural surroundings.

Nuclear Power: Clean & Green

What about Nuclear Reactor Accidents??

Nuclear disaster due to Great Tohoku Earthquake - 2011, Japan

Nuclear disaster at Chernobyl *- 1986, Russia : 16000 People Died*

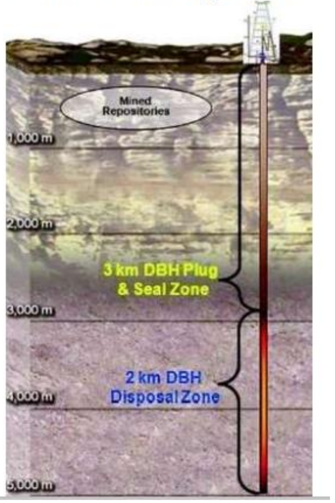
Safety Measures for Nuclear Power Plants

- A nuclear power plant should be constructed **away** from human habitation (exclusion zone of 160km radius)
- The materials used for construction should be of **required standards.**
- Waste **water** should be **purified**.
- Should have a proper safety system, **plant** could be **shut down** when required.
- Regular **periodic checks** to be performed to evaluate not to exceed the permissible radioactivity value
- While **disposing** off the **wastes** it should be ensured that it doesn't contaminate the **river or sea**.

Nuclear Waste Disposal

Geological Disposal

- The process of geological disposal centers on burrowing nuclear waste into the ground to the point where it is out of human reach.
- The waste needs to be properly protected to stop any material from leaking out. Seepage from the waste could contaminate the water table if the burial location is above or below the water level. Furthermore, the waste needs to be properly fastened to the burial site and also structurally supported in the event of a major seismic event, which could result in immediate contamination.



Reprocessing

- Reprocessing has also emerged as a viable long term method for dealing with waste. As the name implies, the process involves taking waste and **separating** the **useful components** from those that aren't as useful. Specifically, it involves taking the **fissionable material** out from the irradiated nuclear fuel.

Transmutation

- Transmutation also poses a solution for **long term disposal**. It specifically involves converting a **chemical element** into another **less harmful one**.
- Common conversions include going from **Chlorine to Argon or from Potassium to Argon.**
- The driving force behind transmutation is chemical reactions that are caused from an outside stimulus, such as a proton hitting the reaction materials.

Natural transmutation : can also occur **over a long period** of time. Natural transmutation also serves as the principle force behind **geological storage** on the assumption that giving the **waste enough isolated time** will allow it to become a non-fissionable material that poses little or no risk

Application of Nuclear Byproducts

Industrial Applications :

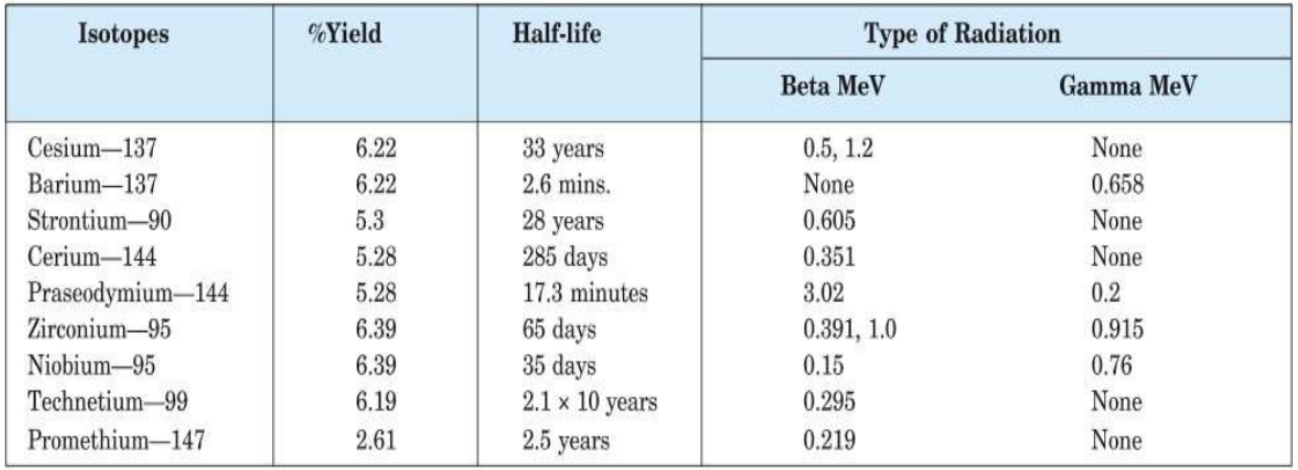
(1) **Position location** : **Buried pipelines** can be traced by using portable geiger Counters.

(2) Flow patterns in pipes can be detected by injecting radioactive isotopes into the flow. The radiation will be different for laminar and turbulent flows.

(3) Leakage detection can be done by injecting isotopes into fluid in pipes. The reactivity will be different at leakage points.

Byproduct of Nuclear Generation

- The Nuclear plants supply many by-products like isotopes which have many useful applications in our day-to-day life.
- The radioactive isotopes are widely used in **Biology**, **Medicine**, Agriculture and **Industries**.



Isotopes	%Yield	Half-life	Type of Radiation	
			Beta MeV	Gamma MeV
Cesium—137	6.22	33 years	0.5, 1.2	None
Barium—137	6.22	2.6 mins.	None	0.658
Strontium—90	5.3	28 years	0.605	None
Cerium—144	5.28	285 days	0.351	None
Praseodymium—144	5.28	17.3 minutes	3.02	0.2
Zirconium—95	6.39	65 days	0.391, 1.0	0.915
Niobium—95	6.39	35 days	0.15	0.76
Technetium—99	6.19	2.1 × 10 years	0.295	None
Promethium—147	2.61	2.5 years	0.219	None

(5) **Thickness gauges**.

(6) Liquid level gauges.

(7) Radiography (**Flaw detection**): X-rays, which are having a high penetrating power are made to pass through castings, welds etc. and on the other side, the photographic plate receives the radiation.

(8) **Density and content gauges:** The Through Gauge is used for this purpose. If the reactivity is a function of density of the material and thus the density of the content can be measured. This method is used in **cigarette packing line** and a relay arrangement is made to reject the faulty cigarettes.

(9) **Application in chemistry :** Substances **deteriorate** when exposed to radiation and the destroyed molecules are rejoined

(10) **Sterilization of foods and drugs :** Bacteria are produced in food-stuffs and vegetables and cause fermentation. Heating process can help in **sterilization** (complete destruction of Bacteria) and pasteurization (90% **destruction of Bacteria**).

But this **heating process cannot be done** for fruits, vegetables and drugs. Because the materials are kept in an **air-tight**

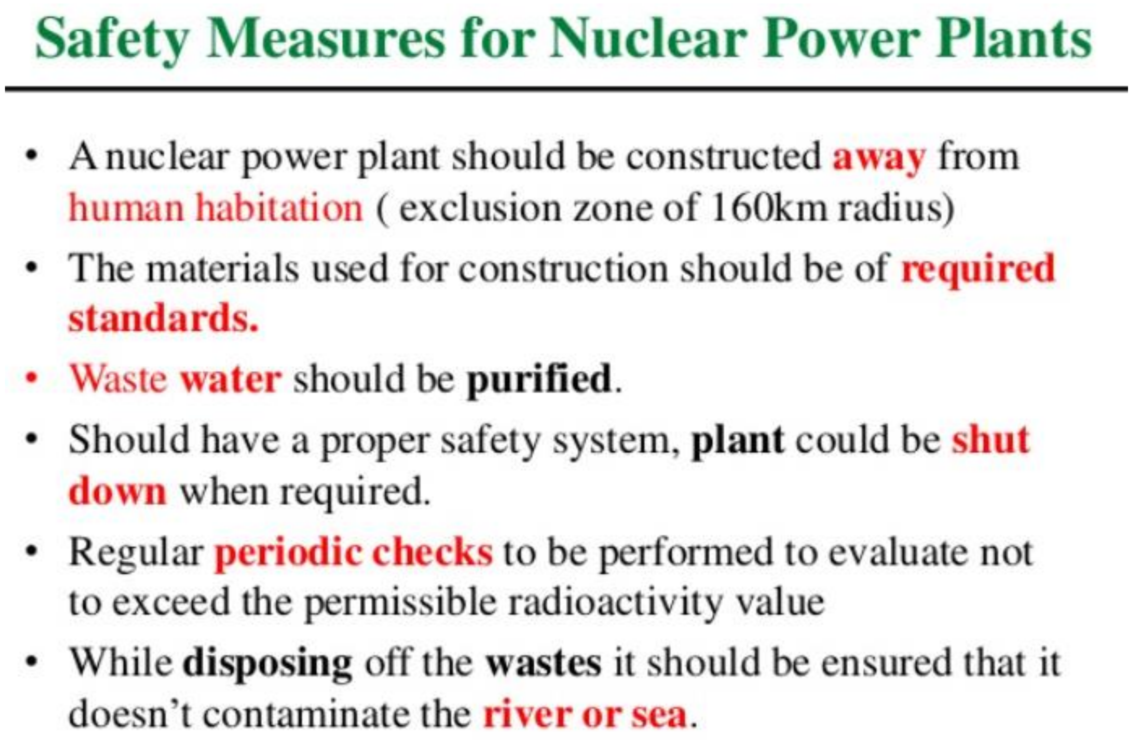
Future of nuclear power

- India has **hydro-power** potential, and some **coal reserves**; unfortunately these are **not very well distributed** throughout the country.
- Moreover, most of the economically feasible hydropower schemes have already been developed.
- The quality of **Indian coal** is not very **good**, and the reserves are concentrated in one or two parts of the country. These reserves are also being **depleted** at a **fast rate**, the railways consuming a large quantity in the past.

- On the other hand, India has **adequate deposits** of fissionable material-**thorium**, which can eventually be used for generation of power. Therefore, **development** of **nuclear power**, to supply the growing electricity demand of the country is quite logical and necessary. Thus the future of nuclear power is **quite bright**.

Following three factors need discussion

1. Cost of Power Generation
2. Availability of nuclear fuel, breeder reactor.
3. Safety of nuclear plants.



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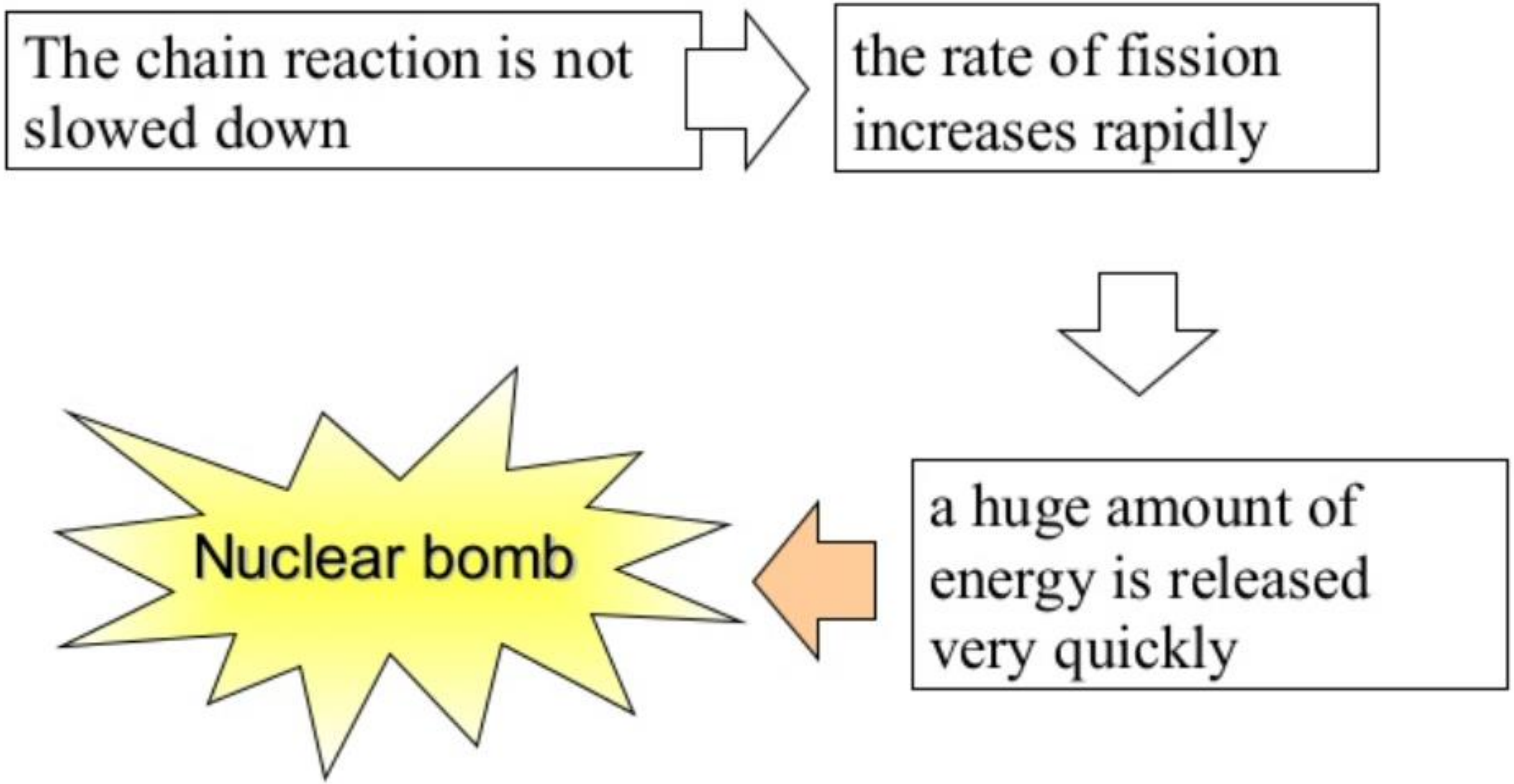
Uncontrolled nuclear reaction



The chain reaction is not slowed down

the rate of fission increases rapidly

a huge amount of energy is released very quickly

Nuclear bomb