LECTURE 3
NUCLEAR POWER PLANT

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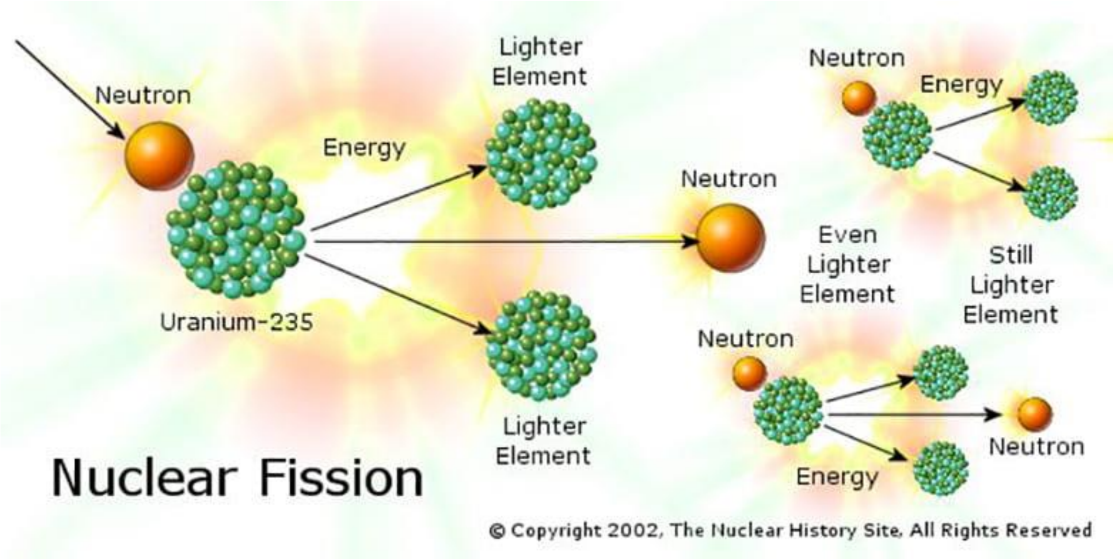
Topics

A.2.1	Nuclear Energy Fundamentals
A.2.2	Nuclear Reactors: Types, Components and Layout
A.2.3	Nuclear Fuel Cycle and Environmental Effects
A.2.4	Case Study: Rooppur Nuclear Power Plant

What is Nuclear energy (NE)?

- **Nuclear energy** is energy released from the **nucleus (core) of an atom**. It comes from changes in the nucleus itself—not from chemical reactions like burning fuel.



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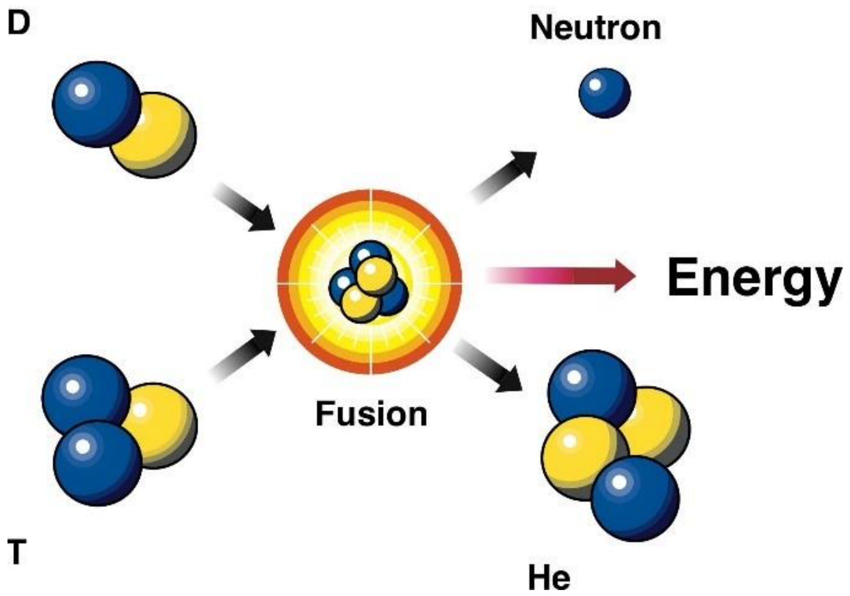
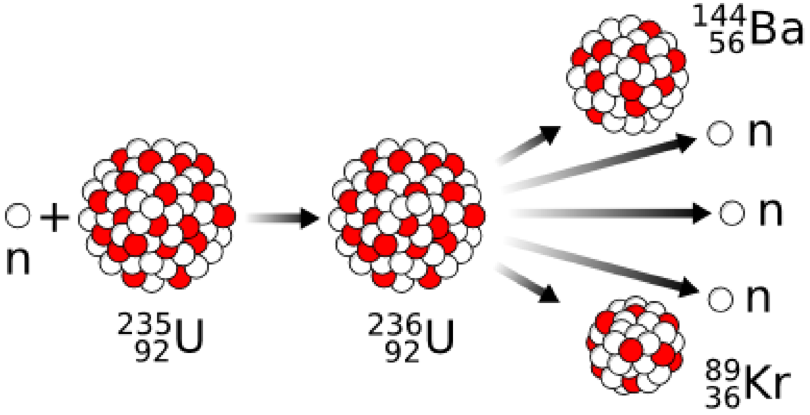


Brief history of NE

1896-Radioacitivity discover → 1939 Fission reaction identified → 1945 Nuclear bomb in WW II → 1950 NE in power generation



Mass defect and binding energy

- The **mass defect** is the **difference between**:
  - the **sum of the masses of individual protons and neutrons**, and the **actual mass of the nucleus**.

$\Delta\text{m}{=}Zm_p + Nm_n - m_{nucleus}$ where: Z = number of protons, N = number of neutrons

The **binding energy** is the **energy required to completely break a nucleus into free protons and neutrons**.

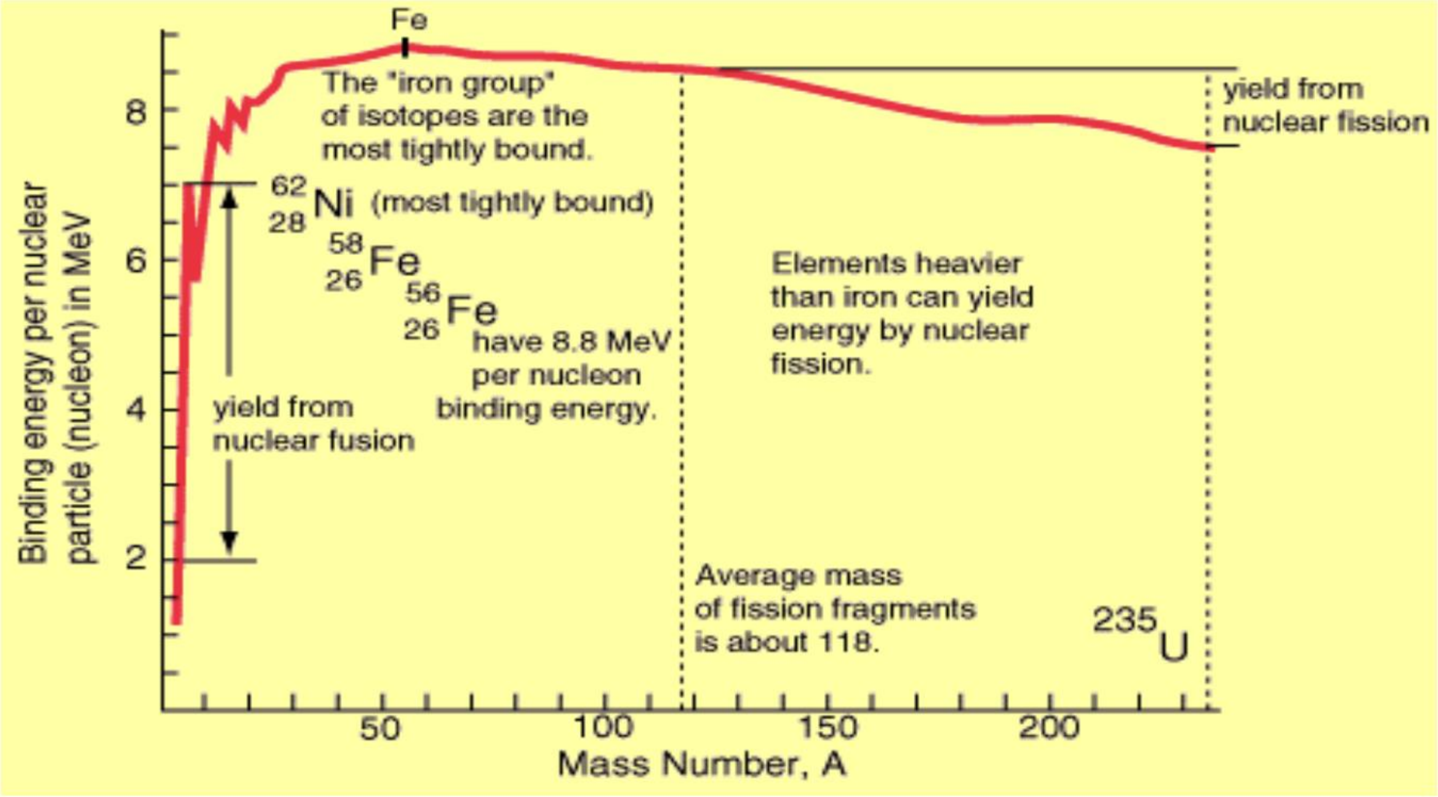
- It is directly related to mass defect by Einstein's equation:

$$\text{BE} = \Delta mc^2$$

- Higher binding energy → **more stable nucleus**
- Lower binding energy → **less stable nucleus**

Mass defect and binding energy, cont’d

- As the number of particles in a nucleus increases that is the atomic mass number (A) increases, the total binding energy also increases. The rate of increase, however, is not uniform. This lack of uniformity results in a variation in the amount of binding energy associated with each nucleon within the nucleus as depicted in BE/A vs. Atomic Mass number (A) curve.



Mass defect and binding energy, cont’d

- As the atomic mass number increases, the binding energy per nucleon, BE/A increases up to a maximum value of 8.79 MeV at A = 56 and than decreases to about 7.6 MeV for A = 238.
- As the atomic number (Z) increases, the repulsive electrostatic forces among protons within the nucleus increase.
- To overcome this increased repulsion and maintain stability, the proportion of neutrons in the nucleus must increase. This increase in the neutron-to-proton ratio only partially compensates for the growing proton-proton repulsive force in the heavier, naturally occurring elements.
- As the repulsive forces are increasing, less energy must be supplied to remove a nucleon from the heavier nucleus. In other words, the BE/A has decreased.
- The heaviest nuclei require only a small energy addition for the relatively large coulomb forces to overcome the attractive nuclear forces, in order to split the nucleus into two halves. Consequently, the heaviest nuclei are easily fissionable compared to lighter nuclei.

Radioactivity and radioactive decay

- The atomic instability of heavier atoms leads to so called "Radioactivity" that is: Spontaneous emission of energy and particles due to the breaking down of unstable atoms.
- Radiation decreases with time over periods of time varying from seconds to years.
- Radioactive decay is the disintegration of an unstable atom with an accompanying emission of radiation. As a radioisotope atom decays to a more stable atom, it emits radiation only once.
- The decay of radioactive elements occurs at a fixed rate. The half-life of a radioisotope is the time required for one half of the amount of unstable material to degrade into a more stable material.
- For example, a source will have an intensity of 100% when new. At one half-life, its intensity will be cut to 50% of the original intensity. At two half-lives, it will have an intensity of 25% of a new source. After ten half-lives, less than one-thousandth of the original activity will remain.

Radioactive decay law

$$N(t) = N_0 \left(\frac{1}{2}\right)^{t/t_{0.5}}$$

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

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

$N_0 : Active\ Atoms\ at\ t = 0$

$N(t) : Active\ Atoms\ at\ t = t$

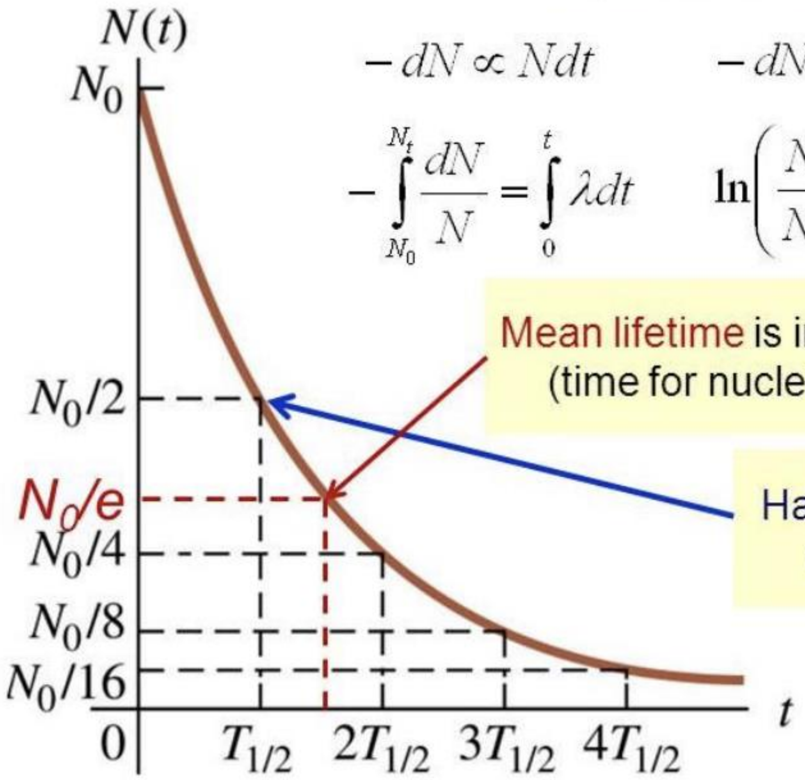
$t_{0.5} = Half\ life$

$\tau = Mean\ Life$

$\lambda = Decay\ Cons\tan t$

Decays are statistical – cannot predict when any particular nucleon will decay.

For N nuclei present at time t, the number *dN* decaying in time *dt* is proportional to N.



$$-dN \propto N dt \qquad -dN = \lambda N dt \qquad -\frac{dN}{N} = \lambda dt$$

$$-\int_{N_0}^{N_t} \frac{dN}{N} = \int_0^t \lambda dt \qquad \ln\left(\frac{N_t}{N_0}\right) = -\lambda t$$

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

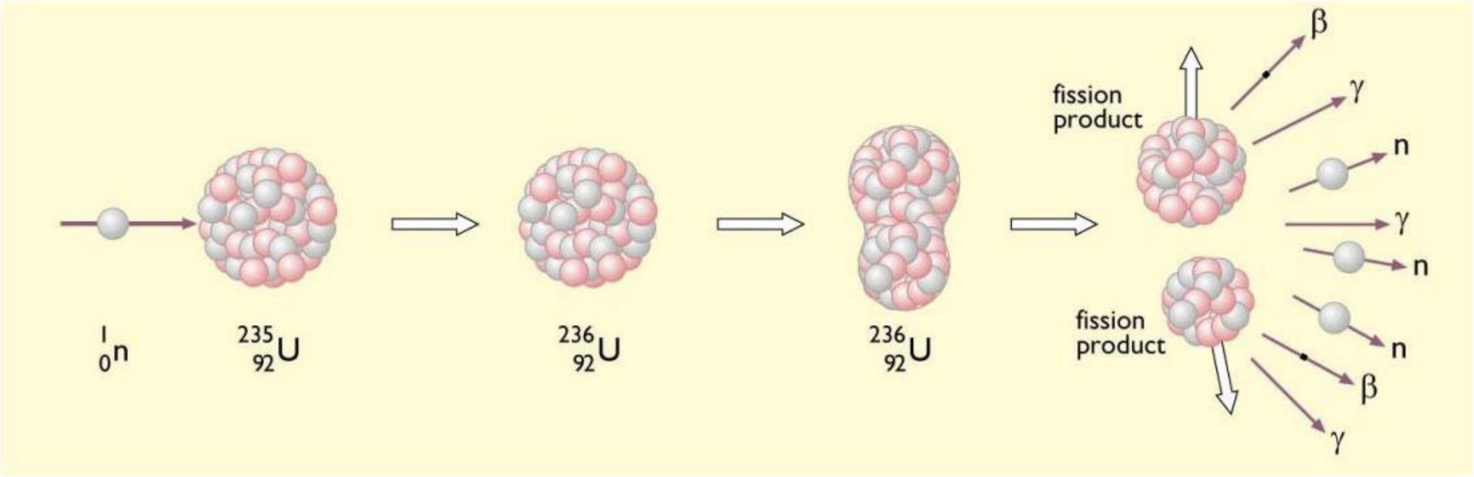
Mean lifetime is inverse of decay constant (time for nuclei to reduce by 2.718…) $\tau = \dfrac{1}{\lambda}$

Half life is time for half of nuclei to decay $t_{1/2} = \dfrac{\ln 2}{\lambda}$

$$t_{1/2} = \frac{0.6932}{\lambda}$$

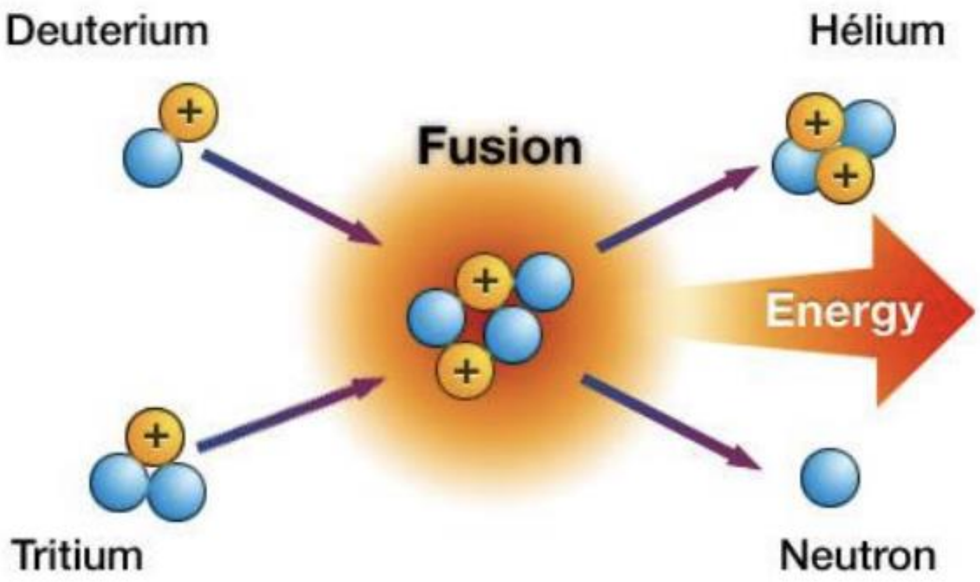
Nuclear fission

- Nuclear fission is the process in which a large nucleus splits into two smaller nuclei with the release of energy. In other words, fission the process in which a nucleus is divided into two or more fragments, and neutrons and energy are released.

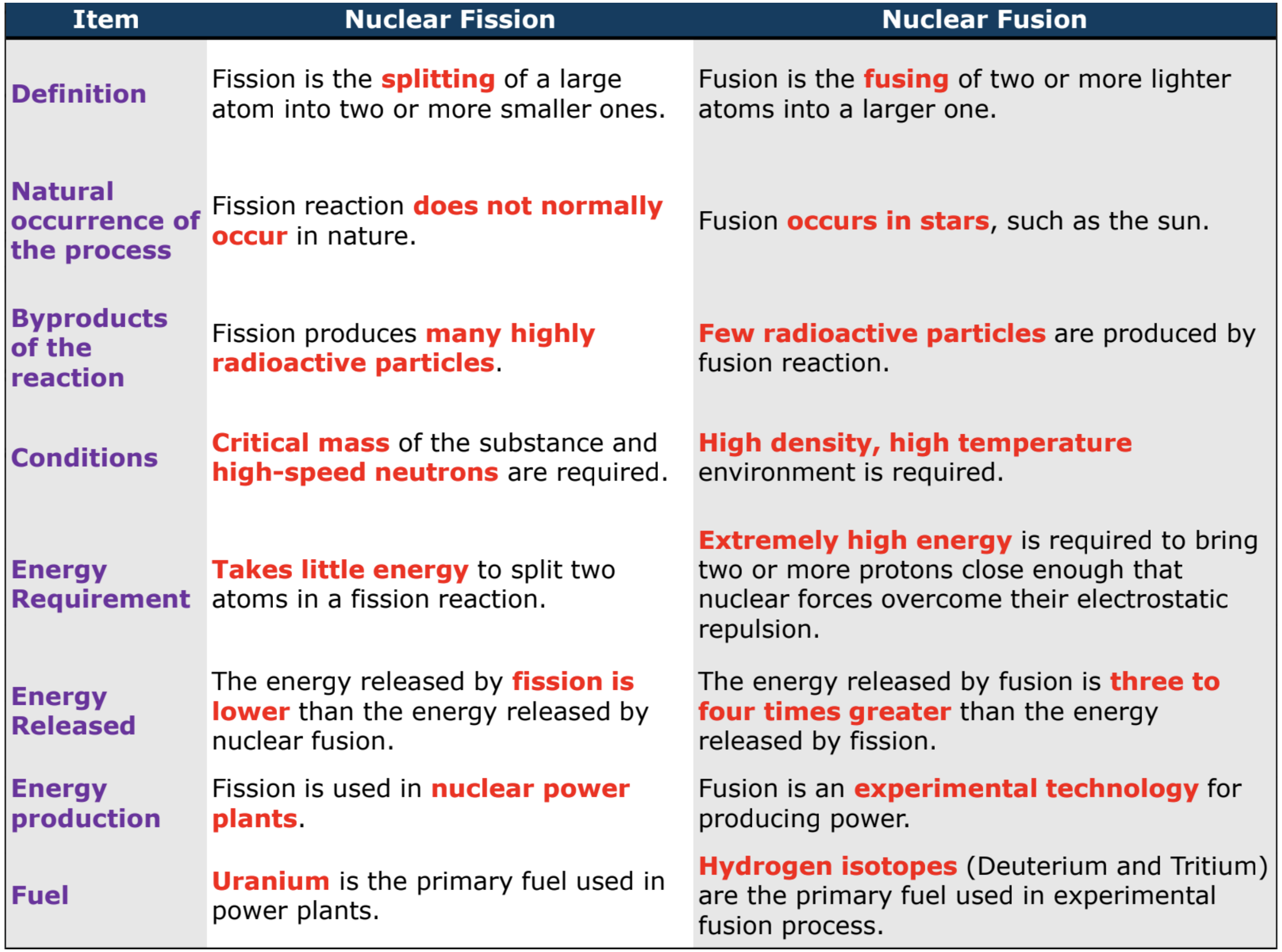


Nuclear fusion

- Nuclear reaction is a process in which two or more atomic nuclei are combined to form one or more different atomic nuclei and subatomic particles (neutrons or protons).
- Lighter elements, such as hydrogen and helium, are in general more fusible



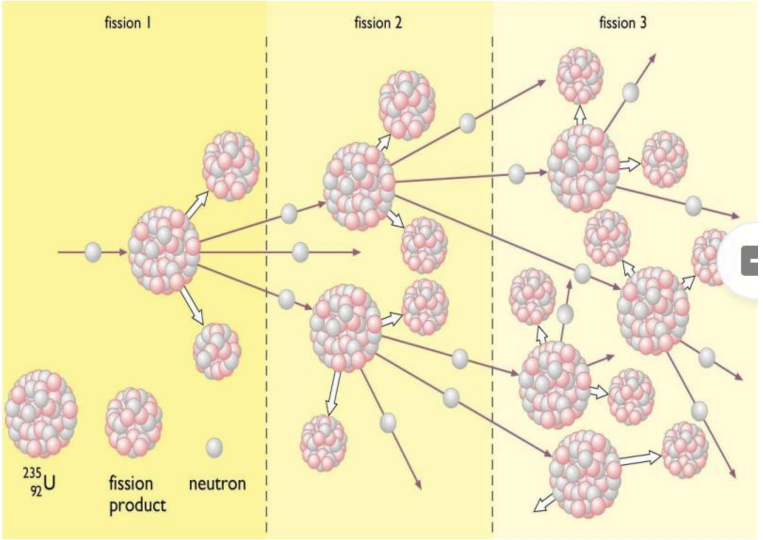
Fission vs fusion



Item	Nuclear Fission	Nuclear Fusion
Definition	Fission is the **splitting** of a large atom into two or more smaller ones.	Fusion is the **fusing** of two or more lighter atoms into a larger one.
Natural occurrence of the process	Fission reaction **does not normally occur** in nature.	Fusion **occurs in stars**, such as the sun.
Byproducts of the reaction	Fission produces **many highly radioactive particles**.	**Few radioactive particles** are produced by fusion reaction.
Conditions	**Critical mass** of the substance and **high-speed neutrons** are required.	**High density, high temperature** environment is required.
Energy Requirement	**Takes little energy** to split two atoms in a fission reaction.	**Extremely high energy** is required to bring two or more protons close enough that nuclear forces overcome their electrostatic repulsion.
Energy Released	The energy released by **fission is lower** than the energy released by nuclear fusion.	The energy released by fusion is **three to four times greater** than the energy released by fission.
Energy production	Fission is used in **nuclear power plants**.	Fusion is an **experimental technology** for producing power.
Fuel	**Uranium** is the primary fuel used in power plants.	**Hydrogen isotopes** (Deuterium and Tritium) are the primary fuel used in experimental fusion process.

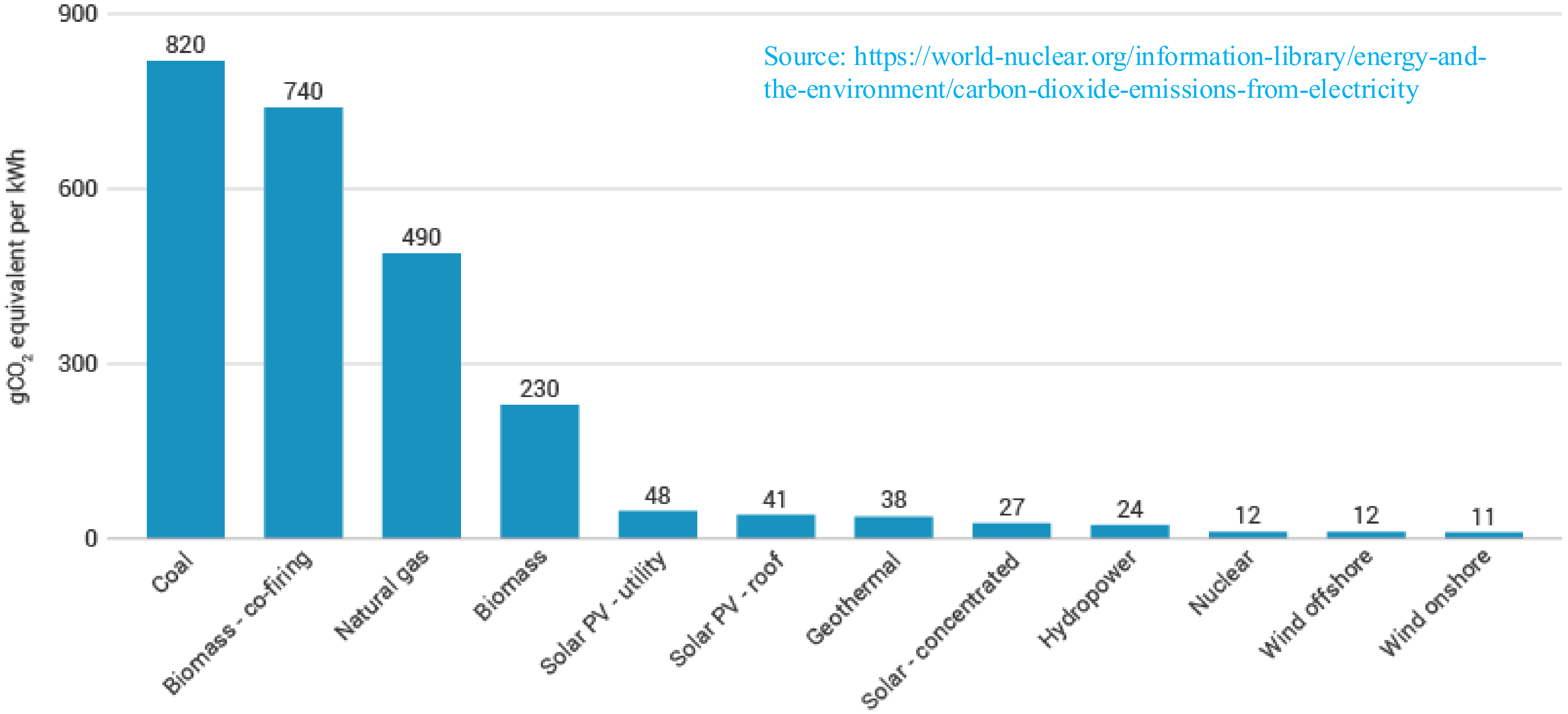
Nuclear chain reaction

- A chain reaction is a sequence of reactions where a reactive product or by-product causes additional reactions to take place. In case of nuclear chain reaction, a neutron plus a fissionable atom causes a fission resulting in a larger number of neutrons than the single one that was consumed in the initial reaction.



- The chain reaction is then a self-propagating and thus self-sustaining. And is the principle for nuclear reactors and atomic bombs.
- What is the important factors for nuclear chain reactions? What is the effective neutron multiplication factor, critical mass and size?

Why NE?



Source: https://world-nuclear.org/information-library/energy-and-the-environment/carbon-dioxide-emissions-from-electricity

gCO_2-equivalent per year (gCO_2e/yr) is a way to express **how much climate-warming impact** is produced **each year**, measured as an **equivalent amount of carbon dioxide**.

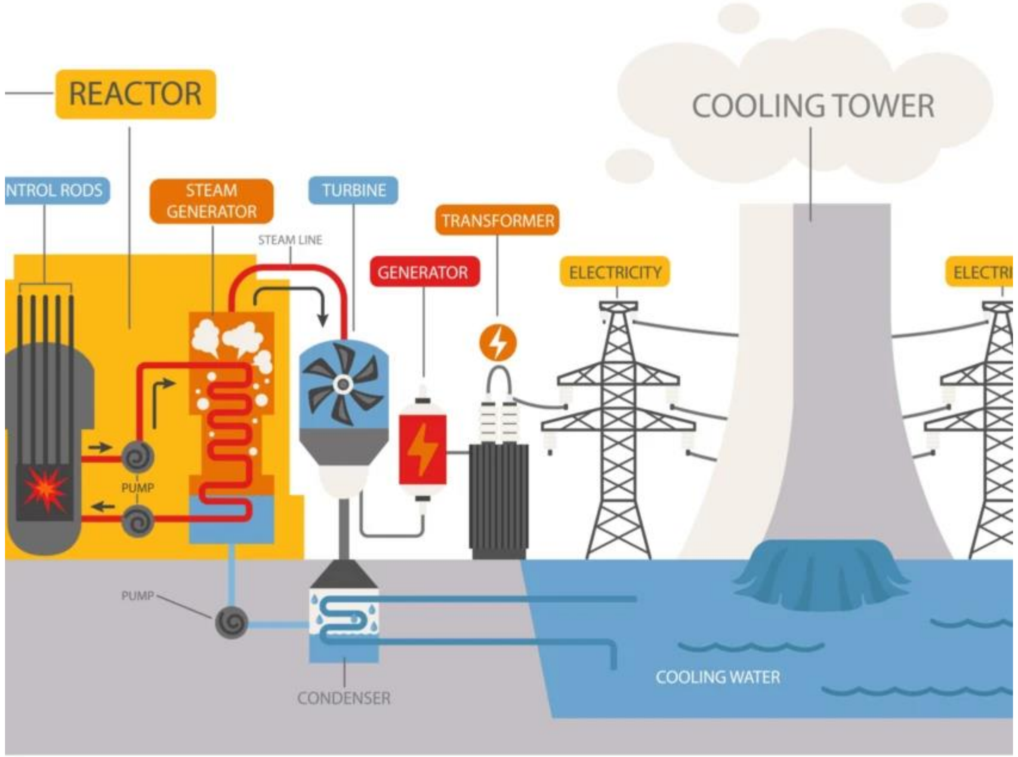
Why NE?

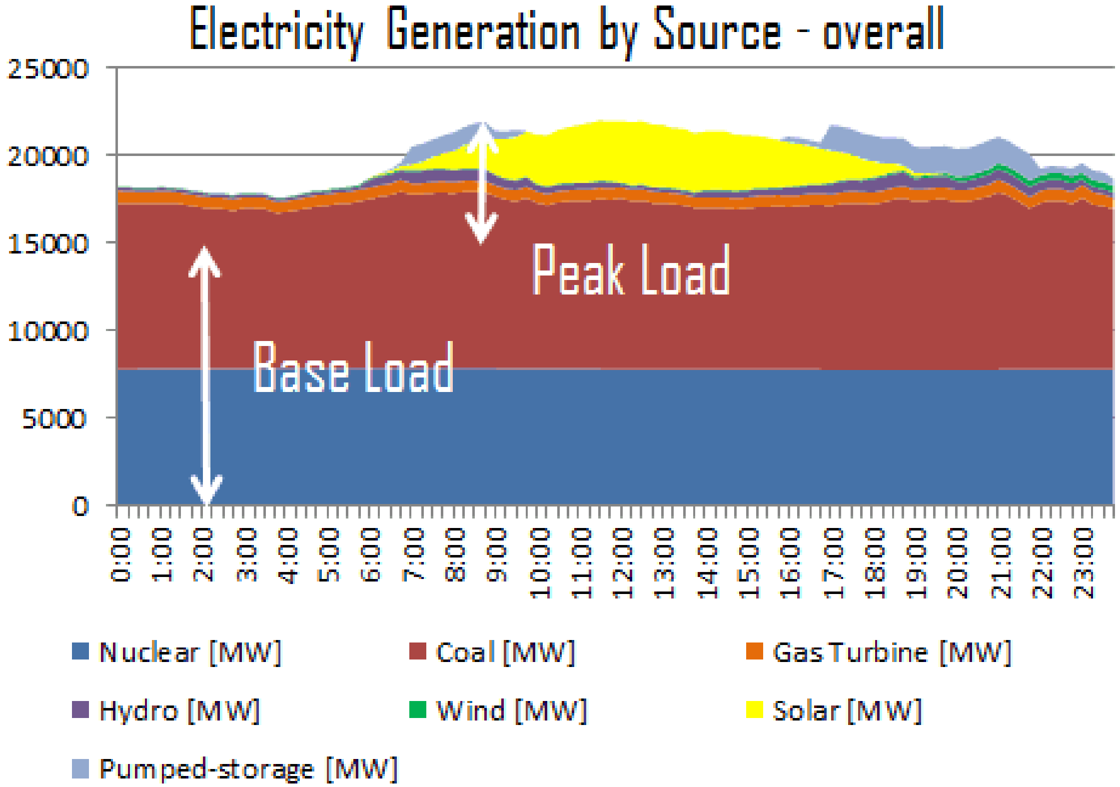
Sl. No.	Fuel	Heat Value (MJ*/kg)
1.	Firewood	16
2.	Brown coal	9
3.	Black coal (low quality)	13 - 20
4.	Black coal	24 - 30
5.	Natural Gas	39
6.	Fuel Oil	45 - 46
7.	Uranium** in light water reactor	500,000

The **heat value** of a fossil fuel—also called **calorific value**—is the **amount of heat released when a unit of fuel is completely burned**.

Why NE?

- Reliable baseload power

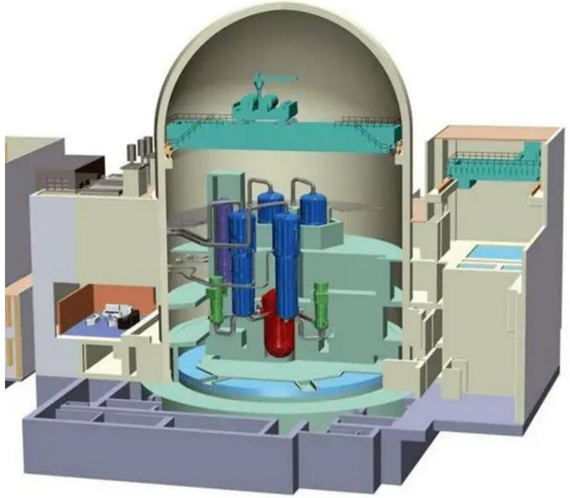




Is NE safe?

- **Very low death rate:** When measured as **deaths per unit of electricity produced**, nuclear power is **safer than coal, oil, and even hydropower**.
  - Coal: air pollution causes **millions of deaths** worldwide
  - Nuclear: very few fatalities over decades of operation

- **Modern reactors are much safer.**
- Modern nuclear plants use **multiple layers of protection**:
  - Fuel pellets (ceramic, stable)
  - Metal fuel rods
  - Steel reactor vessel
  - Thick concrete containment building



- **Radiation exposure is very small:** Average annual radiation dose:
  - Natural background (earth, food, air): **~2.4 mSv/year**
  - Living near a nuclear plant: **~0.01 mSv/year**

Is NE safe?

Two major accidents:

- Only two major nuclear accidents occurred so far, namely

  : Three Mile Island (TMI) accident in 1979 and

  : Chernobyl accident is 1986.

Is NE safe?

- Three Mile Island is a pair of PRW's.
- The second one was built in a hurry for tax purposes (started operation on December 30, 1798 to meet deadline).
- On March 28, 1979, the Pilot Operated Relief Valve was stuck open and caused pressure to be released from the primary cooling system. The fuel rods came apart and radioactive material discharged into the sky. Two days later 3,500 pregnant women and children were evacuated. Although there were no official instructions to do so, many others left as well. Numerous residents in the aftermath developed various cancers and thyroid diseases.

TMI accident

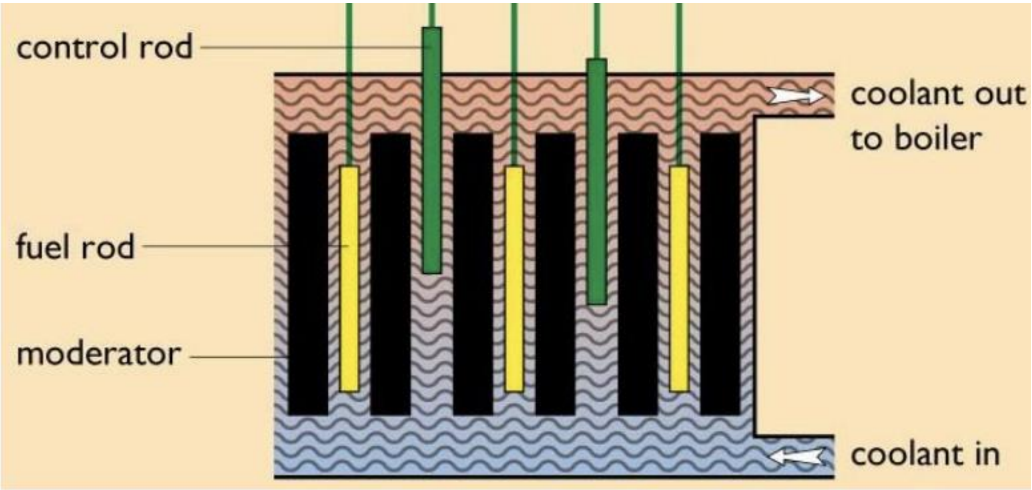
Is NE safe?

- Chernobyl had the RBMK (graphite moderated nuclear power reactor) design.
- In an experiment, technicians let the power of reactor 4 fall, and **on April 26, 1986** the result was rapid power levels rising inside the core—melting fuel and causing a reactor containment breach—in addition to an internal hydrogen explosion.
- The top of the reactor blew off and spewed radioactive material into the atmosphere for 10 days.

Chernobyl accident

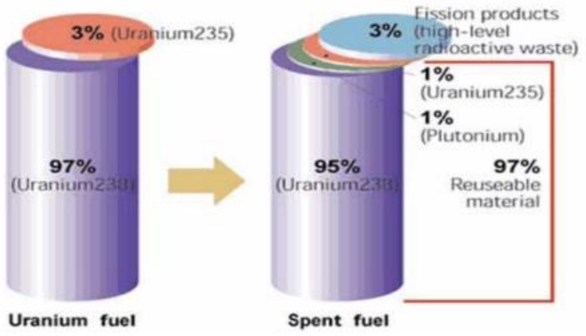
Thermal fission reactor

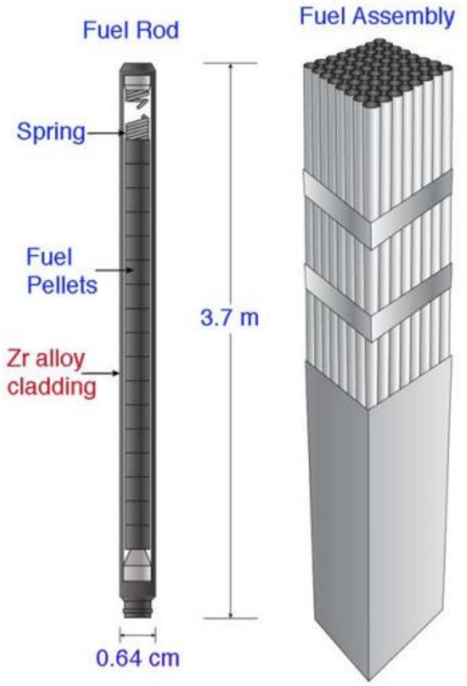
- A thermal-neutron reactor is a nuclear reactor that uses slow or thermal neutrons.
- "Thermal" does not mean hot in an absolute sense, but means in thermal equilibrium with the medium it is interacting with, the reactor’s fuel, moderator and structure, which is much lower energy than the fast neutrons initially produced by fission.
- Most nuclear power plant reactors are thermal reactors and use a neutron moderator to slow neutrons until they approach the average kinetic energy of the surrounding particles.
- Four essential parts of a thermal fission reactor:
  - Fuel rod
  - Moderator
  - Coolant
  - Control rod



Thermal Fission Reactors: fuel

- A number of early power plants used natural uranium fuel (0.7% U-235) but younger nuclear power plants use enriched uranium with U-235 content between 2% and 5%.
- Plutonium-239 bred in uranium reactor can also be used as fuel.
- Fuel in Uranium reactor is used usually in the form of the oxide UO2 , a hard ceramic suitable for forming into pellets. If the fuel is to include plutonium, it can be in the form of plutonium oxide (PuO2). In this case the fuel is called mixed oxide (MOX).
- The fuel pellets must be contained in a way that allows replacement of batches of spent fuel and fuel rods.
- The containers or cladding holding the fuel that are usually metallic. However, steel is not used as it absorbs due to its high neutron absorption.
- A typical reactor might hold in the order of 100 tones of fuel, a third of this being replaced every year or 18 months. The resulting heat output of 2-3GW is sufficient for supplying 600-1000 MW of electric power.



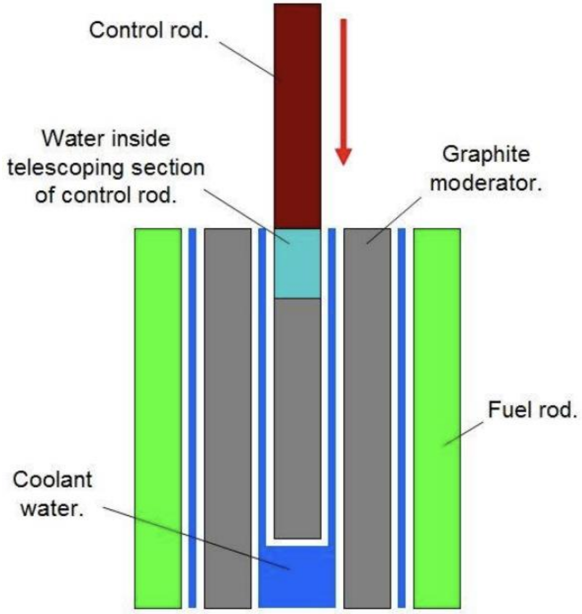


Thermal Fission Reactors: moderator

- The material that slows down the neutrons in a reactor to maintain the chain reaction is called moderator.
- The main requirements for an efficient moderator is that it should rapidly reduce the speed of the neutrons without absorbing them. The best moderators have light atoms as if a fast neutron collides with a stationary light nucleus, it will share it energy, reducing its speed. However, if it collides with a much heavier nucleus it will be deflected without much change of speed.
- A number of different types of moderator have been used since the first reactor. Hydrogen should be ideal as it is light and its single proton nucleus has almost same mass of a neutron. It is plenty in the form of ordinary water (light water). However, rather that just colliding, a free neutron tends to combine with any available proton to a form a new particle that will cause neutron loss. It means that light water can only be used as moderator if enriched uranium is used as fuel.
- The combination of a neutron with proton is called a deuteron. The addition of a neutron with hydrogen nucleus results in an isotope of hydrogen called deuterium while addition of two neutrons with hydrogen nucleus results in another isotope of hydrogen called tritium. Deuterium is an excellent moderator, fairly light with the great advantage that colliding neutrons don’t combine with deuterons. Deuterium in the form of heavy water (D2O) can be used as an effective liquid moderator in nuclear reactor using natural uranium fuel

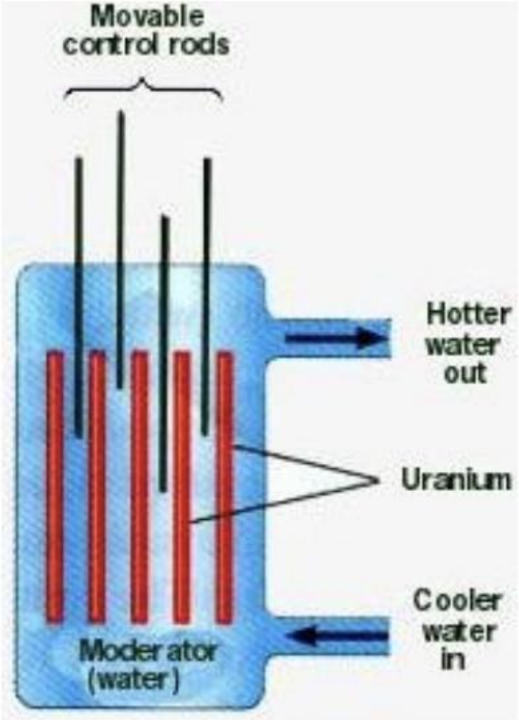
Thermal Fission Reactors: moderator, cont’d

- The most easily available effective solid moderator is carbon which can be obtained in the form of pure graphite. Although carbon nucleus is quite heavier than deuteron, its neutron absorption is so low that it can be used with natural uranium.
- Among all operating nuclear reactors of the world at present, 75% use regular water (H_2O) as moderator, while 20% use graphite and 5% use heavy water (D_2O).
- Beryllium and beryllium oxide (BeO) have been used occasionally, but they are very costly.



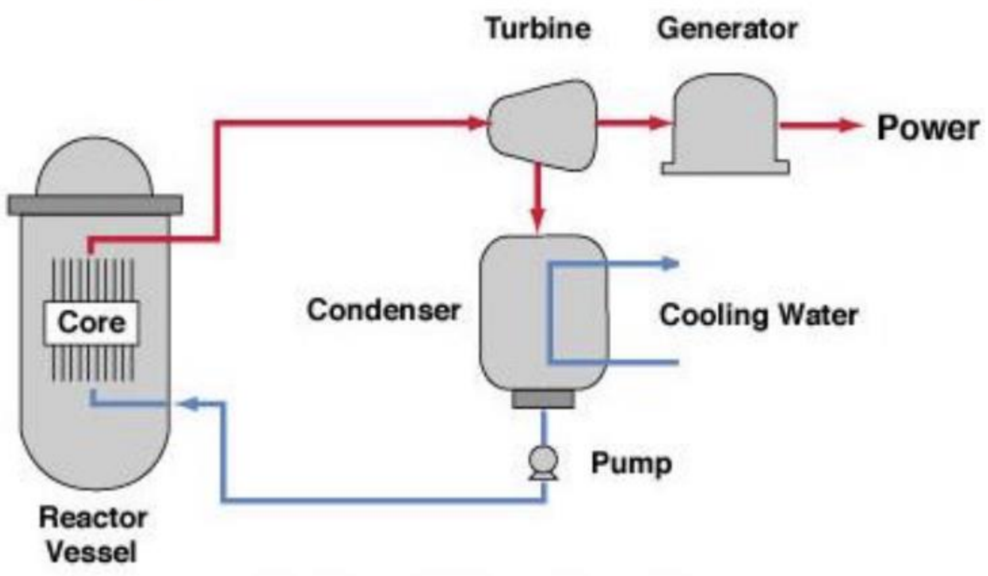
Thermal Fission Reactors: coolant

- The coolant of the nuclear reactor is the heat exchange medium: the fluid, gas/liquid that carries heat from the reactor core.
- A significant advantage of liquid moderator (light water/heavy water) is that it also acts as coolant. While in case of graphite-moderated reactor it requires another material as coolant like CO_2 gas.
- In order be an effective coolant, it:
  - must have efficient heat transfer properties.
  - must also be a fluid that can fill the interstices of the core and be pumped to a steam generator or turbine.
  - should be chemically stable at high temperatures, non- corrosive.
  - Must be poor neutron absorber which can be achieved by ensuring that the coolant has a low absorption cross section. In the cases when coolant does absorb neutrons, however, the resulting radioactivity should have a short lifetime.
  - Must be cost-effectiveness is a relevant consideration for reactors.
  - Commonly used coolant include water, Deuterium Oxide, CO_2, Molten Sodium, Molten Lead.



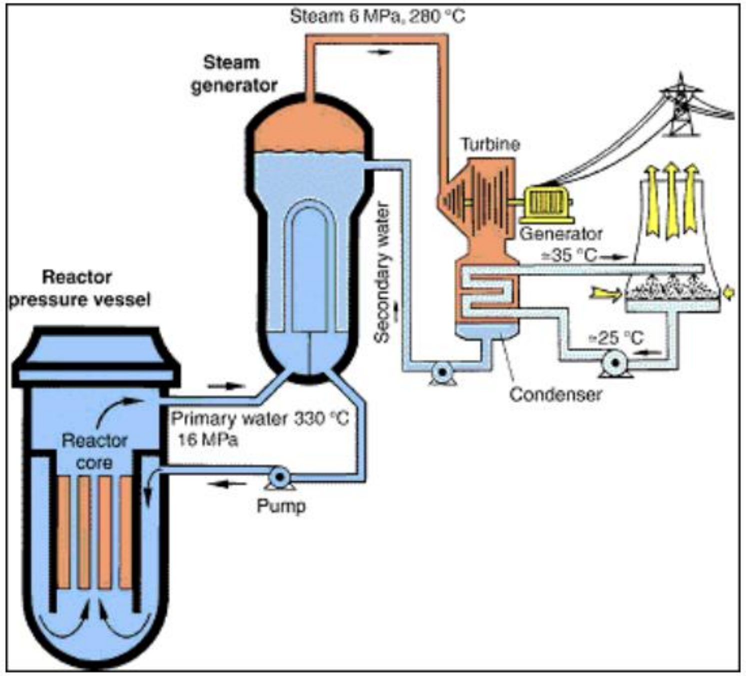
Thermal Fission Reactors: coolant, cont’d

Cooling Circuit of Nuclear Power Plant



Single Cooling Circuit (Boiling water reactor)

More Chance of Radioactive Leakage



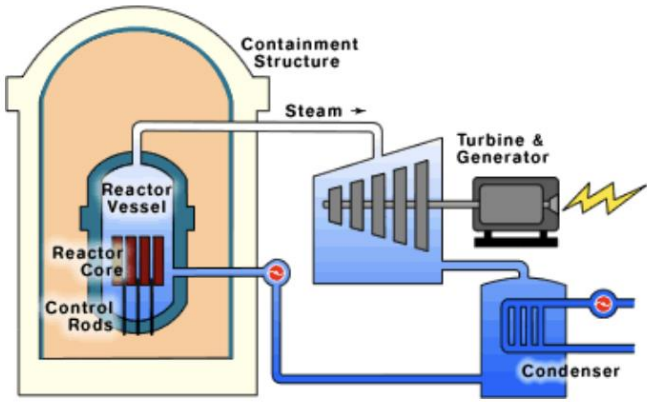
Double Cooling Circuit (Pressurized water reactor)

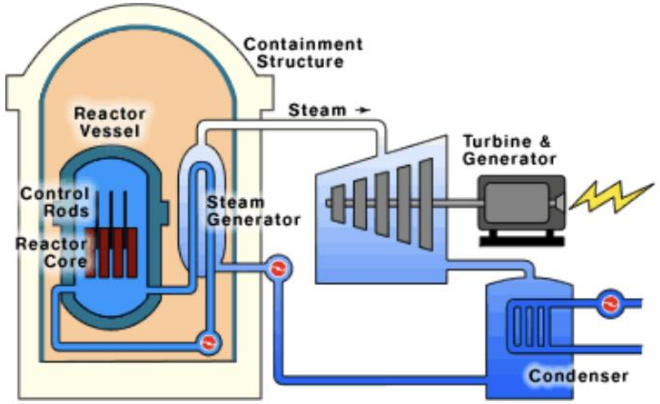
Primary Circuit: Reactor Cooling

Secondary Circuit: Steam Generator

Thermal Fission Reactors: control rod

- Control Rods of a nuclear reactor govern the heat output of the reactor which is achieved by incorporating a neutron absorbing material in the system.
- Cadmium (Cd) and Boron (B) are good absorbers and the reaction can be well controlled by increasing or decreasing the amount of these in the reactor core:
  - either by adding absorber in the moderator or
  - with control rods that can be moved in or out of the reactor core.
- In PWRs, the control rod drive mechanisms are mounted on the reactor pressure vessel head and the rods are inserted from above the core while in BWR's the control rods are inserted from underneath the core due to the necessity of having a steam dryer above the core.





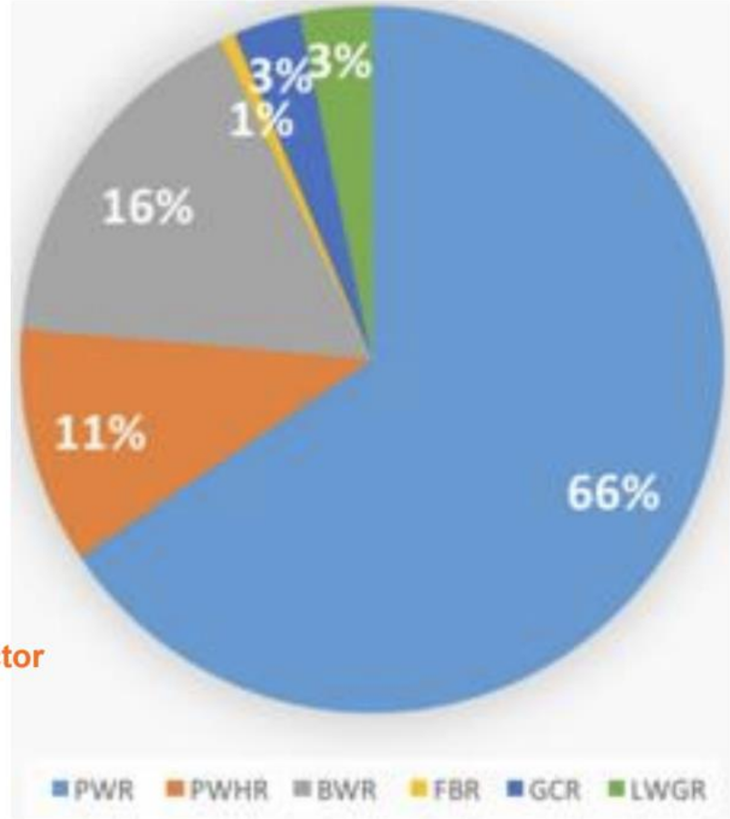
Types of Thermal Fission Reactors

Currently operating thermal fission reactors belong to **four main categories** essentially **on the basis of moderator and coolant used** as:

- Light water (H_2O) **for both moderator and coolant**
- Heavy water (D_2O) **for both moderator and coolant**
- Graphite moderator (C) with **gas coolant** (CO_2)
- Graphite moderator (C) with **light water coolant** (H_2O)

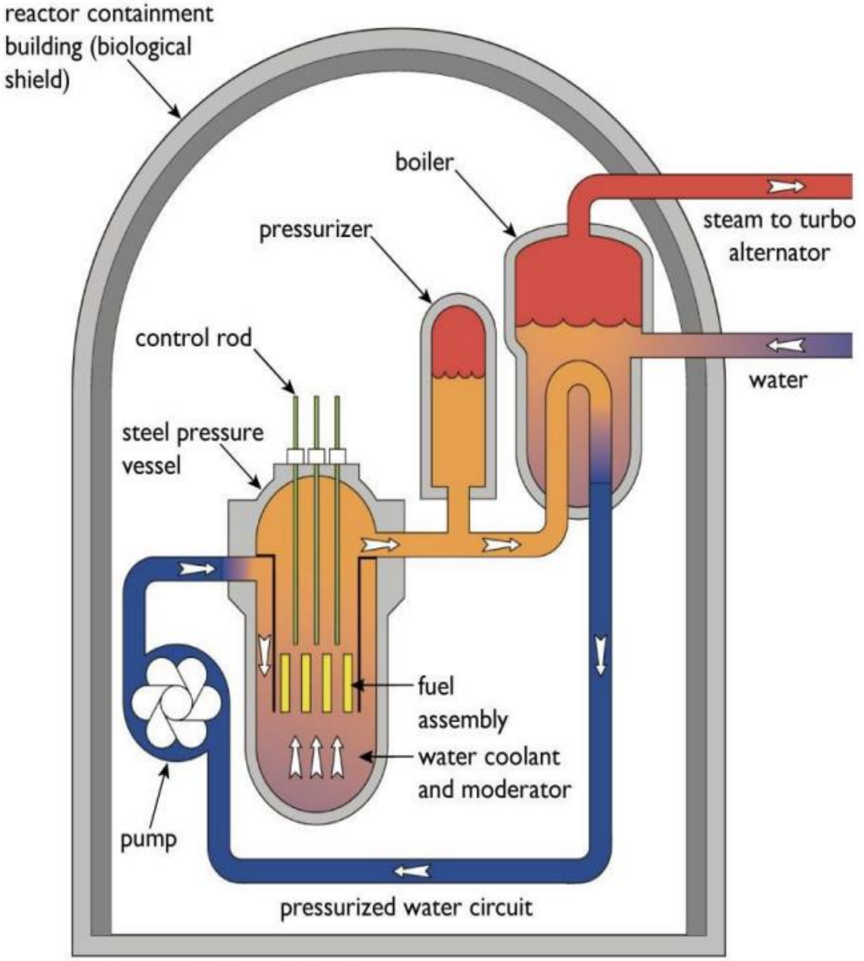
PWR: Pressurized Water Reactor
BWR: Boiling Light Water Moderated and Cooled Reactor
PHWR: Pressurized Heavy Water Moderated and Cooled Reactor
FBR: Fast Breeder Reactor
GCR: Gas Cooled Graphite Moderated Reactor
LWGR: Light Water Cooled Graphite Moderated Reactor

Nuclear Reactor's Trend



Light Water Reactor: LWRs

- The great majority of the world's reactors fall in the first category (Light Water Reactor: LWRs).
- Ordinary water under high pressure is used as both moderator and coolant.
- Two main types are:
  - pressurized water reactors (PWRs) developed in USA and
  - Water-water-energy reactor (VVER) developed in Russia.
- The core of the reactor consists of hundred of fuel assemblies in between top and bottom plates of the core. Each fuel assembly is a cluster of few hundred long fuel rods (zirconium alloy tube, few meters long and about 1 cm in diameter, packed with uranium oxide fuel pallets).
- The open core structure allow water to act as moderator and coolant, to flow freely at high pressure past the fuel rods.

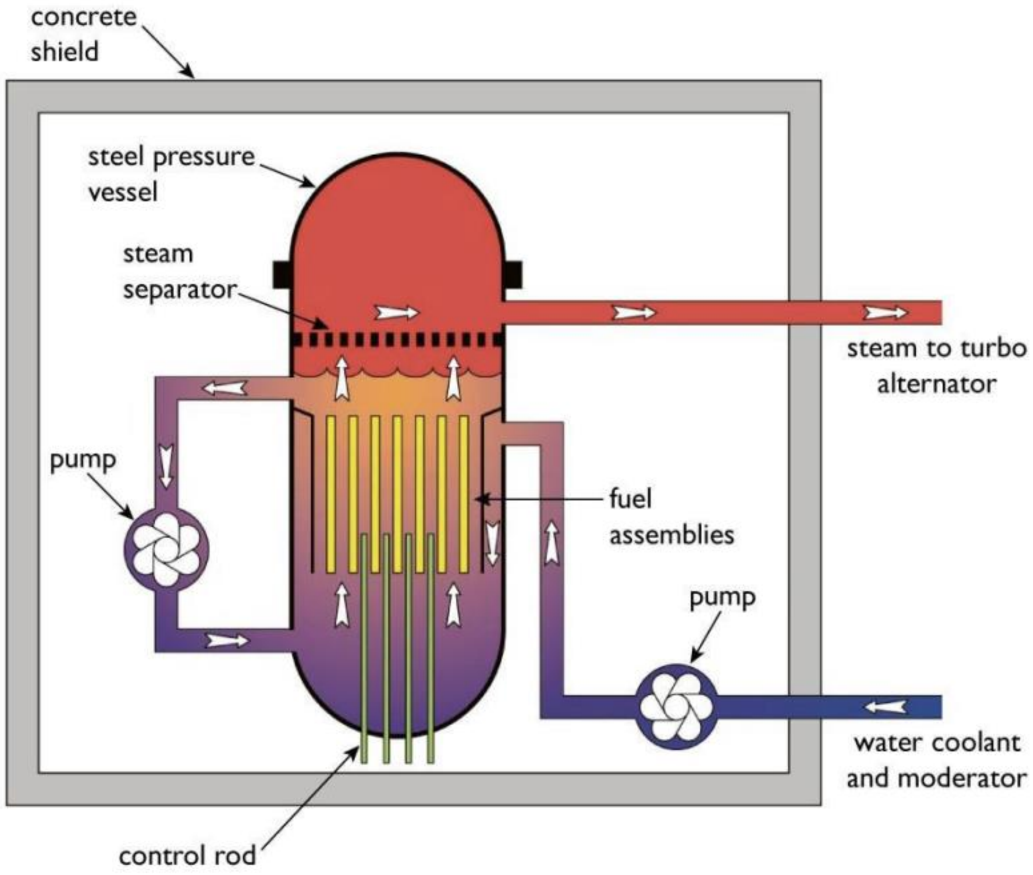


Light Water Reactor: LWRs, cont’d

- The hot pressurized coolant water transfer heat to one or more steam generator to produce steam for turbine. As the coolant water is to remain in liquid state, so at a temperature of about 300°C, the pressure should be about 100 atm.
- In PWR, the core surrounded by a primary concrete shield and the entire system including the steam generator is enclosed in a concrete containment structure to prevent escape of radioactive material with a steel lining to capture high energy radiation. In VVER reactors have several separate cooling circuits rather a single one in PWR reactors.
- Maintaining high pressure coolant water flow is critical for PWRs and hence fast and effective cooling system in case of failure of pressurized water circuit is must for PWRs.
- With significant modification in original design for higher efficiency, reduced cost and enhanced safety, at preset Advanced Pressurized Water Reactors (APWRs) are available.

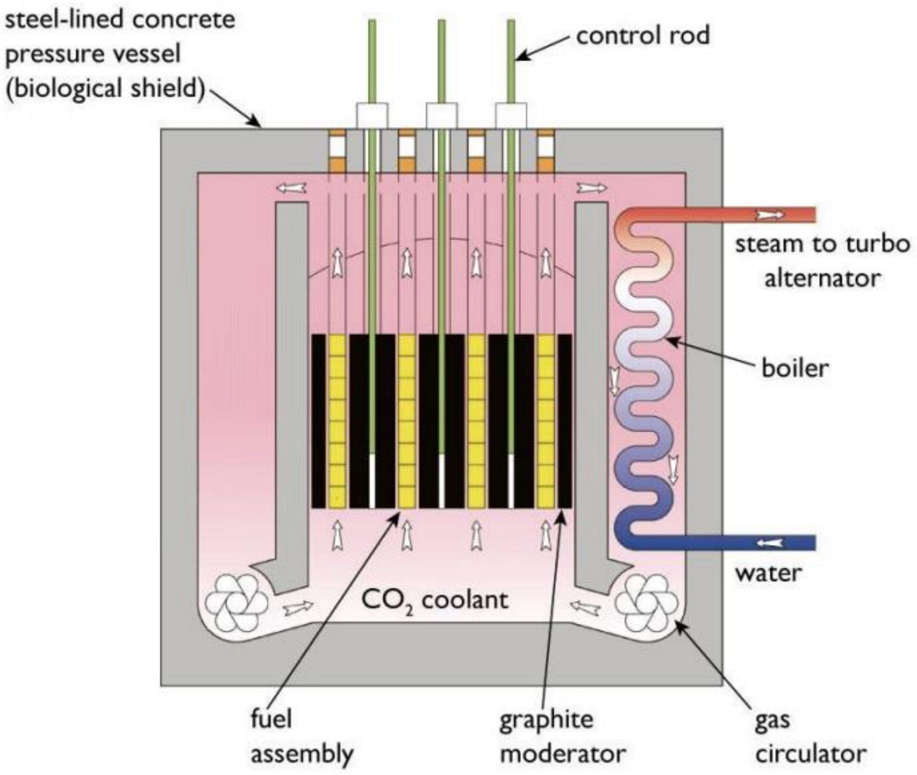
Boiling Water Reactor: BWRs

- Boiling Water Reactors (BWRs) is also developed in USA and the second to the PWRs in the number in use worldwide.
- The BWR is similar to the PWR in many aspects but differ it from PWR in the sense that the water that is used as moderator and coolant is allowed to boil in to steam to run the turbine.
- BWR has the disadvantage that the turbines are exposed to the potentially radioactive coolant, however, as no separate steam generation unit is used, it is economic and reduce heat loss. However, BWRs are operated at lower temperatures and pressures than PWRs. So their heat to electricity efficiencies are not very different.
- With significant modification in original design for higher efficiency, reduced cost and enhanced safety features, at preset Advanced Boiling Water Reactors (ABWRs) are available.



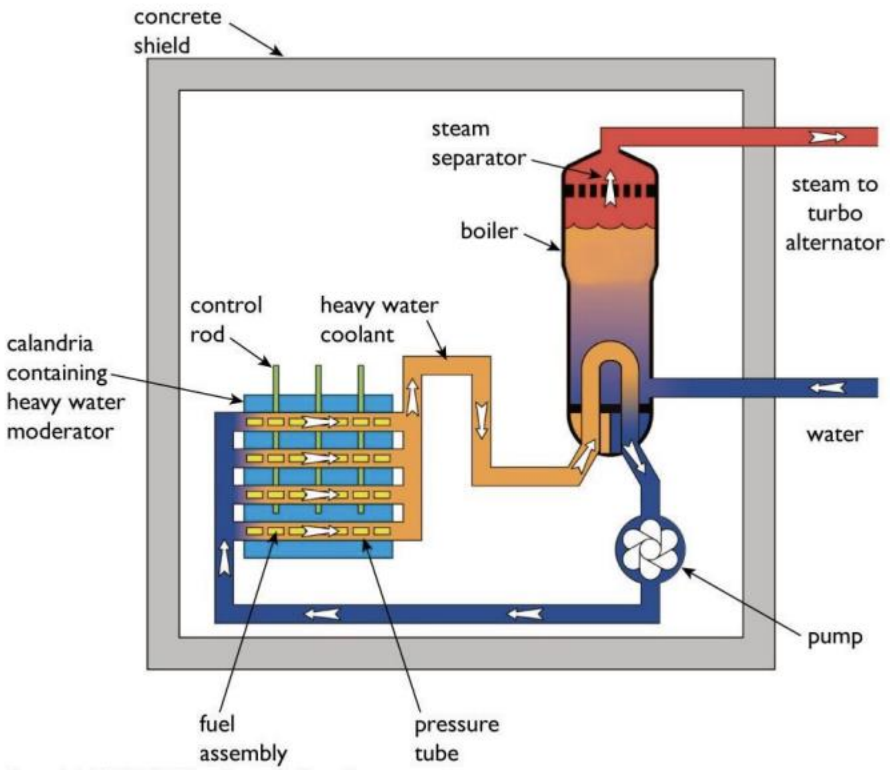
Gas Cooled Reactors: GRs

- Developed in UK, the original Magnox reactors use graphite as moderator, CO2 as coolant and magnesium alloy for fuel cladding (instead of neutron-absorbing steel) suitable for use of natural uranium as fuel. However, its efficiency was limited by the maximum temperature and pressure that the material and structure can with stand and it was about 30%.
- The Advanced Gas-cooled Reactor (AGRs) also use graphite as moderator and CO2 as coolant however it used enriched uranium as fuel (2.3%U-235).
- The main core is effectively solid graphite with vertical channel extended up to reactor pile cap for the insertion of fuel elements and control rods from above. The fuel clusters are not so long and thin as in case of PWRs or BWRs rather they are short and chunky stacked above each other.
- CO2 gas is circulated at 40 bar that absorbed heat from the fuel and deliver it to the boilers.
- The reactor is encased in a concrete pressure vessel which acts as the container for CO2 coolant gas and as a radiation shield.



Heavy Water Reactors: HWRs

- The Canadian-Deuterium-Uranium (CANDU) reactors is the third in the world of dominance of PWRs and BWRs.
- The CANDU was initially designed to use natural uranium as a fuel.
- Use of heavy water as coolant moderator and coolant greatly reduce the neutron loss.
- The coolant under pressure as a temperature of 300□C flows through hundreds of horizontal tubes holding the short fuel bundles.
- The major advantages of very low neutron absorption by heavy water is that the coolant tubes can be double walled insulating the hot high pressure coolant from the surrounding moderator that essentially remains below 100^{o}C.
- The moderator fills horizontal cylinder called Calandria with insulated tubes carrying hot pressurized coolant in and out.
- CANDU reactors are relatively of low thermal efficiency but their high neutron economy allows the use of a range of different fuels.
- With improvement in design, ithas been named as pressurized heavy water reactors (PHWRs) /advanced CANDU reactor (ACR)



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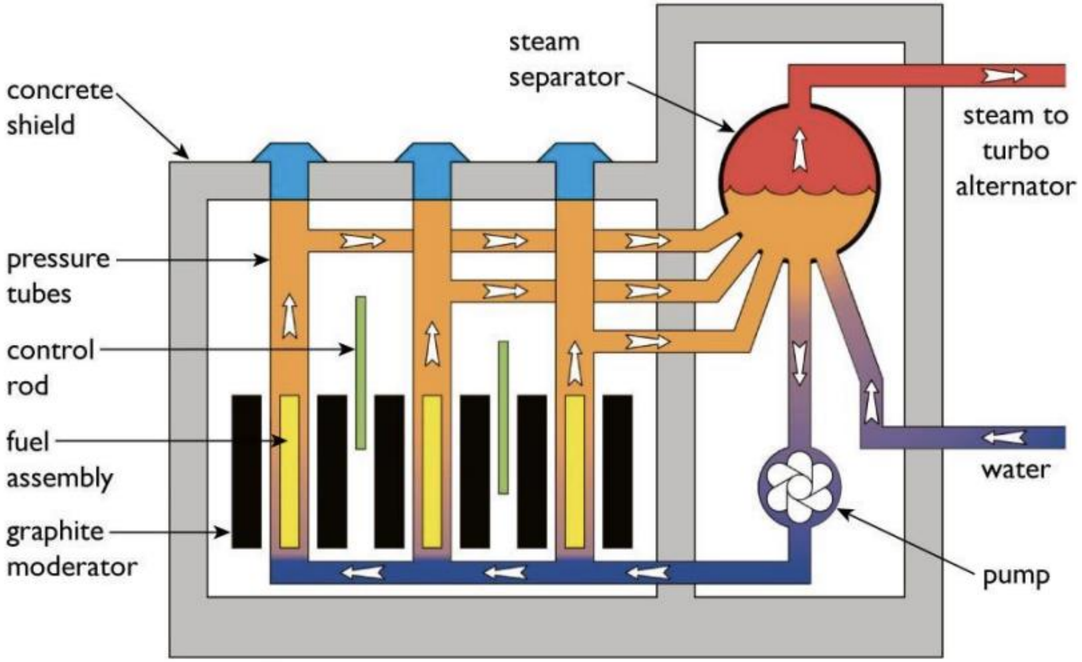
RBMK Reactors

- In addition to VVER, Russians developed other types of reactor among which the main is high power channel type reactor (RBMK).
- RBMK reactors uses graphite as moderator and light water as coolant.
- The RBMK was initially designed to use natural uranium as a fuel but subsequently moderated to use enriched fuel.
- The Chernobyl reactors was of this kind. Following the nuclear accident in 1986 at Chernobyl, some RBMK reactors were shut down in Russia and elsewhere but there are still dozen in operation.

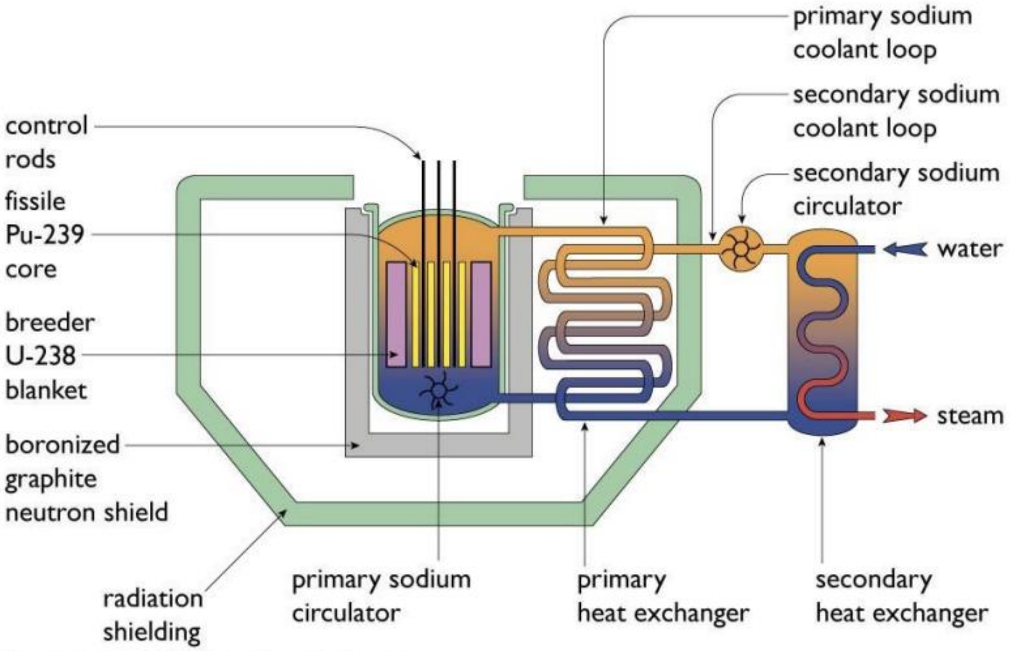


Fast Neutron Reactors: FNRs

- A fast-neutron reactor or simply a fast reactor is a category of nuclear reactor in which the fission chain reaction is sustained by fast neutrons (energy level: 5 MeV or greater), as opposed to thermal/slow neutrons used in thermal reactors (energy level: 1-20 eV or even lesser).
- Fast reactors more deliberately use the uranium-238 as well as the fissile U-235 isotope used in most reactors.
- If they are designed to produce more plutonium than the uranium and plutonium they consume, they are called fast breeder reactors (FBRs) while if they produce more fissile material (U-235, Pu etc.) than consumed they are called burners.
- If the ratio of final to initial fissile content is the burn ratio or breeding ratio.
  - Burn ratio: more than 1 for breeders and less than 1 for are burners.
- Generation IV reactor designs are largely FNRs, and international collaboration on FNR designs is proceeding with high priority as they offer the prospect of vastly more efficient use of uranium resources and the ability to burn actinides which are otherwise the long-lived component of high-level nuclear wastes.
- The rich/concentrated fuel generates more heat per unit volume of the core than a thermal reactor.

Fast Neutron Reactors: FNRs

- Therefore the coolant in FBR's must be able to carry out this extra heat and also should be heavier not to moderate the neutrons.
- Majority of FBR's use Liquid sodium (melting point: 100 ^{o}C, boiling point: 900 ^{o}C). The core temperature is about 600^{o}C and therefore, sodium remains in liquid state in the core and FBR's operate at low pressure.
- In FBR's, the core is surrounded by a blanket of U_{238} for breeding occurs to produce Pu_{239}.



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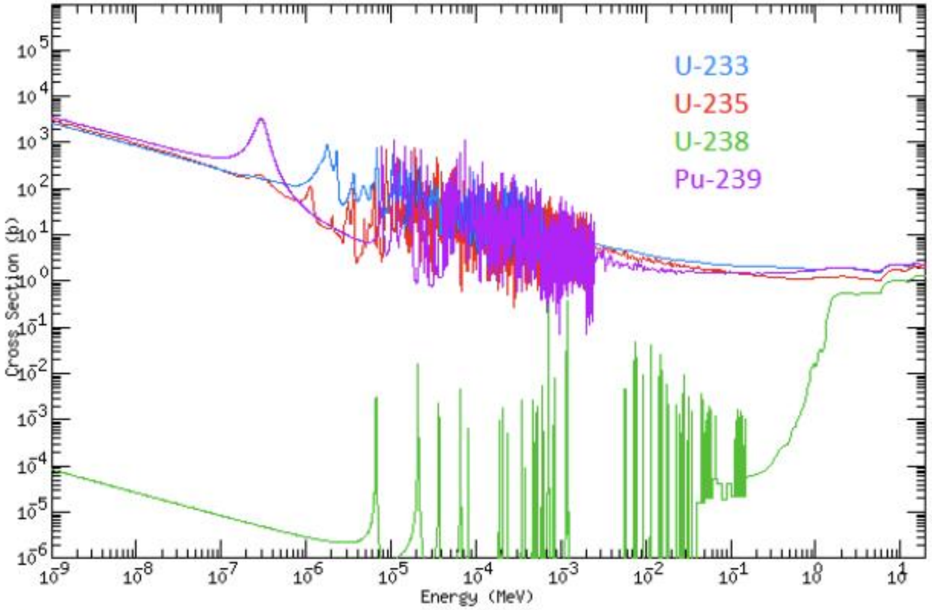
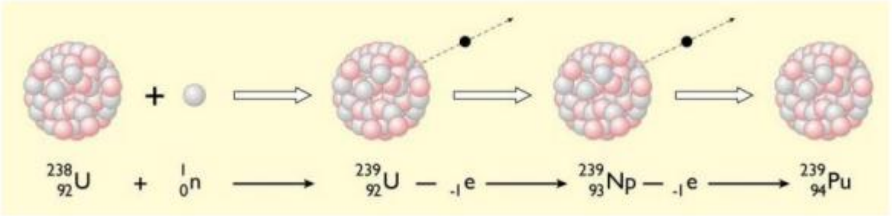
Why No Moderator in FNRs?

- The fast reactor has no moderator and relies on fast neutrons alone to cause fission, which for uranium is less efficient than using slow neutrons. Hence a fast reactor usually uses plutonium as its basic fuel, since it fissions sufficiently with fast neutrons to maintain chain reaction. At the same time the number of neutrons produced per plutonium-239 fission is 25% more than from uranium, and this means that there are enough (after losses) not only to maintain the chain reaction but also continually to convert U-238 into more Pu-239. Furthermore, the fast neutrons are more efficient than slow ones in doing this breeding, due to more neutrons being released per fission.
- In thermal fission reactors, main fuel is U-235 that has a high neutron cross-section for lower energy spectra of neutrons. So, moderator is used to reduce the energy level.
- In fast neutron reactors, main fuel is U238 that has a high neutron cross-section for higher energy spectra of neutrons so no moderator is used hence energy level of neutrons remains higher.





Thermal/Slow Neutron Reactors Vs. Fast Neutron Reactors

Neutrons produced by fission have high energies and move extremely quickly. These so-called fast neutrons **do not cause fission in Uranium-235 isotopes as efficiently** as slower-moving ones so they are slowed down in most reactors by the process of moderation. **A liquid or gas moderator, commonly water or helium, cools the neutrons** to optimum energies for causing fission. These slower neutrons are also called thermal neutrons because they are brought to the same temperature as the surrounding coolant.

In contrast to most normal nuclear reactors, however, a fast reactor **uses a coolant that is not an efficient moderator**, such as liquid sodium, so its neutrons remain high-energy. Although these fast neutrons are not as good at causing fission, they are readily captured by an isotope of **uranium (U_{238})**, which then becomes **plutonium (Pu_{239})**. This plutonium isotope can be reprocessed and used as more reactor fuel or in the production of nuclear weapons.

Natural uranium consists primarily **of U_{238}, which does not fission readily, and U_{235}, which does**. **Natural uranium** is unsuitable for use in a nuclear reactor, **because it has only 0.72% U_{235}**, which is not enough to sustain a chain reaction. Commercial nuclear reactors normally use uranium fuel that has had its U_{235} content enriched to 3-8% by weight. Although the U_{235} does most of the fissioning, more than 90 percent of the atoms in the fuel are U_{238} that are potential neutron capture targets and future plutonium atoms.

Fast neutrons are ideal for plutonium production because **they are easily absorbed by U_{238} to create Pu_{239}, and they cause less fission** than thermal neutrons.