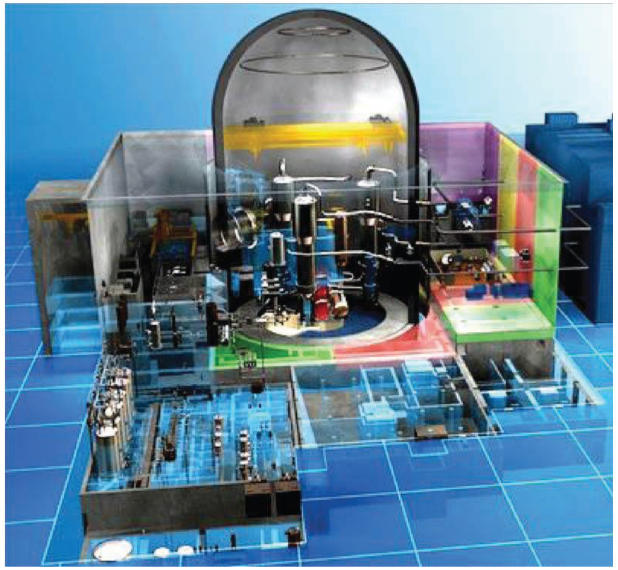
NUCLEAR REACTOR SYSTEM



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Objectives of topic

- Introduce the important components in a nuclear reactor.
- Students able to explain the functions for each of the components.

Reactor System

A **nuclear reactor** used for the purpose of **power generation** or for the **production of radioisotopes.**

It is **defined** as a system wherein a **nuclear fission** is carried out as a **controlled chain reaction**

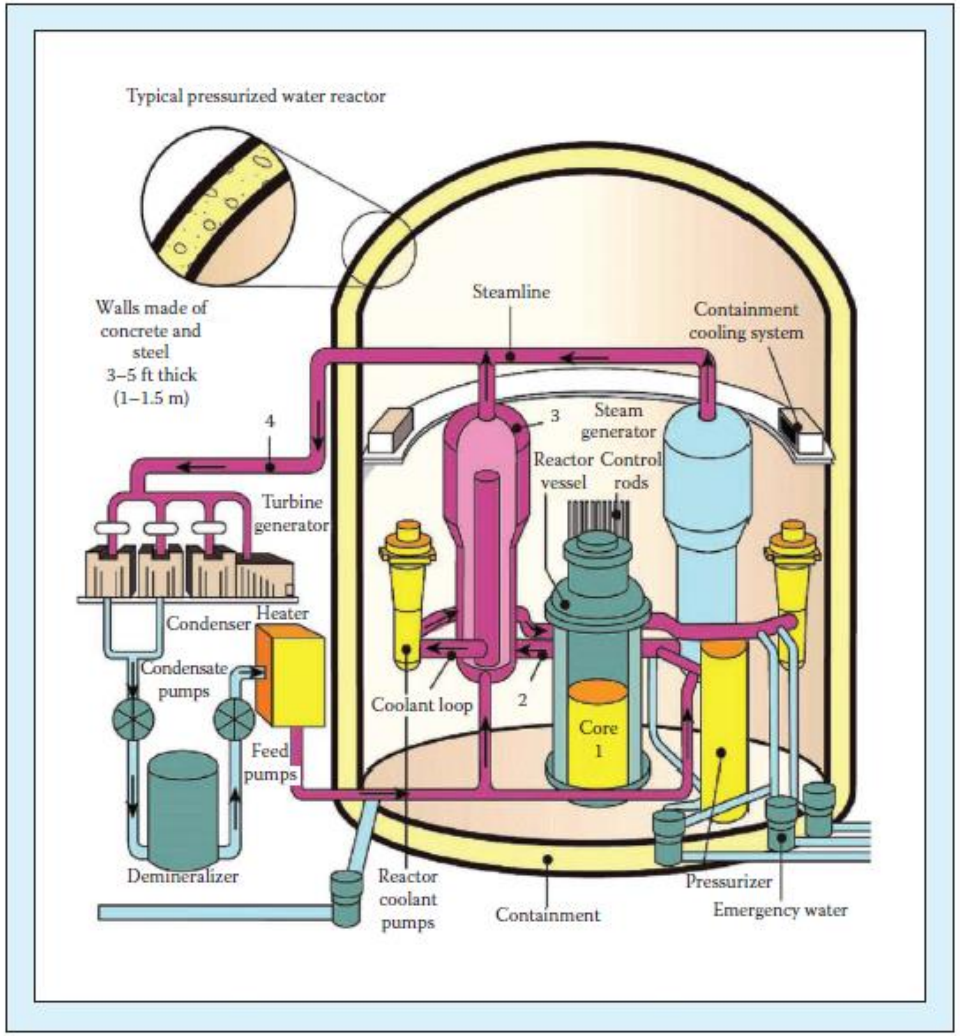
Nuclear reactors that utilize **thermal neutrons** to initiate and sustain fission are called **thermal reactors**

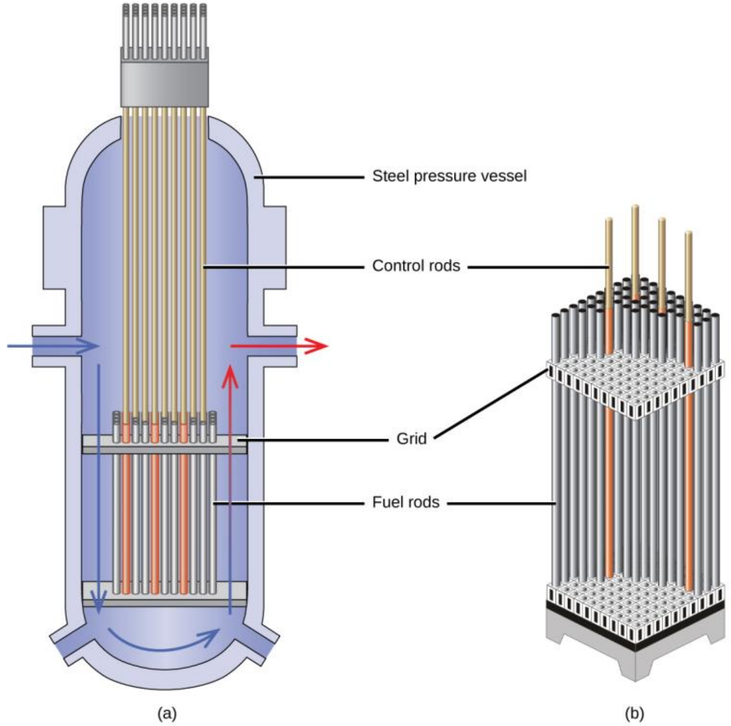
Nuclear reactors utilize fast neutrons are called **fast reactors**.

Reactor System

- Fuel
- Cladding
- Moderator
- Coolant
- Reflector
- Control material
- Shielding materials

Overview of Nuclear Reactor Components





A typical PWR. Here, 1 denotes the core, 2 denotes the primary loop, 3 denotes the SGs, and 4 denotes the secondary loop. (Courtesy of the U.S. NRC.)

Nuclear Fuel

Materials that undergo nuclear fission when bombarded with thermal neutrons are called **fissile** material and their respective nuclei called **fissile nuclei**.

The nuclei with higher σ_f/σ_γ are suitable as fuel as U-235, Pu-239 and U-233 have higher σ_f/σ_γ ratio. Hence, they can be used as fuel in **nuclear reactor**.

U-235 is the only fissile nucleus that is available in nature, while **Pu-239** and **U-233** are produced in nuclear reactors.

Nuclear Fuel

Cross sections for some nuclei for thermal neutrons (**Kinetic energy = 0.025 eV**)

Nucleus	Cross sections (b)			
	σ_γ	σ_f	σ_T	σ_a
U-235	95	586	700	681
Pu-239	270	752	1028	1022
U-238	2.73	11.8e-6	12.2	2.7

Cross sections for some nuclei for thermal neutrons (**Kinetic energy = 1 MeV**)

Nucleus	Cross sections (b)		
	σ_γ	σ_f	σ_a
U-235	0.11	1.2	2.7

Nuclear Fuel

Most of the nuclear reactors for **power generation** use **uranium** as fuel.

U-235 is not present in nature in **pure** form. It is present as a mixture with **U-238**, the major component present to the extent of **99.3 %**.

In other words, the **isotopic abundance** of natural U-235 in a mixture of **U-235** and **U-238** is only **0.7 %**.

In **most** reactors the **fuel** is in oxide form as **UO2**.

Pu-239 is used as fuel in **Fast Reactors.**

U-233 is proposed as fuel in **Advanced Heavy Water Reactors**.

Nuclear Fuel Materials

The **nuclear reactors** in operation around the globe utilize **uranium** (or) **plutonium-based** materials as fuel.

The fuel may be in the form:

- Metal
- Metal Oxide
- Metal carbide
- Metal nitride

Nuclear Fuel Materials

Properties	Implications
Nuclear properties: Absorption cross section, fission cross section, fission products, neutron production, energy released	Determines the mass of fissile required, volume of the core
Thermal conductivity	Indicates the ability of a material to transfer heat by thermal conduction.
Melting point	Defines the limiting power of a fuel element.
Dimensional stability	A measure of expansion of a material with increase in temperature.
Chemical properties	In case of cladding failure in terms of cracks, there will be direct contact between fuel and coolant.
Coefficient of thermal expansion	A measure of expansion of a material with increase in temperature.

Oxide Fuels

Oxide fuels are

- ❑ **UO_2 (Uranium oxide)**
- ❑ **Mixed oxide (UO_2-PuO_2).**

The major **disadvantages** of oxide fuels:

- **Lower density** (leads to the requirement of a **larger core diameter**).
- **Lower thermal conductivity** (**poor transfer** of heat from the **centre** of the fuel pin to the edge of the pin and to the **cladding**).

Metallic Fuels

Metallic uranium has **better thermal conductivity** compared to that of **UO_2**. The **density** of metallic uranium is also **higher** than that of UO_2.

The major **disadvantages** of oxide fuels:

- **Metallic uranium** undergoes a **change in crystalline** phase at **660 °C.**
- A substantial **change** in the **volume** of metal is experienced as a result of this phase change.
- This results in **damage** to the integrity of the **fuel elements**. Owing to this, metallic uranium is **not used** as fuel in **power reactors**

Metal Carbide and Nitride Fuels

Uranium carbide and **uranium nitride** have **higher density** and **thermal conductivity** than uranium dioxide.

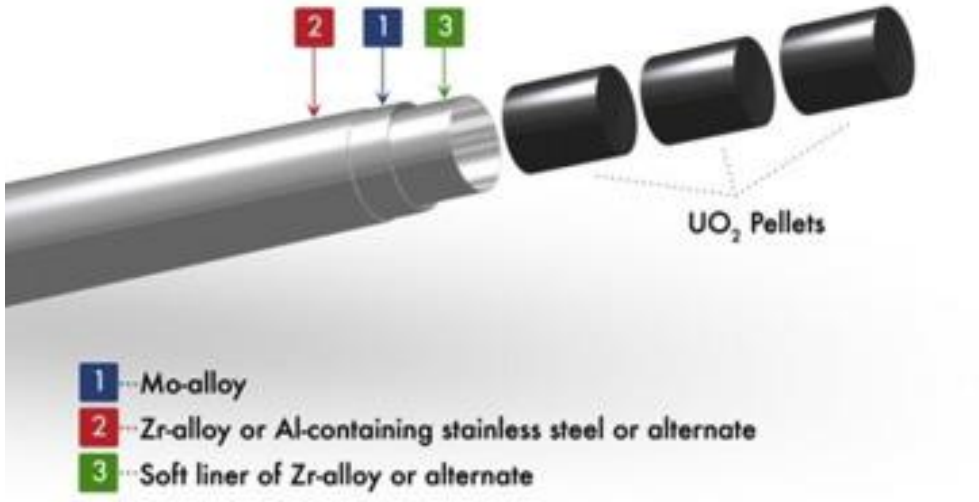
These fuels are **inferior** to **uranium dioxide** as far as the **compatibility** with **cladding**, **swelling** under **irradiation** and **retention** of fission gas are concerned.

These were used in **test reactors** only.

Cladding

The purpose of cladding in a nuclear reactor

- Cladding gives the physical configuration by housing fuel pellets.
- Cladding retains the fission products and prevents direct contact between coolant and fuel.



Cladding

The **material** of **choice** for **cladding** must:

- **Possess ductility**, impact **strength** and **creep** adequate enough to maintain cladding **unaltered** during the operation of the reactor.
- **Resistance** to **corrosion** by coolant must be high for a material to be used as cladding.
- Possess **high melting point**.
- Possess **high thermal conductivity**.
- **Not** be **damaged** due to sustained **neutron irradiation**.

Cladding

The nuclear properties of clad material are

- must possess **low absorption** cross section for **neutrons**.
- **Aluminum**, **beryllium**, **magnesium** and **zirconium** have **low absorption** cross section for neutrons and possess **high melting point**.
- **Aluminum** is used in **small**, **research reactors**.
- **Magnox**, an alloy of Magnesium is used in **gas-cooled reactors**.

Cladding

Continue..

- **Zircaloy**, the alloy of zirconium is used in most **thermal reactors**.

- These alloys (**Zircaloy-2** and **Zircaloy-4**) possess **good mechanical properties** and have superior **resistance to corrosion**.

- But **low absorption cross** section for neutrons was **not comprised** to a large extent.

- The requirement of **low absorption cross section** need not be satisfied for **fast reactors**.

- **Stainless steel** is used as cladding material in **sodium cooled fast reactors**.

Moderator

Moderation with respect to nuclear reactors implies **slowing down** of **neutrons**.

Neutrons with **higher kinetic energy** (fast neutrons) are allowed to undergo **elastic scattering** with a **light nucleus** resulting in **reduction** in **speed** and change in **direction** of neutrons.

As a result, the **neutron energy** is brought down to **thermal levels** (**0.025 eV**).

Comparing the **fission cross sections** of **U-235** with fast neutrons and thermal neutrons, it is clear that the probability of fission in **U-235** with **thermal neutrons** is **more** than with **fast neutrons**.

Moderator

The **neutron energies** must be brought **down** or in other terms, the neutron needs to be **slowed down**.

The most widely used **moderators** are the one that contain **light nuclei** like

- **Hydrogen,**
- **Deuterium,**
- **Carbon**
- **Water (H2O, also called light water),**
- **Heavy water (D2O)**
- **Graphite**

Coolant

The **purpose** of **coolant** is to **remove** the **heat liberated** during **fission** and to utilize the same for steam generation.

The **coolant supply** to a **nuclear reactor** must be **continued** even if the **chain reaction** has **ceased** and **reactor shut down**. This is to ensure the removal of **decay heat** and to **avoid** the **melting** of **reactor core**.

Water and **heavy water** are the most common liquid coolants in **thermal reactors**.

Liquid sodium is used as coolant in **fast reactors**.

Helium and **CO2** are used as gaseous coolants in **Gas-cooled reactors**.

Reflector

The **purpose** of **reflector** in a nuclear reactor is to **reflect** the **neutrons escaping** or **leaving**, **back to the core**.

The essential **characteristics** required for a **reflector material**:

- **Low cross section** for neutron **capture** or **absorption**
- **High cross section** for **neutron scattering**
- **High energy loss** per collision event between **neutron** and **reflector**
- **Temperature** and **radiation stability**

Reflector

Most **thermal reactors** use **water** as both the **moderator** and **reflector**.

The reflector in **PHWR** is the **heavy water**.

In **graphite-moderated reactors**, **graphite** acts as reflector.

Control Materials

Control materials are essential for **regulating the power** of a reactor, apart from bringing about **rapid shut down** when required.

These are the materials that have **high tendency** to absorb neutrons through **neutron capture**.

These are the materials that possess **high σ_γ**.

Boron and **Cadmium** have high capture cross sections and hence are used as **control materials** in the form of **rods or plates**.

Control Materials

Control elements are meant to **control** the **reactor power** through **absorption of neutrons**.

Hafnium, **silver-indium-cadmium** alloys and **boron carbide** are the widely used control materials.

Hafnium use as control material in **water-cooled reactors**. However, the **availability** of Hafnium is **limited** and hence it is **expensive**.

Silver-indium-cadmium alloys are **easily fabricated** must be **enclosed** in a **stainless steel** enclosure to protect the same from **corrosion**.

Boron has very **high absorption cross section** and **low cost** and must incorporated in a **metallic enclosure**.

Shielding Materials

The **types** of **radiations** in a nuclear reactor are **neutrons**, **gamma**, **alpha** and **beta** radiation.

Shielding materials are **not required** for **α** and **β radiation**.

For **absorption of neutron radiation**, a material with **low mass number** and **high cross section is suitable**. (Water)

Iron and **concrete** are good **neutron absorbers**. They can be easily fabricated as well.

Shield **gamma radiation** must be composed **of high mass number element**. (**Lead, iron and concrete**) for shielding

Lead is attractive due to its **low cost,** but its **lower melting point** is a **disadvantage**.

Shielding Materials

Other components

Apart the above four important components of a nuclear reactor, other components include **structural components** and **control systems**.

Thank You

Stay safe!