Subject: Power Plant (ME 403)

Topic: Nuclear Power Plant

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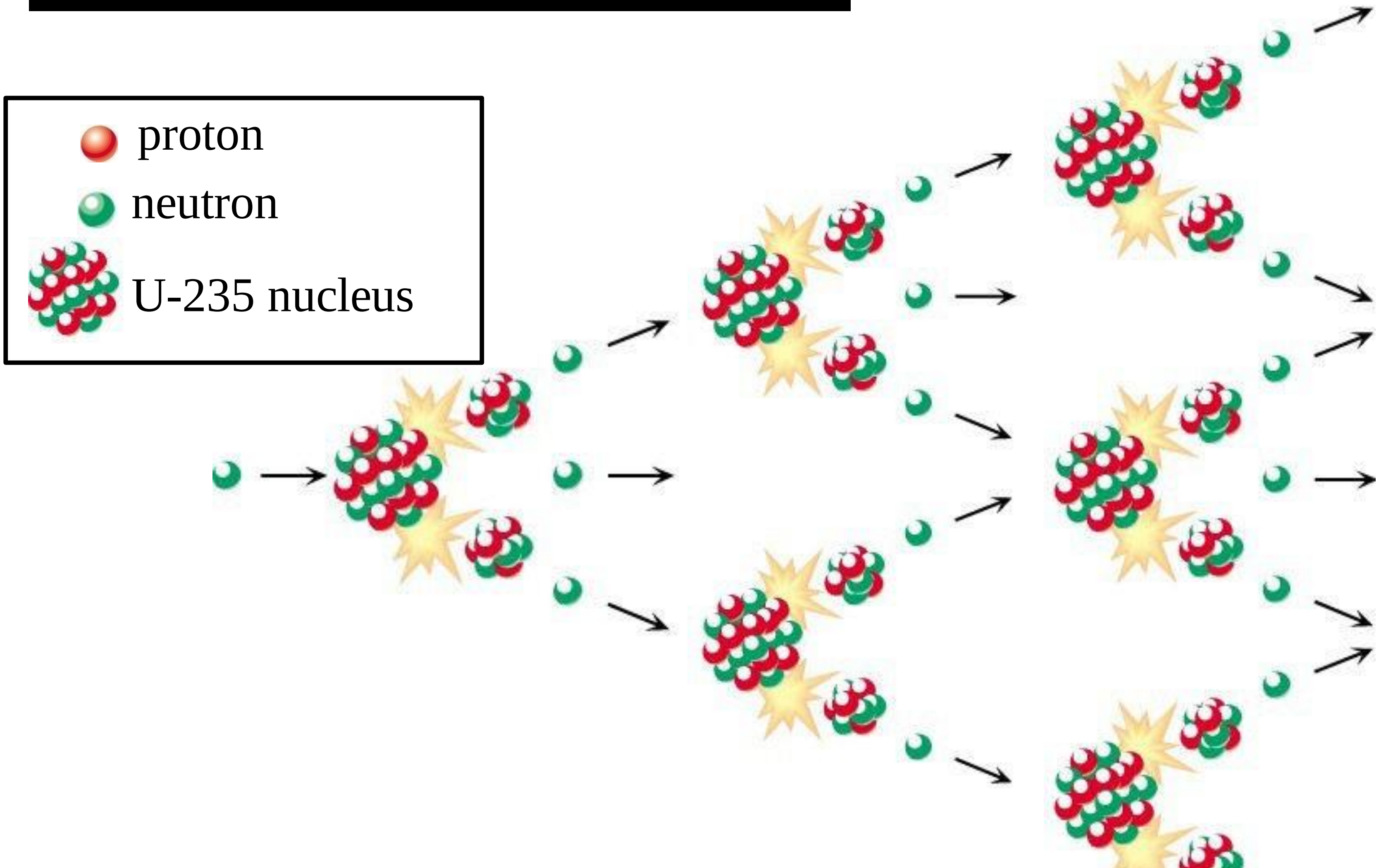
Nuclear (Atomic) Power Plant

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

Nuclear (Atomic) Power Plant…

Chain Reaction…

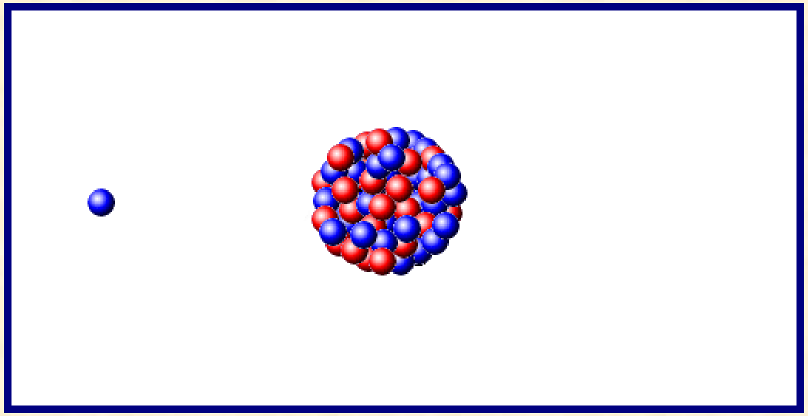
- Uranium exists as an isotope in the form of U^{235} which is unstable.

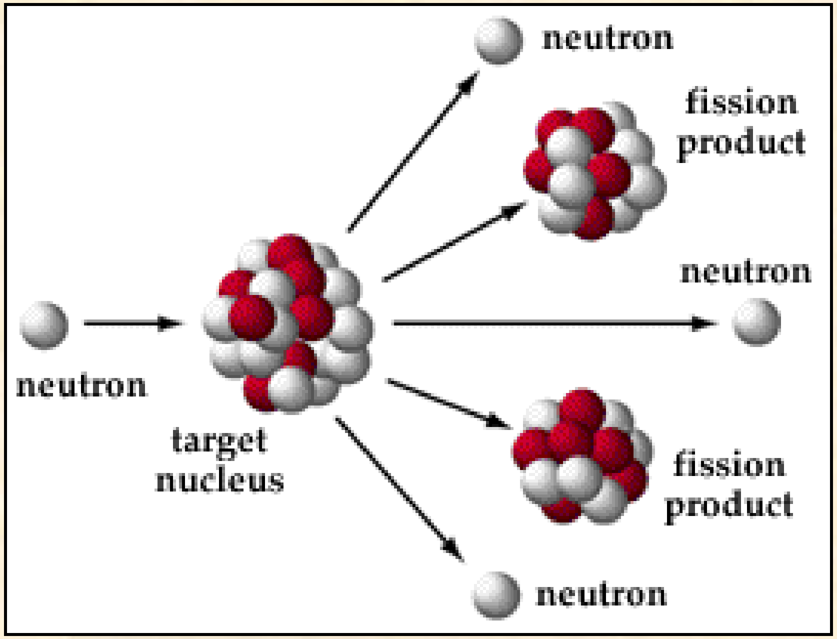
- When the nucleus of an atom of Uranium is split, the neutrons released hit other atoms and split them in turn. More energy is

  released each time another atom splits. This is called a chain reaction.

Nuclear (Atomic) Power Plant…

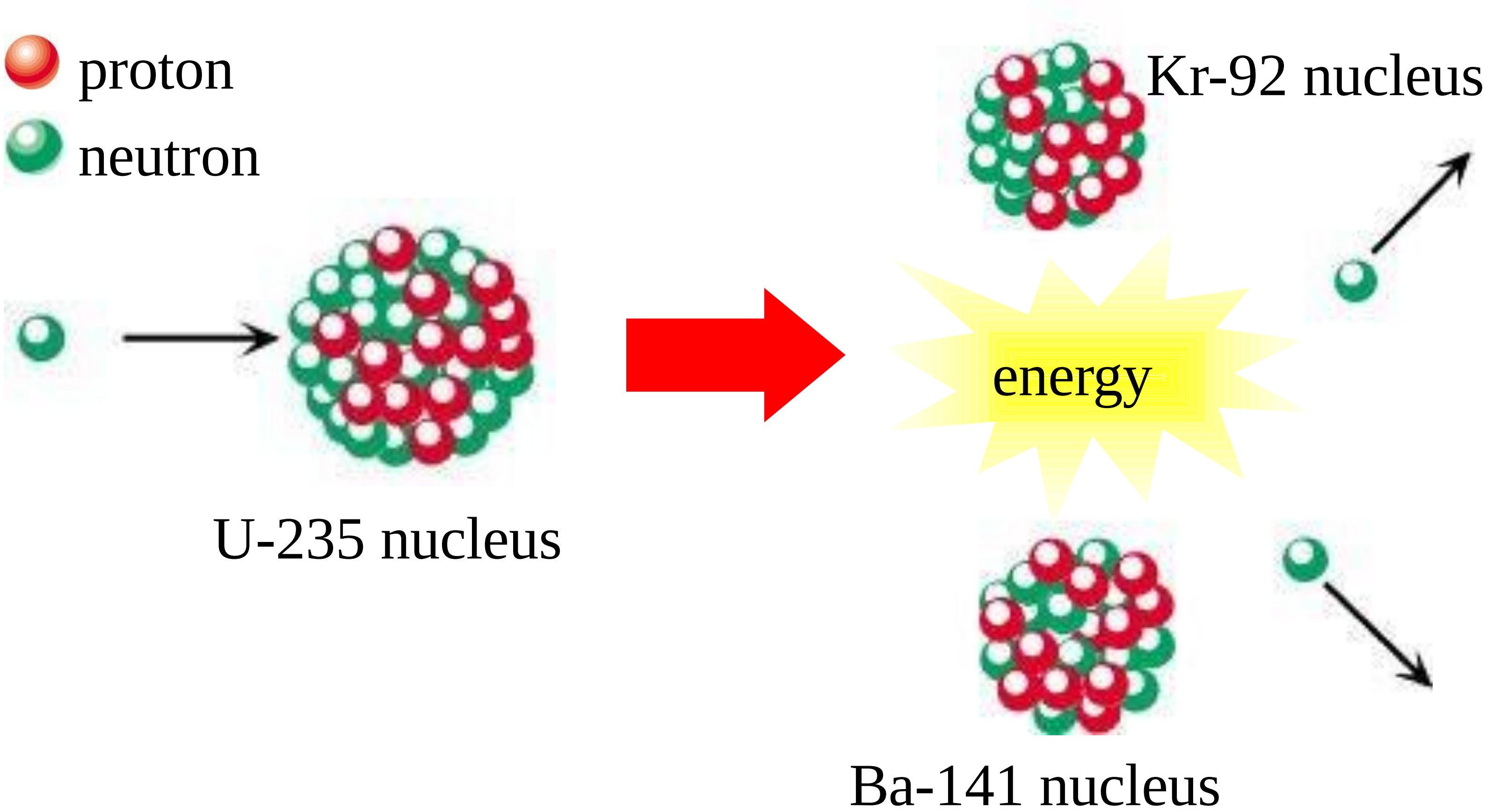
Nuclear fission:





Nuclear fission…

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



Nuclear Fission…

- 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.

$1 \text{ eV} = 1.6 \times 10^{-19}$ joule.

$1 \text{ MeV} = 10^6 \text{ eV}$

Nuclear (Atomic) Power Plant…

Nuclear fission…

- 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.

reaction.

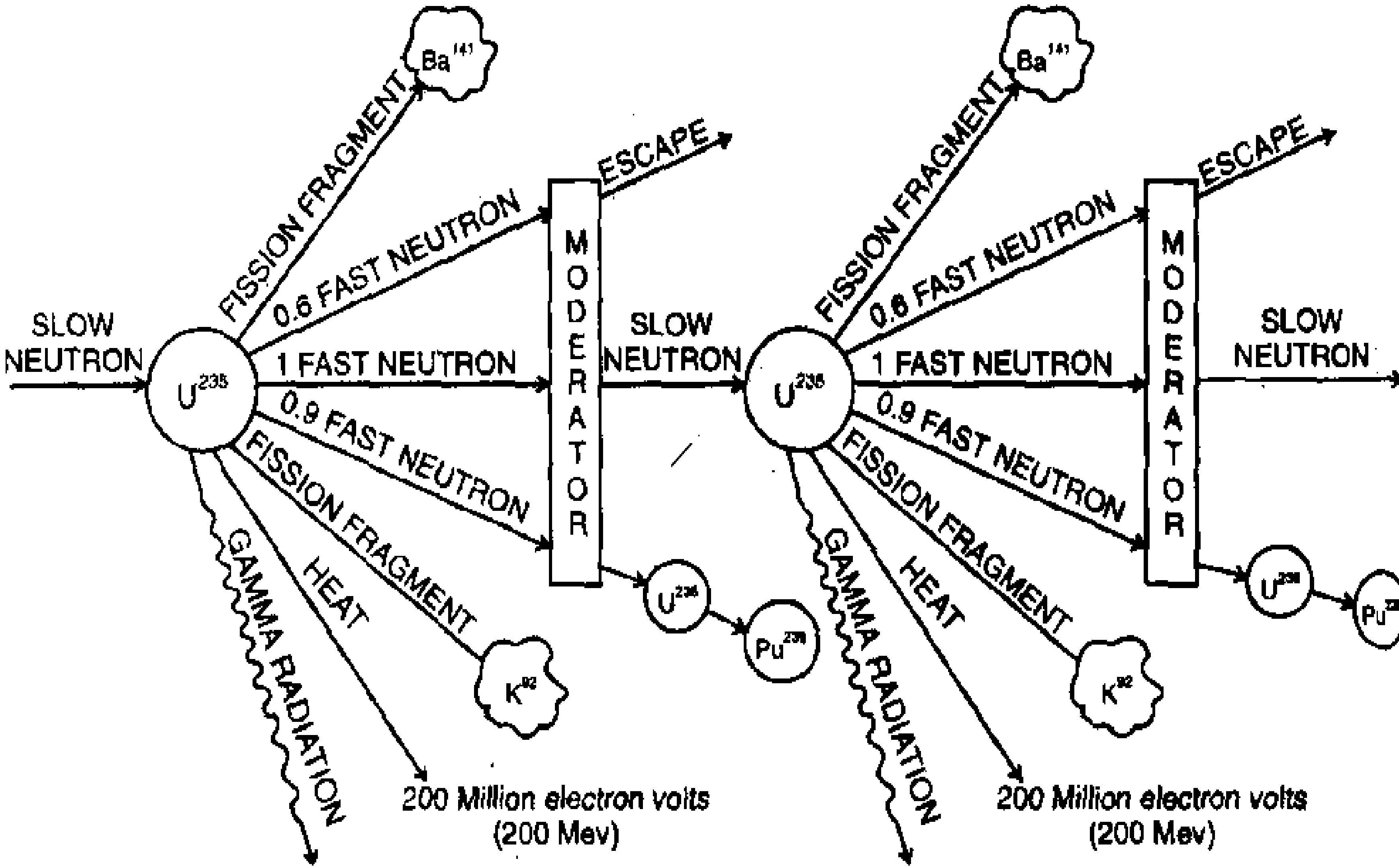


Fig. 3.7: CONTROLLED CHAIN REACTION IN A NUCLEAR REACTOR

Half Life

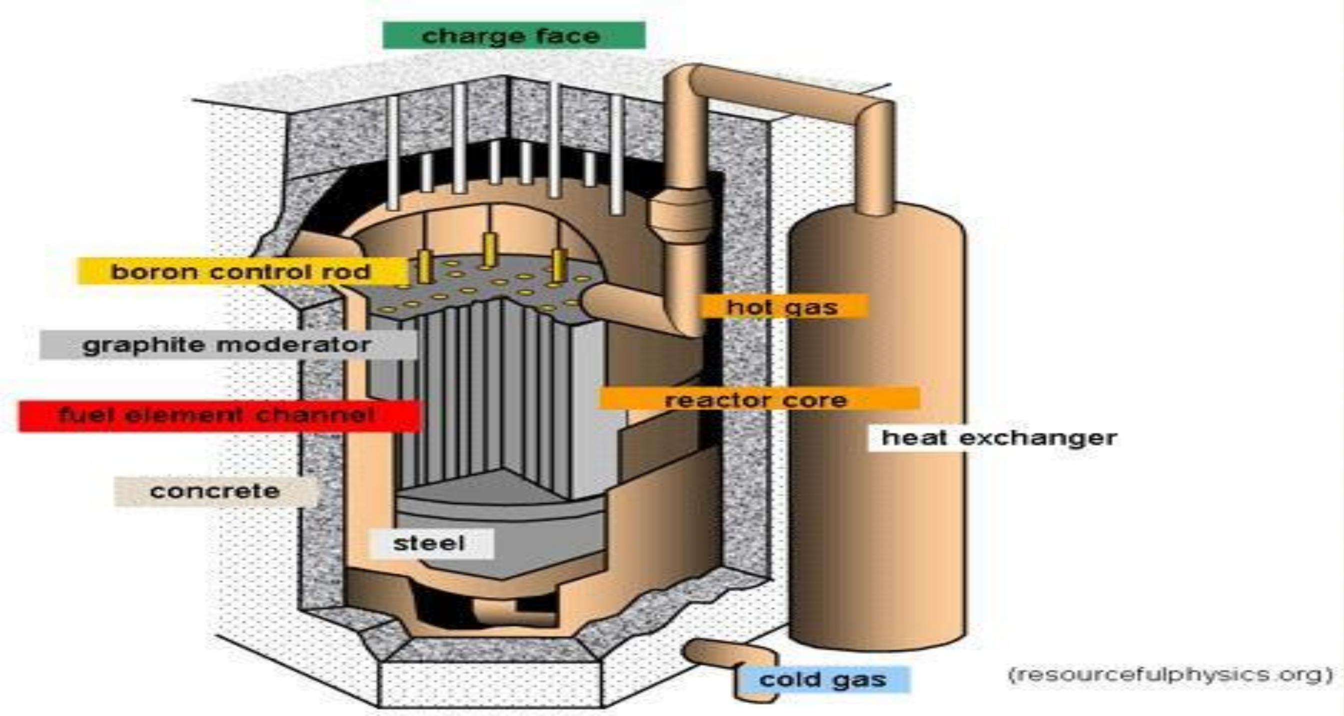
Half-life (symbol $t_{1/2}$) is the time required for a quantity to reduce to **half** of its initial value. The term is commonly used in **nuclear** physics to describe how quickly unstable atoms undergo, or how long stable atoms survive, radioactive decay.

In uranium 238, the half of atoms takes 4.5 billion years to convert in lead which is non radioactive.

Isotope	Emits	Half Life
Uranium-238	Alpha	4500 000 000 years
Thorium-234	Beta, Gamma	24.1 days
Proactinium-234	Beta, gamma	60 seconds
Uranium-234	Alpha, Gamma	245 000 years
Thorium-230	Alpha, Gamma	76 000 years
Radium-226	Alpha, Gamma	1600 years
Radon-222	Alpha	3.8 days
Polonium-218	Alpha	3 minutes
Lead-214	Beta, Gamma	27 minutes
Bismuth-214	Beta, Gamma	20 minutes
Polonium-214	Alpha	160 microseconds
Lead-210	Beta, Gamma	22 years
Bismuth-210	Beta, Gamma	5 days
Polonium-210	Alpha	138 days
Lead-206		Stable

Nuclear (Atomic) Power Plant…

- Principal parts of a nuclear reactor:



Core : Here the nuclear fission process takes place.

Moderator : This reduces the speed of fast moving neutrons. Most moderators are graphite, water or heavy water.

Nuclear (Atomic) Power Plant…

Principal parts of a nuclear reactor…

Control rods :

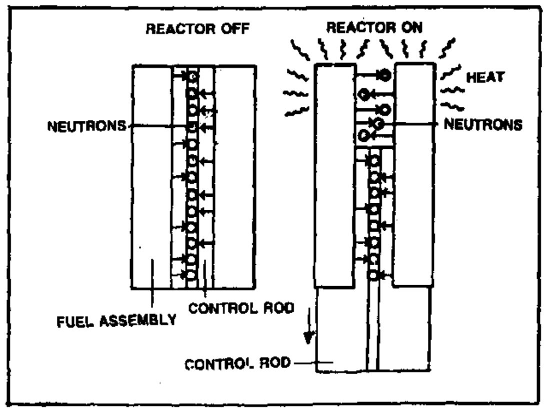


Fig. 3.8: CONTROL RODS

Control rods limit the number of fuel atoms that can split. They are made of boron or cadmium which absorbs neutrons

Coolant : They carry the intense heat generated. Water is used as a coolant, some reactors use liquid sodium as a coolant.

Fuel : The fuel used for nuclear fission is U235 isotope.

Radiation shield : (thermal shielding) To protect the people working from radiation and radiation fragments.

Uncontrolled nuclear reaction

The chain reaction is not slowed down

the rate of fission increases rapidly

energy is released very quickly

Nuclear bomb

Nuclear reactors

- Nuclear power plant: Rate of fission is controlled by artificial means to generate electricity

The Daya Bay Nuclear Power Station

Nuclear (Atomic) Power Plant…

- Types of Nuclear power plant:

Main two types are :

* Pressurised Water Reactor (PWR)
* Boiling Water Reactor (BWR)

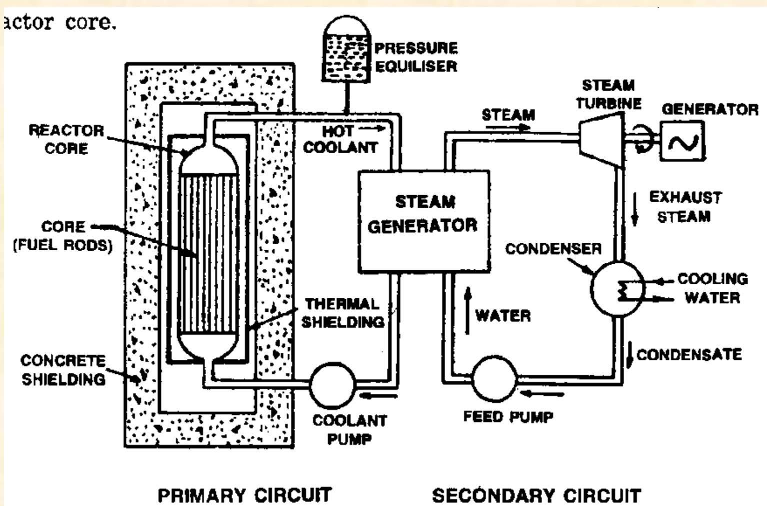


Fig. 3.9: PRESSURISED WATER REACTOR PLANT

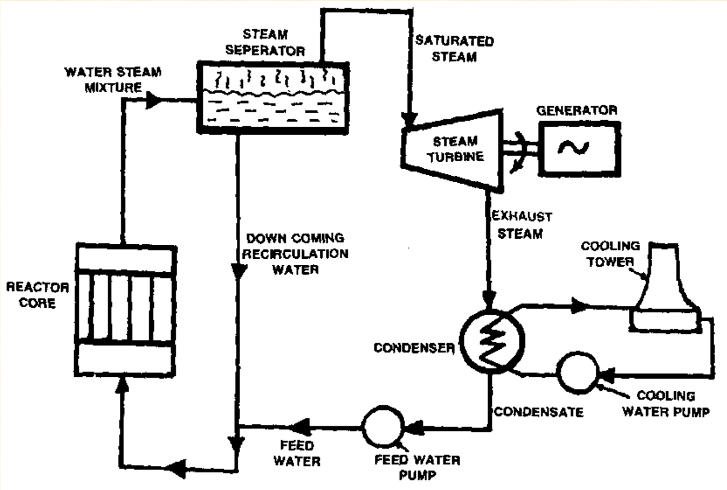


Fig. 3.10: BOILING WATER REACTOR PLANT

actor core.

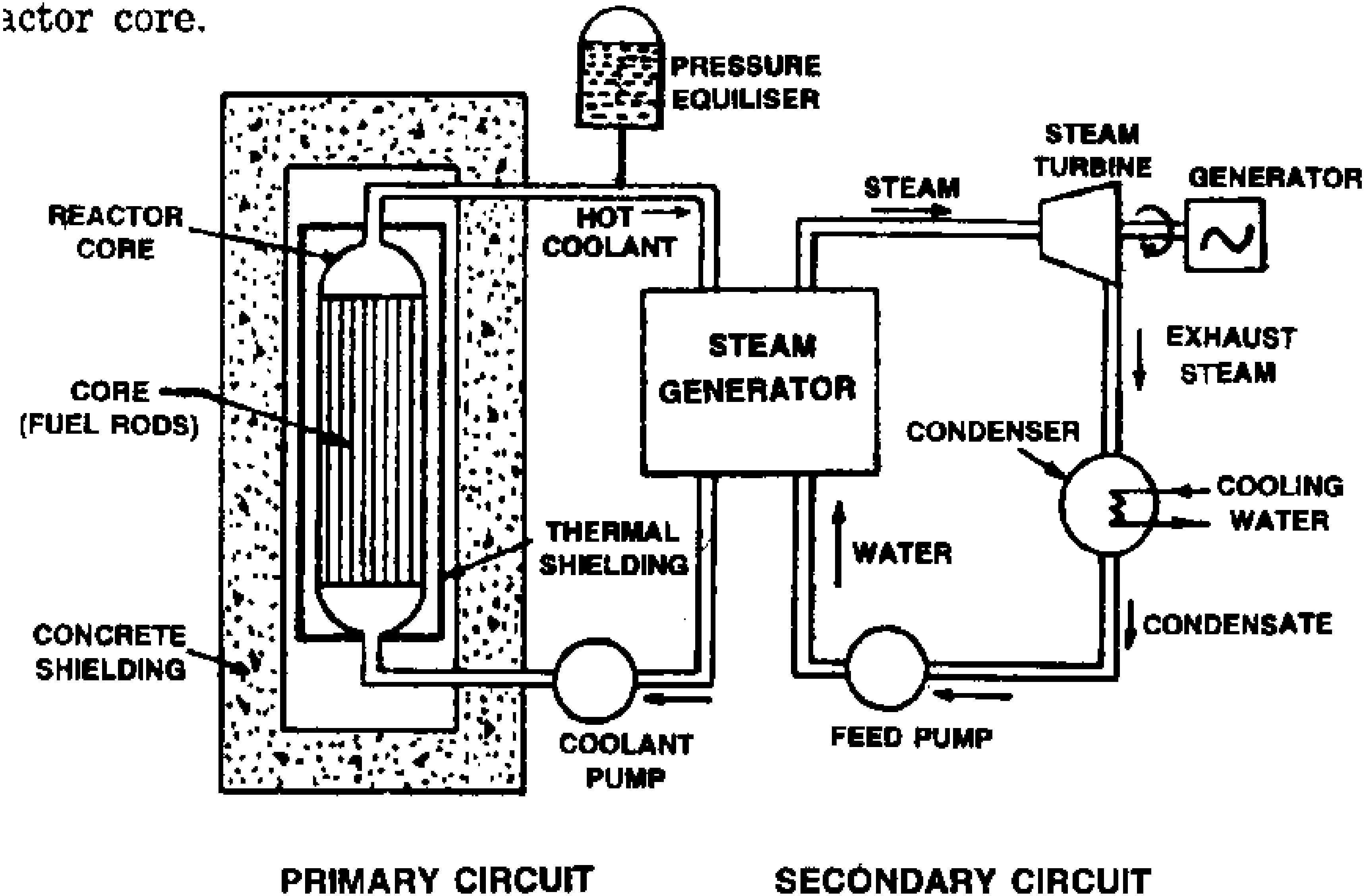


Fig. 3.9: PRESSURISED WATER REACTOR PLANT

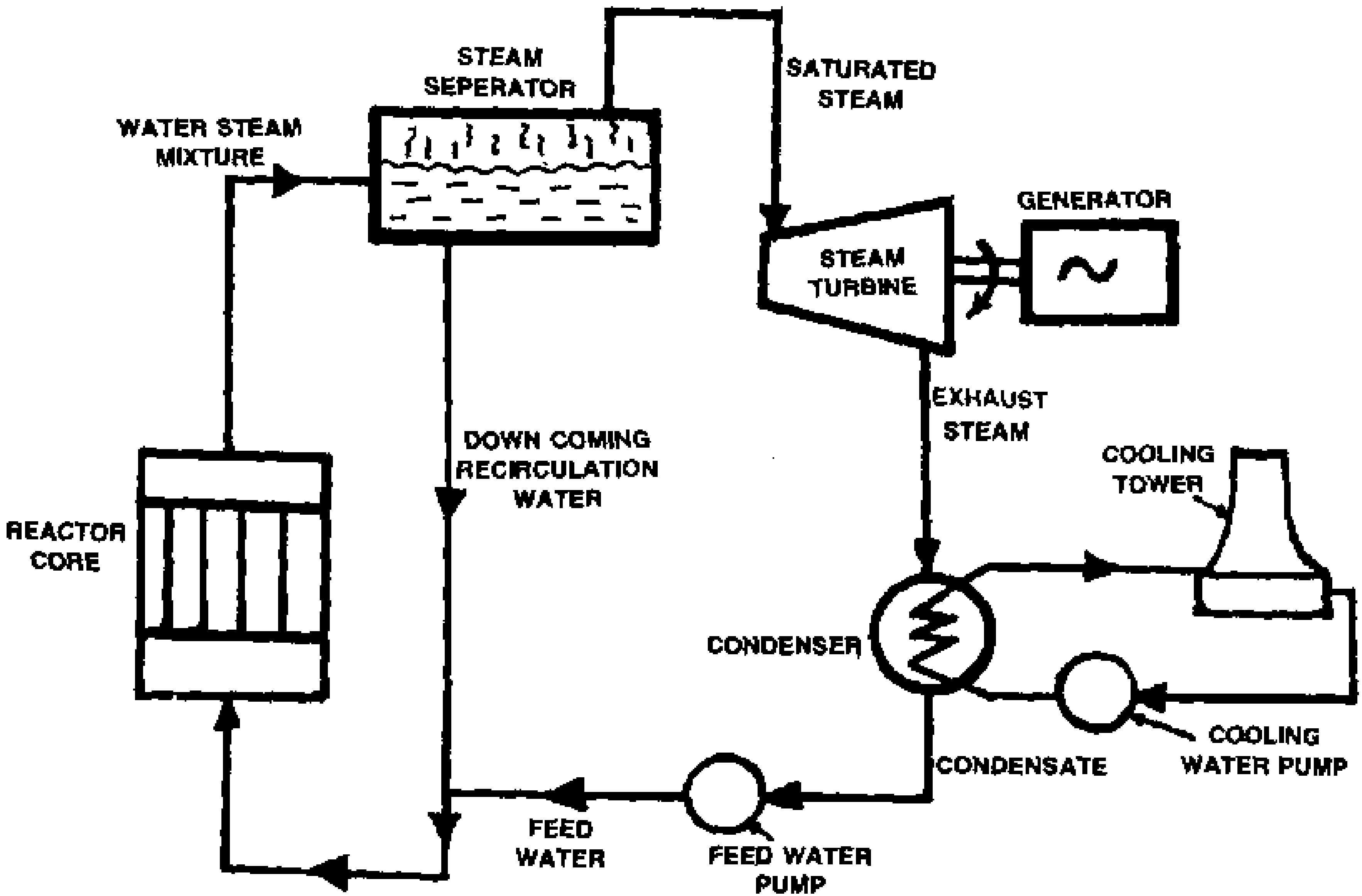


Fig. 3.10: BOILING WATER REACTOR PLANT

Nuclear (Atomic) Power Plant…

- 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.

actor core.

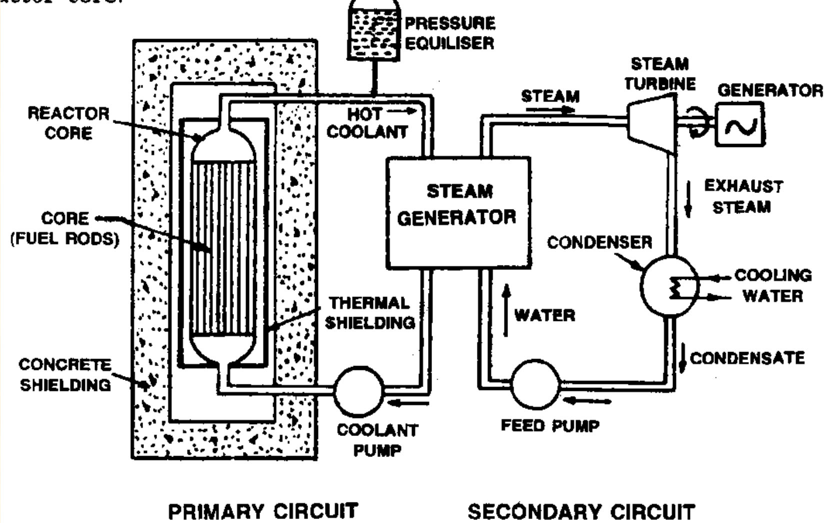
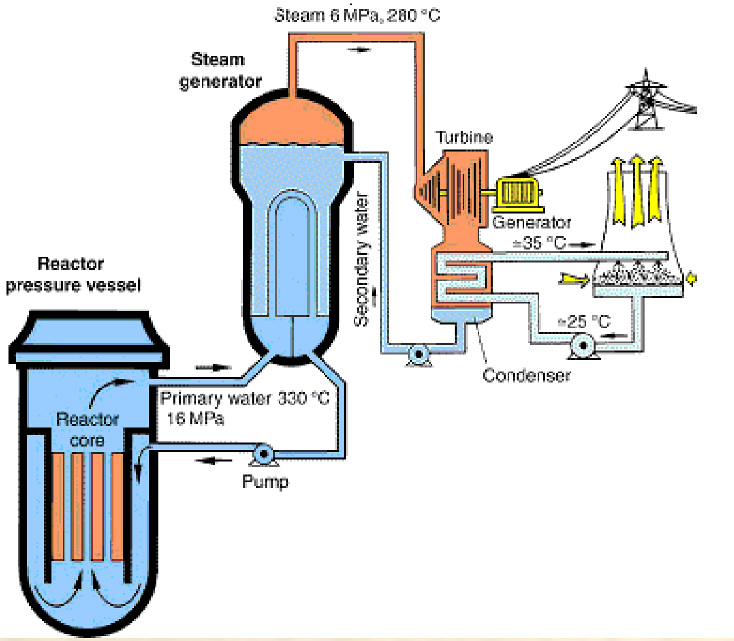


Fig. 3.9: PRESSURISED WATER REACTOR PLANT



Nuclear (Atomic) Power Plant…

- Pressurised Water Reactor (PWR)

✓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

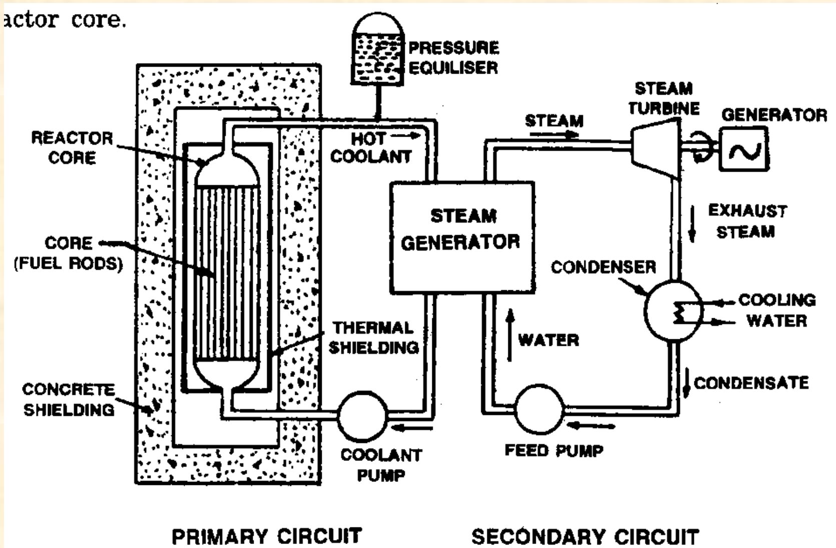
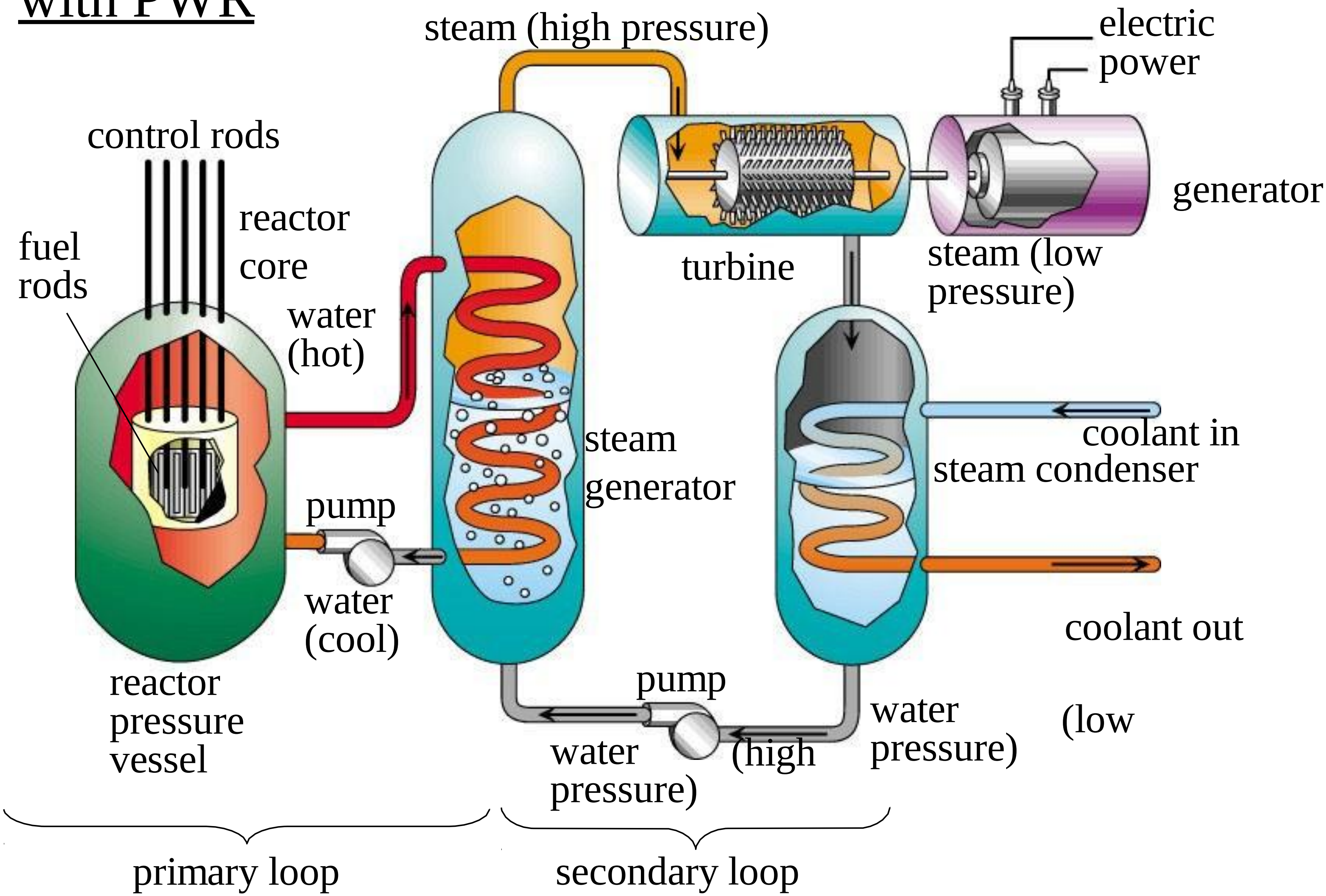
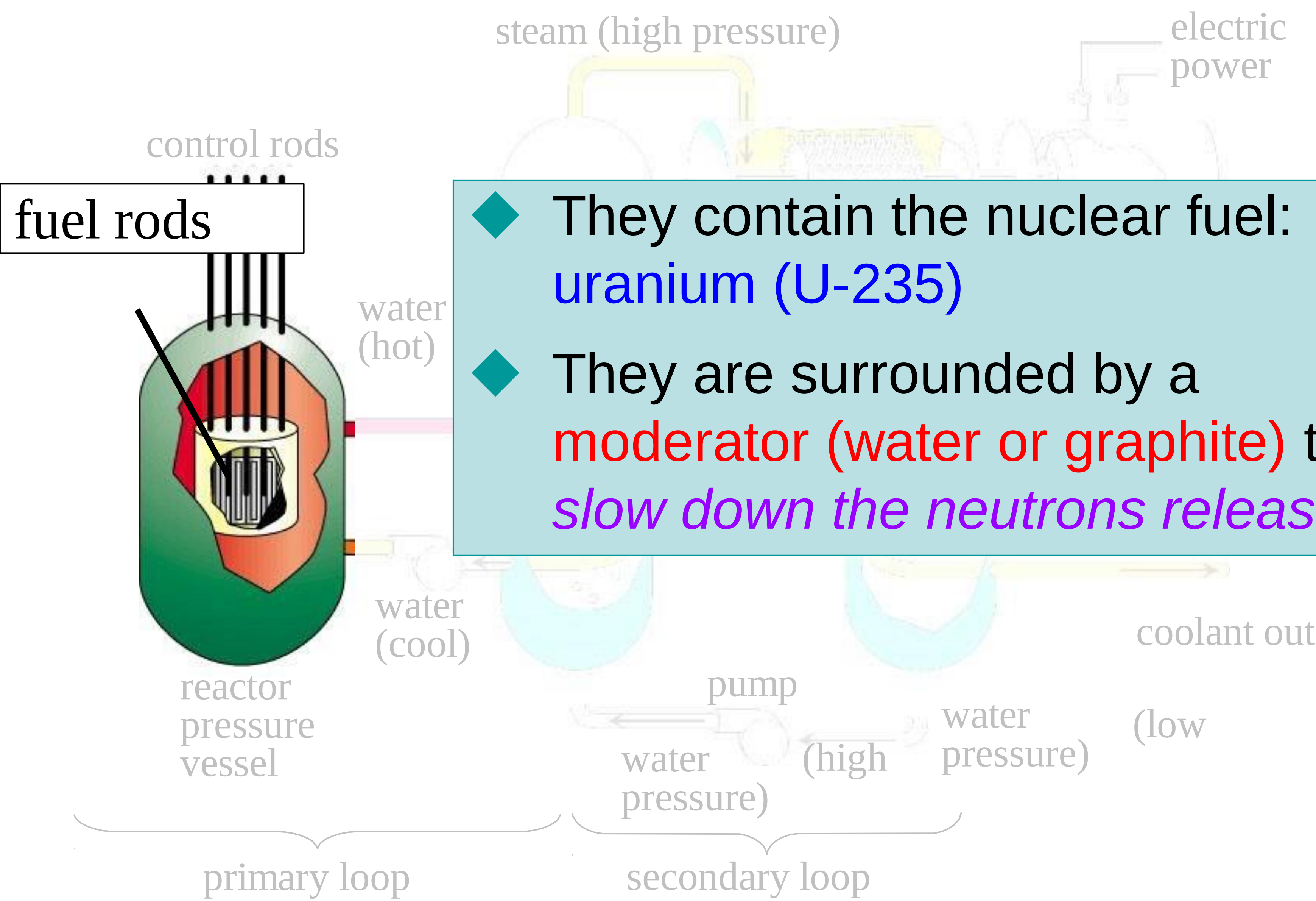


Fig. 3.9: PRESSURISED WATER REACTOR PLANT

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

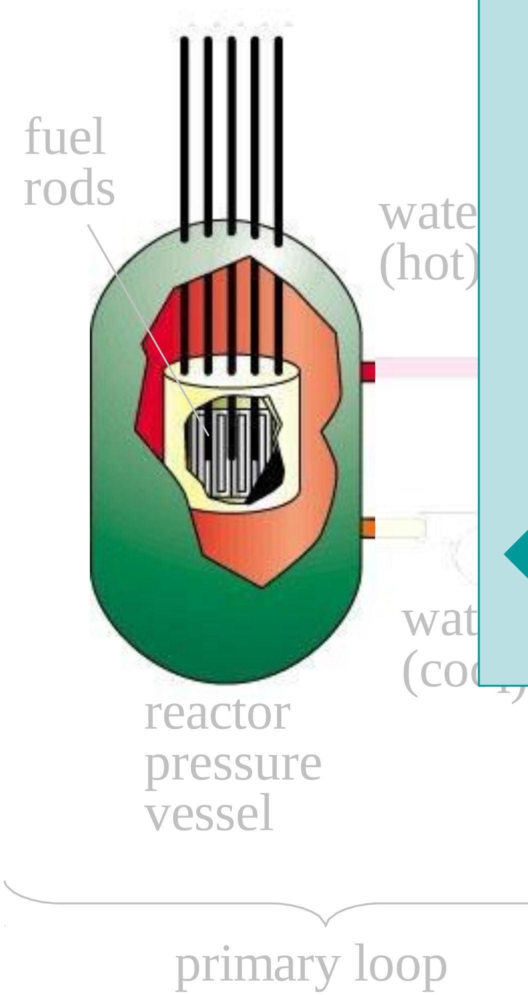
Schematic diagram of a nuclear power plant with PWR



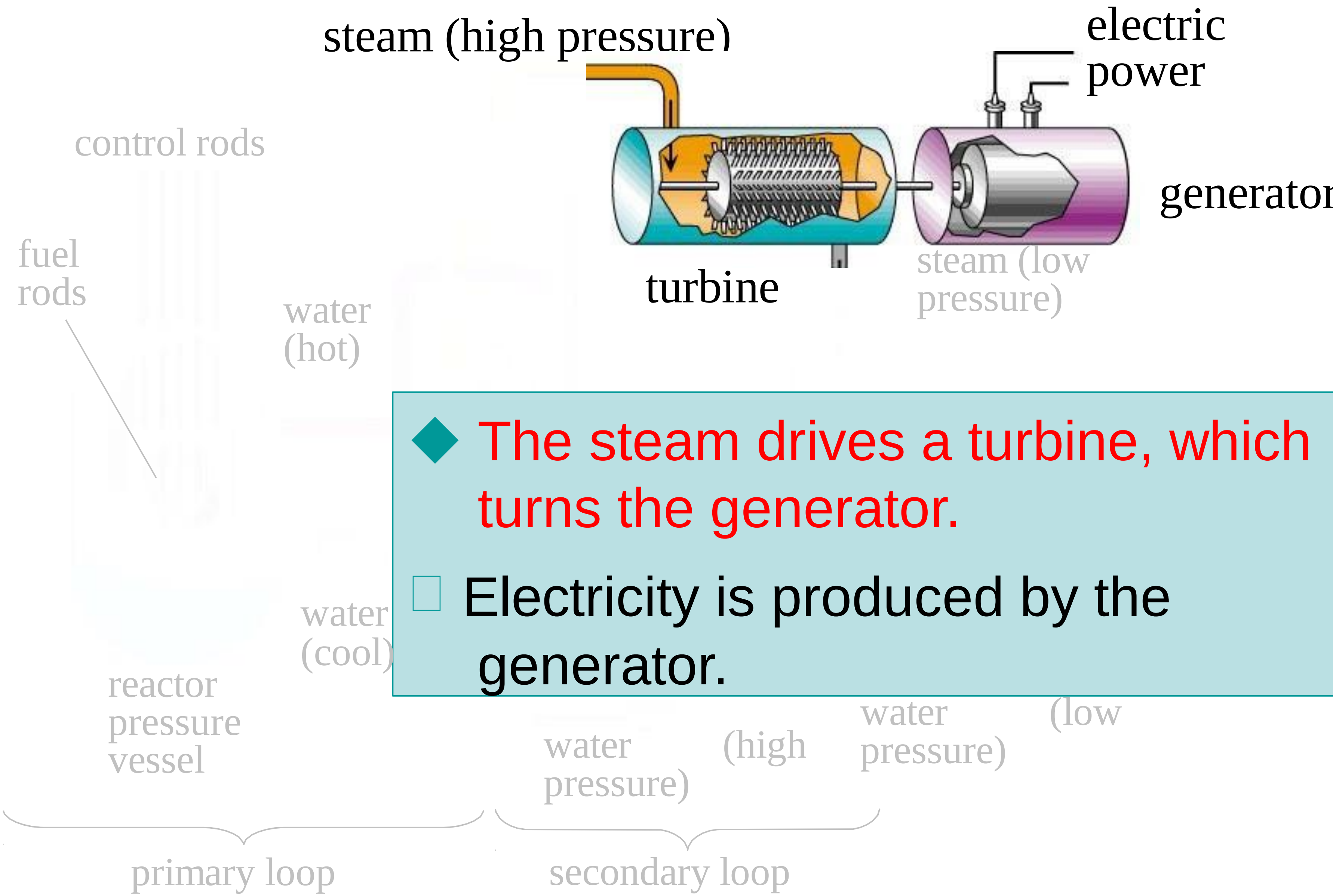


- They contain the nuclear fuel: uranium (U-235)
- They are surrounded by a moderator (water or graphite) to *slow down the neutrons released.*

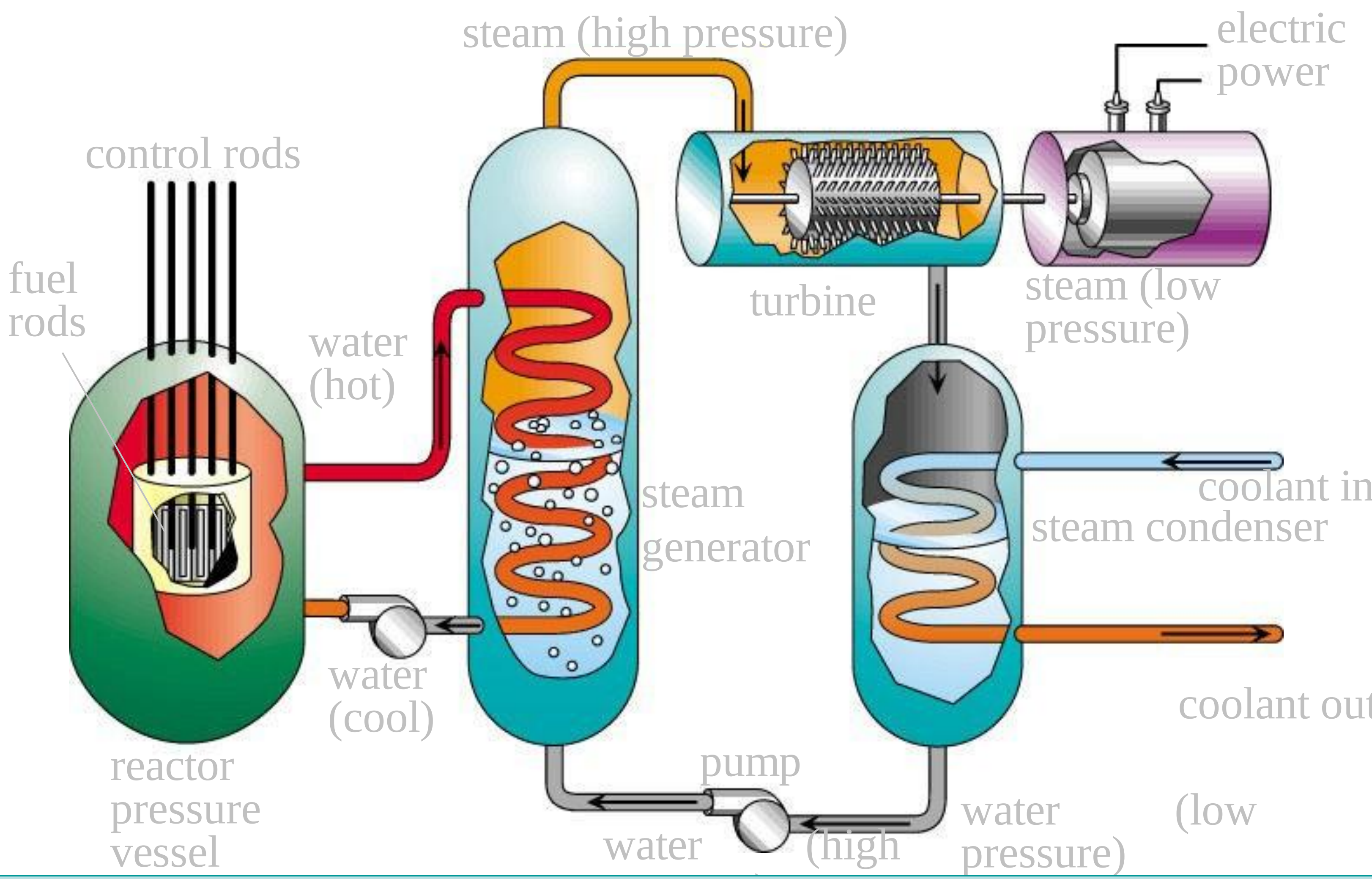
control rods



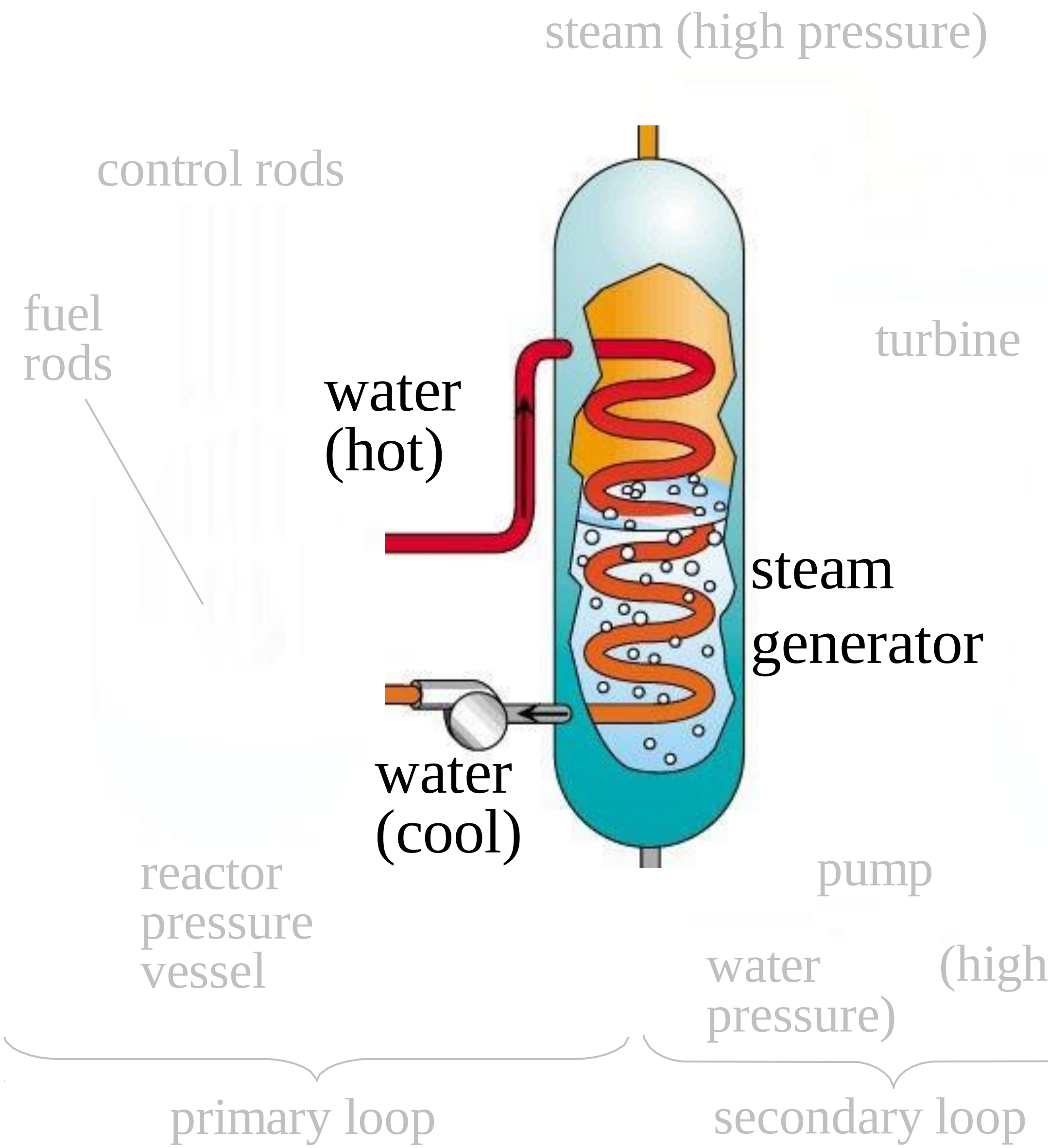
- They control the rate of reaction by moving in and out of the reactor.
  - Move in: rate of reaction □
  - Move out: rate of reaction □
  - All are moved in: the reactor is shut down
- They are made of boron or cadmium that can *absorb neutrons.*



- 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.

Nuclear (Atomic) Power Plant…

- Boiling Water Reactor (BWR)

➢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.

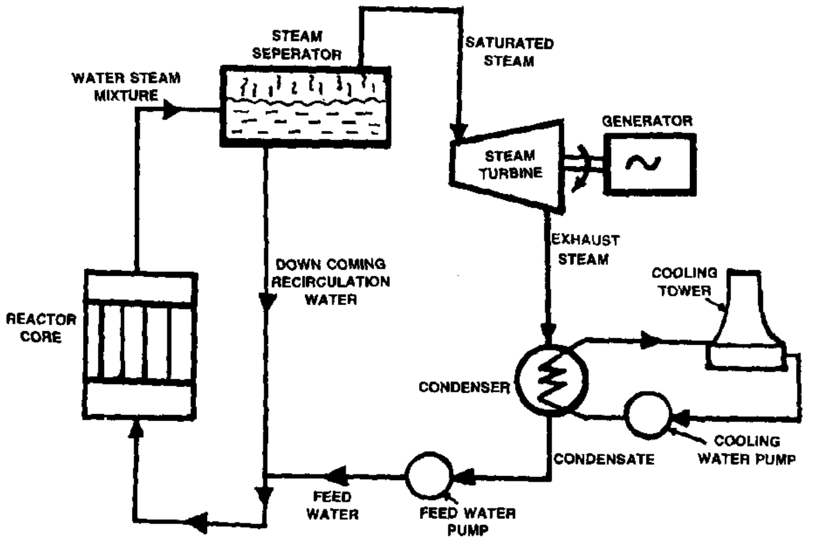


Fig. 3.10: BOILING WATER REACTOR PLANT

Nuclear (Atomic) Power Plant…

Steam power plant means any plant that uses steam to produce electricity.

E.g. Thermal and Nuclear power plants.

Nuclear (Atomic) Power Plant…

Advantages of Nuclear power plant:

- Space required is less when compared with other power plants.
- Nuclear power plant is the only source which can meet the increasing demand of electricity at a reasonable cost.
- A nuclear power plant uses much less fuel than a fossil-fuel plant.
  1 metric tonne of uranium fuel = 3 million metric tonnes of coal = 12 million barrels of oil.

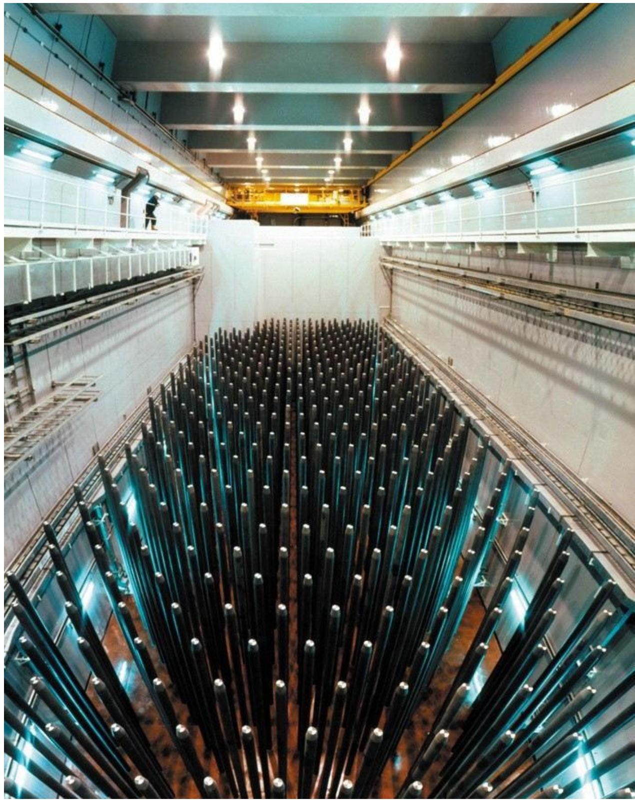
Disadvantages of Nuclear power plant:

- Radioactive wastes must be disposed carefully, otherwise it will adversely affect the health of workers and the environment as a whole.
- Maintenance cost of the plant is high.

Nuclear waste

- They are highly radioactive
- Many of them have very long half-lives.

 Radioactive waste must be stored carefully.

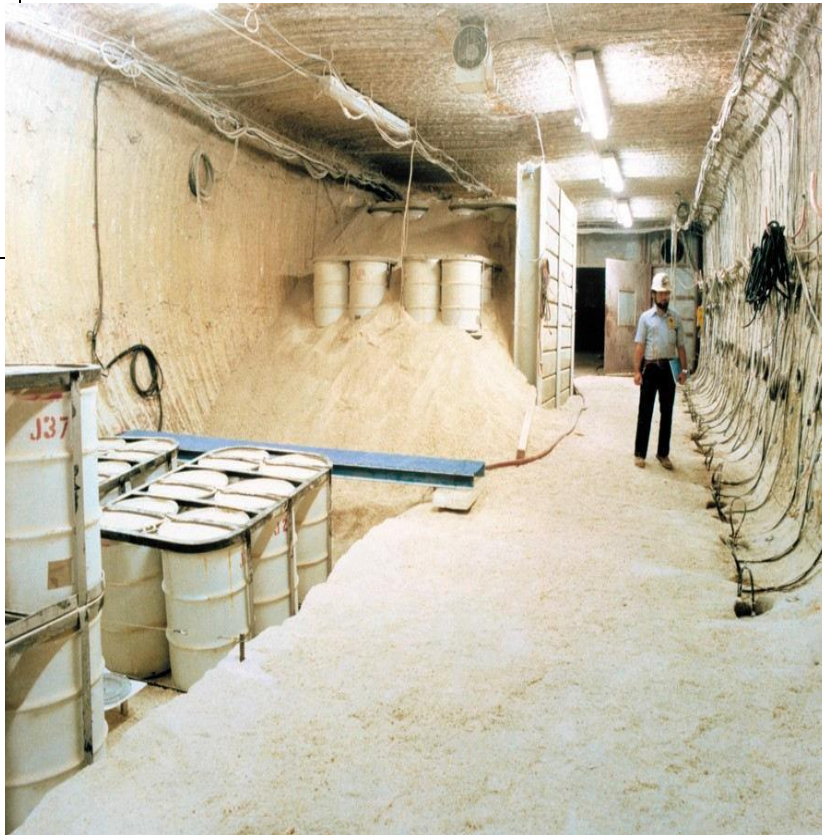


Low level radioactive waste

- cooling water pipes, radiation suits, etc.
- stored in storage facilities
- radioactivity will fall to a safe level after 10 to 50 years.

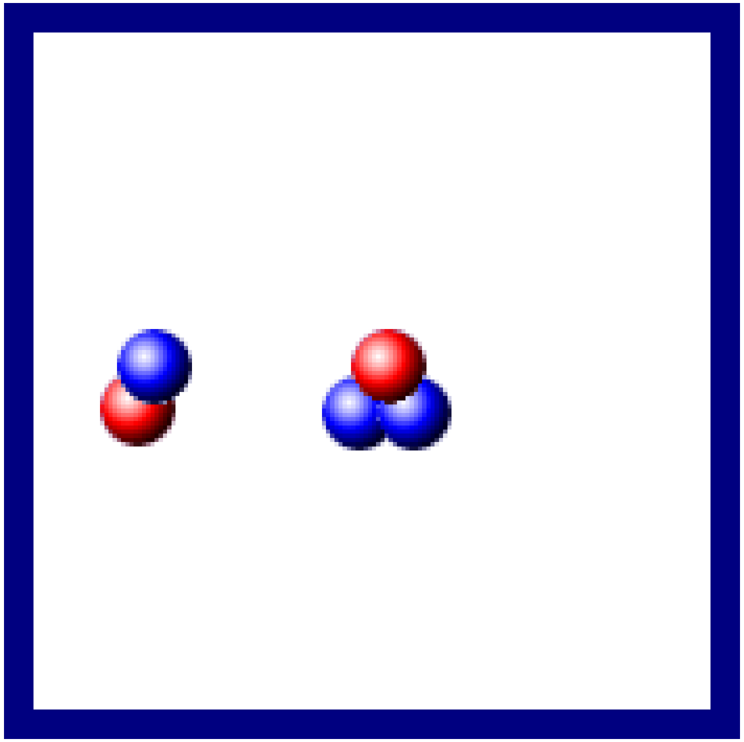
High level radioactive waste

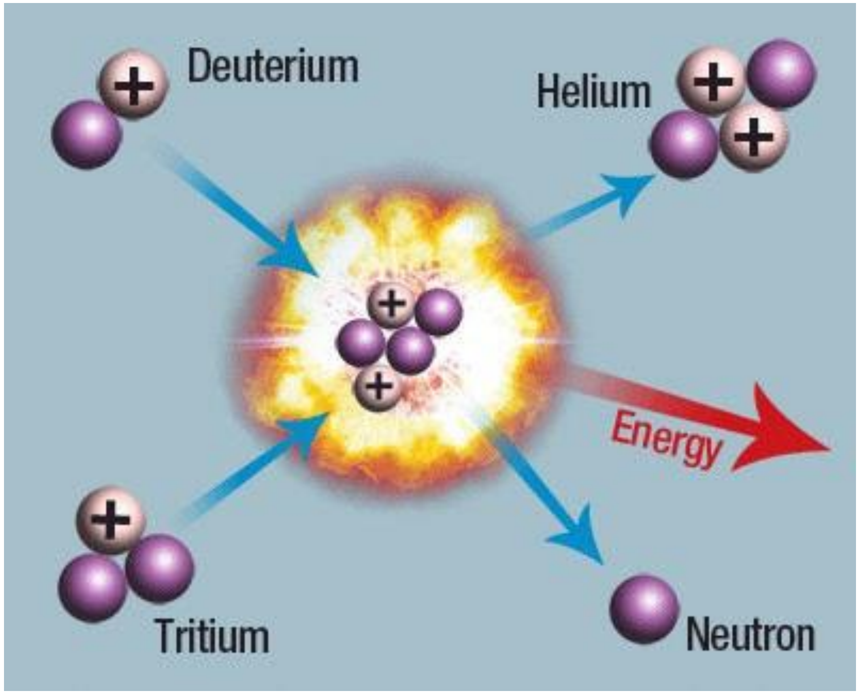
- used nuclear fuel
- highly radioactive
- embedded in concrete and stored deep underground for several thousand years



Nuclear fusion

- Nuclear fusion: light nuclei fuse together to form a heavier nucleus





Nuclear fusion…

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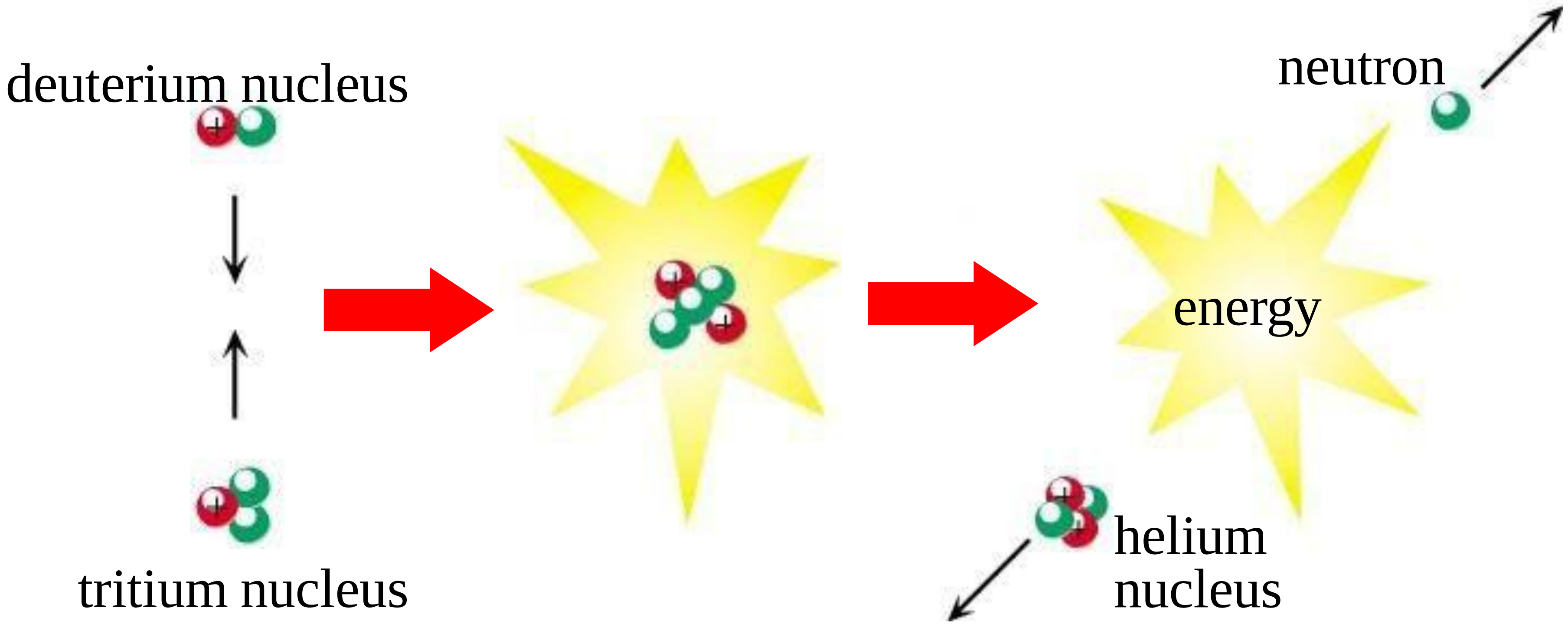

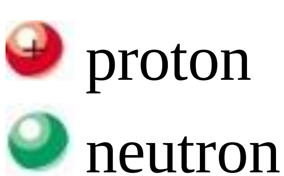

H-2 + H-3 □ He-4 + n + energy

16.3.3 Nuclear Fuels Used in the Reactors

Nuclear reactions, namely *fission* and *fusion*, result in the generation of enormous amount of energy. In *fission reactions*, a heavy atom is split by neutrons into two lighter fragments. In *fusion reactions*, two lighter atomic nuclei are fused together to form a single, heavy nucleus. To carry out nuclear reactions, fissionable materials are used as fuels.

1. *Natural fuels*

Uranium is the only fissionable nuclear fuel occurring in nature. It consists of 99.3 per cent of ${}_{92}U^{238}$, 0.7% ${}_{92}U^{235}$ and small traces of ${}_{92}U^{234}$. Out of these isotopes, only ${}_{92}U^{235}$ is used in fission reaction.

2. *Artificial fuels*

Plutonium, ${}_{92}Pu^{239}$, and Uranium, ${}_{92}U^{238}$, are the fissionable materials produced artificially from ${}_{92}U^{238}$ and Thorium, ${}_{90}Th^{232}$, respectively. Uranium-238 and Thorium-232 are available in nature. They are known as fertile materials. These *fertile materials* when placed close to ${}_{92}U$ in a reactor absorb the emitted neutrons to produce fissionable materials as follows:

1. ${}_{92}U^{238} + {}_{0}n^{1} \rightarrow {}_{92}U^{239} + \gamma$ radiation

   ${}_{92}U^{239} \rightarrow {}_{93}N_{p}{}^{239}$ (Neptunium) $+ {}_{-1}e^{0}$ (Electron)

   ${}_{92}N_{p}{}^{239} \rightarrow {}_{94}Pu^{239} + {}_{-1}e^{0}$

2. ${}_{90}Th^{232} + {}_{0}n^{1} \rightarrow {}_{90}Th^{233} + \gamma$ radiation

   ${}_{90}Th^{233} \rightarrow {}_{91}Pa^{233}$ (Protactinium) $+ {}_{-1}e^{0}$ (Electron)

   ${}_{91}Pa^{233} \rightarrow {}_{92}U^{233} + {}_{-1}e^{0}$

Advantages over solid fuels

(i) Under favourable conditions, the cost of generation of nuclear power is competitive with coal-based power generation.

(ii) Isotopes produced as by-products can be used in agriculture, medicine, scientific research and industrial processing.

(iii) Used in transportation systems, especially in nuclear-powered submarines.

(iv) Complete fission of 1 kg of fissile uranium produces about 23×10^6 kWh of energy, which is equivalent to the energy generated by burning 3300 tons of bituminous coal.

Disadvantages

(i) The radiation emitted during the reaction is highly hazardous.

(ii) Nuclear waste disposal is a major problem and if not disposed off properly it is dangerous to all living things on the earth.

Different stages involved in fuel elements development are listed in Table 16.3.

Table 16.3 *Stages in Fuel Element Development**

1.	**Define the reactor type: purpose, coolant and performance.**
2.	**Calculate fuel element dimensions, heat fluxes, design features, physics and critical assemblies.**
3.	**Consider the range of available fuels and cladding materials and pick the one that is most suitable for the design.**
4.	Consider fuel and cladding properties, both out-of-reactor and in-reactor.
5.	Examine fuel-cladding interactions (chemical and physical).
6.	Develop a preliminary fuel element design.
7.	Develop fabrication procedures for fuel, cladding and fuel element, if necessary.
8.	Develop mathematical models of the fuel element; specify and obtain input data.
9.	Test fuel elements: out-of-reactor (thermal-hydraulics), in-reactor (on increasing scale) and transient tests.
10.	Analyse test: post-irradiation examination, failure mechanisms, run beyond cladding breach, feedback to models and improvements in design.
11.	Optimize through 8, 9 and 10 iterations. Write detailed design and manufacturing specifications.
12.	Plan production: quality assurance, NDE, SPM assay, safeguards, safety, critical control, economics and automation.
13.	Establish interfaces with the rest of the fuel cycle: mining, enrichment, reprocessing and waste management.