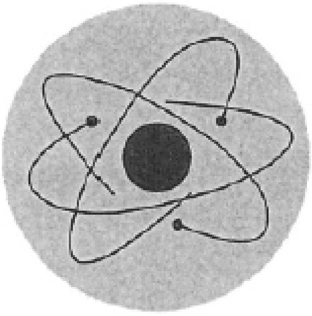
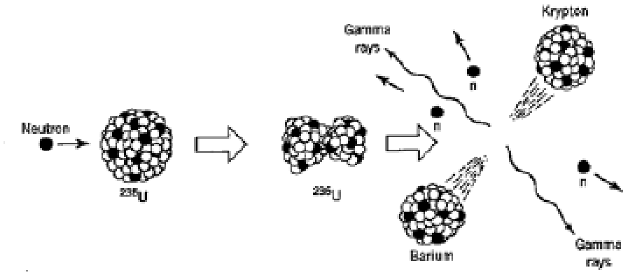


Fuel and Energy

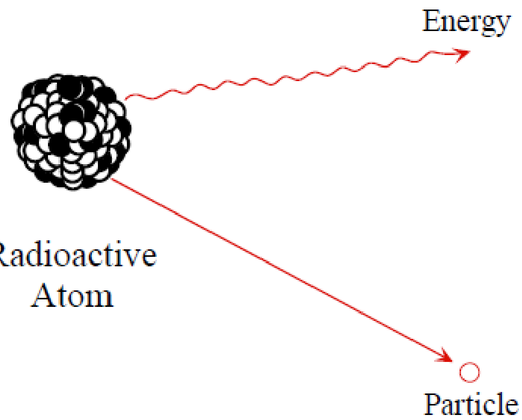
Nuclear Energy

Dr.-Eng. Zayed Al-Hamamre



Content

- **Nuclear Reactions**
- **Nuclear Reactors**



Nuclear Reactions

<u>Fusion</u>: 2 or more light nuclei fuse to form a heavier nucleus

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

↑ positrons

mass decrease of 0.0265 amu corresponding to 24.7 MeV

- fusion reactions called "thermonuclear" because of the very high temperatures required to trigger and sustain reactions.

<u>Fission</u>: heavy nucleus is split into two or more lighter nuclei

- fission can be triggered by a neutron (doesn't experience a repulsive force)

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Nuclear Fission

- Accompanying the fission process is the release of several neutrons, which are all-important for the practical application to a self-sustaining chain reaction

$${}^{235}_{92}U + {}^{1}_{0}n \rightarrow {}^{140}_{54}Xe + {}^{14}_{38}Sr + 2\,{}^{1}_{0}n$$

196 MeV released ↑ 2 neutrons released

- numerous fission reactions releasing distribution of energies.

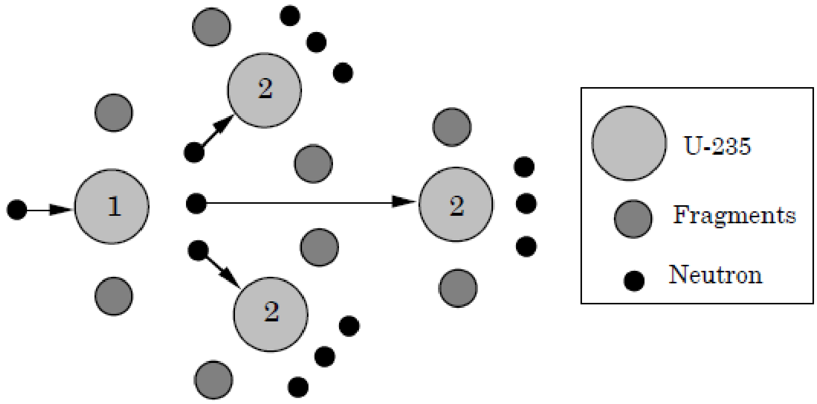
(*) on average, U-235 fission yields 193 MeV.

(*) 1 g fissionable material generates approximately 1 MW-day of energy.

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

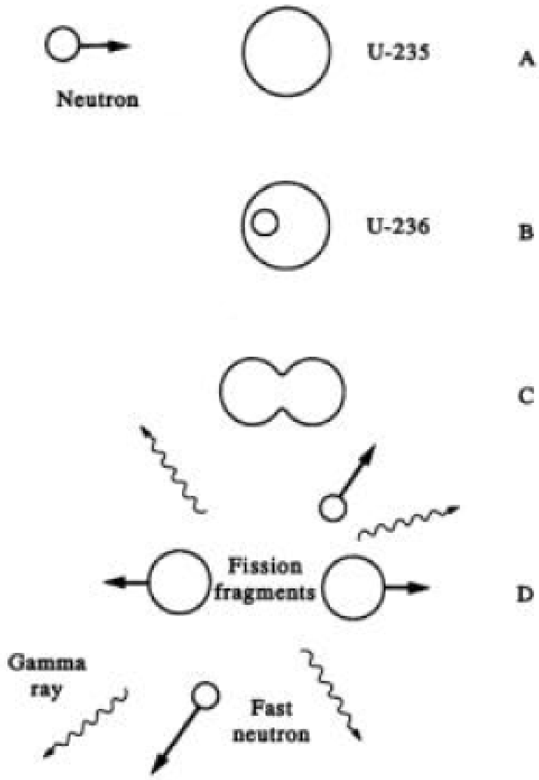
Nuclear Fission

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



A representation of a chain reaction

Nuclear Fission



Nuclear Fission

mass balance:

$$235.0439\ \text{amu} + 1.00867\ \text{amu} \rightarrow 136.9061\ \text{amu} + 96.9212\ \text{amu} + 2(1.00867\ \text{amu})$$

$$236.0526\ \text{amu} \rightarrow 235.8446\ \text{amu}$$

$$\Delta m = -0.2080\ \text{amu}$$
$$\Delta E = -193.6\ \text{MeV}$$

(-) indicates exothermic reaction

- The total energy from fission, after all of the particles from decay have been released, is about 200 MeV

Nuclear Fission

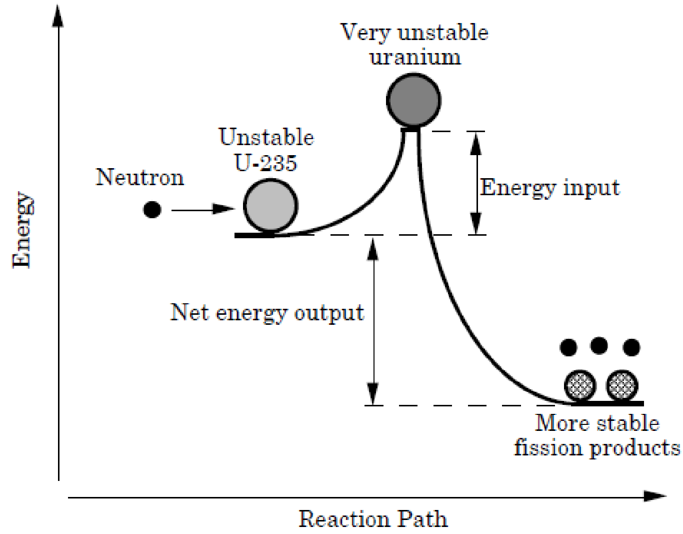
Energy from Fission, U-235.

	MeV
Fission fragment kinetic energy	166
Neutrons	5
Prompt gamma rays	7
Fission product gamma rays	7
Beta particles	5
Neutrinos	10
Total	200

- Neutrinos accompany the beta particle emission, but since they are such highly penetrating particles their energy cannot be counted as part of the useful thermal energy yield of the fission process.
- Thus only about 190 MeV of the fission energy is effectively available

Nuclear Fission

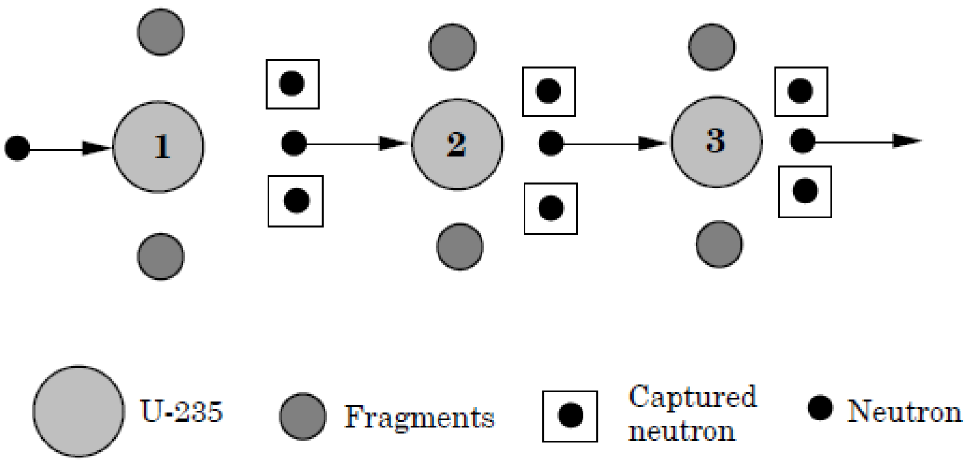
- "prompt" energy released at fission event



- "delayed" energy released during (1) radioactive decay of fission fragments into fission products & (2) non-fission capture of excess neutrons.

  ↑ major concern for nuclear reactor control

Nuclear Fission



self-sustained (controlled) chain reaction.

Nuclear Fission

$$E_n \equiv \text{kinetic energy} = \frac{1}{2g_c} m_n v_n^2$$

$m_n = 1.00866$ amu

$$0.075 \le E_n \le 17 \text{ MeV}$$

- when travelling through matter, neutrons collide with nuclei and are decelerated (mainly by lighter nuclei) — scattering

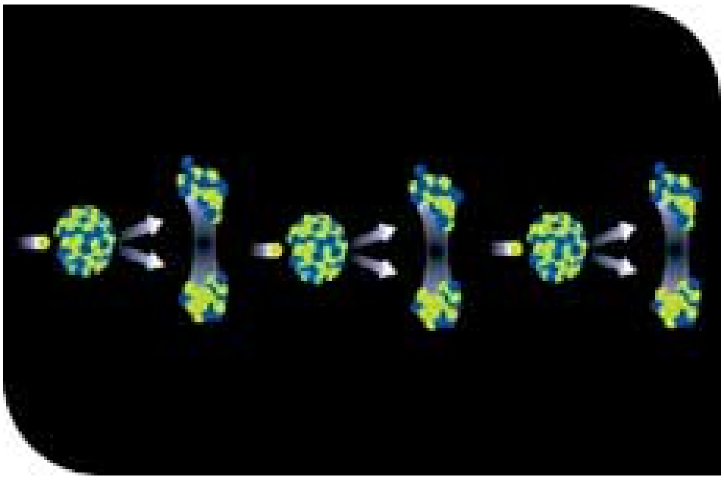
Categories of neutron energy

fast $> 10^5$ eV ← fast reactors utilize

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Linear Chain Reaction

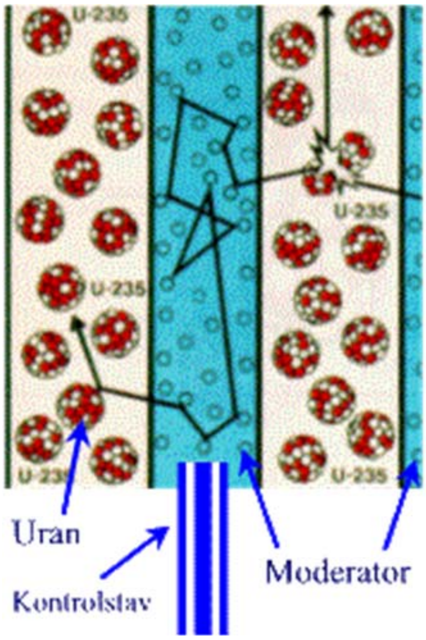
- Obviously, an expanding chain reaction cannot be sustained for long (bomb). For controlled nuclear power, once we reach our desired power level we want each fission to produce exactly one additional fission



Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Moderator

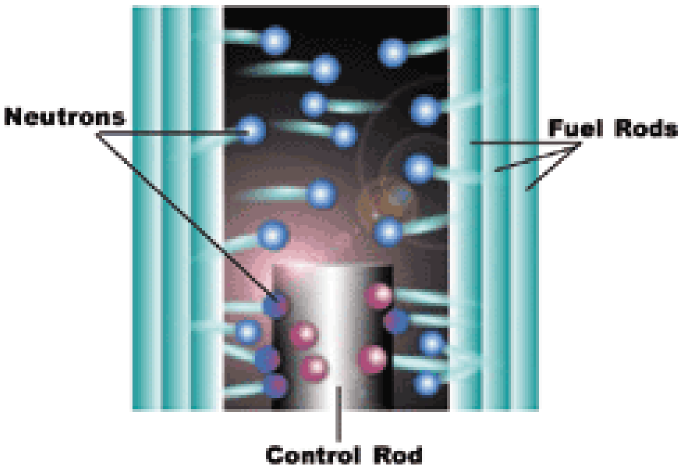
- Neutrons are slowed down by having them collide with light atoms (Water in US reactors).
- Highest level of energy transfer occurs when the masses of the colliding particles are equal (ex: neutron and hydrogen)



Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Control Rods

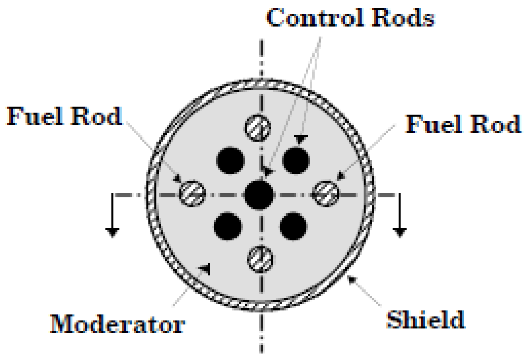
- Control rods are made of a material that absorbs excess neutrons (usually Boron or Cadmium).
- By controlling the number of neutrons, we can control the rate of fissions

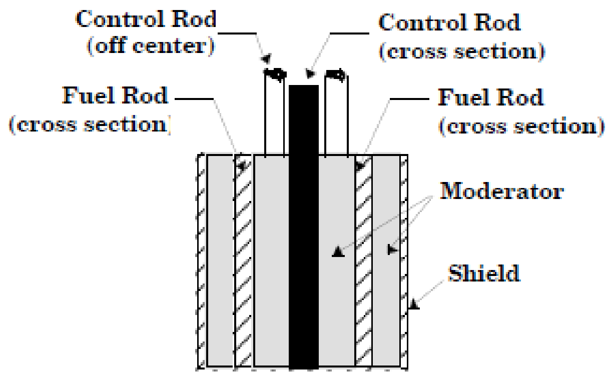


Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Thermal Neutrons Reactors

- The reproduction constant of a reactor is regulated by the positioning of the control rods inside the core.
- It also depends on the quantity of fissionable material inside the core; this issue is discussed in the next section.





Neutrons Energies

intermediate

slow < 1 eV ← thermal reactors utilize

cold < 0.025 eV

- newly released fission neutrons carry about 2% of a reactor fission energy
  - prompt, released at time of fission, 10^{-14} seconds
  - delayed, released during radioactive decay of fission fragments

Neutrons Energies

Thermal Neutrons

- Fission neutrons scattered (slowed) by materials in reactor core
  - Moderators (Scattering Media)
    - small nuclei with high neutron scattering & low neutron-absorption probability

    ^1_1H, ^2_1H in H_2O, D_2O, C (graphite), Be, BeO

- lowest energy a neutron can reach is that which puts it in thermal equilibrium with surrounding environment

- neutron becomes "thermalized" → thermal neutrons

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Thermal Neutrons Reactors

- need controlled, self-sustaining chain reaction; with at least 1 neutron with sufficient energy to induce another fission event.

- 2.4 to 2.9 neutrons on average produced from slow neutron fission of U-235 and Pu-239, respectively.

  - not all neutrons survive to generate fission
  - some are captured by U-235 or U-238 with γ-ray emission
  - some are captured by other reactor materials (fuel cladding, structural, ...) and emit γ-ray
  - some escape reactor core into surrounding shielding and containment vessel

- Most US commercial reactors are based on thermal neutrons, enriched uranium, and normal water as a neutron moderator

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Thermal Neutrons Reactors

→ thermal neutrons because of high fission probability

→ enriched uranium because of neutron flux and moderator

- natural uranium has ~ 0.72% U-235
- enriched uranium ~ 2.3% U-235
- depleted uranium < 0.72% U-235

- separation by (i) electromagnetic – ionized isotopes are ionized and accelerated in an arc. Difference in mass results in slightly different trajectories

  (ii) centrifugal acceleration – similar to electromagnetic, but using gravitational field instead of electromagnetic field

Thermal Neutrons Reactors

(iii) gaseous-diffusion → UF_6 (uranium hexafluoride)
– fluorene is used because there is only one stable isotope of fluorine, F-19

→ water is used as a moderator because it is easy to handle, can be used directly in Rankine cycle, allows for superheat cycles, can be used as a coolant

- U-235 fission neutrons have ~ 2 MeV energies
  - moderator is used to slow neutrons to 0.025 MeV
  - moderator is placed so that a neutron is more likely to be thermalized <u>before</u> being absorbed by a non-fissionable nucleus
  - geometric arrangement of reactor is important to insure 1 new fission event
  - below critical mass, neutron losses are too great to sustain reaction

Thermal Neutrons Reactors

- average distance neutron travels to slow down

  water ~ 5.7 cm
  graphite ~ 18.7 cm
  } transfers of energy of neutron until neutrons are in thermal equilibrium with surroundings
  $\frac{1}{2g_c} m v^2 = kT$

- natural uranium reactors (CANDU) have to use heavy water (D_2O) because absorption of neutron in light water (H_2O) prevents sustained reaction

➢ By slowing down neutrons so that they are more likely to react with the fissile uranium-235 than with uranium-238 which captures neutrons without fissioning.

➢ Light water also acts as a moderator but because light water absorbs more neutrons than heavy water, reactors using light water must use enriched uranium rather than natural uranium, otherwise criticality is impossible

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Thermal Neutrons Reactors

- fast neutrons can fission U-238
  - low probability, ~ 3 orders of magnitude less probability than thermal neutron absorption and fission of U-235

- U-238 fission provides heat & neutrons
- U-239 decay

$$^{238}U + n \longrightarrow {}^{239}U \xrightarrow[t_{1/2} = 24\,min]{\beta^-} {}^{239}Np \xrightarrow[t_{1/2} = 2.3\,days]{\beta^-} {}^{239}Pu$$

⊕ ^{239}Pu ($t_{1/2} = 2.4 \cdot 10^4$ years) lasts long enough to fission due to thermal neutrons
⊕ higher probability of fission than U-235

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Thermal Neutrons Reactors

④ during operation P_u-239 accumulates

- over the life time of the fuel, starting with enriched uranium & no P_u-239, 1/3 of the total energy is from P_u-239 fission
- at the end of the fuel cycle, ~60% of fission events are from Pu-239

➢ This normal operation is often described in terms of a *reproduction constant,* K. This is the average number of neutrons from each fission event that will cause another fission event.

K<1 : Reactor is 'subcritical' (chain reaction stops)
K=1 : Reactor is 'critical' (self-sustained chain reaction)
K>1 : Reactor is 'supercritical' (power increases; the chain reaction may run away and even lead to explosion)

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Example

If 0.190 a.m.u. are converted to energy for every nucleus of U- 235 that undergoes the fission process, what is the released energy in the process.

$$\Delta E = \Delta m\, c^2$$

$$= (0.190 \text{ a.m.u.}) \left(\frac{1.66056\text{x}10^{-27} \text{ kg}}{1 \text{ a.m.u.}}\right) \left(3\text{x}10^{8} \frac{\text{m}}{\text{s}}\right)^2 = (2.84\text{x}10^{-11} \text{ J}) \left(\frac{6.242\text{x}10^{12} \text{ MeV}}{1 \text{ J}}\right) = 177 \text{ MeV/nucleus}$$

$$= \left(177 \frac{\text{MeV}}{\text{nucleus}}\right) \left(\frac{1 \text{ nucleus}}{235 \text{ nucleons}}\right) = 0.75 \text{ MeV/nucleon}$$

For fission of U-235, taking into account that there are $6\text{x}10^{23}$ atoms in one mole (Avogadro's number) and that the molar mass is 235 grams, we have:

$$\left(\frac{177 \text{ MeV}}{1 \text{ nucleus U-235}}\right) \text{x}$$

$$\text{x} \left(\frac{1 \text{ nucleus U-235}}{1 \text{ atom U-235}}\right) \left(\frac{6\text{x}10^{23} \text{ atoms}}{1 \text{ mol}}\right) \left(\frac{1 \text{ mol}}{0.235 \text{ kg U-235}}\right) \left(\frac{1.52\text{x}10^{-16} \text{ BTU}}{1 \text{ MeV}}\right) =$$

$$= 6.90\text{x}10^{10} \text{ BTU/kg U-235}$$

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Example

Calculate how much U-235 is needed for the lifetime of a nuclear power plant that produces 1000 MW of electricity. Consider that the lifetime of the plant is 30 years and that its efficiency is 34%. Assume that the efficiency of conversion of nuclear energy to heat is 100% and that the power plant operates at 100% capacity.

1 kg of U-235 can be converted into approximately 10^{11} BTUs of kinetic energy.

The representative power plant used as an example produces 1000 MW of electricity

$$\left(10^9 \frac{J}{s}\right)\left(\frac{3.15 \times 10^7\ s}{1\ year}\right)\left(\frac{1\ BTU}{1055\ J}\right) = 3.0 \times 10^{13}\ BTU/year$$

Over a lifetime of 30 years, the quantity of thermal energy required for one plant will be:

$$\left(\frac{8.8 \times 10^{13}\ BTU}{1\ year}\right)(30\ years) = 2.6 \times 10^{15}\ BTU$$

$$\left(\frac{2.6 \times 10^{15}\ BTU}{1\ plant}\right)\left(\frac{1\ kg\ U\text{-}235}{10^{11}\ BTU}\right) = 26000\ kg\ U\text{-}235/plant$$

about 26 tons of radioactive uranium are needed for a typical nuclear reactor.

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

• Nuclear Power Plants

- The nuclear reactor contains the material and is the vessel for the controlled chain reaction of fissionable materials that will release the energy.
- Usually there is a fissionable enriched material made of 3% U235 and 97% U238 the is fabricated into small beads.
- The beads are enclosed in a fuel rod.
- The **fuel rods** are locked in a fuel rod assembly by locking collars and arranged so that pressurized water can flow around the rods.
- **Control rods** are made of material that can absorb neutrons and are inserted between the fuel rods.

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

– The rate of the chain reaction is controlled by raising or lowering the control rod.

– In a pressurized water reactor the energy is carried way from the reactor by water in a closed pipe called a **primary loop**.

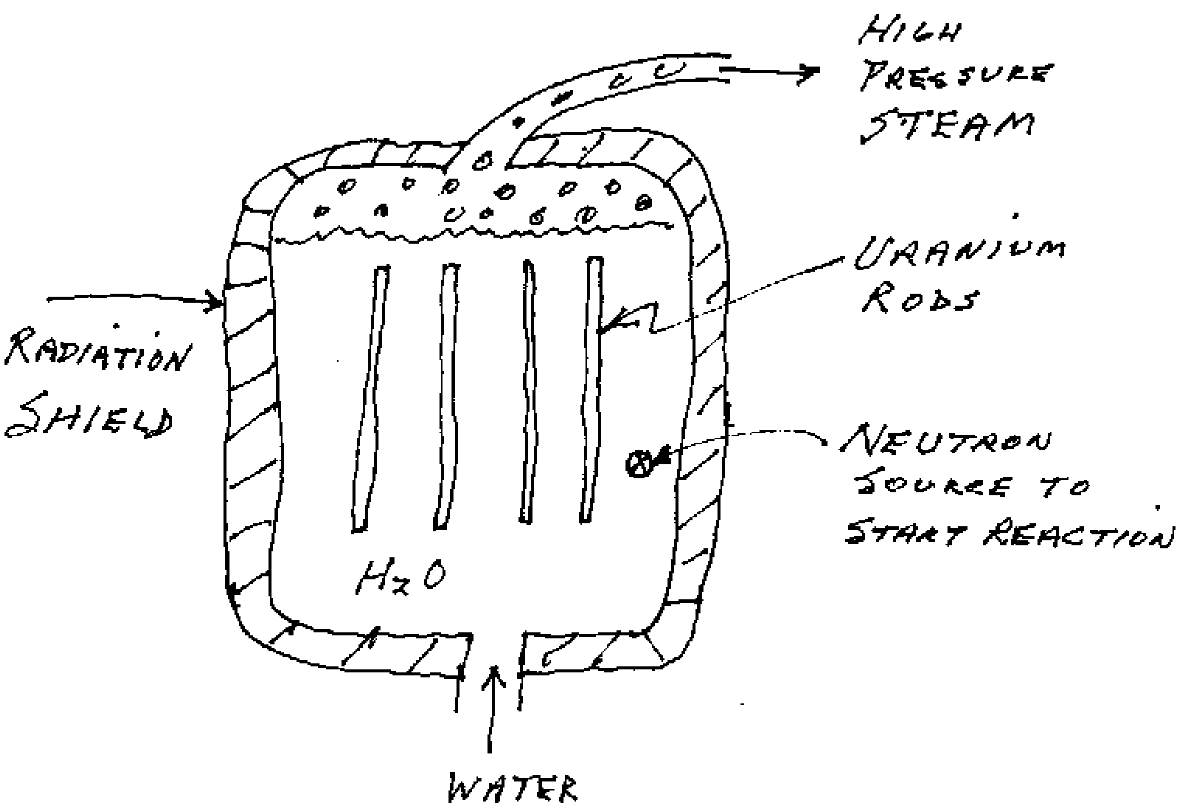
- This water acts as a coolant and also as a moderator to slow neutrons so they can more readily be absorbed by the U235 nuclei.

– The water from the primary loop is circulated to a heat exchanger called a **steam generator**.

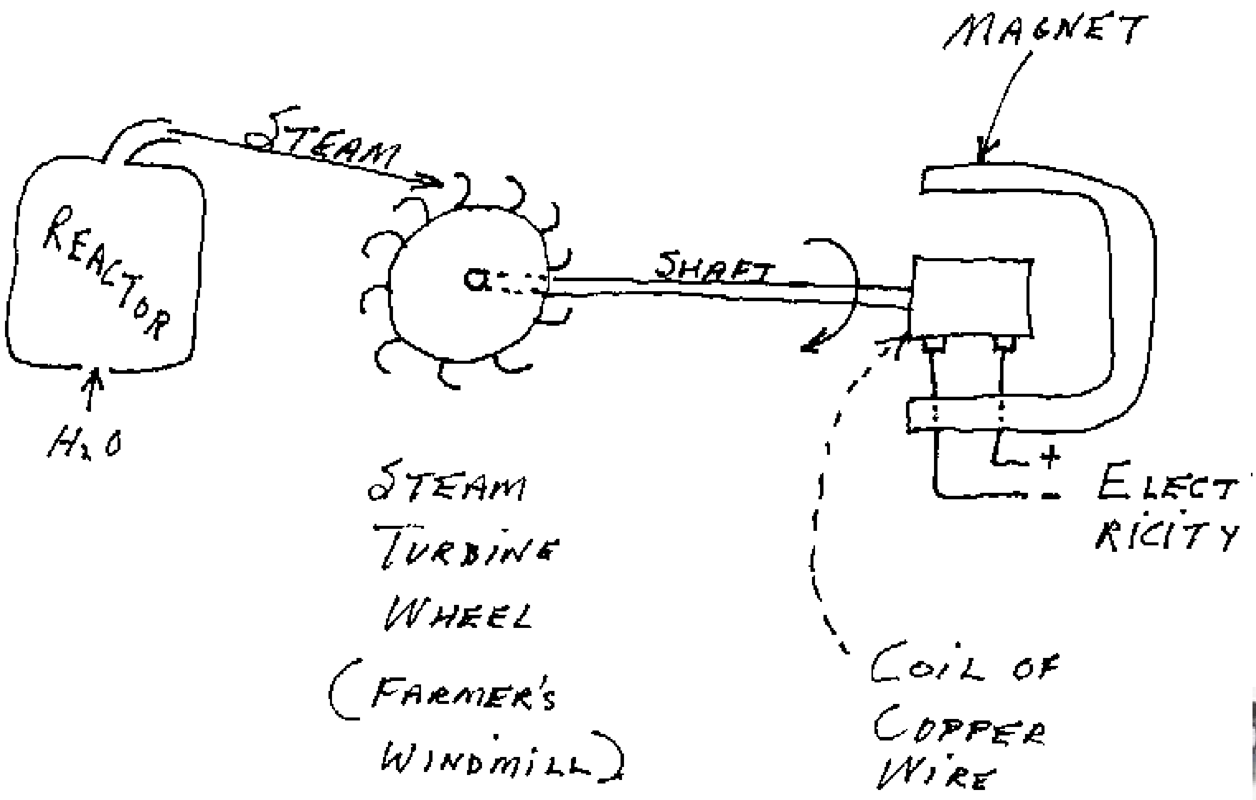
- The water in the heat exchanger moves through hundreds of small loops and heats the feedwater in the steam generator.
- The water then returns to the core to be heated again.

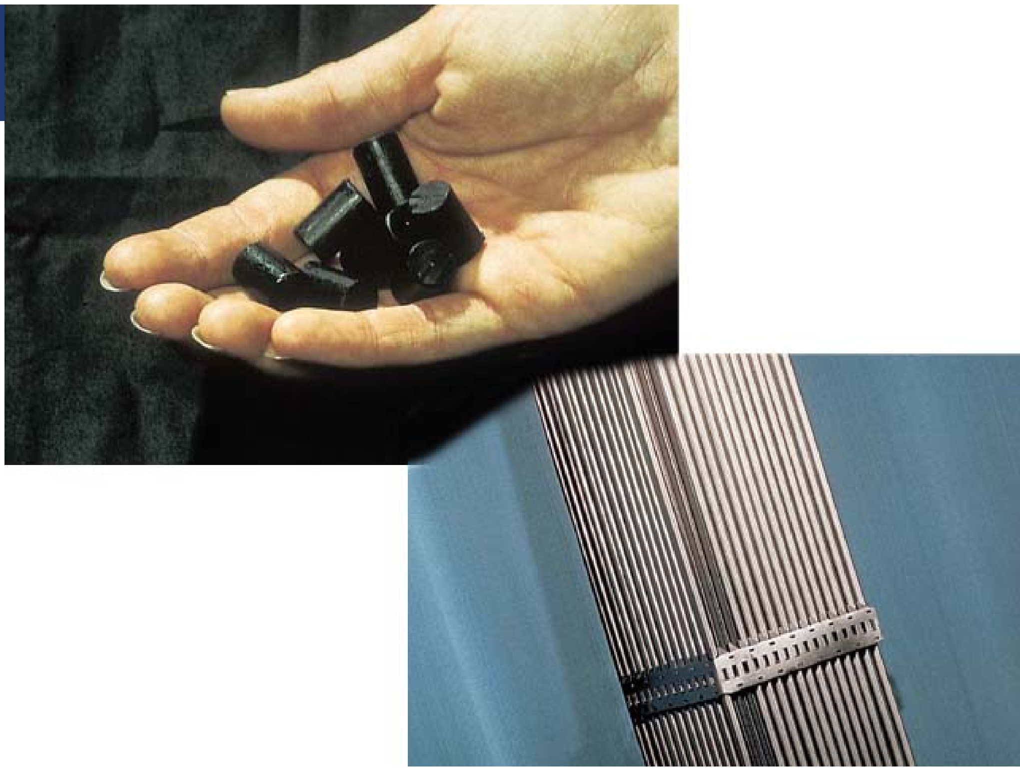
Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Nuclear Reactor (simplified)

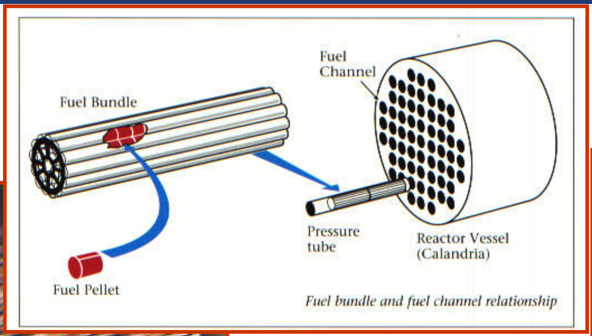


Nuclear Power Plant (simplified)

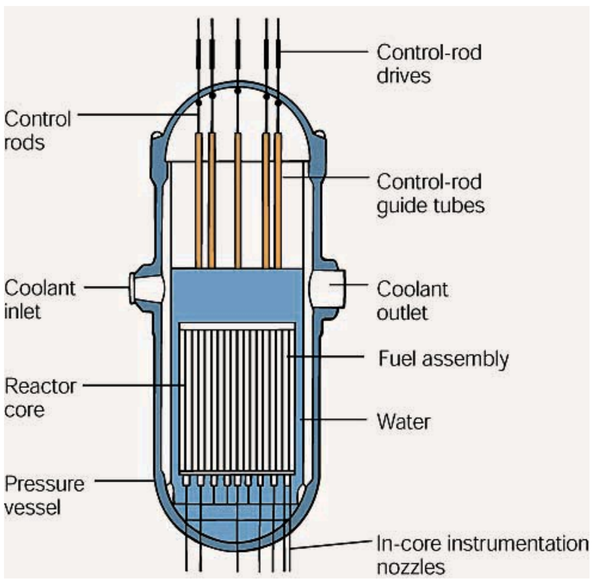


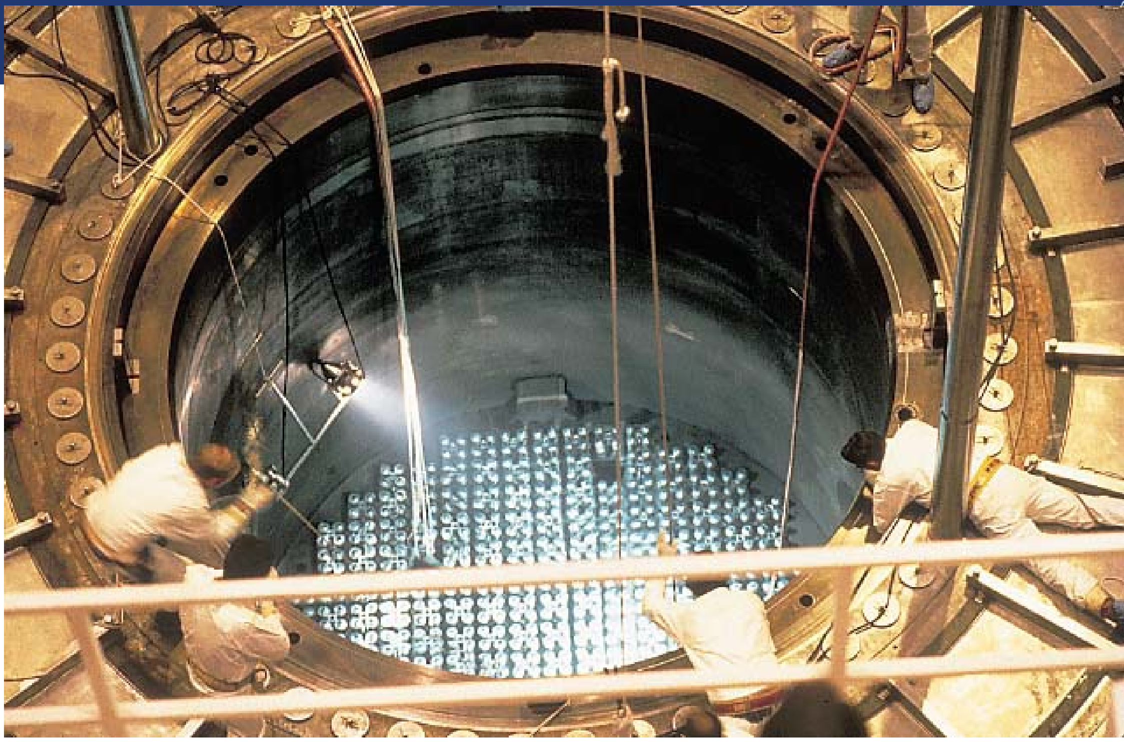


- (A)These are uranium oxide fuel pellets that are stacked inside fuel rods, which are then locked together in a fuel rod assembly. (B) A fuel rod assembly.



- A schematic representation of the basic parts of a nuclear reactor.
- The largest commercial nuclear power plant reactors are nine- to eleven-inch-thick steel vessels with a stainless steel liner, standing about 40 feet high with a diameter of 16 feet.
- Such a reactor has four pumps, which move 440,000 gallons of water per minute through the primary loop.





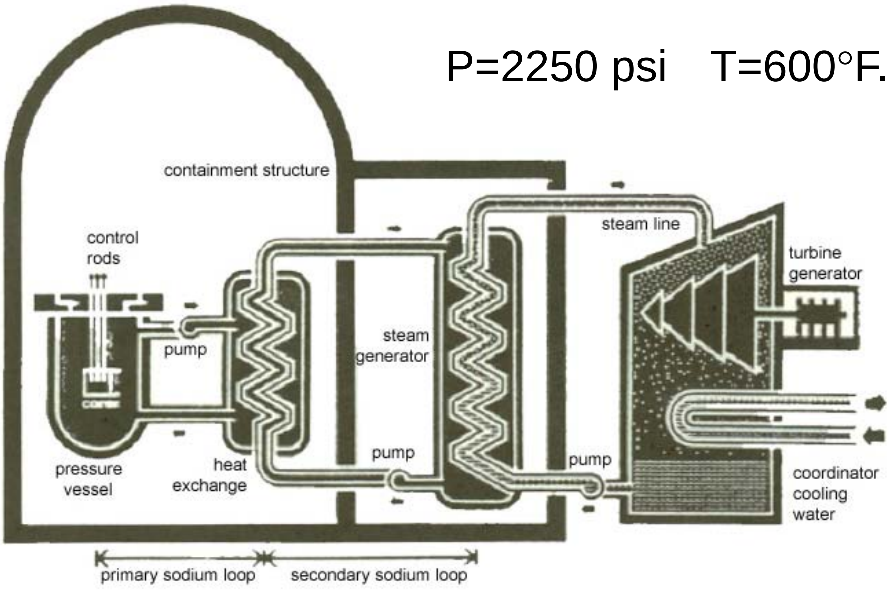
- Spent fuel rod assemblies are removed and new ones are added to a reactor head during refueling. This shows an initial fuel load to a reactor, which has the upper part removed and set aside for the loading.

Pressurized Water Reactor

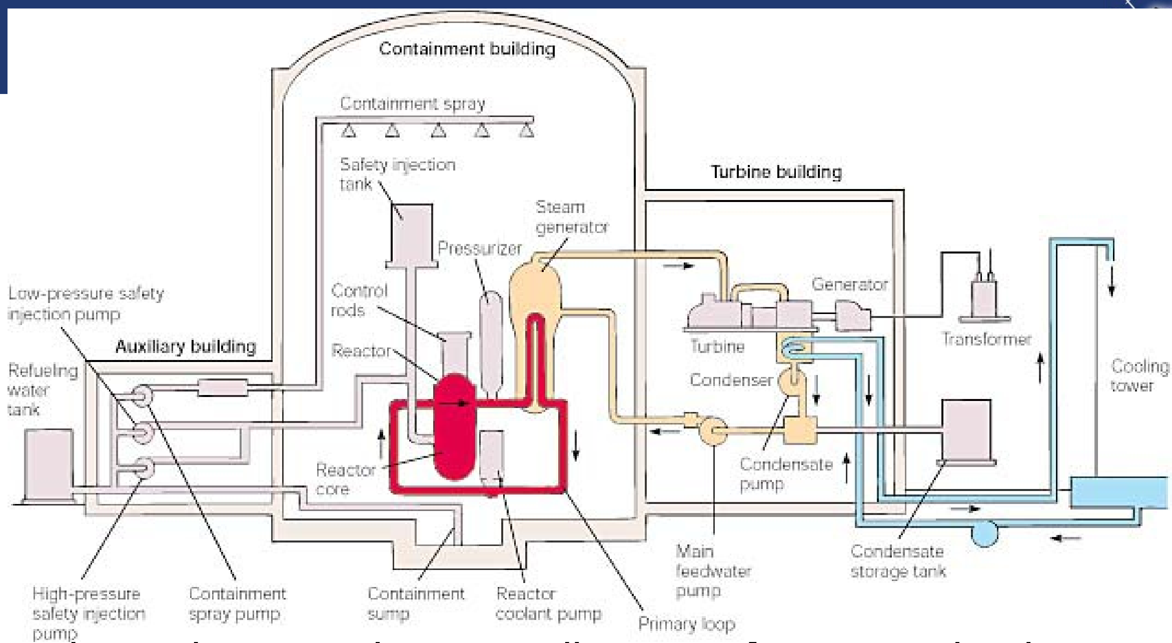
- Water is heated by the nuclear fuel, but is kept under pressure in the pressure vessel, so it will not boil.
- The water inside the pressure vessel is piped through separate tubing to a steam generator.
- The steam generator acts like a heat exchanger.
- There is a second supply of water inside the steam generator.
- Heated by the water from the pressure vessel, it boils to make steam for the turbine.
- Other reactor designs, which use helium gas rather than water to produce steam, are also under development and may eventually be built in the United States.

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

P=2250 psi T=600°F.



Pressurized water reactor (PWR)

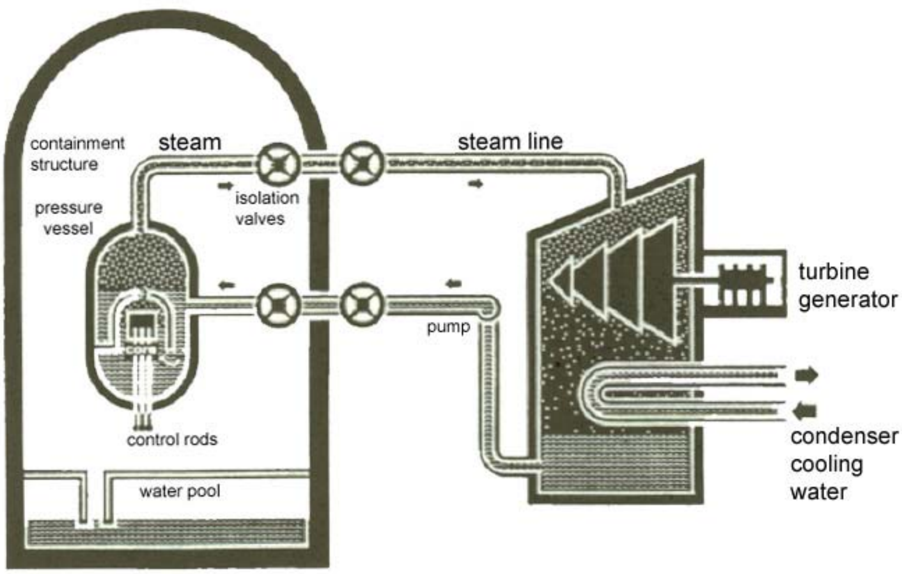


- A schematic general system diagram of a pressurized water nuclear power plant, not to scale. The containment building is designed to withstand an internal temperature of 300^{O}F at a pressure of 60 lbs/in^2 and still maintain its leak-tight integrity.

Boiling Water Reactor

- Inside a boiling water reactor, heat from the chain reaction boils the water and turns it to steam.
- The steam is piped from the reactor vessel directly to the turbine.
- The steam turns the turbine's propeller-like blades, which spins the shaft of a huge generator.
- Inside the generator, coils of wire and magnetic fields interact—and electricity is created

Types of Neutron Reactors

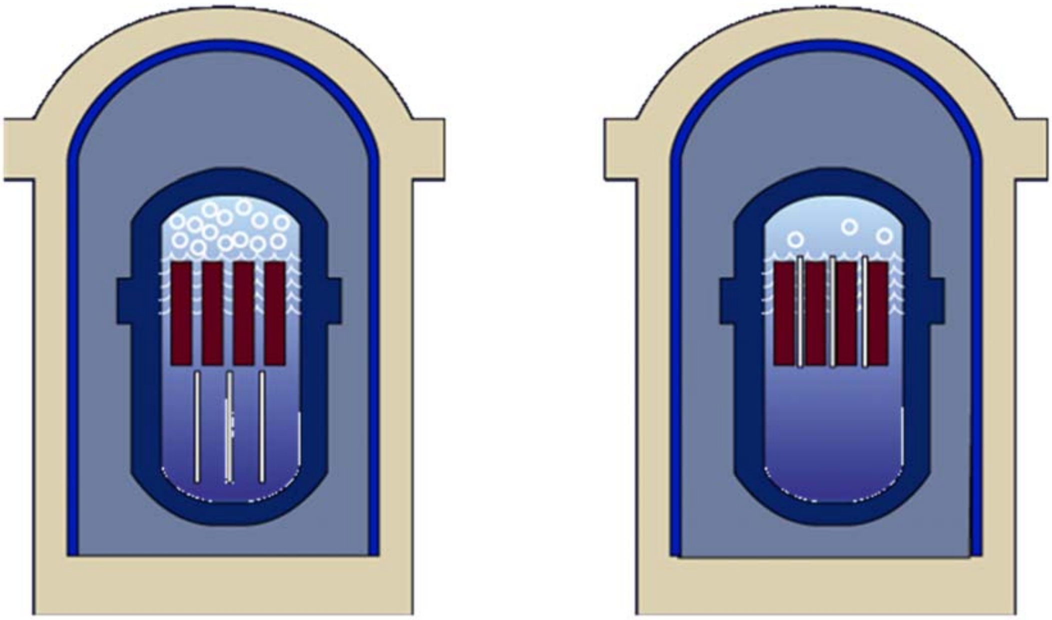


Boiling water reactor (BWR)

P=1000 psi T=545°F

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Boiling Water Reactor



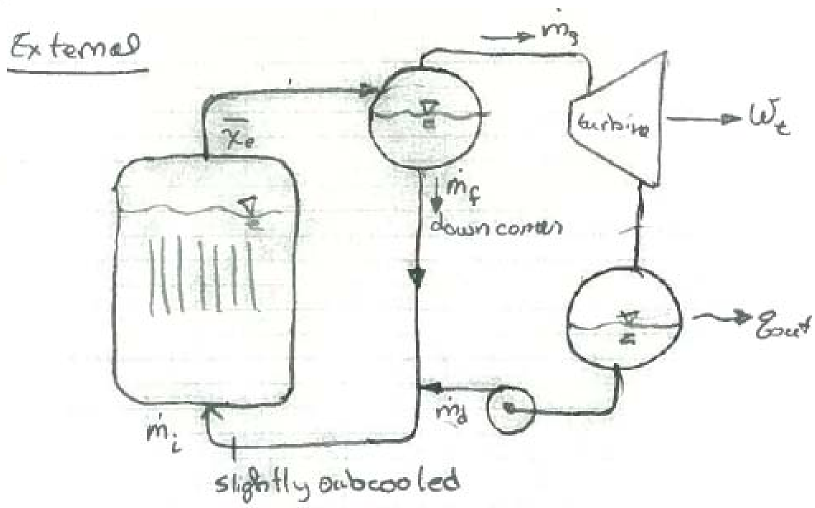
Withdraw control rods,
reaction increases

Insert control rods,
reaction decreases

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

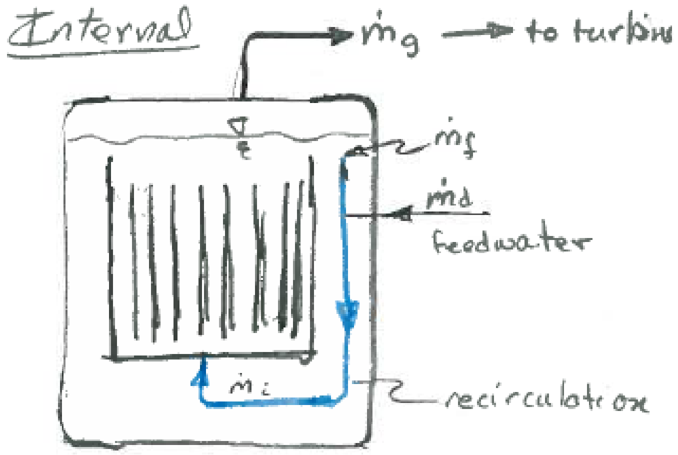
Boiling Water Reactor

- water boils in same location as fuel
  - produces saturated steam ~ 545°F, 285°C
- water has three functions
  - coolant
  - moderator
  - working fluid



Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Boiling Water Reactor



$$R \equiv \text{recirculation ratio} = \frac{\dot{m}_{recirculation}}{\dot{m}_g} = f(\bar{x}_{core})$$

Boiling Water Reactor

$\bar{x}_e \sim 0.10$ to 0.14 (low)
recirculation ratio ~ 6 to 10 } to avoid large void fractions in core

average exit quality, $x_e = \dfrac{\dot{m}_g}{\dot{m}_g + \dot{m}_f} = \dfrac{\dot{m}_g}{\dot{m}_i}$

recirculation ratio $\equiv R = \dfrac{\dot{m}_f}{\dot{m}_g} = \dfrac{1 - \bar{x}_e}{\bar{x}_e}$

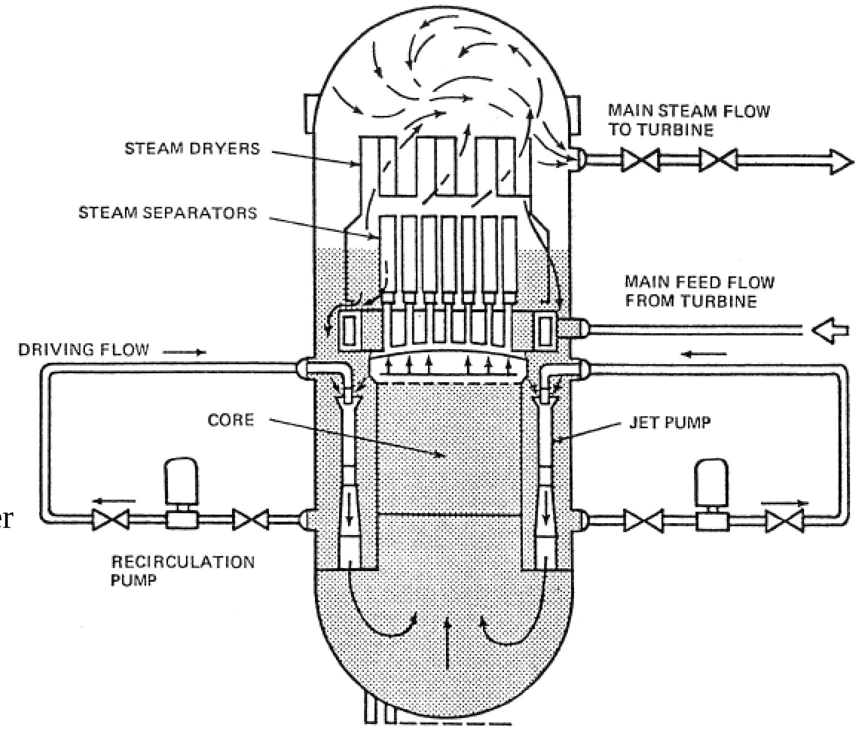
Boiling Water Reactor

$$Q_t = \bar{x}_e \dot{m}_i (h_g - h_d)$$

h_g, the saturated steam enthalpy at the system pressure

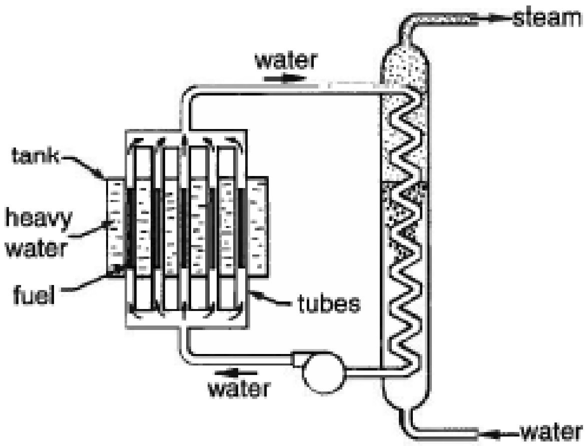
h_d, the feed water enthalpy, are both weak functions of load

$\dot{m}_i$, the flow in the downcomer

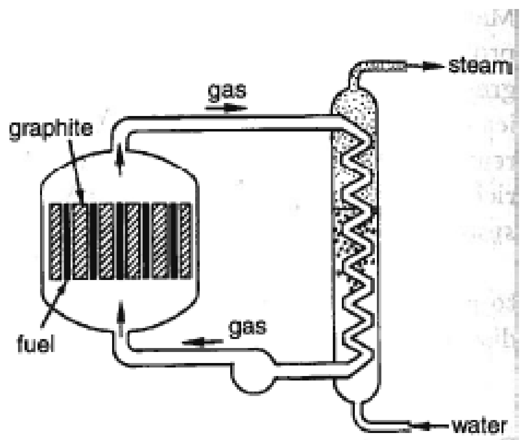


Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Types of Neutron Reactors



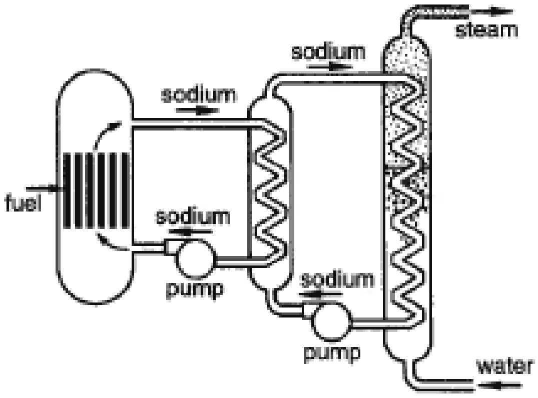
Heavy water reactor (HWR)



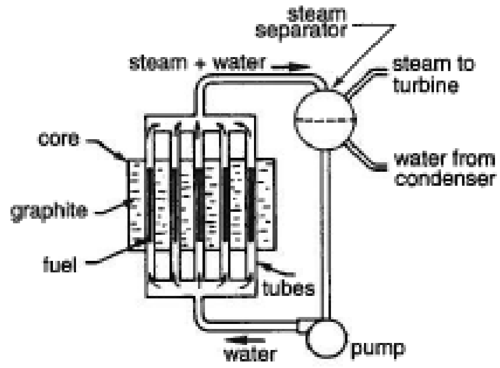
Gas cooled reactor (GCR)

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Types of Neutron Reactors

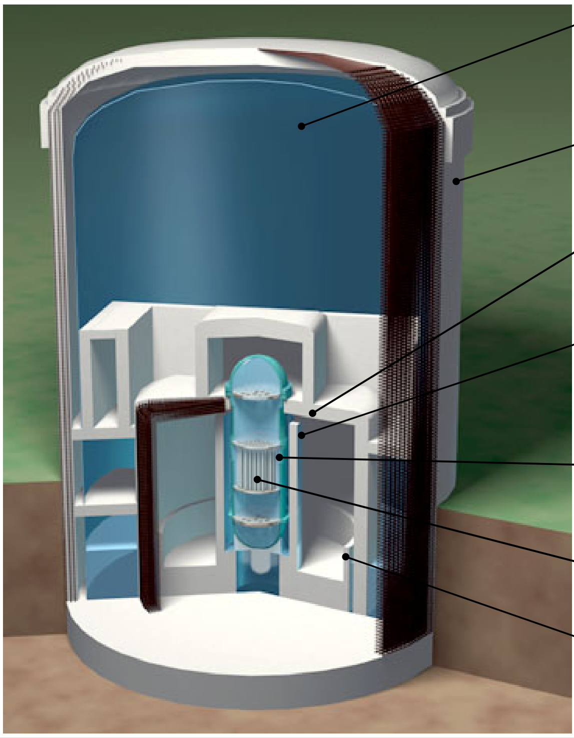


Liquid metal fast breeder re actor (LMFBR).



Graphite-moderated water-cooled reactor (RMBK).

Reactor Safety Design



Containment Vessel
1.5-inch thick steel

Shield Building Wall
3 foot thick reinforced concrete

Dry Well Wall
5 foot thick reinforced concrete

Bio Shield
4 foot thick leaded concrete with
1.5-inch thick steel lining inside and out

Reactor Vessel
4 to 8 inches thick steel

Reactor Fuel

Weir Wall
1.5 foot thick concrete

Reactor is inside a large containment building

Reactor Safety Design

- Nuclear power plants use a series of physical barriers to make sure radioactive material cannot escape.
- In today's water-cooled reactors, the first barrier is the fuel itself: the solid ceramic uranium pellets.
- Most of the radioactive by-products of the fission process remain inside the pellets.
- The pellets are sealed in zirconium rods, 12 feet long and half an inch in diameter.
- The fuel rods are placed inside a large steel reactor vessel, with walls 8 inches thick.
- The vessel is surrounded by 3 feet of concrete shielding.
- At most plants, a leak-tight steel liner covers the inside walls of the containment building.
- The containment building is a massive, reinforced concrete structure with walls 4 feet thick.

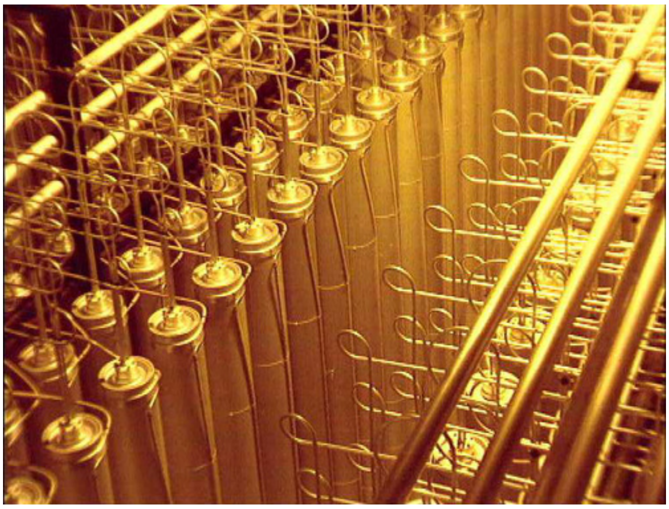
Practicalities

- Processing of Uranium
- Each ton of Uranium ore produces 3-5 lbs of Uranium compounds
- Uranium ore is processed near the mine to produce “yellow cake”, a material rich in U_3O_8.
- Only 0.7% of U in yellow cake is ^{235}U. Most of the rest is ^{238}U which does not work for fission power.

Uranium ore concentrate – “yellowcake”

Enrichment

- Fuel must be 3-5% ^{235}U.
- Yellow cake is converted into UF_6 and this compound is enriched using gaseous diffusion and/or centrifuges.
- There are some reactor designs that run on pure yellow cake.



- NOTE: A nuclear bomb requires nearly 100% pure ^{235}U or ^{239}Pu. The 3% found in reactor grade Uranium CANNOT create a nuclear explosion!

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

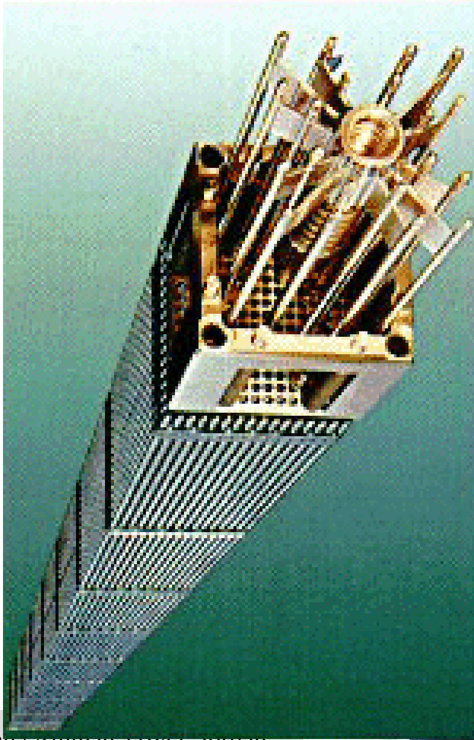
Fuel Pellets

- The enriched UF_6 is converted into UO_2 which is then made into fuel pellets.
- The fuel pellets are collected into long tubes. (~12ft).
- The fuel rods are collected into bundles (~200 rods per bundle
- ~175 bundles in the core

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888

Cladding

- The material that the fuel rods are made out of is called cladding.
- It must be permeable to neutrons and be able to withstand high heats.
- Typically cladding is made of stainless steel or zircaloy.



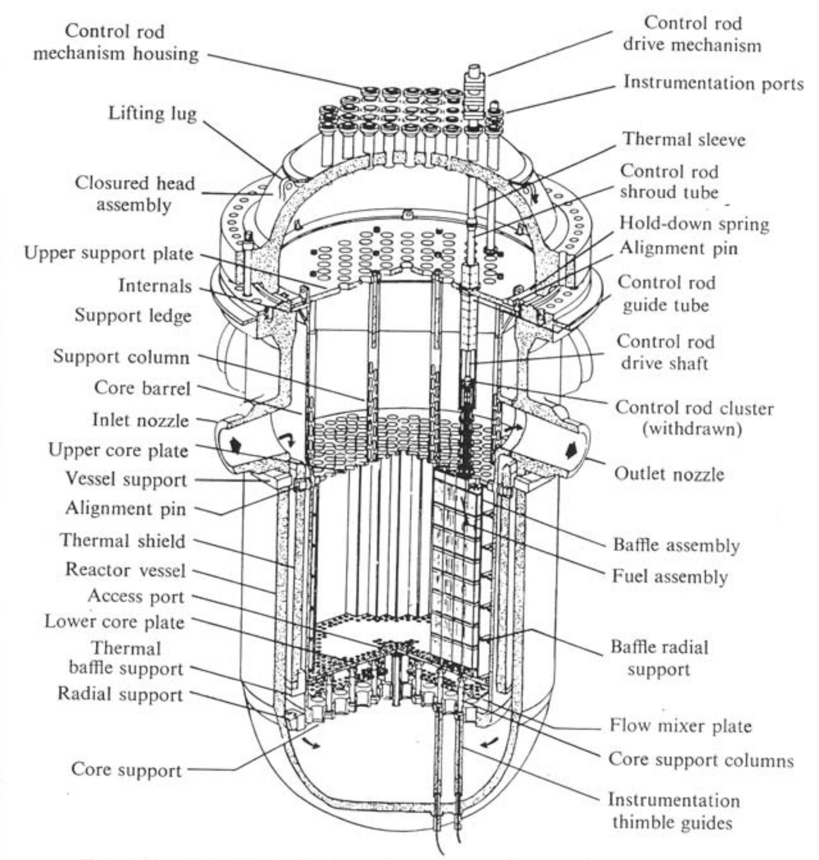


FIG. 1.5 *Connecticut Yankee Pressurized Water Reactor Core.* [*Courtesy Westinghouse Electric Corporation.*]

Controlling the chain reaction depends on

- Arrangement of the fuel/control rods
- Quality of the moderator
- Quality of the Uranium fuel
- Neutron energy required for high probability of fission

Chemical Engineering Department | University of Jordan | Amman 11942, Jordan
Tel. +962 6 535 5000 | 22888