Nuclear power plants

Binding energy of the atomic nucleus

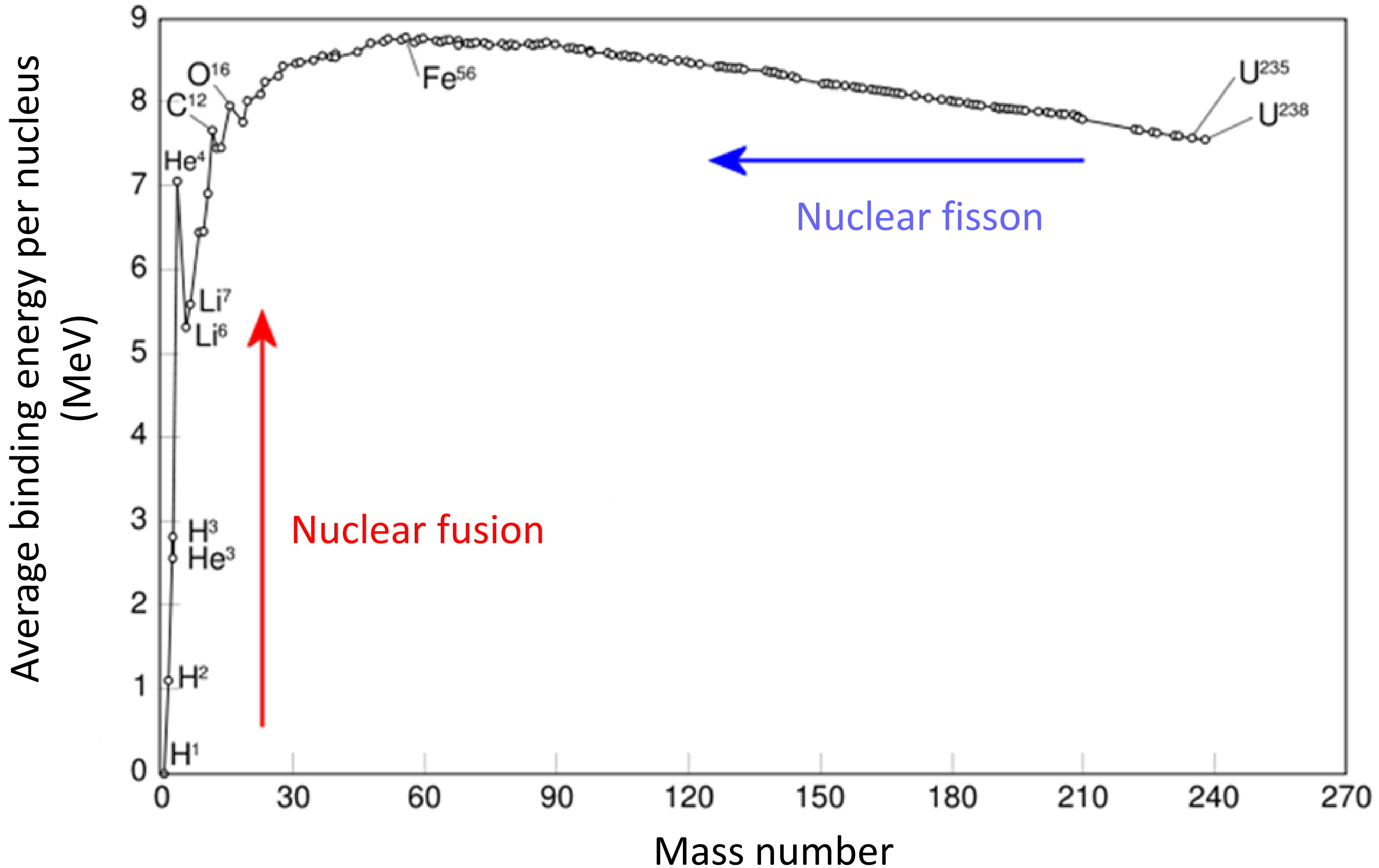
- Nucleus rest mass of all elements and isotopes is less than the sum of masses of all nucleons -> mass defect Δm_j

$$\Delta m_j = N m_n + Z m_p - m_j$$

- where m_n is the rest mass of neutrons, m_p is the rest mass of protons, N is number of neutrons, Z is proton number and m_j is mass of nucleus
- Binding energy W_j can be expressed by Einstein's formula as:

$$W_j = \Delta m_j c^2$$

Binding energy of the atomic nucleus



Radioactive decay

- Law of radioactive decay

$$\frac{dn}{dt} = -\lambda n$$

where *n* is the number of nuclei and λ is a decay constant. The number of decayed atoms in time *t* is:

$$n = n_0 e^{-\lambda t}$$

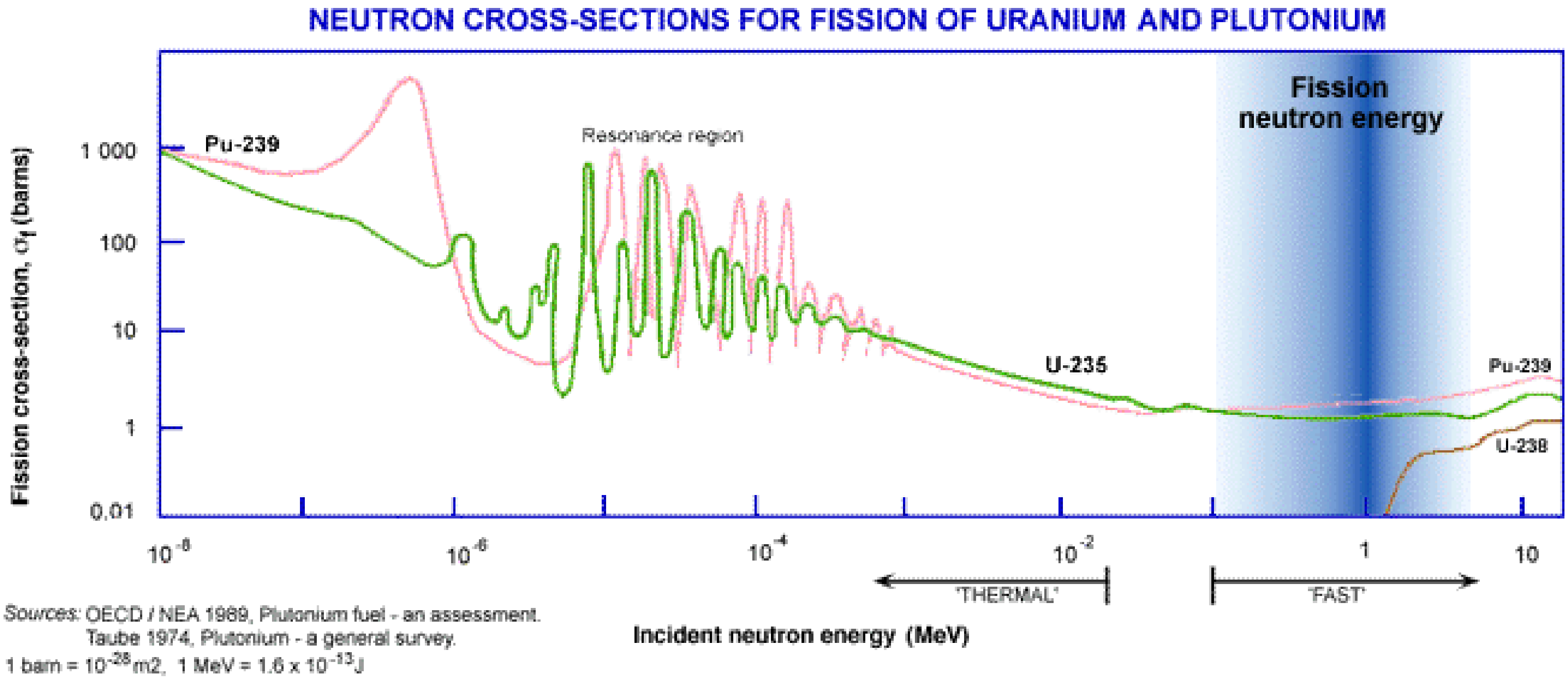
where n_0 is the number of nuclei present initially

- Half-life *T* is the amount of time it takes for a given isotope to lose half of its radioactivity
- New nuclides can be further transformed with a different decay constant

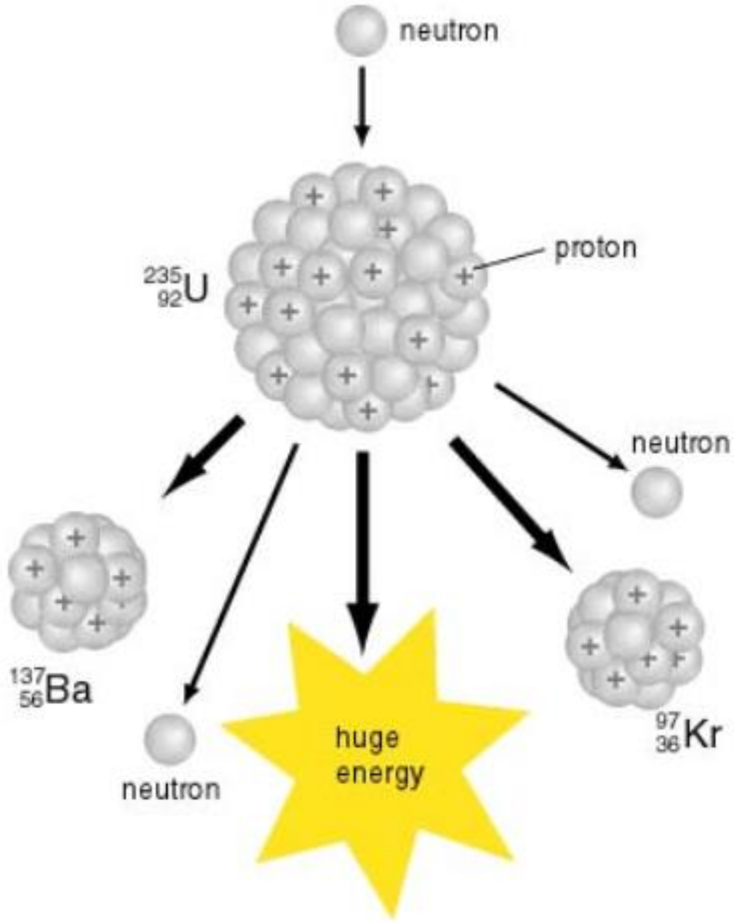
Nuclear reactions

- Conversion of an atom nucleus to different one by the action of elementary particles or other nucleus
- Neutrons need substantially less energy to carry out the nuclear reaction than other particles.
- **Thermal neutrons**– energy up to 0.025 eV
- **Fast neutrons** – energies between 0.1 and 2 or 3 MeV
- **Epithermal neutrons** – energy more than thermal neutrons

Nuclear reactions



Nuclear reaction



Chain reaction

- **Multiplication factor k** – ratio between free neutrons of one generation and number of neutrons in previous generation
  - k>1 system is in supercritical state
  - k=1 system is critical
  - k<1 system is in subcritical state

Controlled chain reaction – achieving and keeping k= 1 in nuclear reaction

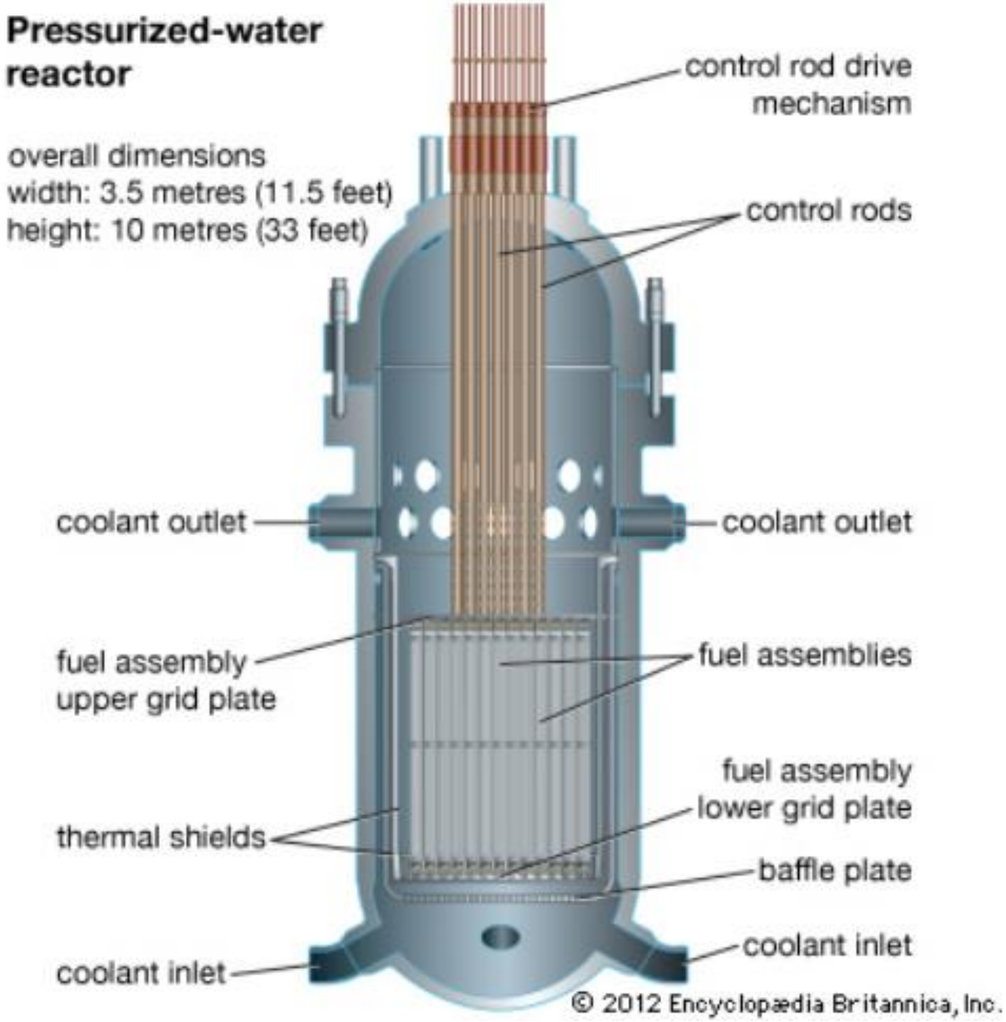
Nuclear reactors

- Fundamental parts of nuclear reactors
  - Nuclear fuel and elements
  - Moderator
  - Coolant
  - Hermetic system
  - Shielding and reflector
  - Active zone and control systems, measurement, protections and diagnostics

Nuclear reactors

- **Homogeneous** – fuel is dispersed in moderator in the form of solution, chemical compound, alloys etc.
- **Heterogeneous** – fuel is separated from moderator using of fuel elements
- Mostly, the heterogeneus reactors are used for the power engineering purposes

Nuclear reactors



Nuclear reactors

- **Thermal reactors** – fission of nuclear fuel mostly by thermal neutrons, moderator has to be present to decrease neutron energy
- **Fast reactors** – fission of nuclear fuel mostly by fast neutrons, at the same time the new fissionable material arise, no moderator is needed

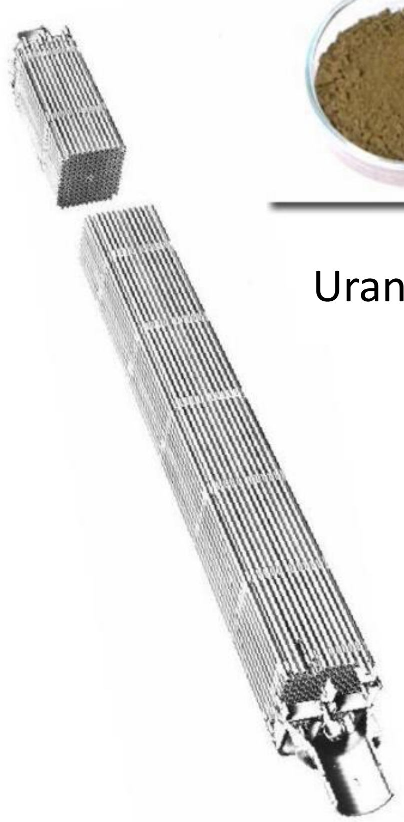
Nuclear reactors

Energy of neutrons	Moderator	Coolant	Name
Thermal	Water (H_2O)	H_2O	Pressurized water (PWR, VVER)
			Boiled water (BWR)
	Grafite	CO_2	Gas cooled (GCR), Advanced (AGR)
		He	High temperature (HTGR)
		H_2O	Light water cooled (LWGR)
	Heavy water (D_2O)	D_2O	Press. heavy water (CANDU) (PHWR)
		H_2O	Heavy water light water (HWLWR)
		CO_2	Heavy water gas cooled (HWGCR)
Fast	-	Na	Fast breeder (FBR)

Nuclear fuel

- Nuclear fuel is mostly:
  - Natural uranium (U238 - 99,276%, U235 – 0,7%)
  - Enriched natural uranium by uranium U235, the average enrichment up to 3%
  - Mixed oxide fuel MOX – manufactured from plutonium recovered from used reactor fuel, mixed with depleted uranium
- Manufactured in the metallic form or in the ceramic form as oxide (UO_2)

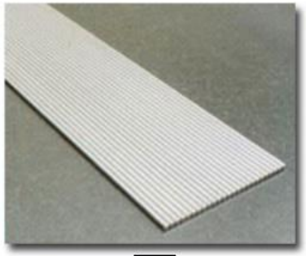
Nuclear fuel



Fuel element

Uranium oxide

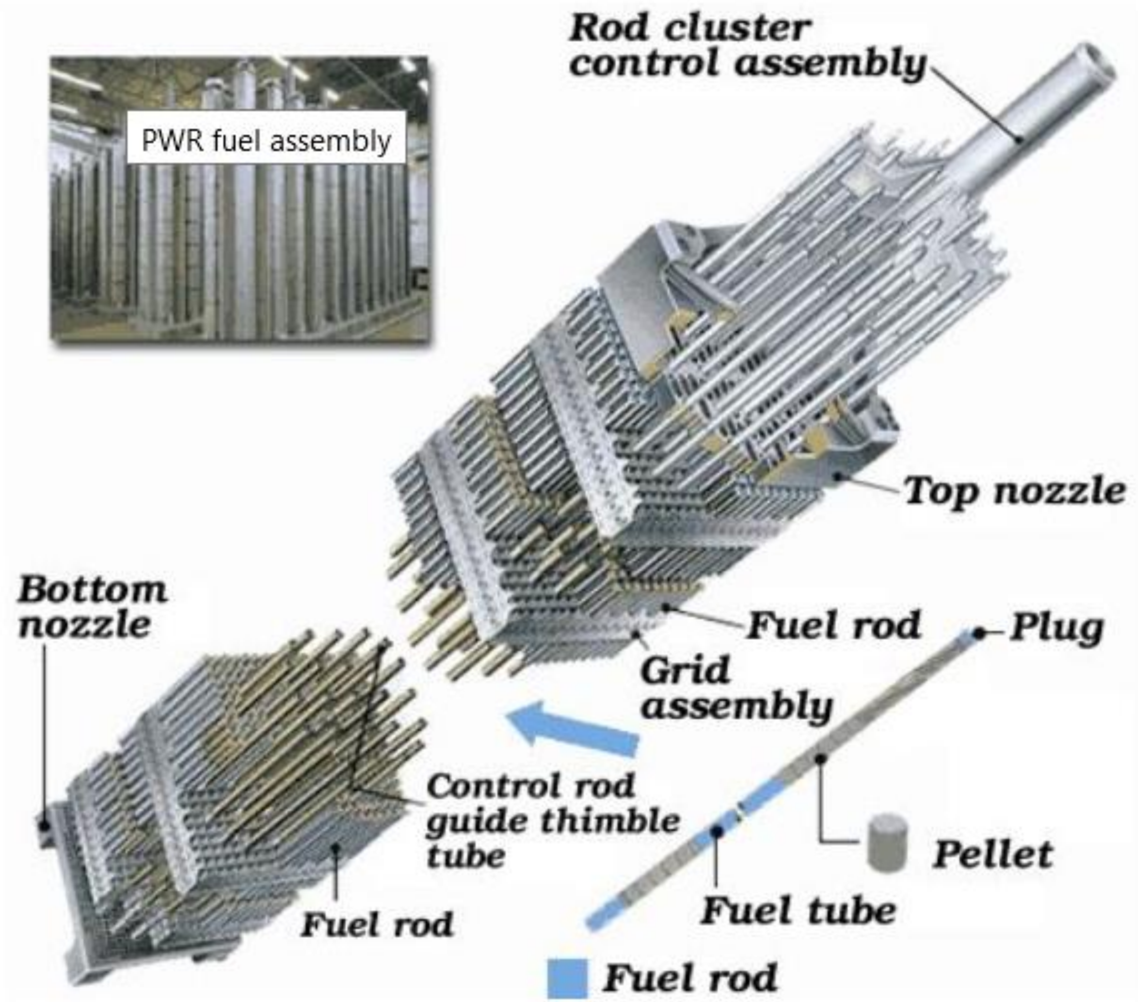
Pressed pellets of uranium oxide



Placement of fuel pellets into zirconium tubes

Assembly of mechanicaly connected fuel elements

Detail of fuel element

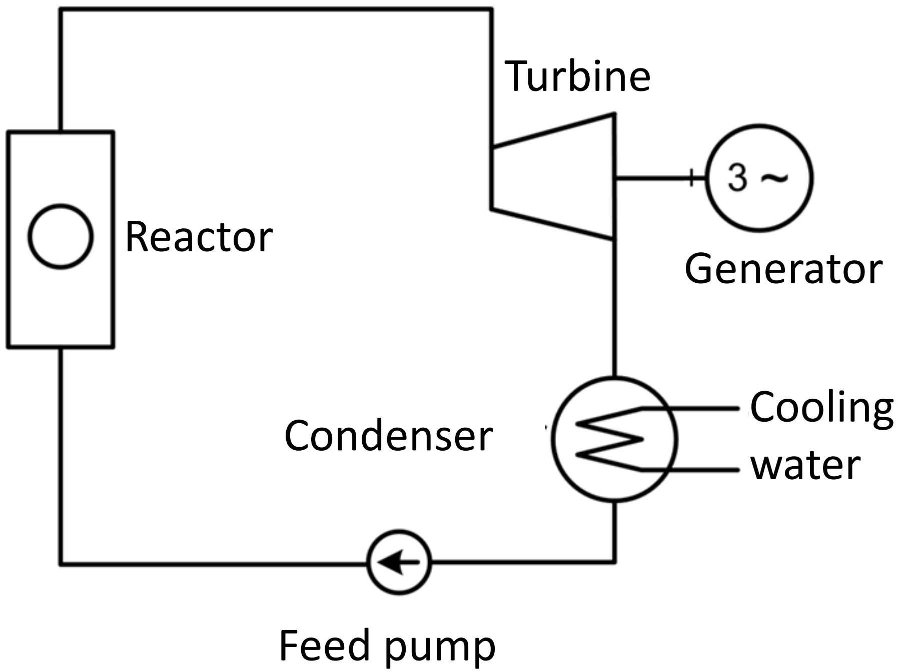


Campaign of nuclear reactor

- Campaign of reactor – time when the reactor is under operation without replacement or rearrangement of fuel
- The nuclear fuel is burned during campaign, after some time it is not possible to keep reactor in the critical state
- To keep chain reaction in reactor (critical mass) the fuel must be periodically replaced or at the beginning of campaign, the higher amount of fuel must be inserted into active zone (supercritical amount) and compensate higher reactivity by absorbers
- If the nuclear fuel burned out to some level the replacement or rearrangement in the active zone is required

Fundamental thermal circuit of nuclear power plants

- One-circuit scheme

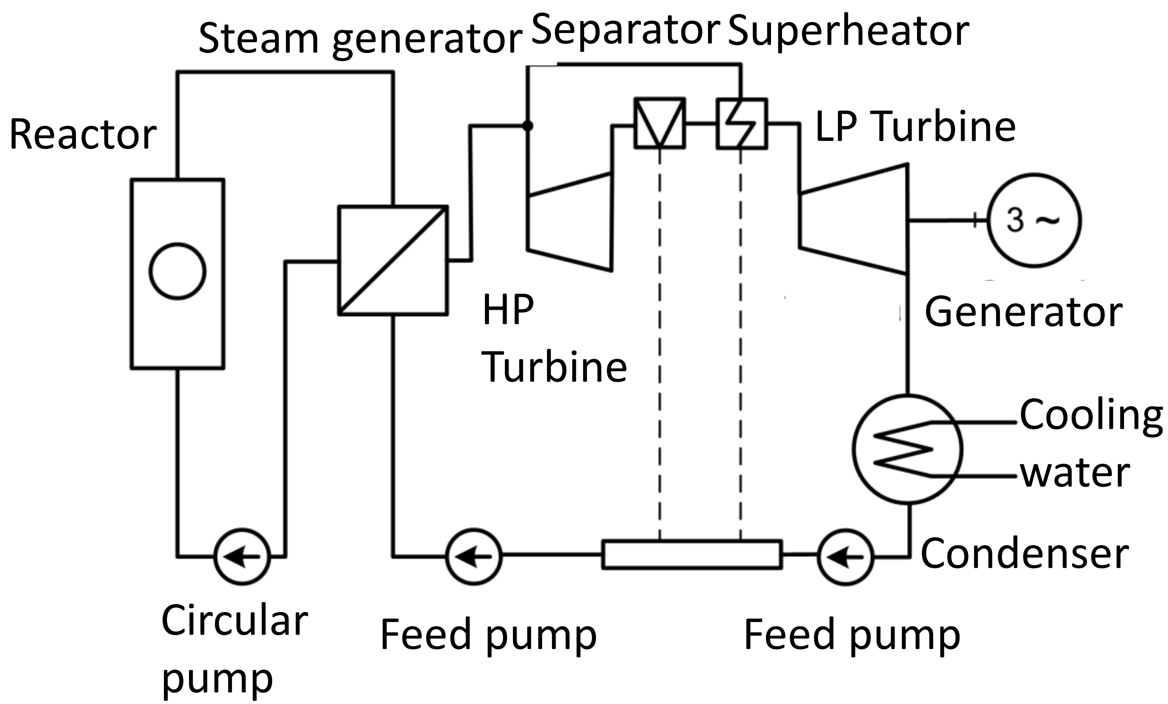


Fundamental thermal circuit of nuclear power plants

- Coolant is also working matter in turbine
- One-circuit scheme is usually used in case of boiled water reactors
- Advantage is the simple heat cycle and its higher efficiency
- Radioactive coolant goes through all the main parts of the nuclear power plant -> special safety measures and increasing demands on reliability and lifetime

Fundamental thermal circuit of nuclear power plants

- Two-circuit scheme

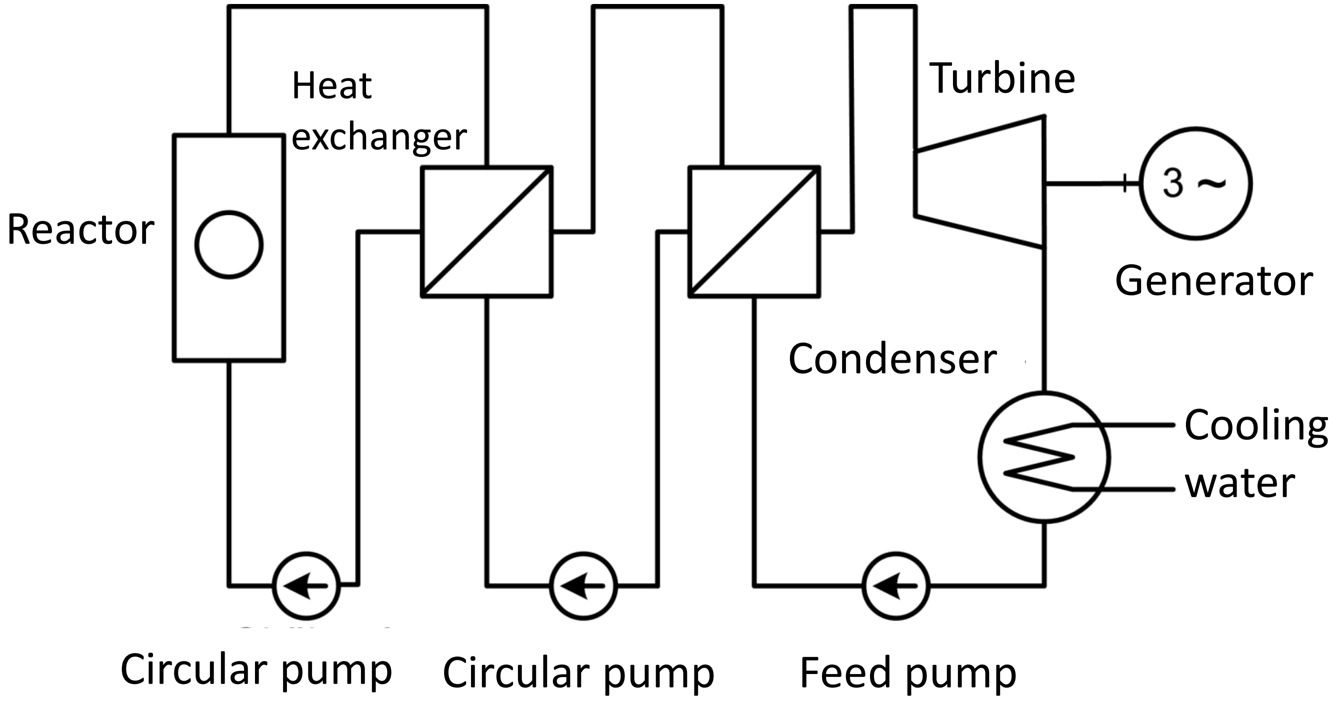


Fundamental thermal circuit of nuclear power plants

- Separation of primary circuit allow to use different types of reactor coolants -> absence of radioactive parts outside the reactor
- The steam from steamgenerator can be used as in conventional thermal power plant
- Machine room of a multi-circuit power plant has significantly simpler safety systems compared to one-circuit power plant

Fundamental thermal circuit of nuclear power plants

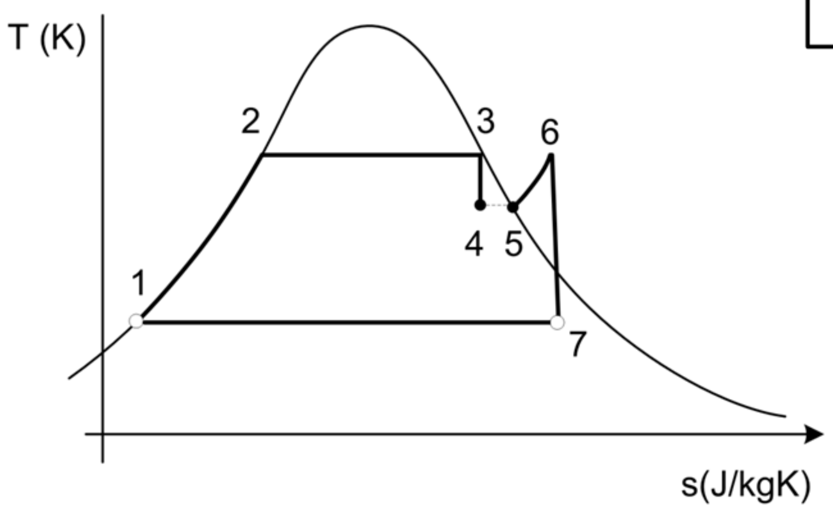
- Three-circuit scheme (liquid metal coolant)

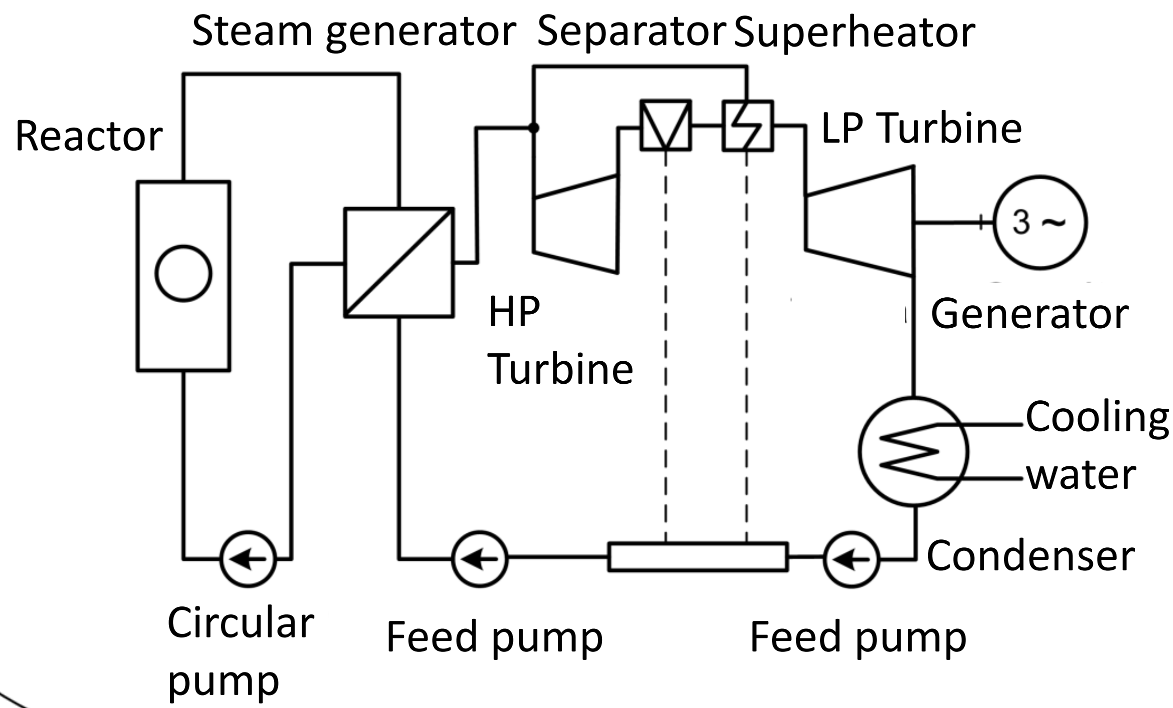


Fundamental thermal circuit of nuclear power plants

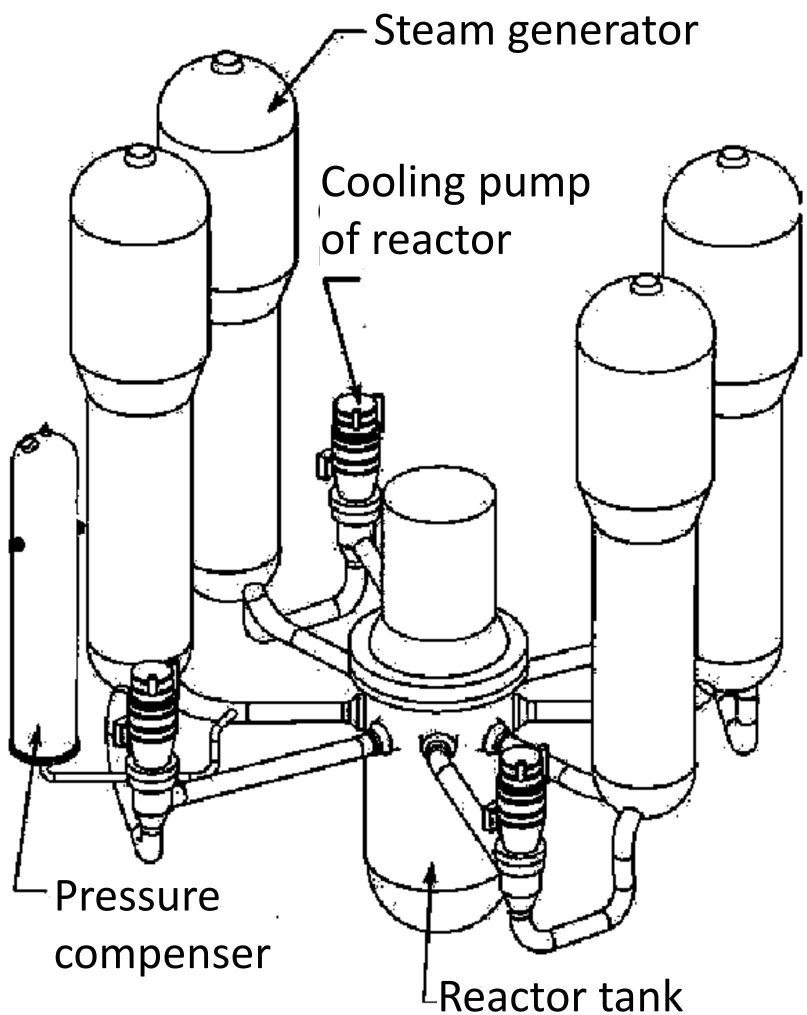
- Enhanced safety at nuclear reactors with fast reactors (liquid-cooled reactors)
- Inserted circuit between primary and secondary circuit is required for two reasons:
  - safer isolation of radioactive isotopes contained in the metallic coolant (higher inlet pressure than primary)
  - when steam penetrates from secondary to primary circuit through a leakage in the exchanger, high affinity of sodium could cause a crash -> transfer sodium / water interface into the secondary area

Heat cycle of two circuit nuclear power plant (PWR)

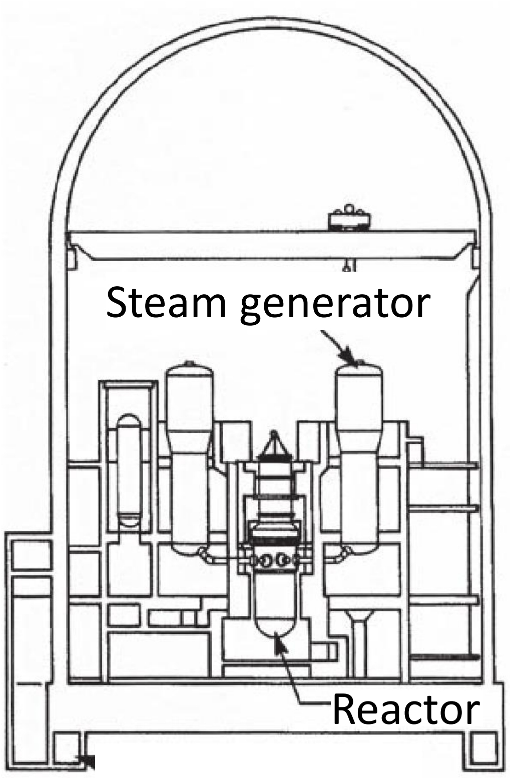


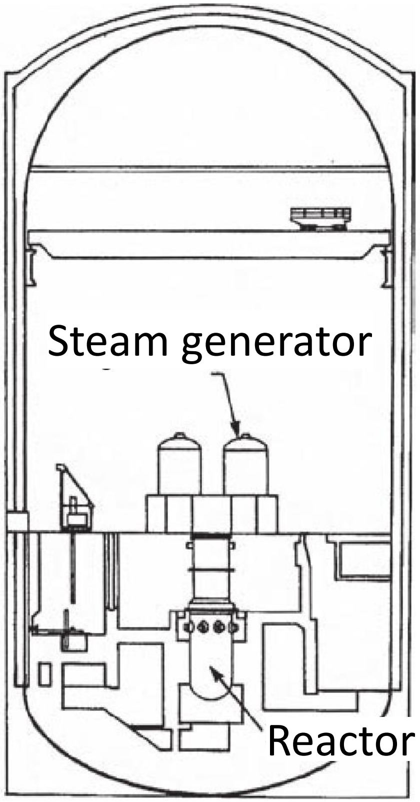


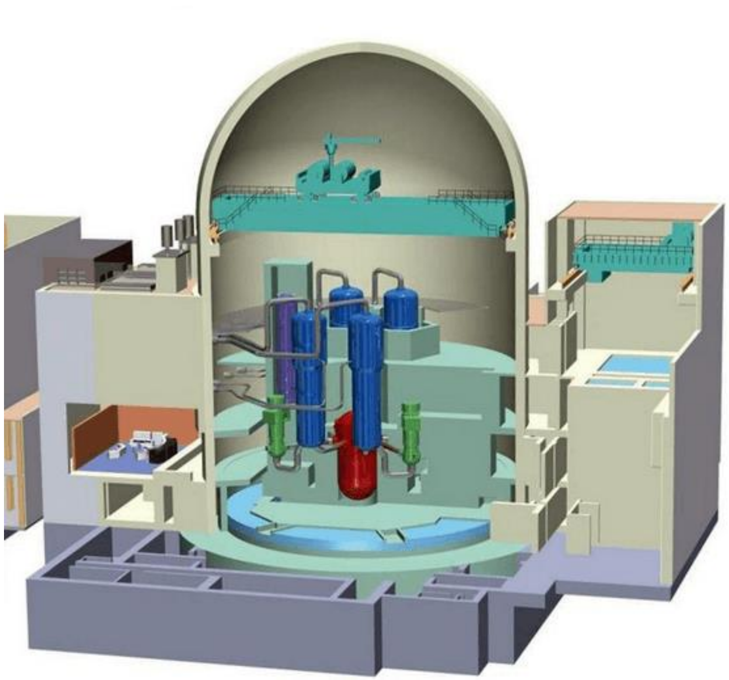
Steam circuit of PWR



Containment building for PWR







Radioactive waste management

- Spent Fuel Pools
  - storage in pools nearby reactor or somewhere outside
  - water transfers the heat and protect against radiation
  - permanent cooling and cleaning of water
  - higher costs
- Dry storage
  - Storage in shielded containers
  - Long-term storage (final repository)
  - Lower costs