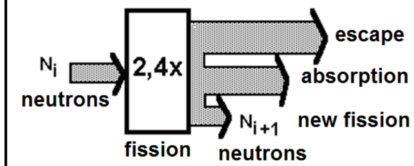
Nuclear Physics
(14th lecture)

Content

- Nuclear chain reaction
    - Methods for achieving self-sustaining chain reaction
    - Moderators, heterogeneous reactor, fuel
    - Over- and under-moderated reactor
- Safety considerations (INES, safety principles)
- Basic components of a nuclear reactor
- Classification of nuclear reactors
- Basic designs of a few types of nuclear power plants
- Short history of nuclear power
- Chicago pile 1942
- How to approach criticality?

Methods for achieving self-sustaining chain reaction



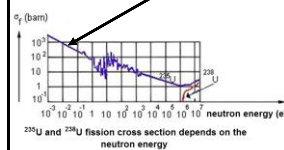
(occurs on the surface)

(^{238}U only absorbs, no fission)

$$k_{eff} = \frac{N_{i+1}}{N_i}$$

The fraction of „new fission" should be increased.
There are several methods for that

- Slow down the neutrons (fission cross section increases)
- Decrease the fraction of „absorption" → increase the ratio ^{235}U/^{238}U (enrichment)
- Decrease the fraction of „escape" → Large size (surface/volume) decreases → Critical mass



^{235}U and ^{238}U fission cross section depends on the neutron energy

Slowing down the neutrons Use a material, where

- mass-number is small (takes off lot of energy in one collision),
- has a large macroscopic neutron-scattering cross-section,
- has a small macroscopic neutron-absorption cross section.

A material with these parameters is called: moderator.
The best moderators are the heavy water and the pure graphite
The hydrogen in the light water absorbs some of the neutrons
by radiative capture: $^1H + n \longrightarrow {}^2H + \gamma$

Possibilities for the realisation of the sustainable chain reaction:

Fuel (enrichment)	*Moderator*
Natural uranium (0,71% ^{235}U)	Heavy water, pure graphite
3-5% enriched uranium	Light water
>40% enriched uranium (>90%)	Moderator is not needed (nuclear weapon)

Important: the moderator ENHANCES the chain reaction!

What is k_{eff} depending on?

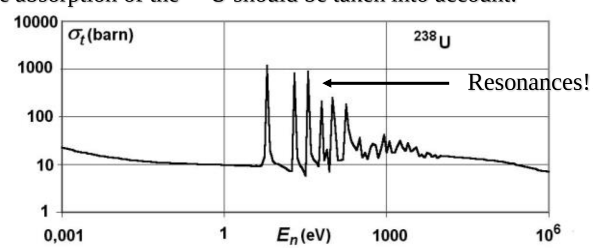
At first we neglect the escape ⟶ „infinitely large" reactor!

This will be characterized by: k_∞

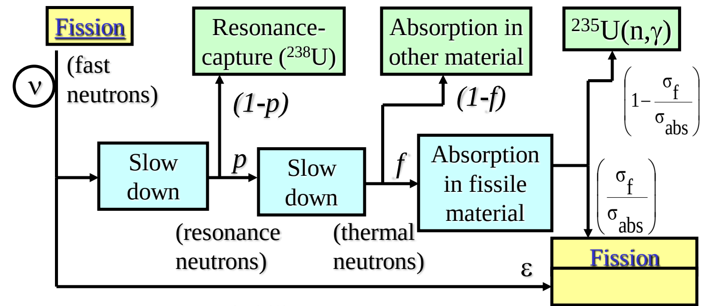
Our reactor will be:

- thermal reactor (with moderator, slow neutrons),
- construction materials (not only fuel)
- fuel is somewhat enriched uranium, (there is also ^{238}U)

The absorption of the ^{238}U should be taken into account:



„Four factor” formula (infinitely large n-multiplying system)



Resonance-escape probability $0{,}6 < p < 0{,}9$

Thermal utilisation factor *(f)*

$$k_\infty = \nu \cdot p \cdot f \cdot \left(\frac{\sigma_f}{\sigma_{abs}}\right) \cdot \varepsilon$$

„Reproduction factor” (depends only on fissile isotope) $\boxed{\eta = \nu \cdot \frac{\sigma_f}{\sigma_{abs}}}$

Fast fission factor $1{,}00 < \varepsilon < 1{,}03$

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„Four factor” formula (contd.)

Summarized: $\boxed{k_\infty = \eta \cdot p \cdot f \cdot \varepsilon}$

Reproduction factor

Resonance-escape probability

Fast fission factor

Thermal utilisation factor

Characteristics of reactor-fuel materials (for thermal neutrons):

	σ_f (barn)	σ_a (barn)	ν	η
^{233}U	531	577	2,50	2,30
^{235}U	584	683	2,43	2,08
^{238}U	$5\cdot 10^{-4}$	2,71	-	-
U_{nat}	4,18	7,69	2,27	1,34
^{239}Pu	750	1021	2,88	2,11

η shows, what should be achieved with the other factors!

For example: with natural uranium $p \cdot f \cdot \varepsilon > 1/1{,}34 = 0{,}746$, otherwise no sustainable chain reaction can be achieved even for infinite reactor!

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Resonance-escape: inhomogeneous nuclear reactor (idea of Leo Szilárd)

Lattice consisting of small diameter fuel rods

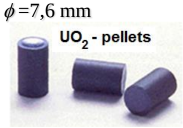
The fast fission neutrons leave the fuel

Slow down in the moderator (escape the resonances)

They diffuse back in the fuel as a slow neutron

Example: the fuel of the NPP Paks

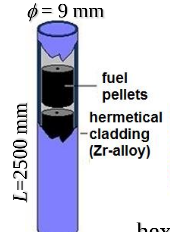
ϕ =7,6 mm



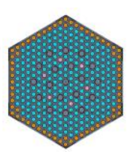
pellets

(UO$_2$ ceramics)

ϕ = 9 mm



fuel rod



hexagonal assemblies (349 pieces)

(126 rod/assembly) size: 144 mm

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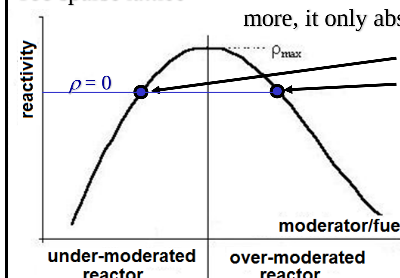
Finite size reactor, taking into account the escape of neutrons

$\boxed{k_{eff} = \eta \cdot p \cdot f \cdot \varepsilon \cdot P}$ The fraction of neutrons remaining in the reactor (escape factor) $P<1$

The lattice parameter is important for the moderated state of the reactor

Too dense lattice ⟶ The neutrons do not slow down enough between the rods ⟶ k_{eff} (and ρ) could increase

Too sparse lattice ⟶ The excess moderator can not slow down more, it only absorbs ⟶ decreases the k_{eff}



Under-moderated operating point

Over-moderated operating point

It is important for the safety of the operation!

In case of incident/accident the moderator disappears sooner than the fuel, the reactor gets lower moderated

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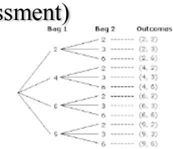
Some considerations about the safety

International Nuclear Event Scale (INES):

Two types of major accidents:

Criticality accidents are, when $k_{eff}>1$ occurs in an uncontrolled way. The worst of this type is the **prompt-criticality**, which is not only uncontrolled, but it is uncontrollable (e.g. Chernobyl)
Loss of coolant accidents (LOCA), when some pipe breaks in the primary circuit, or the circulation of the coolant stops or slows down (pump failure or black out), the cooling of the core gets endangered (e.g. Fukushima)
How to avoid accidents?
Accidents cannot be completely „avoided", but their **probability** can be decreased. (PSA→ probabilistic safety assessment)
For example: the core-melt probability

- for Gen-II reactors was around 10^{-4} /year
- for Gen-III reactors is around 10^{-6} /year
- for Gen-IV reactors will be 10^{-7}/year



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Some considerations about the safety (contd.)

Principles of safety installations

- Multiplication (3-4 times)

- Diversity

- Independency (no single caused failure)
- Inherently safe (the physical laws protect, not the human or computer intervention)

Few examples for inherent safety principles

- „under-moderated" reactor core: boiling of the moderator decreases reactivity (negative „void"-coefficient)
- „resonance-absorption" increases when temperature goes up → decreases reactivity
- negative coefficient for fuel and moderator temperature

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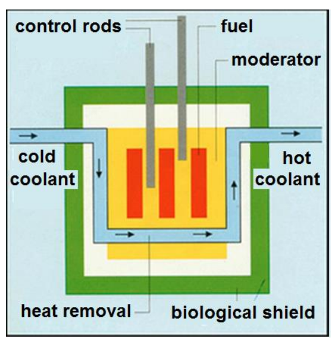
Basic design of a nuclear reactor

- fuel (uranium, plutonium, MOX)
- moderator
  (water, heavy water, graphite)
- coolant
  (liquid, gas)
- control elements
  (borated iron rods, boron acid solved in the coolant)
- biological shield
  (concrete, heavy concrete)
- safety installations



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Classification of nuclear reactors (1)

- **According to their purpose**
  - research reactors
    (isotope production, nuclear research, education)
  - power reactors
    (energy production)
  - breeding reactors
    (production of new fissile material, see later)
  - impulse reactors
    (special nuclear research)
  - material research reactors
    (research on structural materials)

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Classification of nuclear reactors (2)

- **According to their fuel**

- ^{235}U (different enrichment)

- ^{233}U production:

$$^{232}_{90}Th + n \rightarrow {}^{233}_{90}Th \xrightarrow{\beta\ (22,2min)} {}^{233}_{91}Pa \xrightarrow{\beta\ (27\,day)} {}^{233}_{92}U\ (1,6\cdot 10^{5}\ year)$$

- ^{239}Pu production:

$$^{238}_{92}U + n \rightarrow {}^{239}_{92}U \xrightarrow{\beta\ (23,5min)} {}^{239}_{93}Np \xrightarrow{\beta\ (2,35day)} {}^{239}_{94}Pu\ (24390\ year)$$

Breeding! „Production" of fissile material)

- MOX (mixed oxide fuel): mixture of uranium and plutonium oxide. Importance: destruction of ^{239}Pu from nuclear weapons

- **According to fuel arrangement**

- homogeneous reactors (fuel and moderator mixed)
- heterogeneous reactors (fuel and moderator separated)

Classification of nuclear reactors (3)

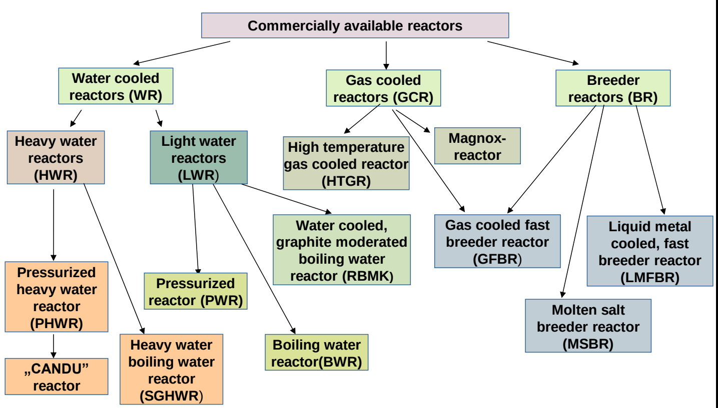
- **According to the moderator**

- H_2O (light water)
- D_2O (heavy water)
- C („reactor grade" purity graphite)
- Be (beryllium)
- organic material (containing C and H)

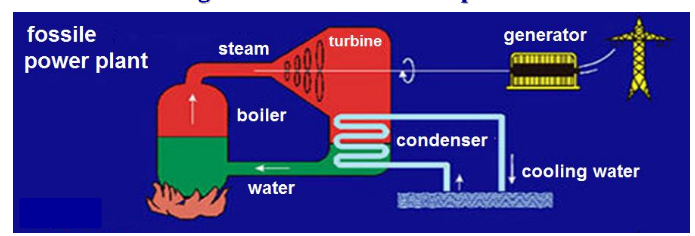
- **According to coolant**

- H_2O (light water)
- D_2O (heavy water)
- liquid metal (Na, Pb…)
- gas (He, CO_2)
- organic material

Classification of the currently available power reactors



Basic design of a fossil and nuclear power station



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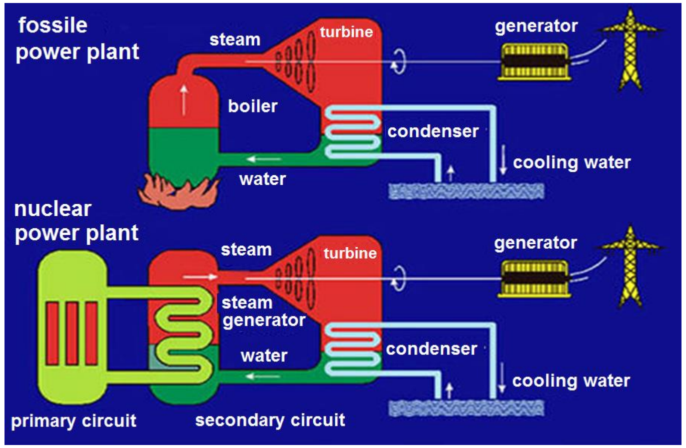

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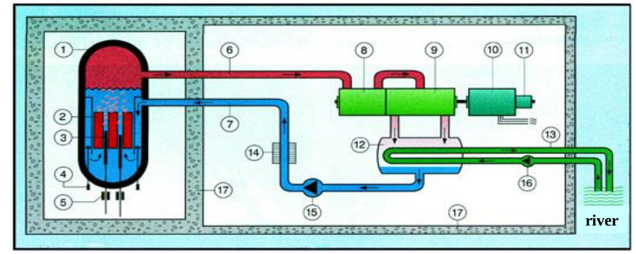
Basic design of a boiling water nuclear power station



1 Reactor vessel
2 Fuel rods
3 Control rods
4 Main circulating pump
5 Control rod drive
6 Fresh steam
7 Feed water
8 High pressure turbine
9 Low pressure turbine
10 Generator
11 Energizing machine
12 Condenser
13 Coolant
14 Feed water preheater
15 Feed water pump
16 Coolant pump
17 Concrete radiation shield

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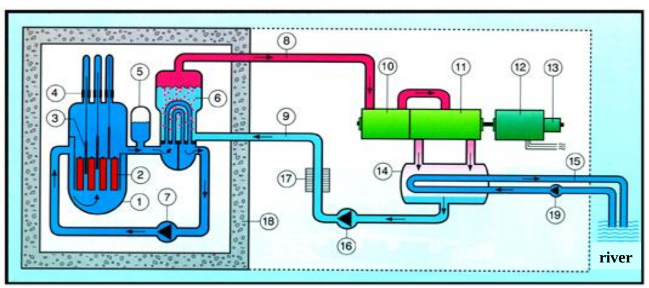
Basic design of a pressurized water nuclear power station



1 Reactor vessel
2 Fuel
3 Control rods
4 Control rods drive
5 Expansion tank
6 Steam generator
7 Main circulating pump
8 Fresh steam
9 Feed water
10 High pressure turbine
11 Low pressure turbine
12 Generator
13 Energizing machine
14 Condenser
15 Cooling water
16 Feed water pump
17 Preheater
18 Biological shield
19 Cooling water pump

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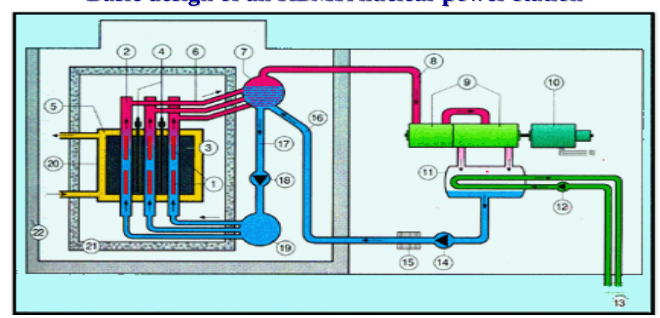
Basic design of an RBMK nuclear power station



1 Uranium fuel
2 Pressure pipe
3 Graphite moderator
4 Control rod
5 Inert, protective gas
6 Water/steam
7 Drops separator
8 Steam to turbine
9 Steam turbine
10 Generator
11 Condenser
12 Cooling water pump
13 Heat removal
14 Feed water pump
15 Preheater
16 Feed water
17 Water backflow
18 Circulating pump
19 Water distributor
20 Steel casing
21 Concrete shield
22 Reactor building

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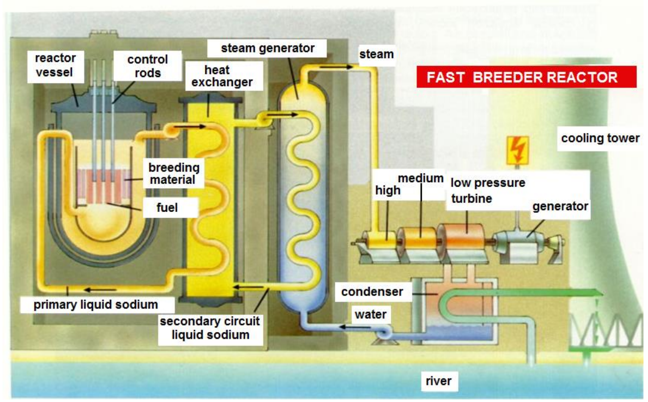
Basic design of a liquid metal cooled fast breeder nuclear power station



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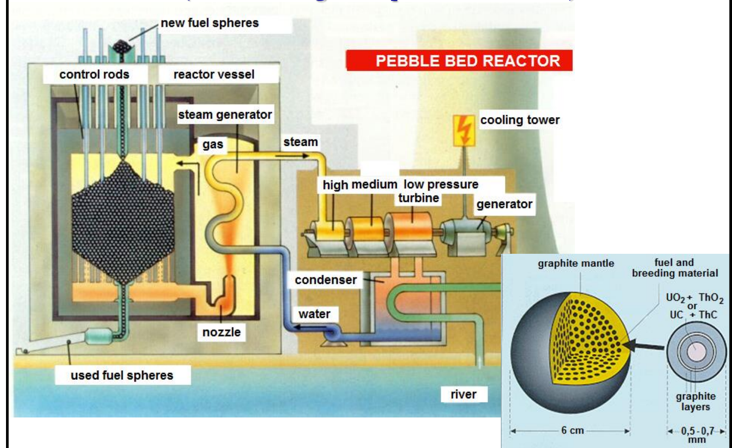
Basic design of Pebble Bed Reactor (Thorium High Temperature Reactor)



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Short history of nuclear power:

1932 Discovery of the neutron (James Chadwick)
1934 Patent of the chain reaction with neutrons (Leo Szilárd)
1938 Discovery of the nuclear fission
(Otto Hahn, Friedrich Strassmann, Lise Meitner)
1942 Dec. 2. First nuclear pile, self-sustained chain reaction (Chicago)
(Enrico Fermi, Leo Szilárd, Eugene Wigner)
1943 High-power nuclear reactors start operating (Hanford)
(Eugene Wigner) Purpose: plutonium production for A-bomb
1939-1945 Manhattan Project (development of nuclear weapon)
Scientific leader: Robert Oppenheimer
1945. July 16. First experimental explosion test („Trinity test”)
Alamogordo desert, USA ^{239}Pu-based nuclear weapon
1945. Aug. 6. Hiroshima explosion (^{235}U-based nuclear weapon)
1945. Aug. 9. Nagasaki explosion (^{239}Pu-based nuclear weapon)
1954 First commercial NPP (Obninsk, Soviet Union, 5 MWe)
1957 Shippingport, first commercial NPP in USA, 60 MWe

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2. December 1942. First nuclear pile (Chicago)

(Enrico Fermi, Leo Szilárd, Eugene Wigner, Arthur Compton…)
Fuel: natural uranium (metal, 6 t)
Moderator: pure graphite (315 t)
Control: cadmium plates (3 pieces)
Coolant: none (max. power 2 W)

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How to approach the critical state?
(Avoid prompt criticality!)

Starting point: $k_{eff} = \frac{N_{i+1}}{N_i}$

From this: $N_{i+1} = k_{eff} \cdot N_i$ if there is only n-multiplication!

Put in a neutron source! The source should emit S neutrons in one generation time! Then it adds to the new generation:

$$N_{i+1} = S + k_{eff} \cdot N_i$$

from source previous generation

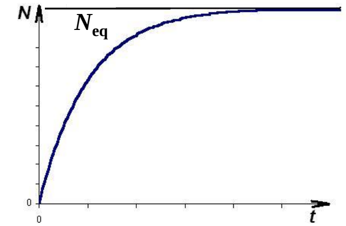
While $k_{eff} < 1$ an equilibrium establishes slowly $N_{i+1} = N_i = N_{equ}$

i.e. $N_{equ} = S + k_{eff} \cdot N_{equ}$ from where $\boxed{N_{equ} = \frac{S}{1-k_{eff}}}$

This way k_{eff} can be measured!!

While $k_{eff} < 1$ equilibrium:

$$\boxed{N_{equ} = \frac{S}{1-k_{eff}}}$$



When we reach the critical state, an exponential increase starts: „exponential experiment"
(Leo Szilárd's idea)