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Nuclear

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PLANAIR

Lausanne, 28/10/2024

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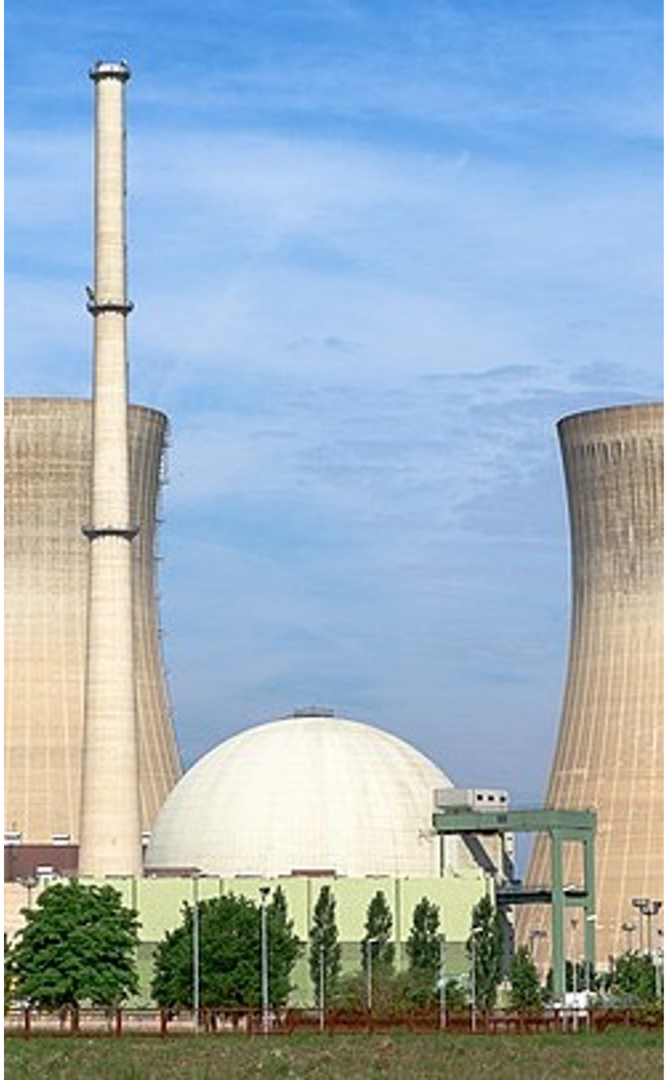
Goals

- **Define the concept of *reactivity*** and **explain** the various factors affecting it

- **Describe** the **operation** and **types** of nuclear power plants



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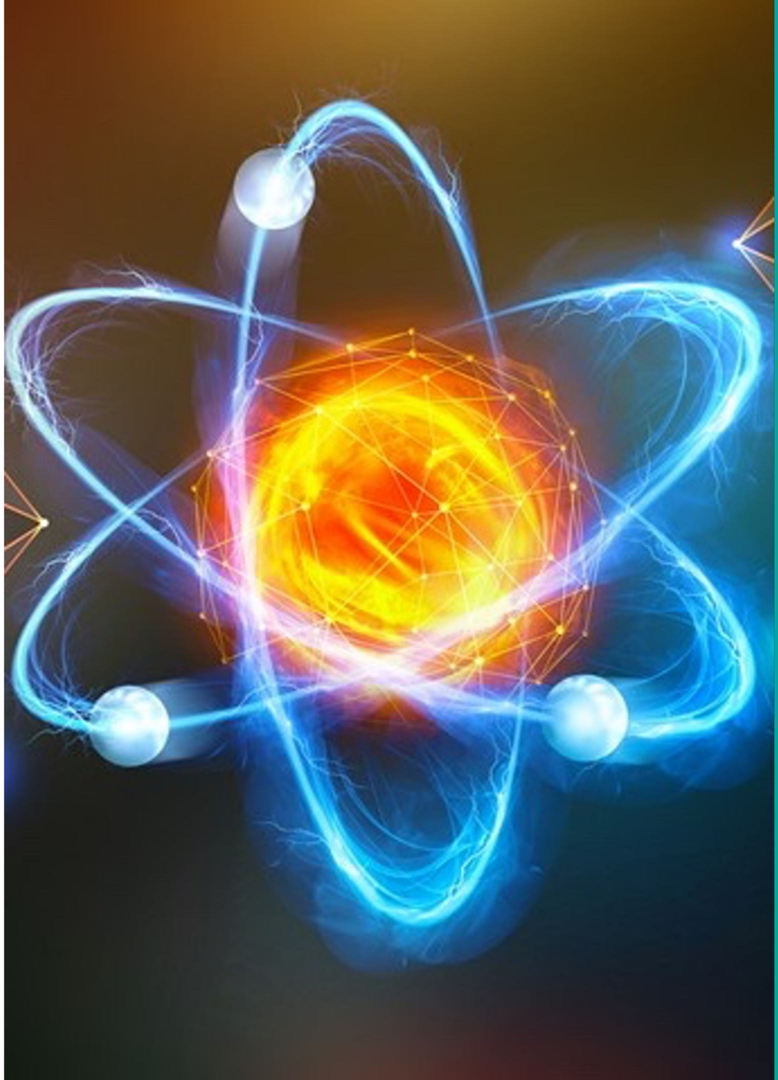

Introduction

The story behind Nuclear

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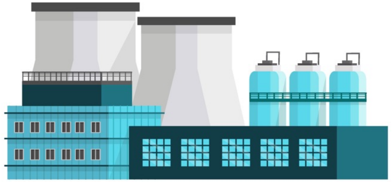
Introduction
– How do we produce electricity today?



HEAT → HEAT ENGINE → ELECTRICITY

Chemical / Nuclear energy (Biomass, Coal, etc.)

- **Nuclear energy : heat from fission reactions**
- Heat engine : a simple **Rankine** cycle

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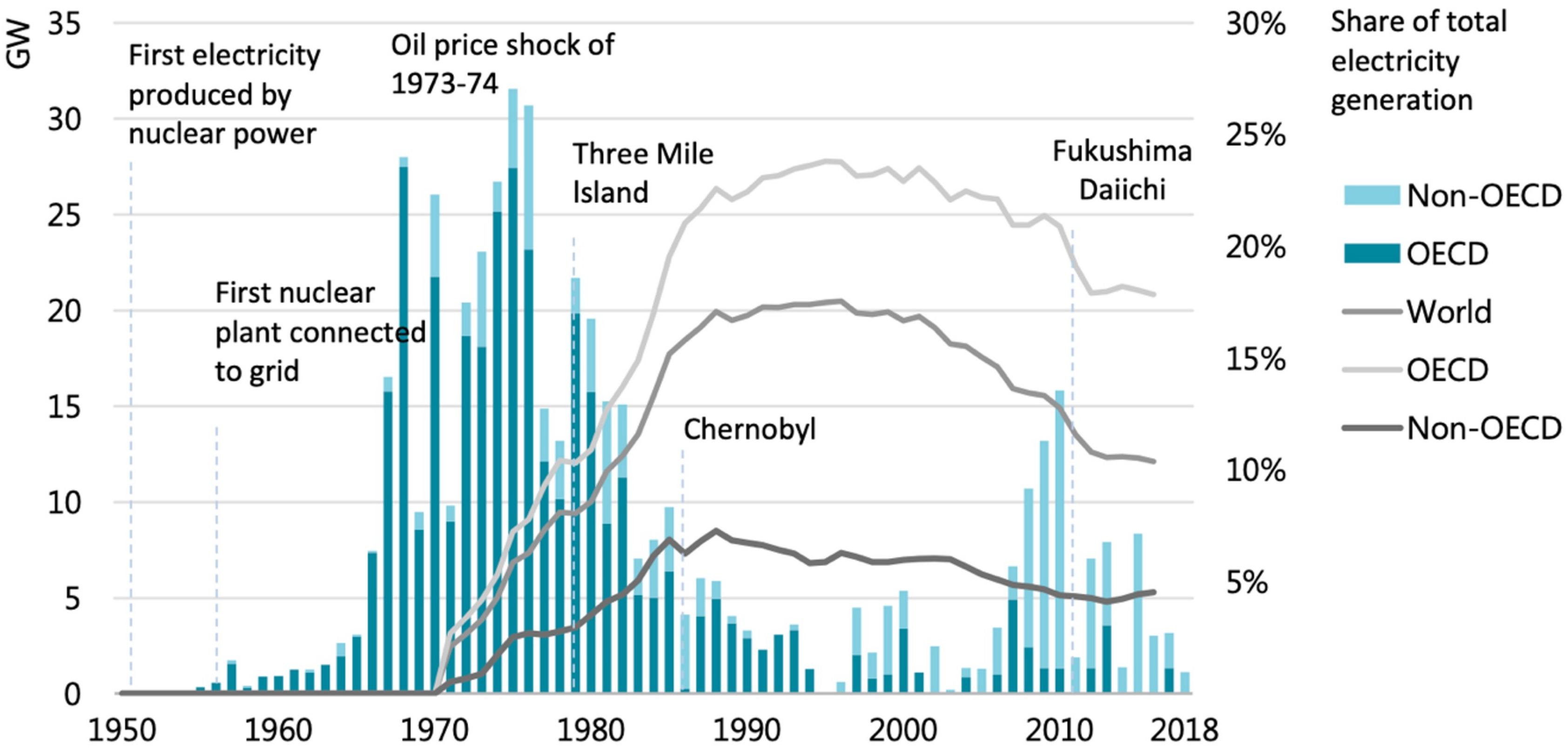
Introduction
– Growth of Nuclear



Source: IEA, Nuclear Power in a Clean Energy System (2021)

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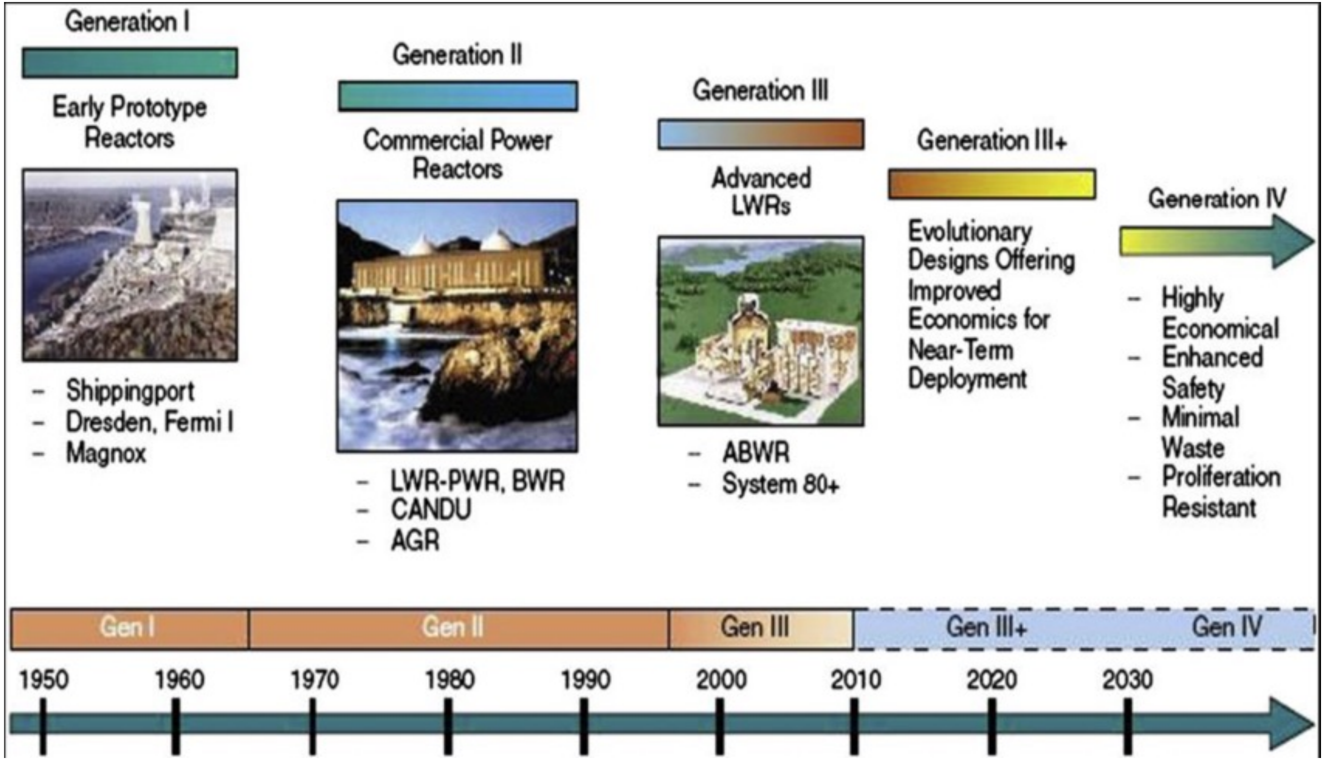
Introduction



- **Beznau nuclear power plant**
- **PWR** type, in operation since 1969

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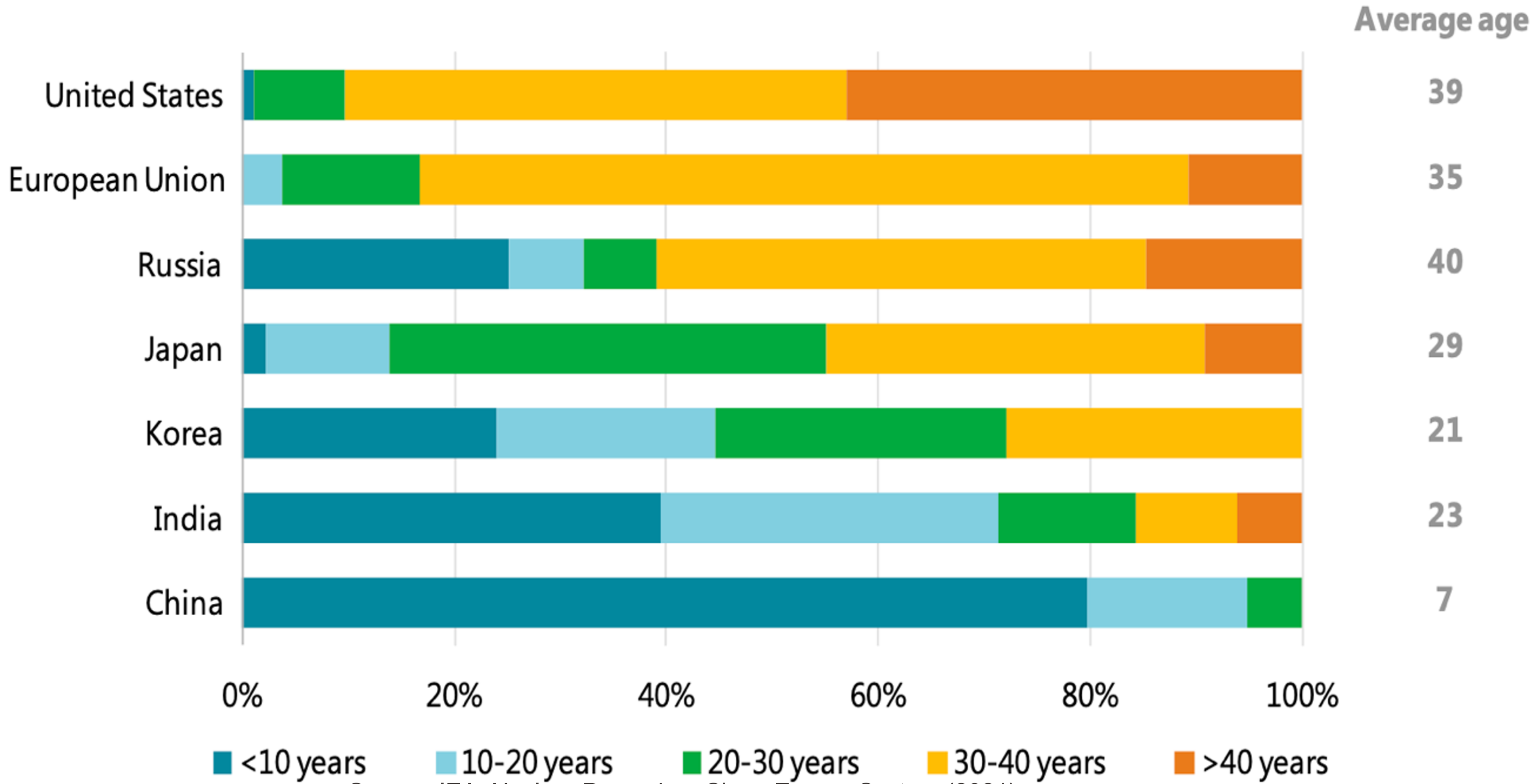
Introduction
– Age profile



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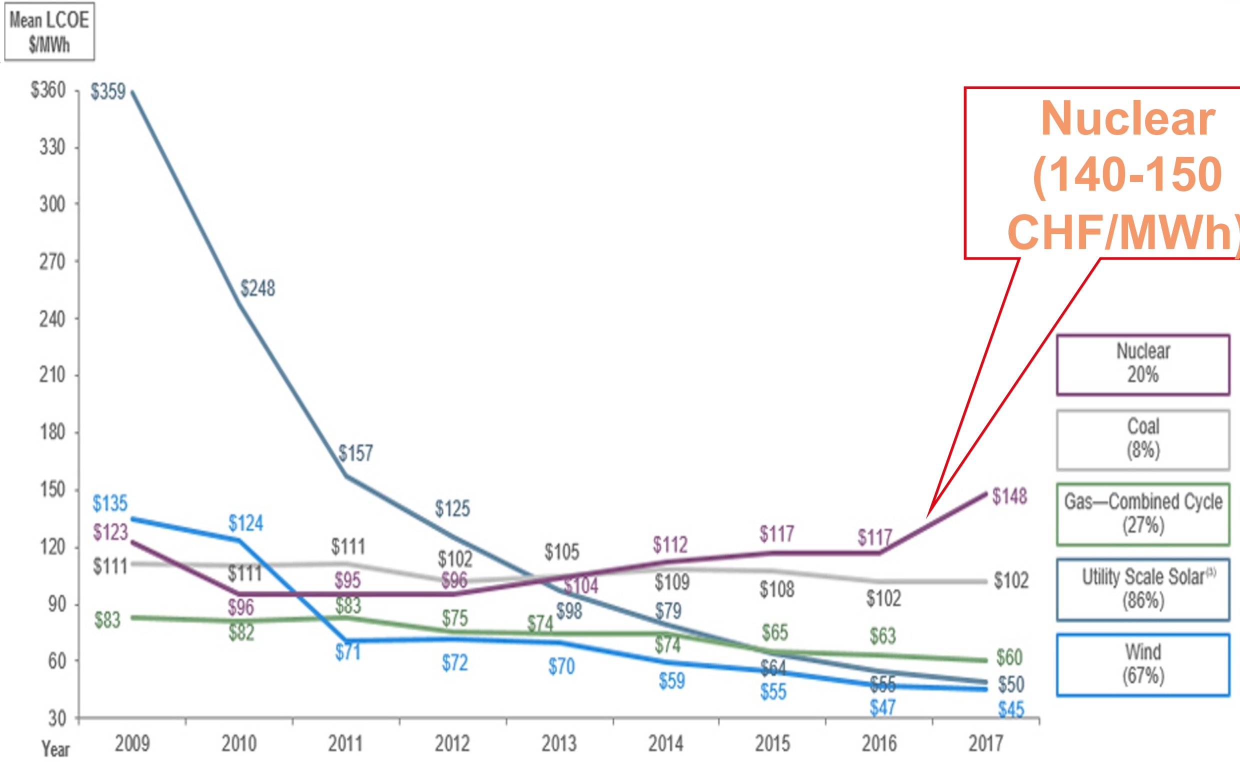
Introduction
– Levelized cost of electricity

LCOE (CHF/MWh)

350

150



Nuclear (140-150 CHF/MWh)

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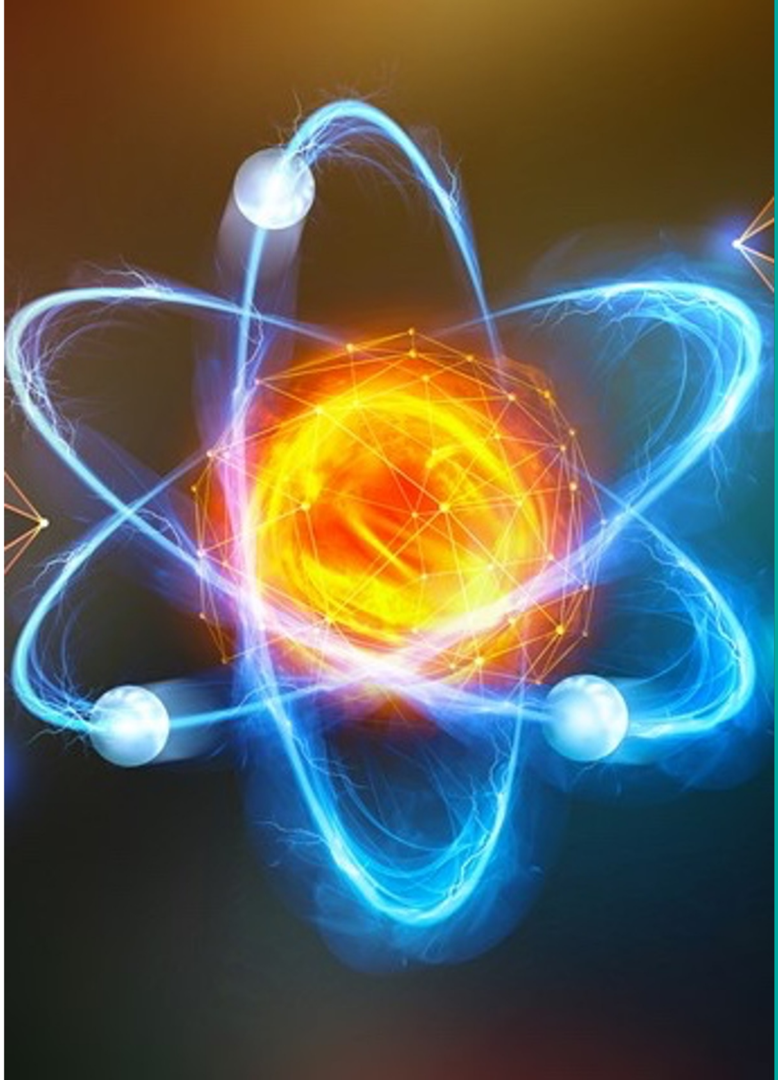

Conversion

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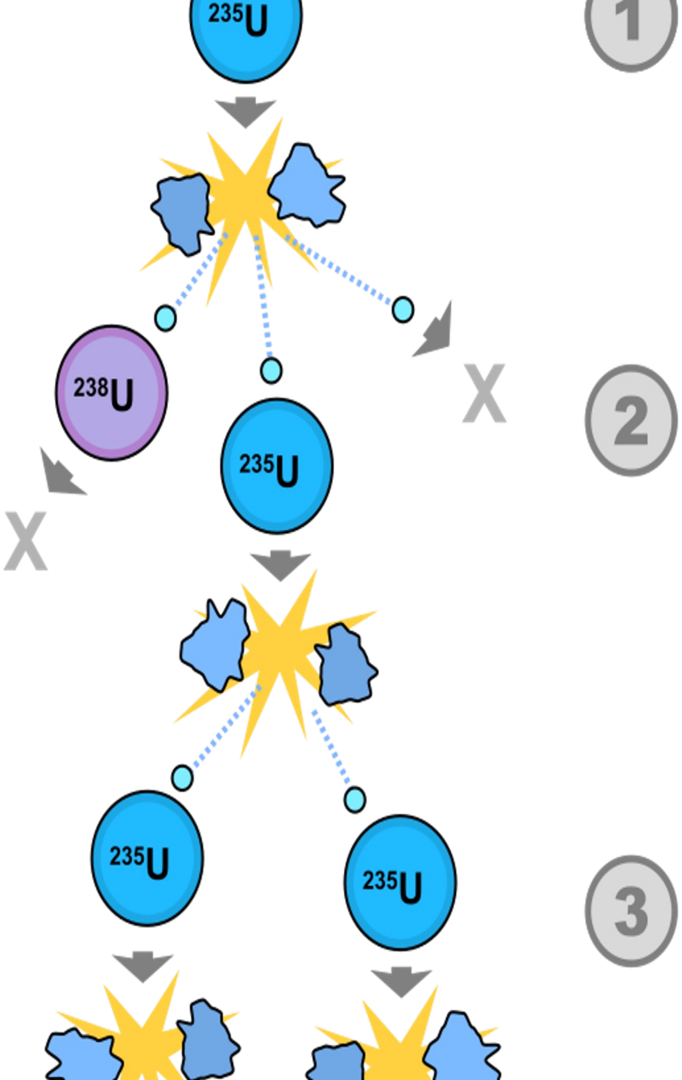

Nuclear physics :
how can we cause nuclear fission?

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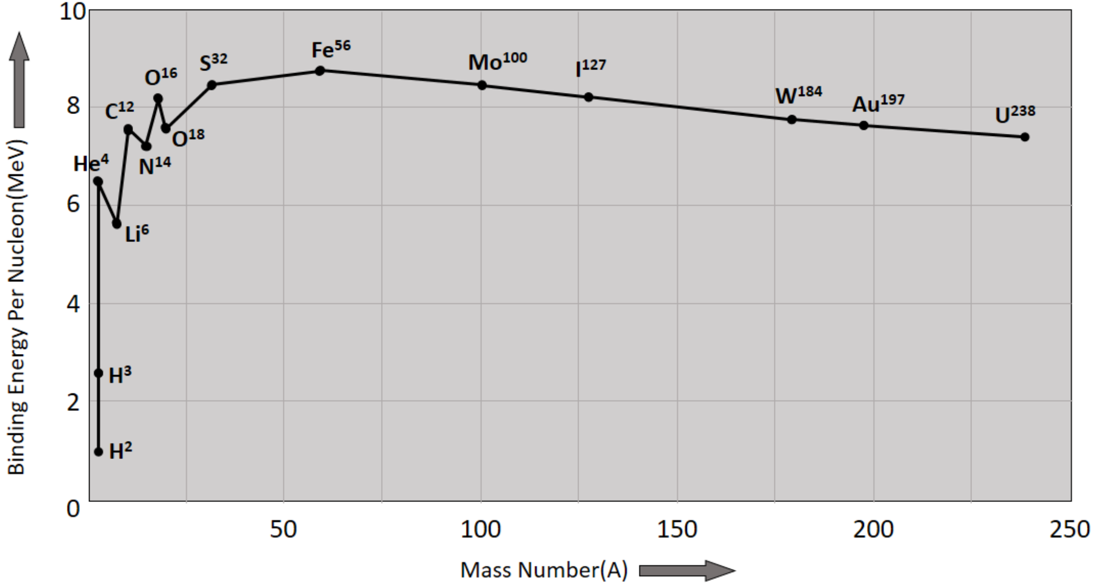
Nuclear physics
Nuclear material

- **Not all atoms** can undergo fission and release energy
- In theory: atoms with a mass number > 56 can release energy by fission (*fissionable*)
- In practice: only some have a high probability of undergoing fission when colliding with neutrons (*fissile*)



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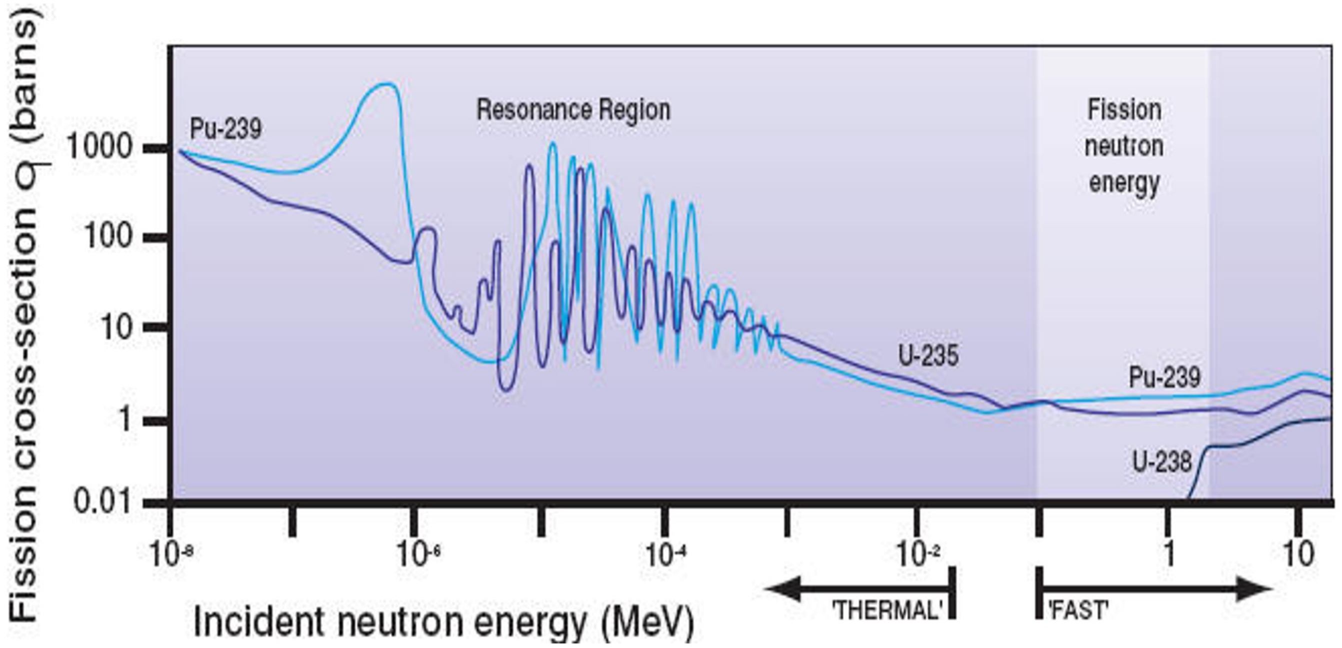
Nuclear physics
Nuclear material

- The probabiliy of undergoing fission = fission cross-section (in barns)
- It depends on the material and speed/energy of the neutron



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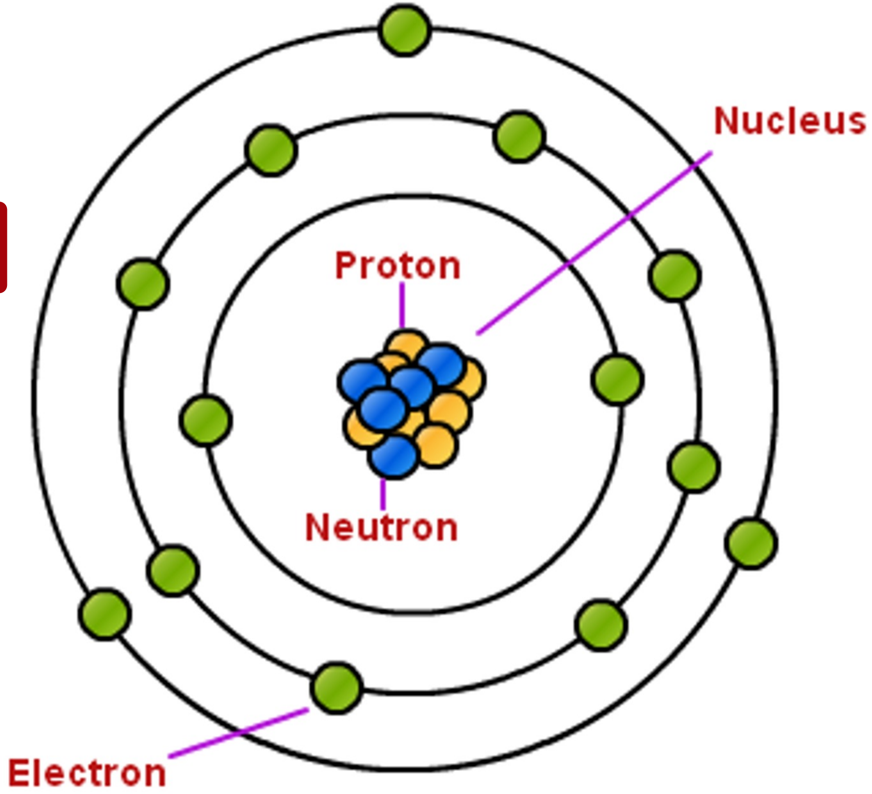
Nuclear physics
Standard Uranium

Uranium **238**: 99.3%

Uranium 235: 0.7%

Others: <0.1%



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Nuclear physics
Collision

- 1 neutron colliding 1 nucleus

$$ {}^{235}_{92}\mathbf{U} + {}^{1}_{0}\mathbf{n} \rightarrow $$

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Nuclear physics
1st possibility – Scattering

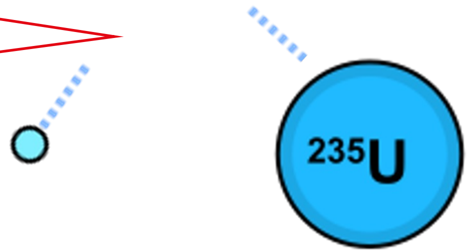
Loss of kinetic energy
= SCATTERING

$${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n}$$

- Loss of kinetic energy

  = **SCATTERING**

  $${}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n}$$



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Nuclear physics
2nd possibility – Absorption

- A new nucleus is **formed,**
  BUT nothing else happens

$$ {}^{235}_{92}\mathrm{U} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{236}_{92}\mathbf{U} $$

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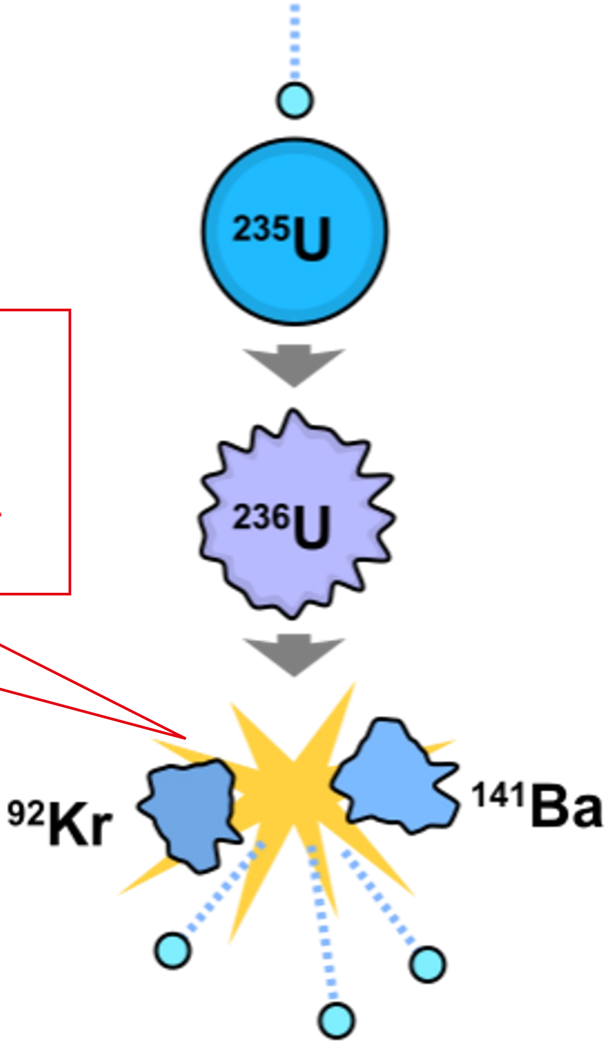
Nuclear physics

3rd possibility – Fission

The new nucleus breaks down

$$^{236}_{92}U \rightarrow {}^{92}Kr + {}^{141}Ba + 3\ {}^{1}_{0}n$$



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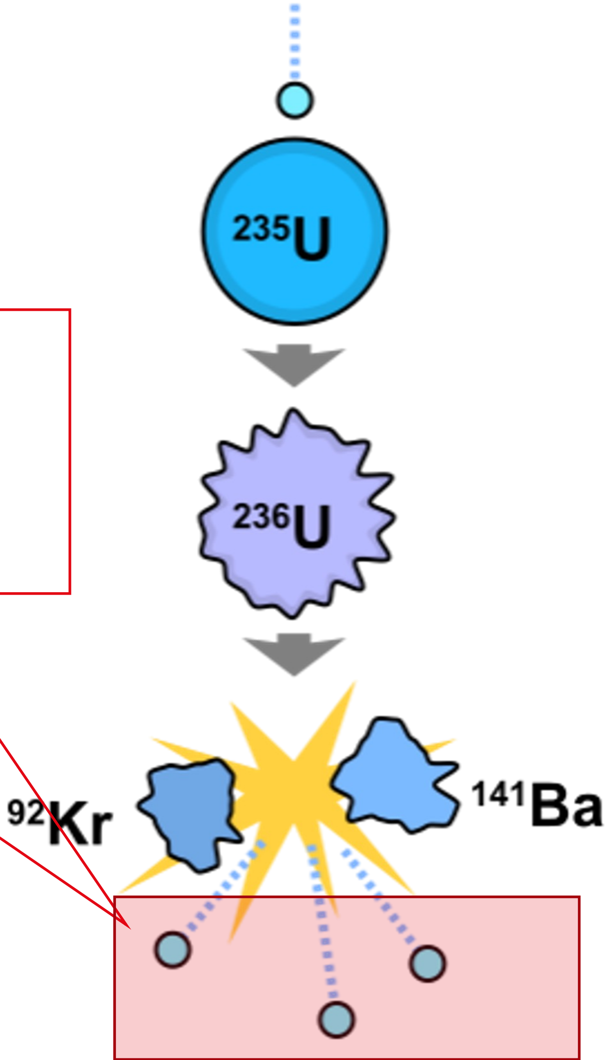
Nuclear physics

3rd possibility – Fission

More neutrons are generated!

$$ {}^{236}_{92}\mathrm{U} \rightarrow {}^{92}\mathrm{Kr} + {}^{141}\mathrm{Ba} + 3\ {}^{1}_{0}\mathrm{n} $$



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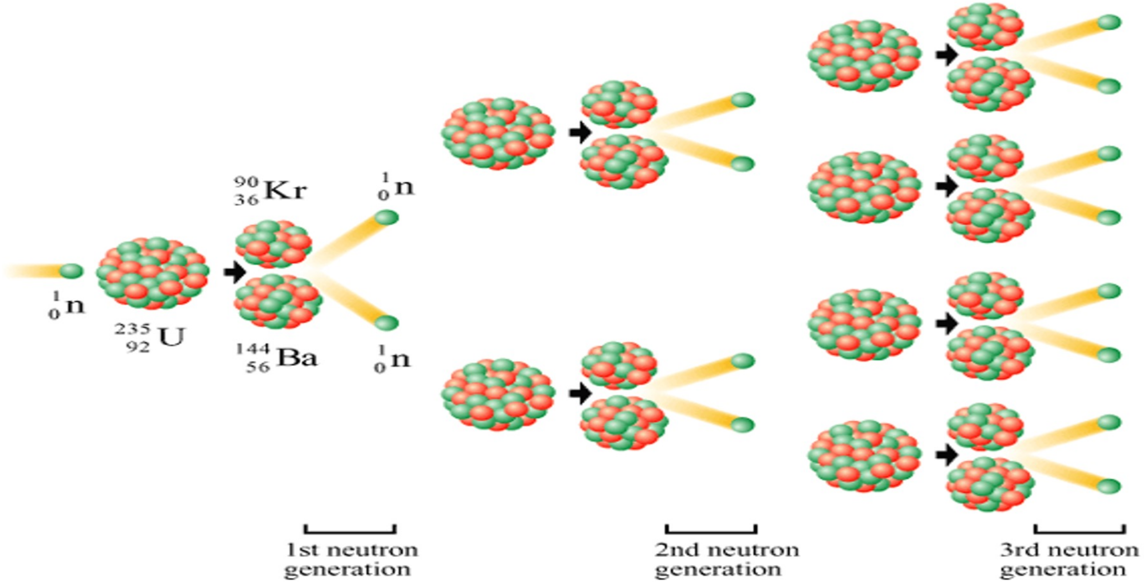
Nuclear physics

Chain reaction

- ↓ fissions = subcritical
- ↑ fissions = supercritical

Normal operations = critical conditions (enough neutrons to keep fissions ongoing, but not too many to be out of control).



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Nuclear conversion

A question of balance

- Normal operations = critical conditions (enough neutrons to keep fissions ongoing, but not too many to be out of control)
- Reactivity = 0

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Nuclear reactivity

which parameters impact the probability of a fission reaction?

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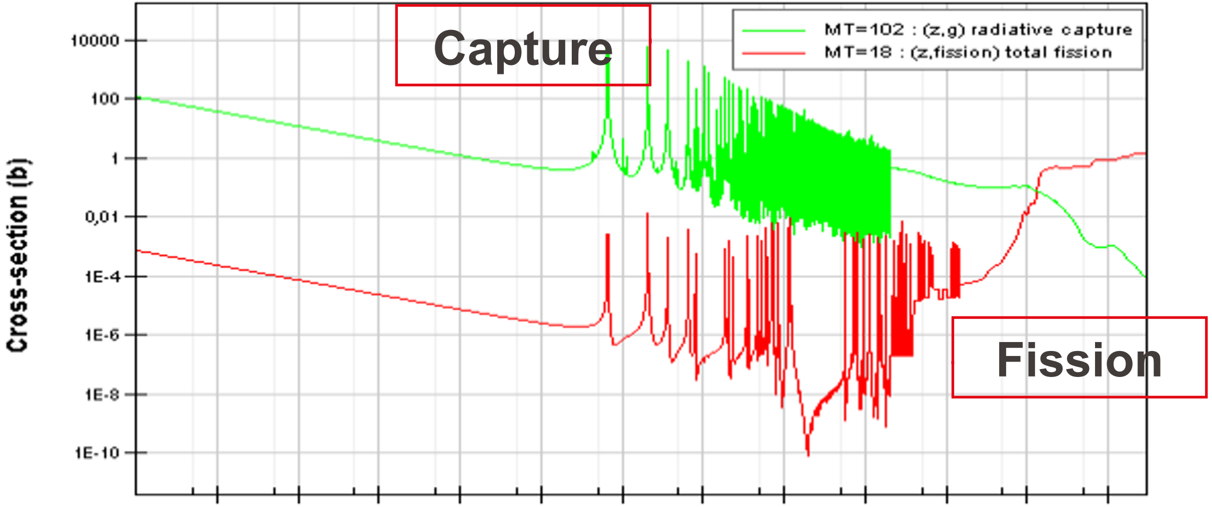
Nuclear reactivity

The concept of cross-sections

- A cross-section ⇔ **Probability** that a nuclear reaction will occur
- Case of ^{238}U



Speed/Kinetic energy of the neutron (MeV)

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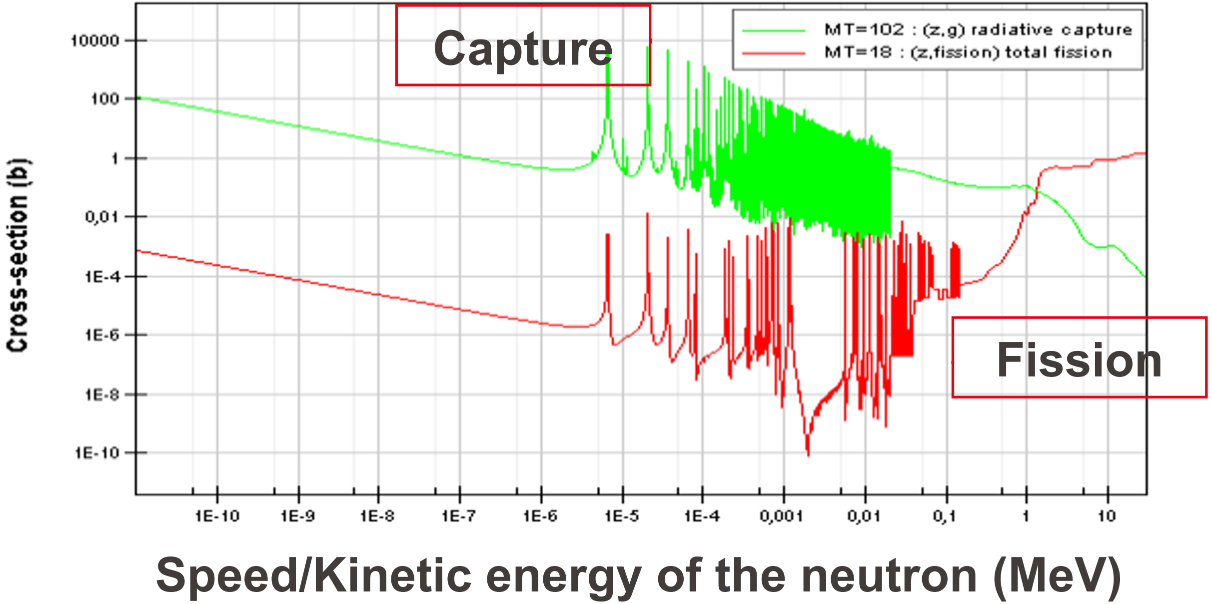
Q: Which of these statements is/are correct?

A. The probability of fission of U-238 is higher at higher speeds
B. Uranium-238 has a higher chance of undergoing fission than of capturing a neutron



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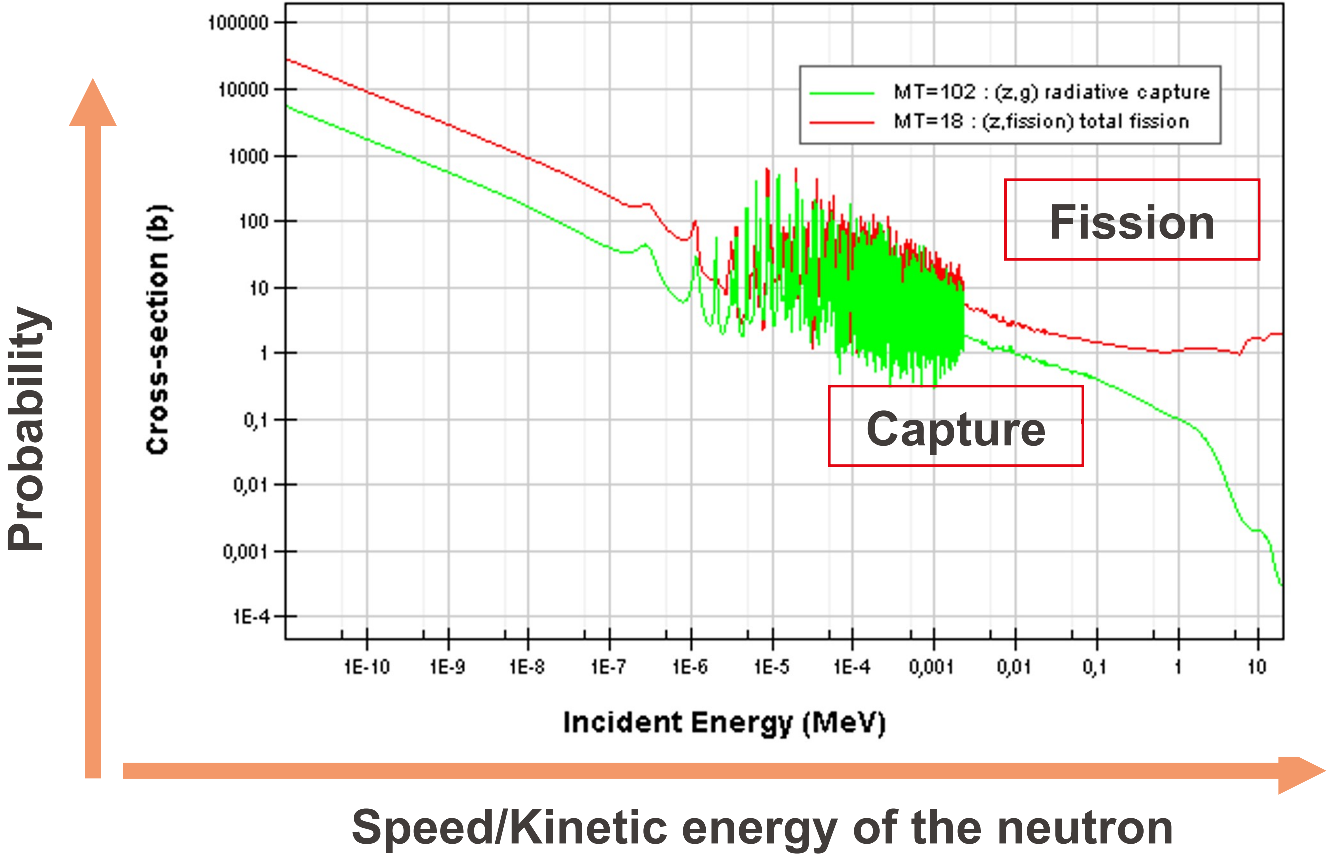
Nuclear reactivity
Case of ^{235}U



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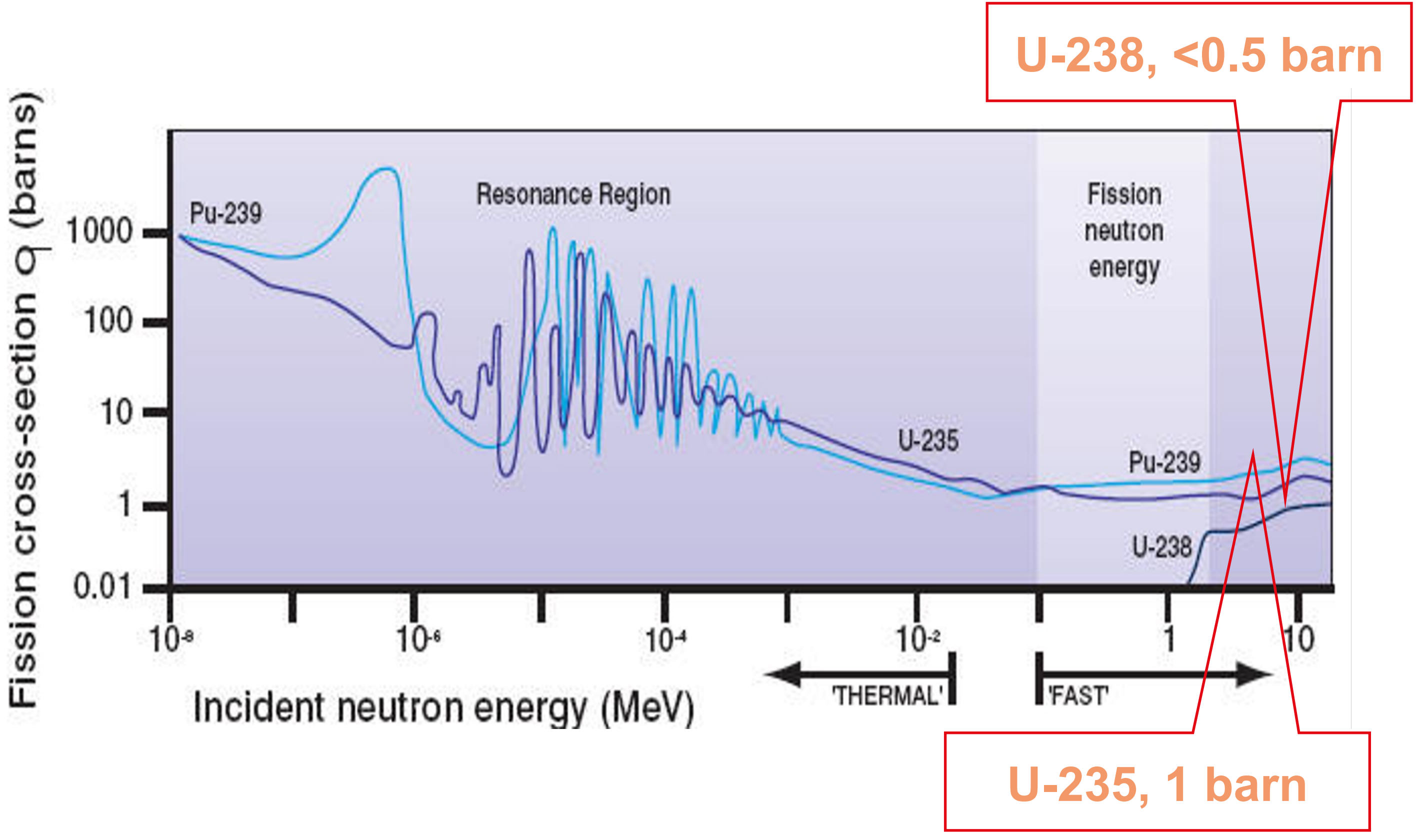
Nuclear reactivity
Fission cross-section



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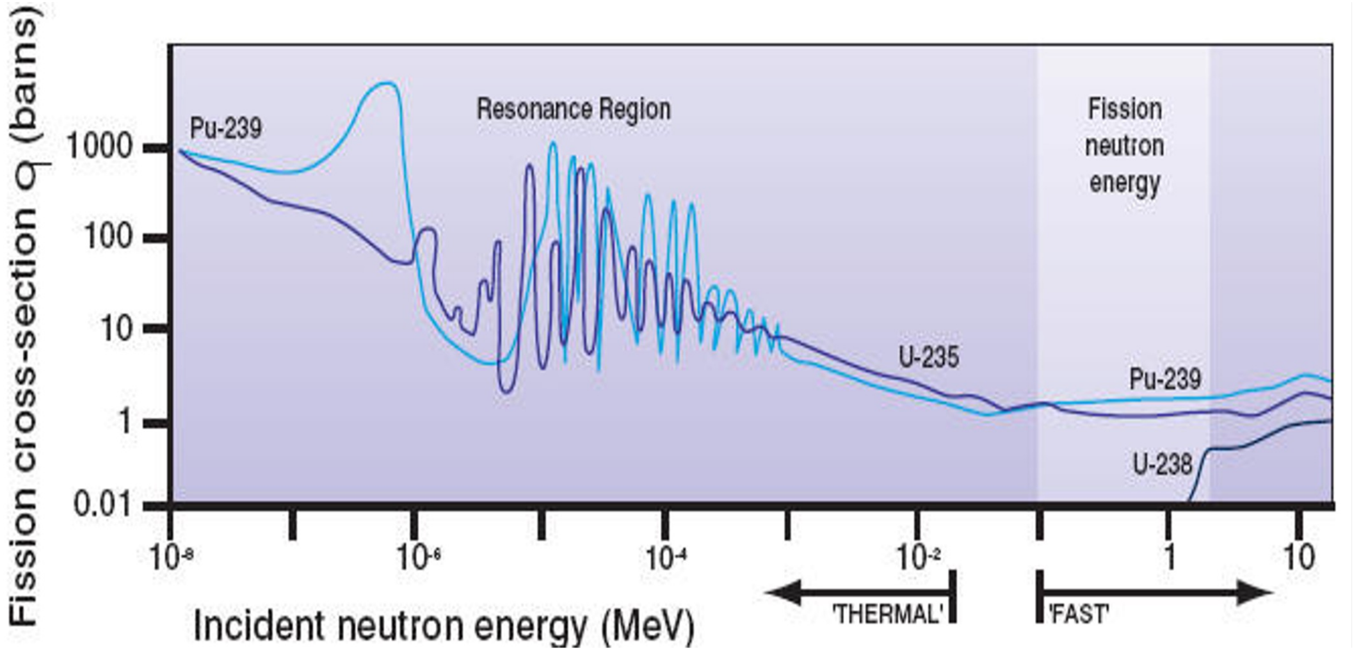
Q: Which of these statements is/are correct?

- There is a higher chance to have fission of U-235 than of U-238.
- Fission of U-235 occurs best at low neutron speeds
- Fission of Pu-239 occurs best at high neutron speeds



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Enrichment, moderation and absorption

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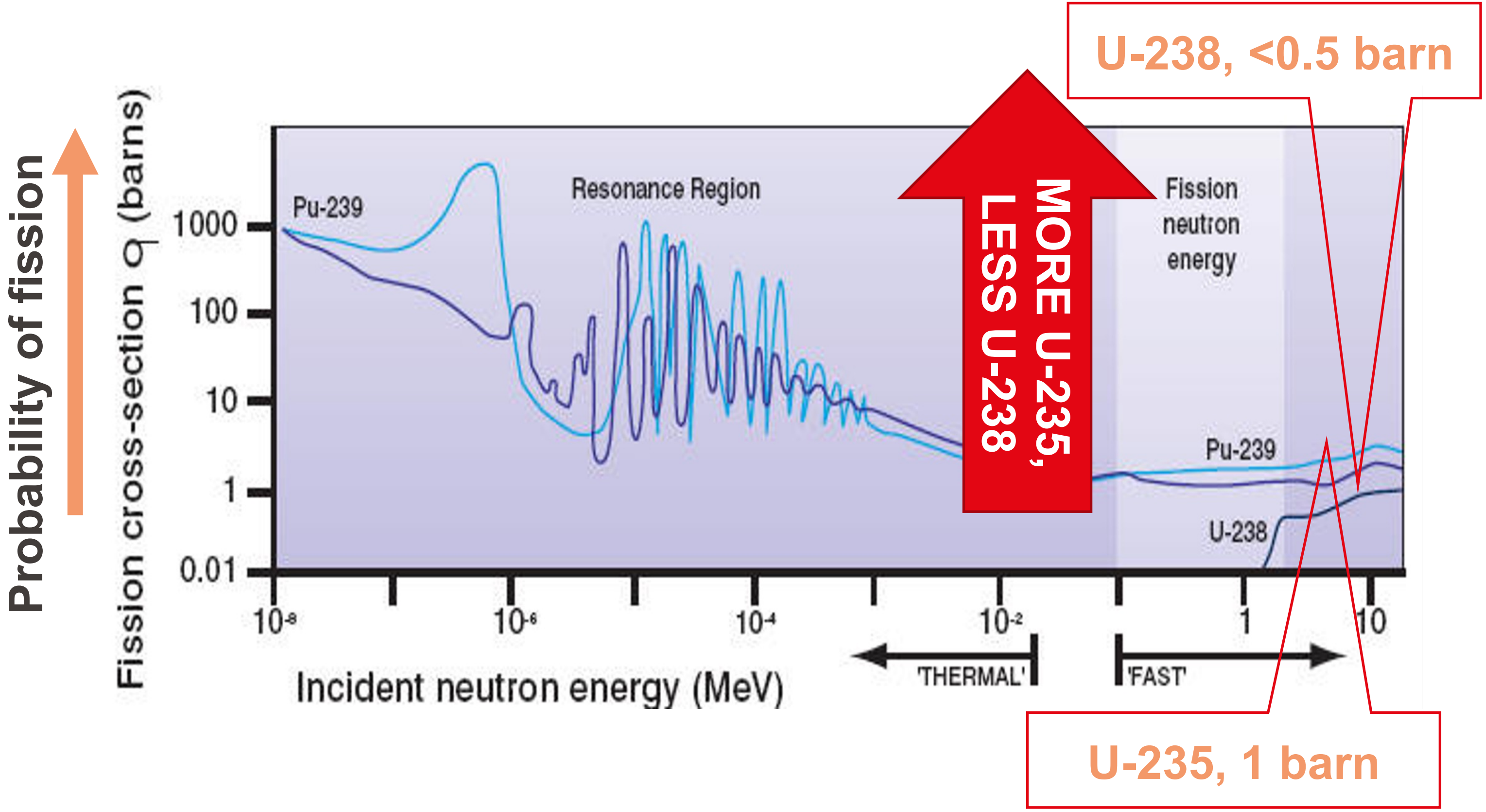
Nuclear reactivity

Enrichment (↑)



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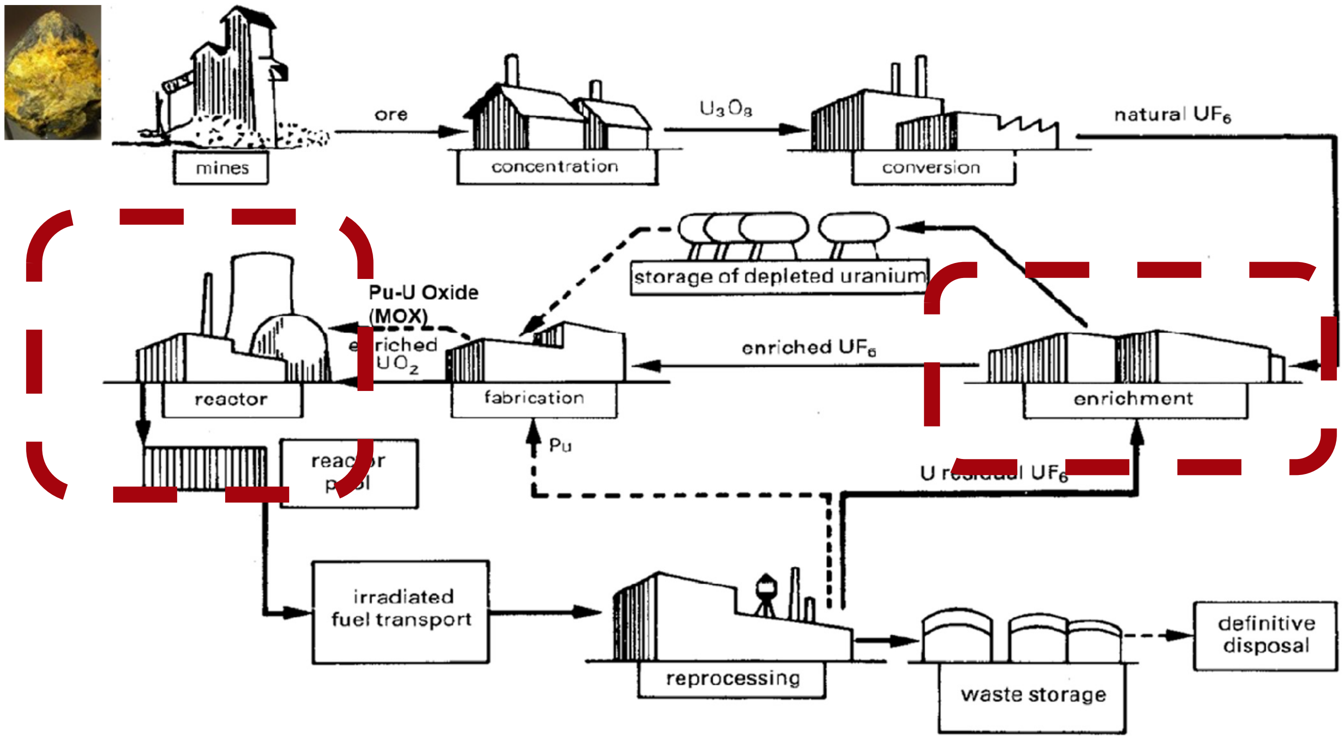
Nuclear reactivity
Enrichment (↑)



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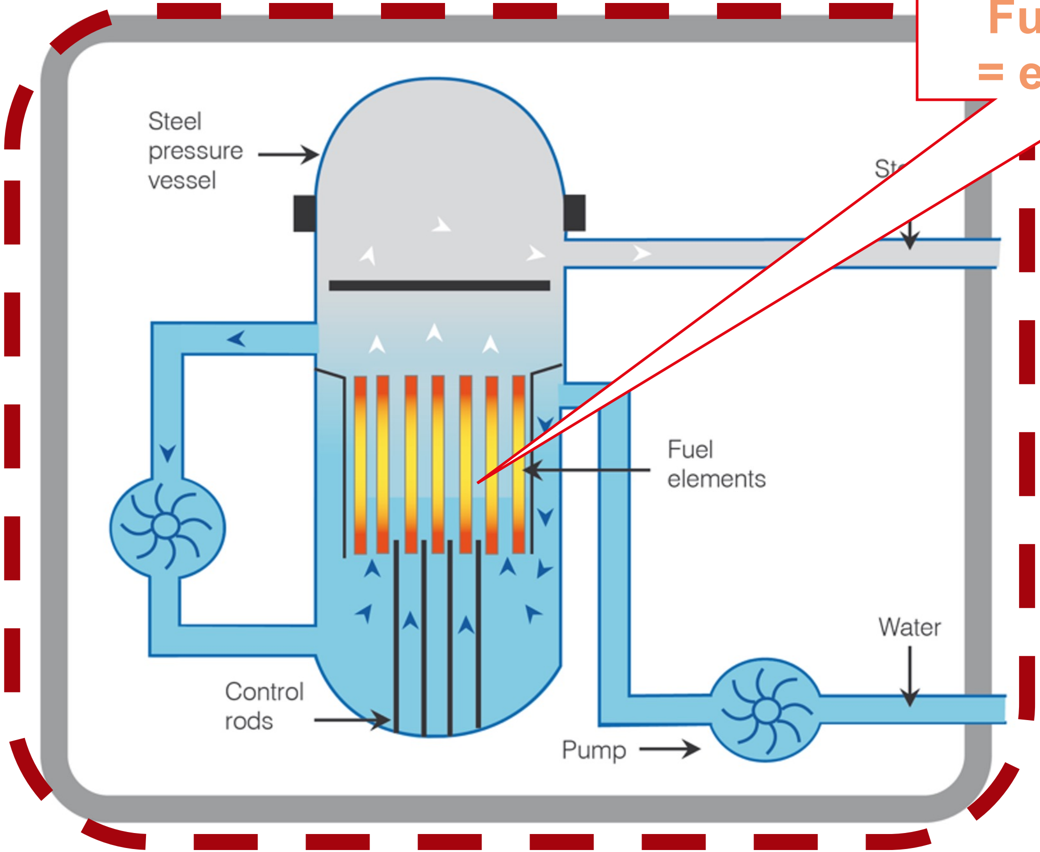
Nuclear reactivity

Enrichment (↑)



Fuel elements
= enriched fuel

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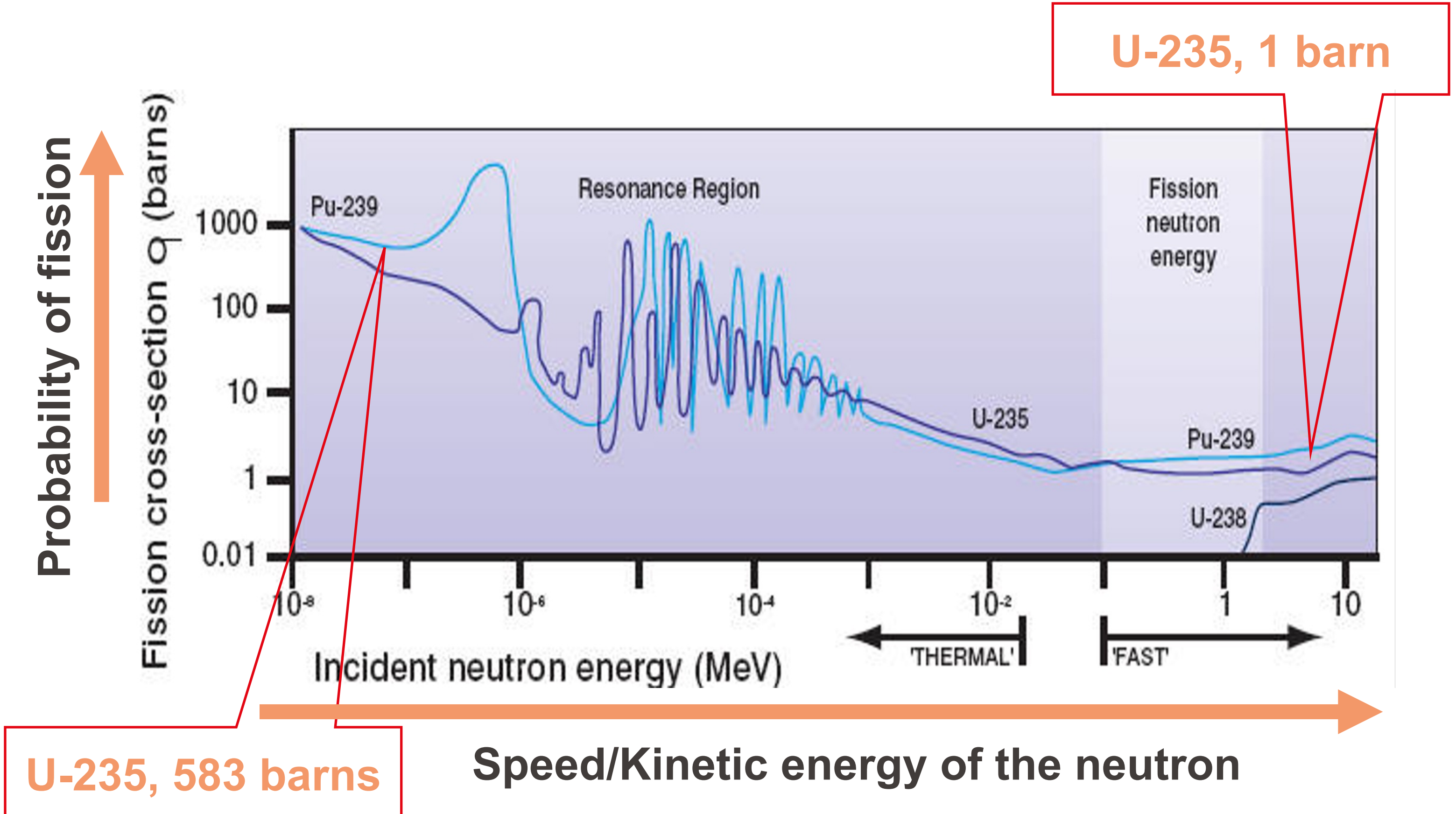
Nuclear reactivity

Moderation (↑)



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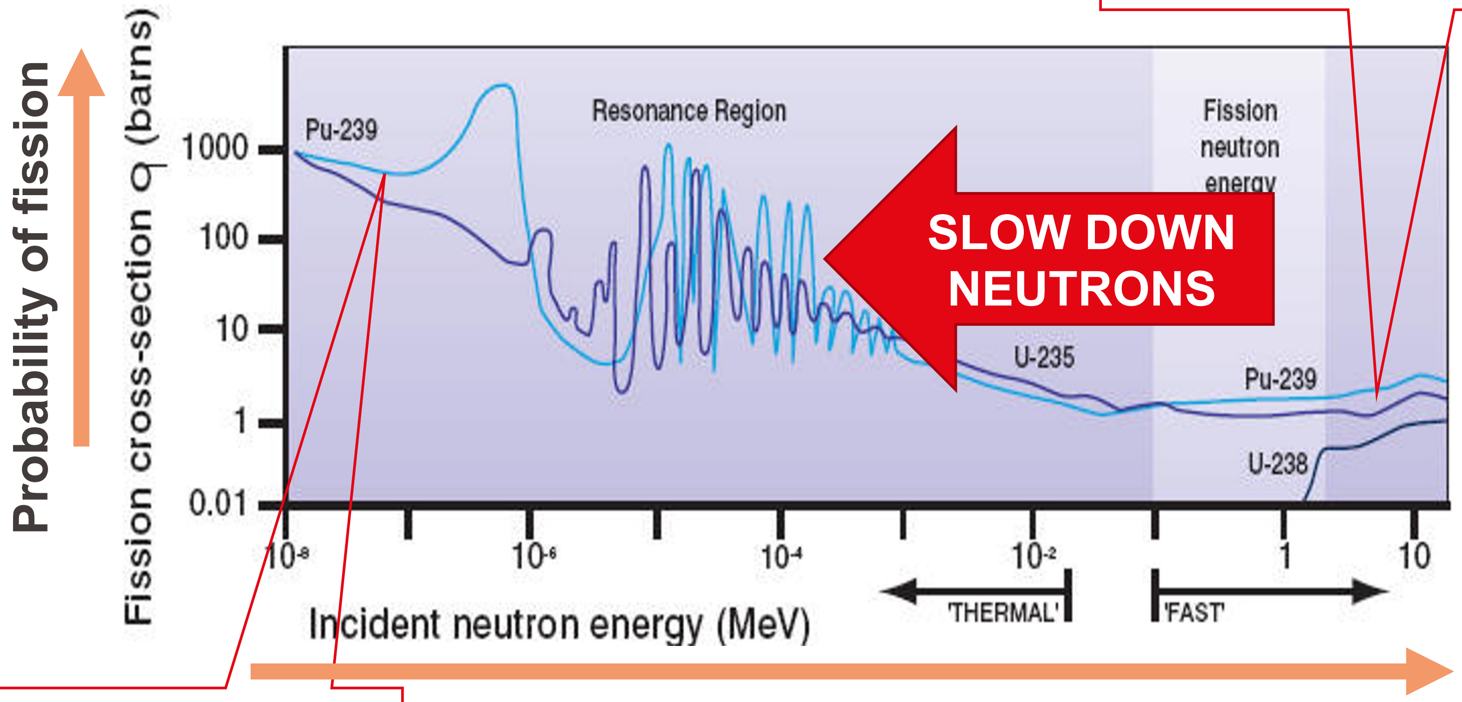
Nuclear reactivity

Moderation (↑)

U-235, 1 barn



U-235, 583 barns

Speed/Kinetic energy of the neutron

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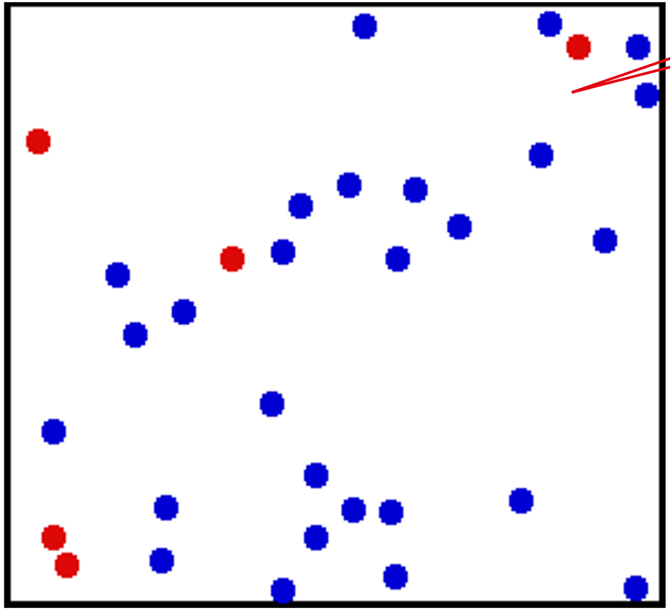
Nuclear reactivity

Moderation (↑)



Red = neutron
Blue = moderator

- Liquid water (H_2O)
- Heavy water (D_2O)
- Graphite (solid C)

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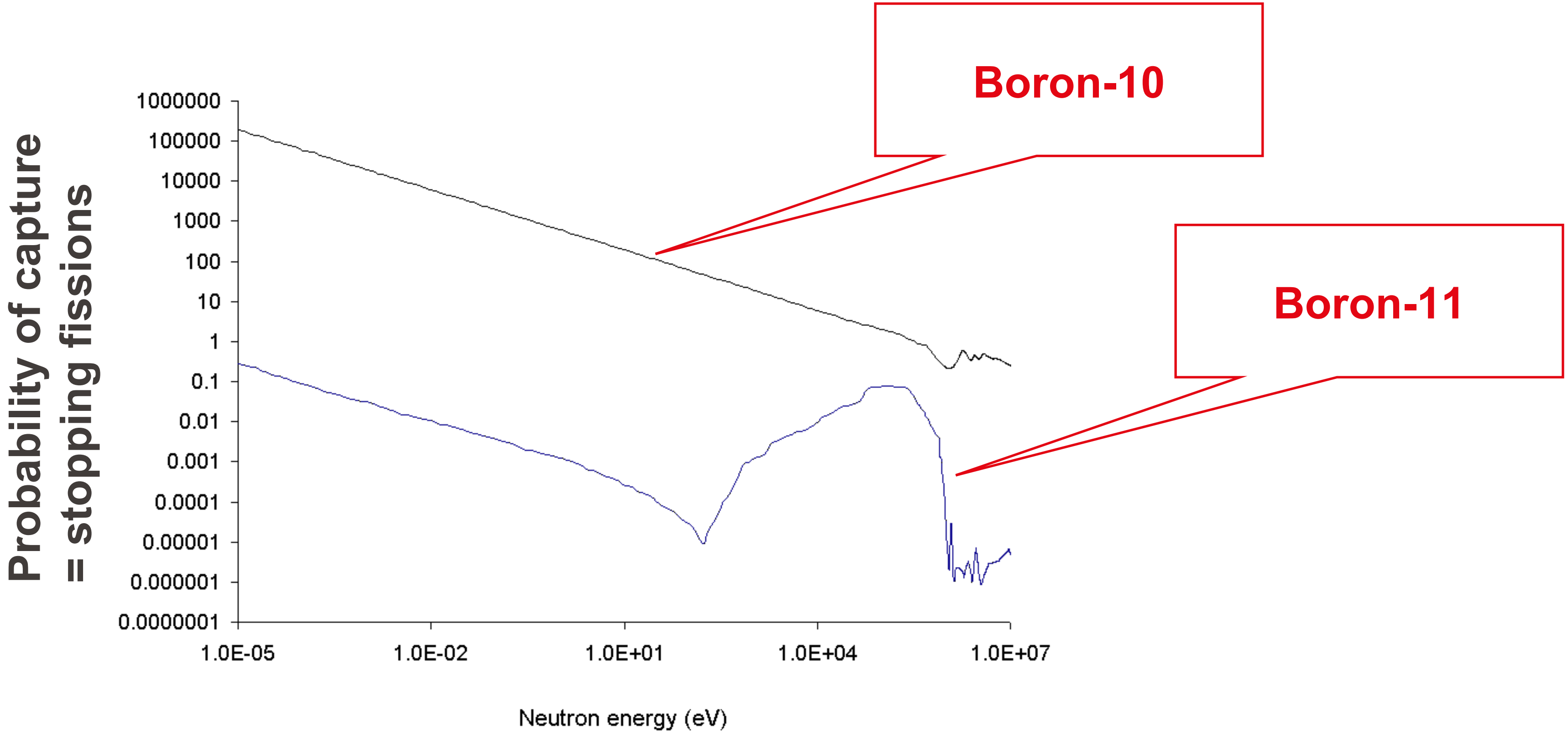
Nuclear reactivity

Absorption in control rods



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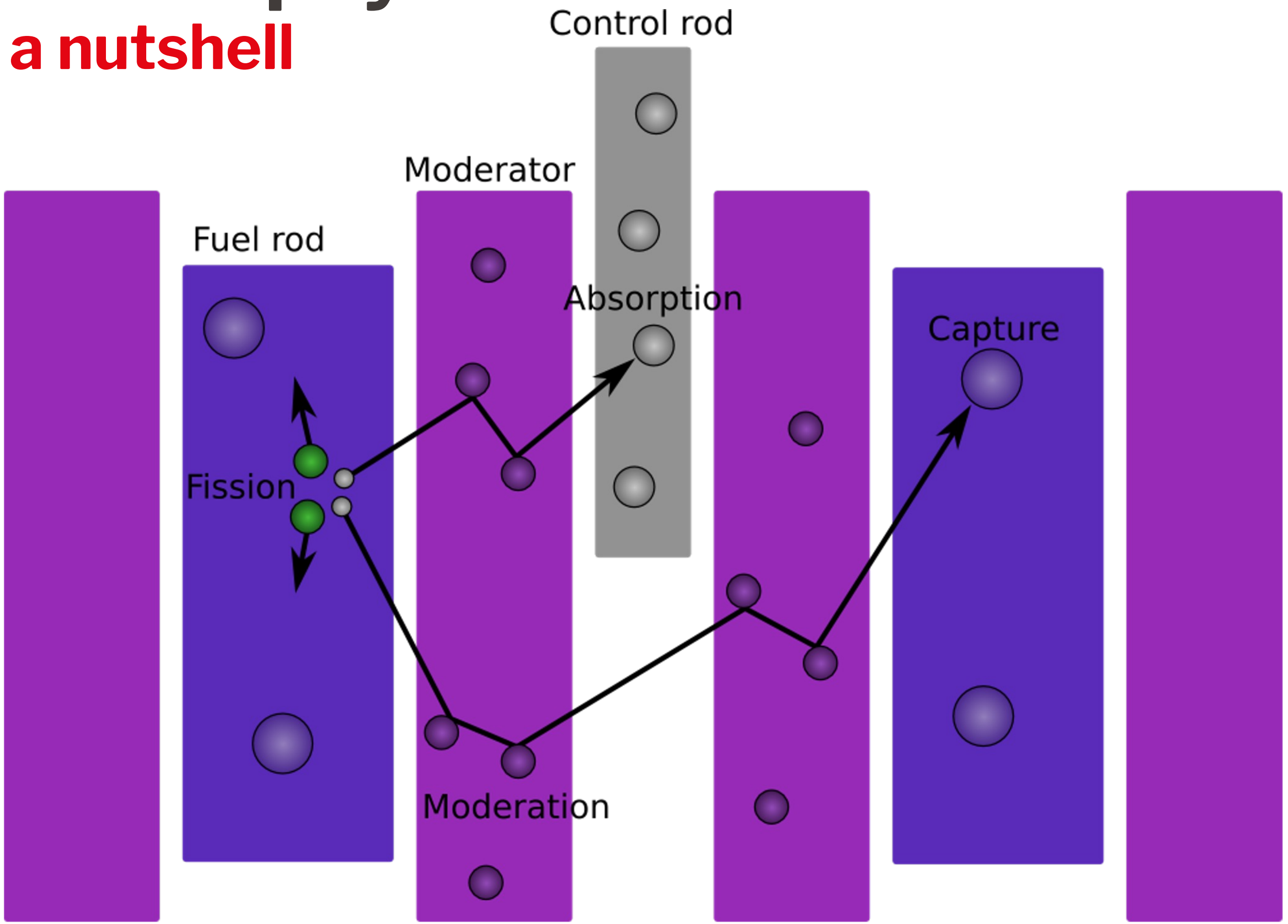
Nuclear physics
In a nutshell



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Nuclear conversion

a question of balance

Reactivity ↑
Heat supply ↑
Power ↑

Reactivity ↓
Heat ↓
Power ↓

- Moderation (water, graphite, etc.)

- Absorption (control rods)
- Poisoning

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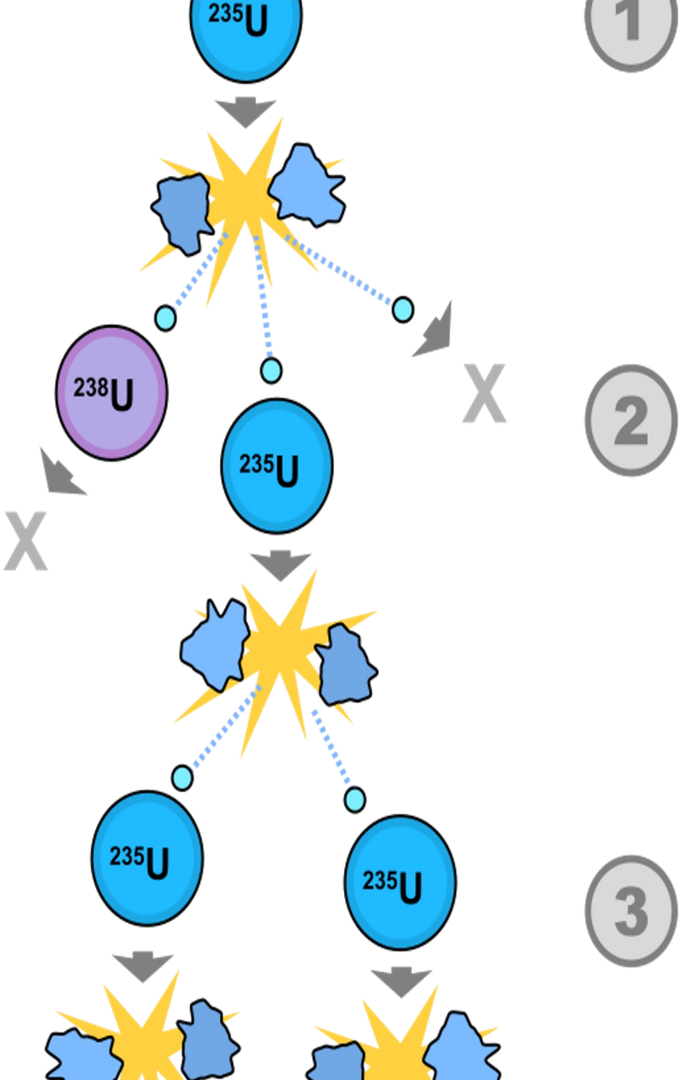

Nuclear power plants

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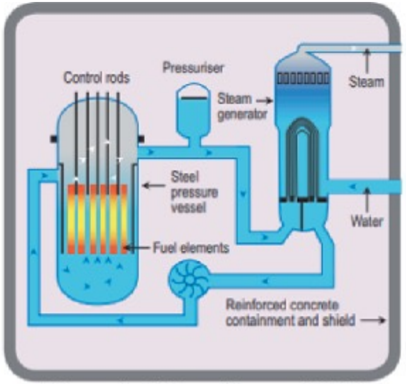
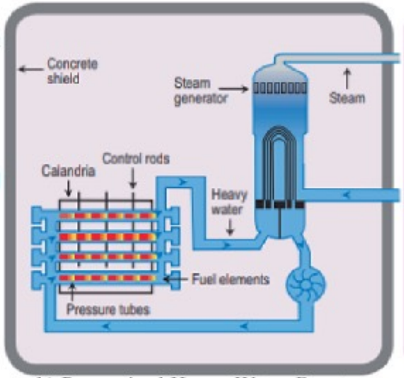
Nuclear power plants

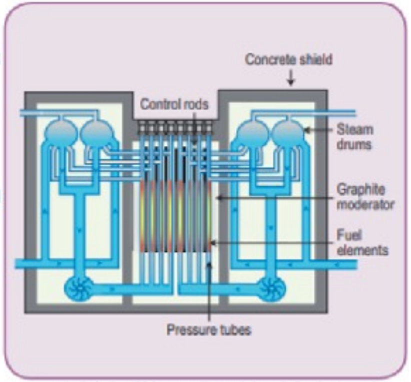
Quick overview



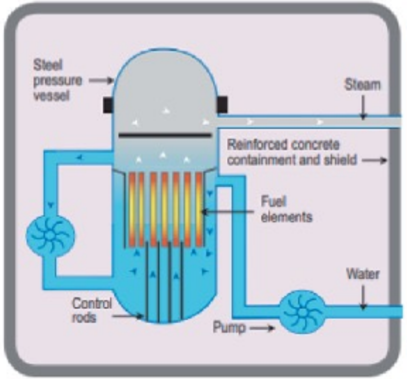
a) Pressurised Water Reactor (PWR)



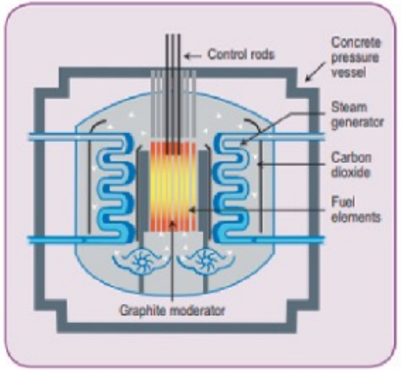
b) Pressurised Heavy Water Reactor (PHWR/Candu)



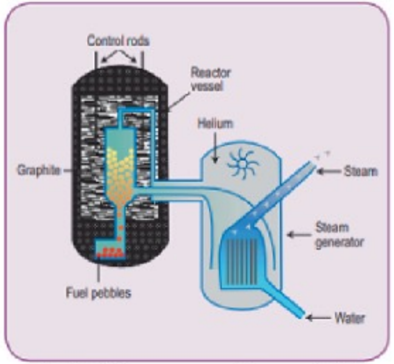
c) Light Water Graphite Moderated Reactor (LWGR/RBMK)



d) Boiling Water Reactor (BWR)



e) Advanced Gas-cooled Reactor (AGR)



f) High Temperature Reactor (HTR)

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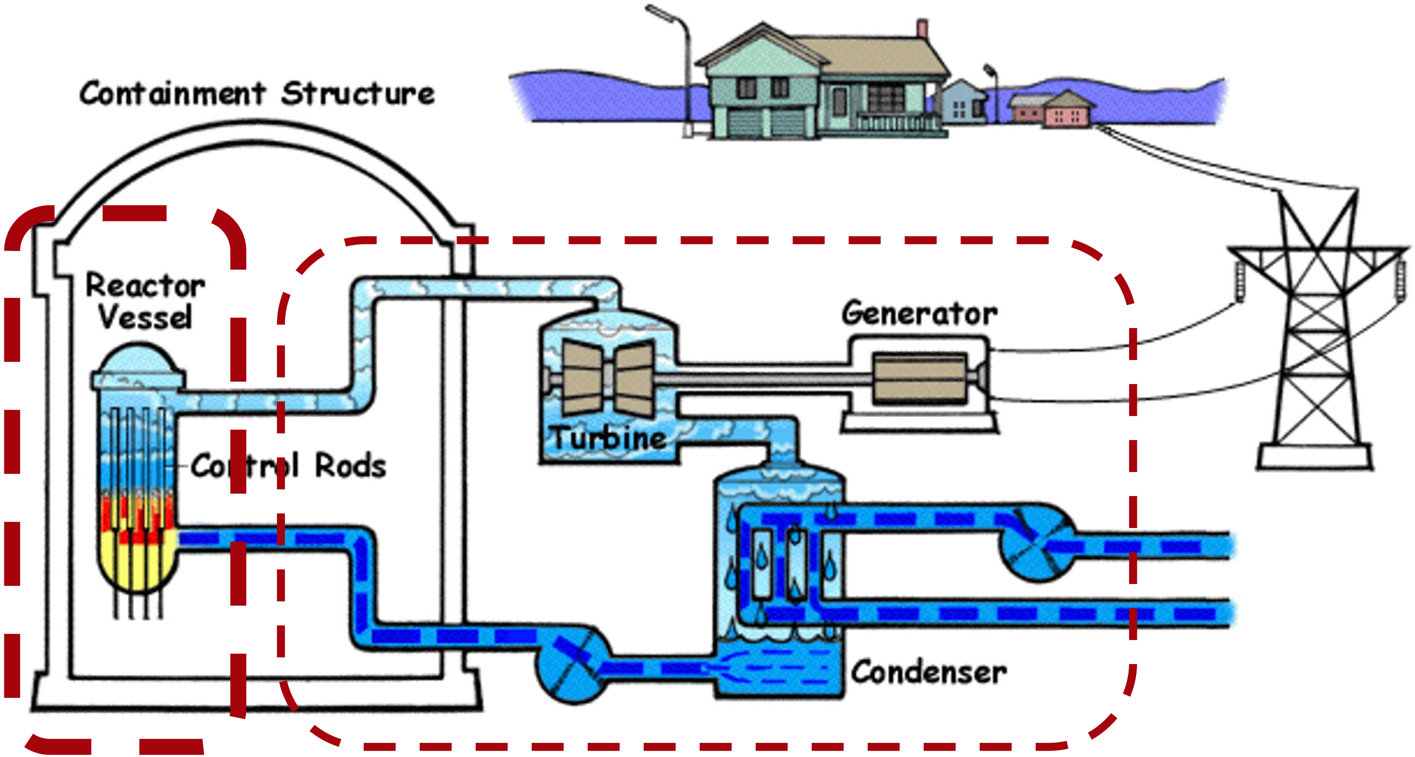
Nuclear power plants

BWR = Boiling water reactor (20% of reactors)



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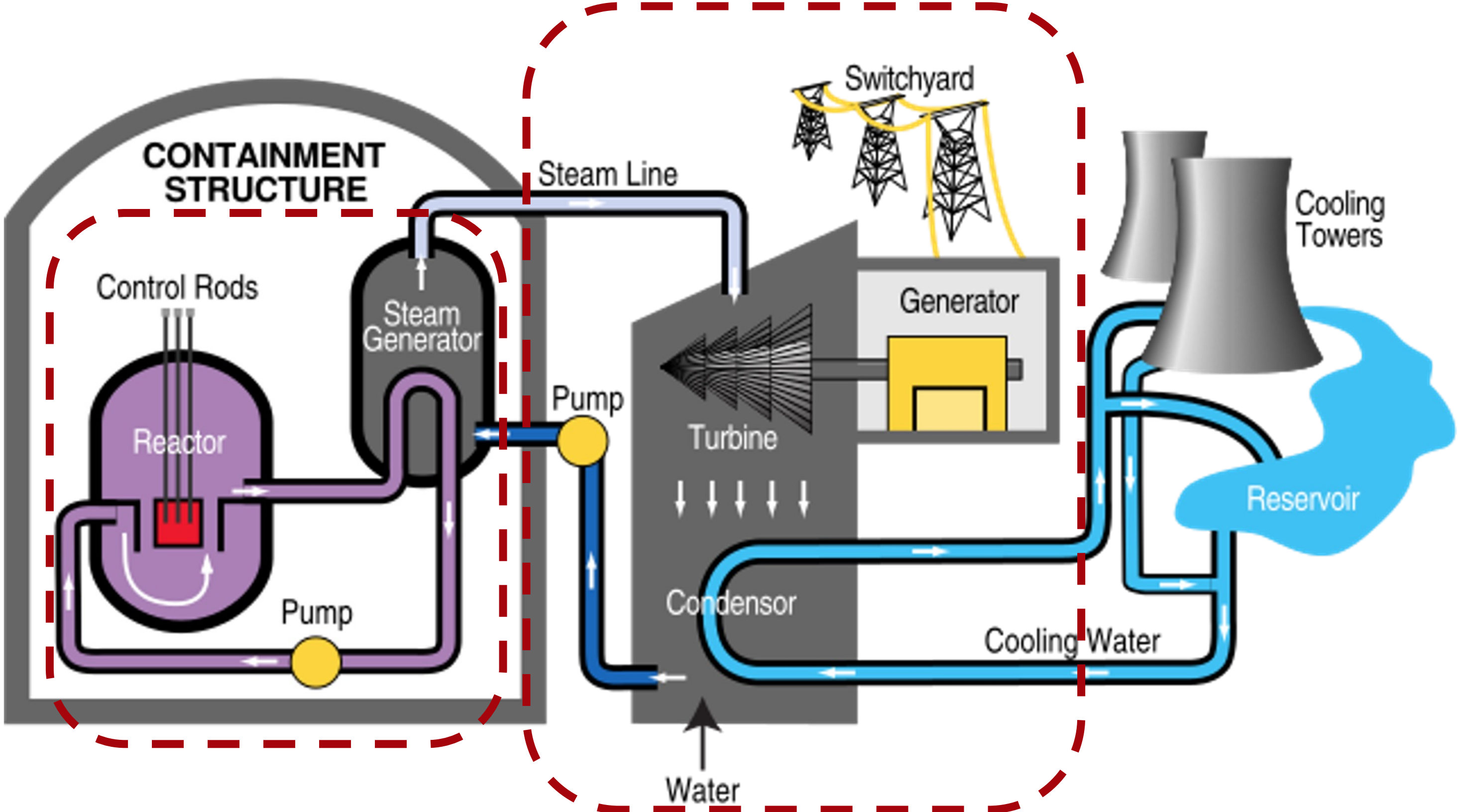
Nuclear power plants

PWR = Pressurized water reactor (70%)



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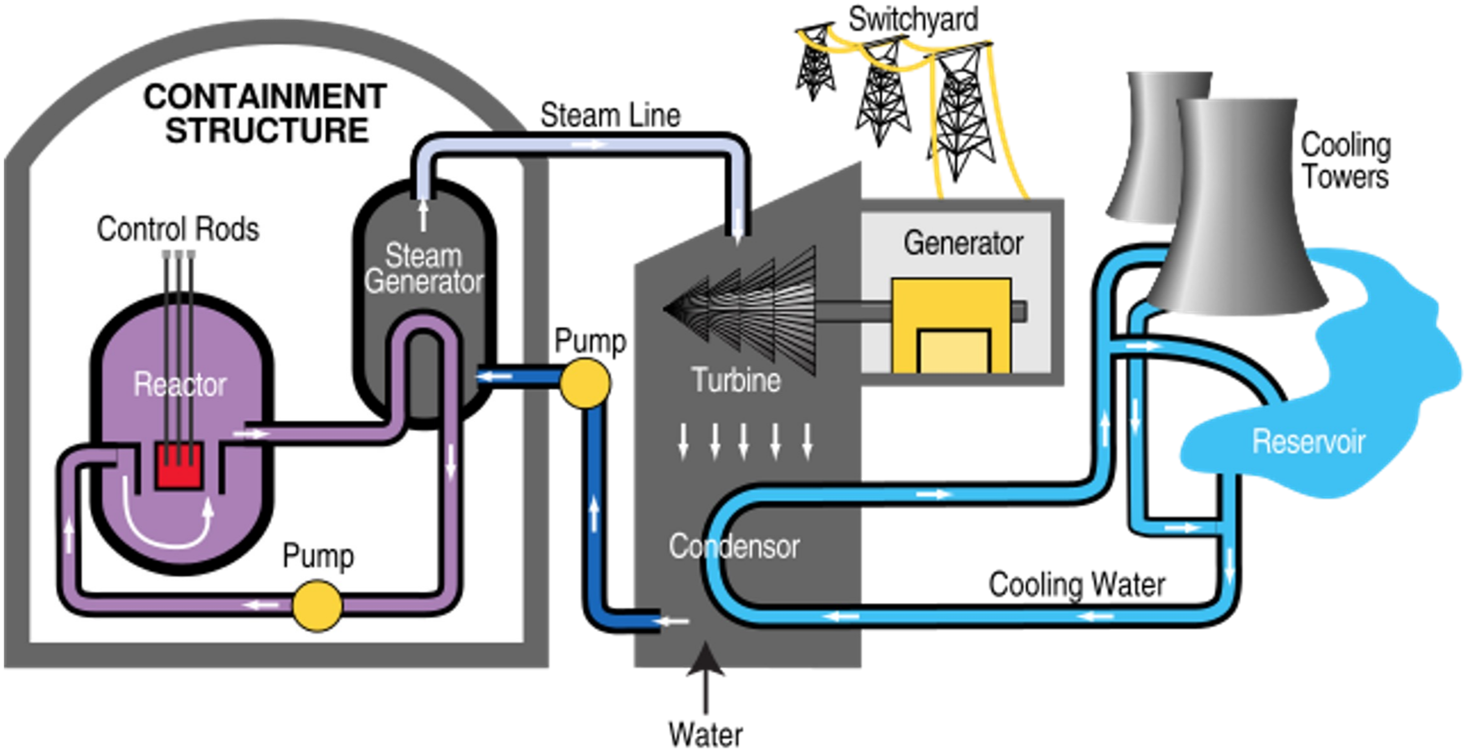
Q: Where are the coolant, moderator and working fluid for power generation in this system ?



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Nuclear conversion
Metrics

- Reaction rate - $\frac{\text{energy demand}}{\text{energy per fission}}$

How many fissions per s are needed in our reactor?

- Fuel burnup - $\frac{\text{energy output}}{\text{quantity of primary fuel}}$

How much fuel is required?

- **Example :** The fuel burnup of the Beznau plant (1130 MW) is 30'000 MW(th)-day per tonne of fuel. How much fuel is needed per year ?

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Take-home message

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Take-home message

- **Nuclear** energy low-CO_2, non-renewable and reliable source of electric power
- High investment and production costs
- **The principle: nuclear fission**
- **Reactivity of 0:**
  - **moderation**
  - **enrichment**
  - **absorption**
- **The power plants:** a simple **Rankine cycle with different reactor set-ups**

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