EPFL

Nuclear

Tuong-Van Nguyen
PLANAIR

Lausanne, 26/10/2025

École
polytechnique
fédérale
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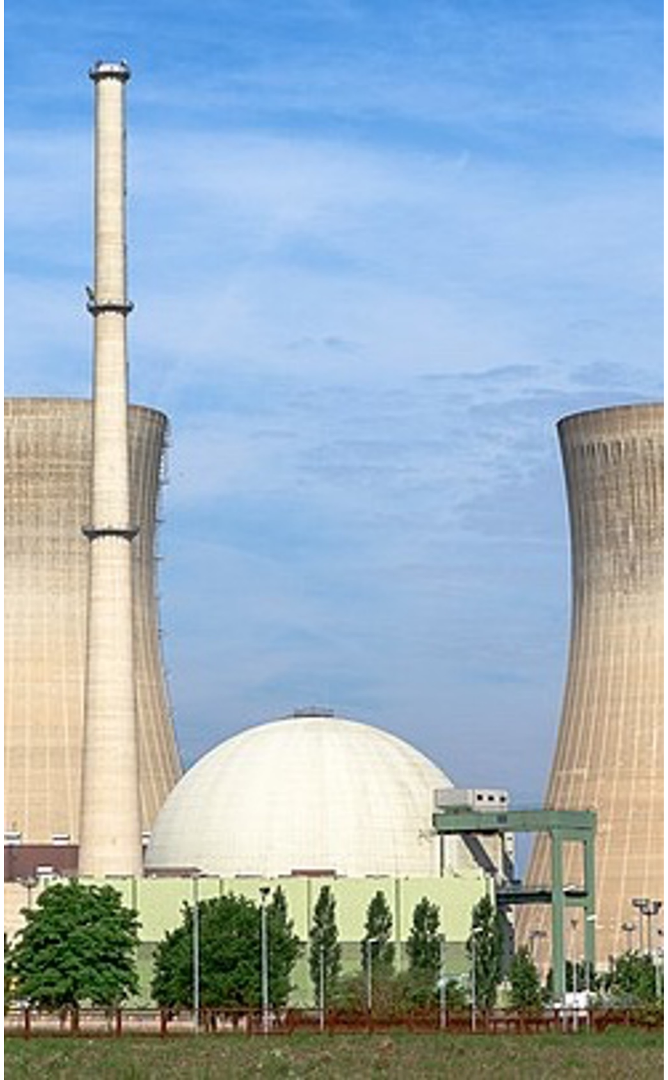
Goals

- **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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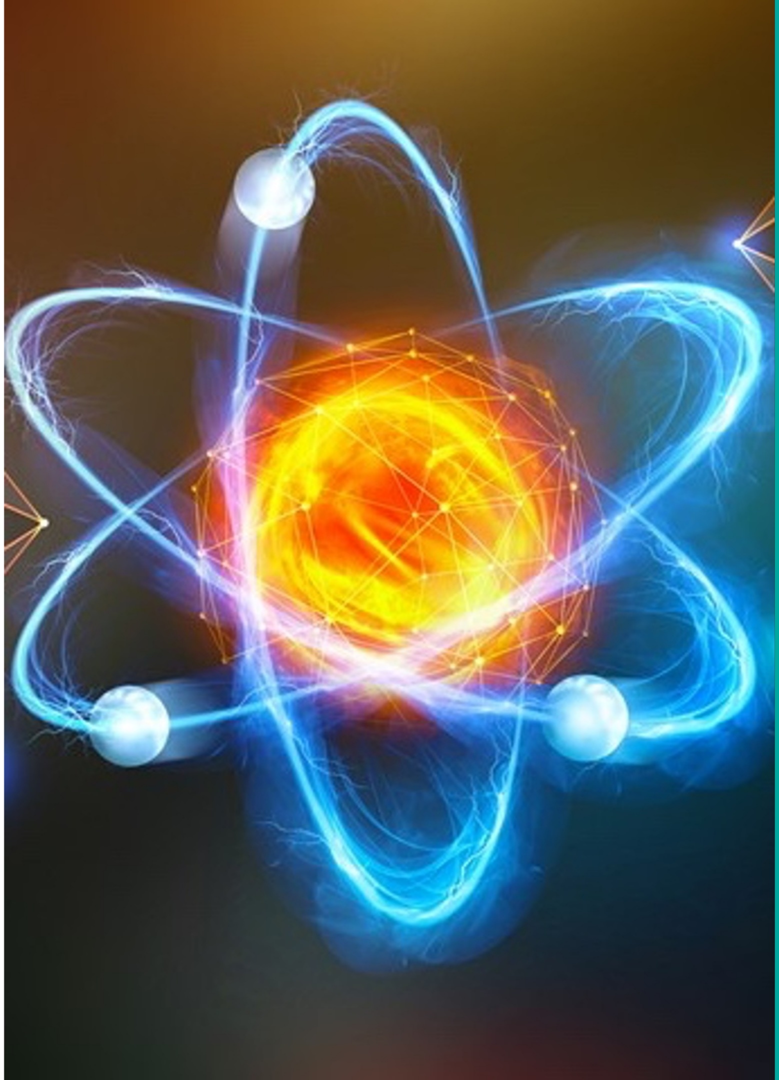

Introduction

The story behind Nuclear

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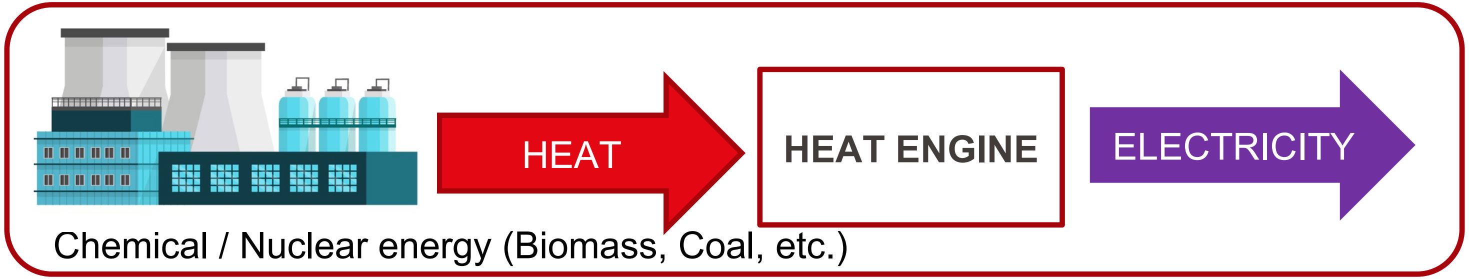
Introduction

– How do we produce electricity today?



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

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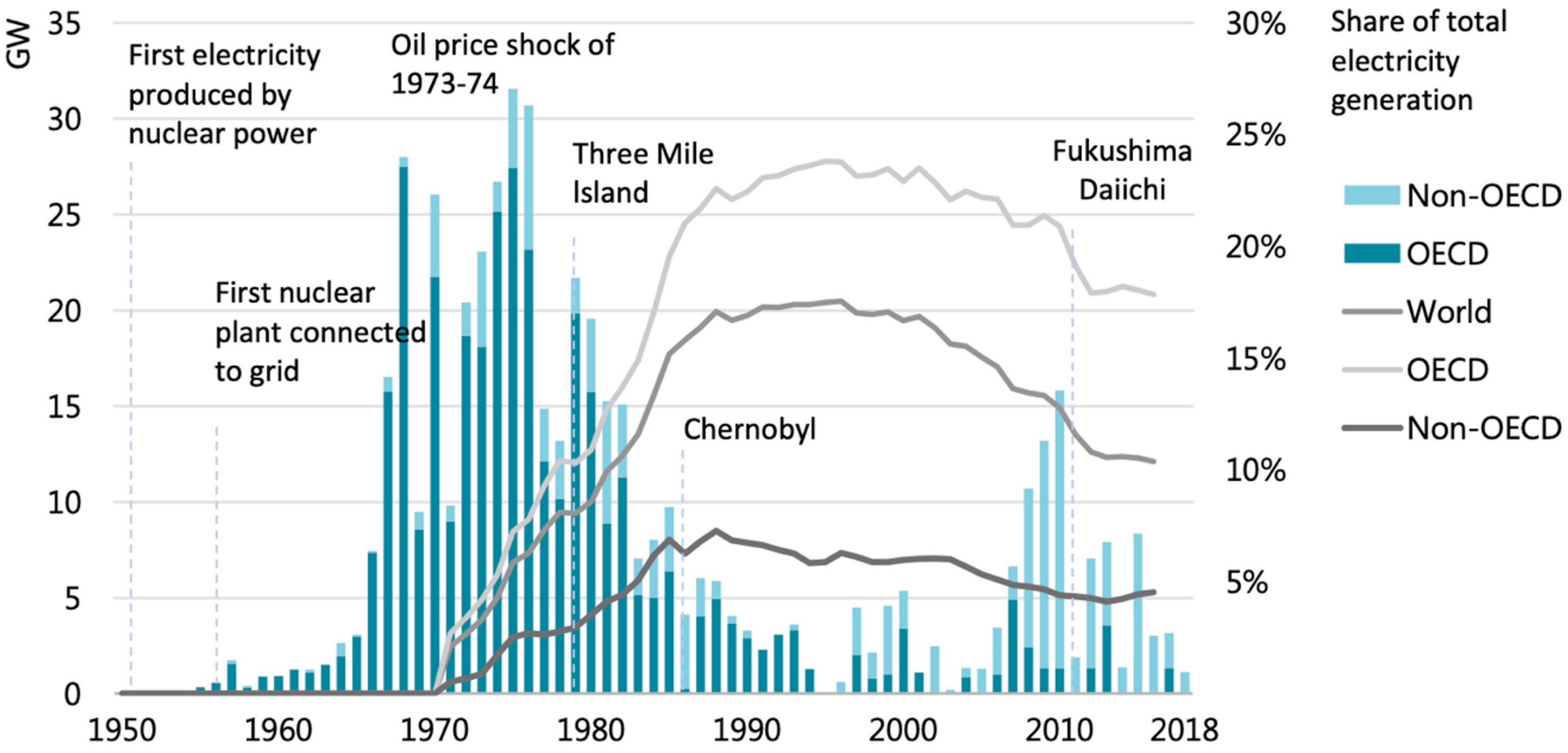
Introduction
– Growth of Nuclear



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

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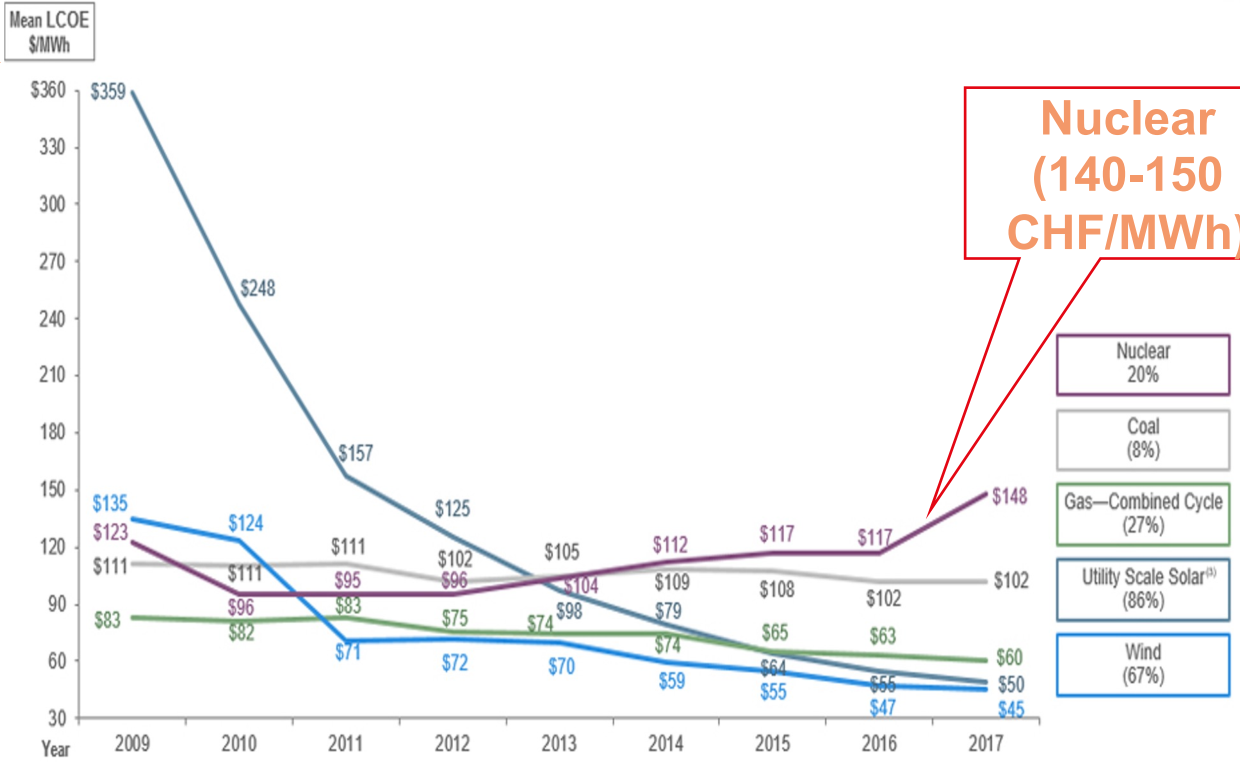
Introduction
– Levelized cost of electricity

LCOE (CHF/MWh)

350

150



Nuclear (140-150 CHF/MWh)

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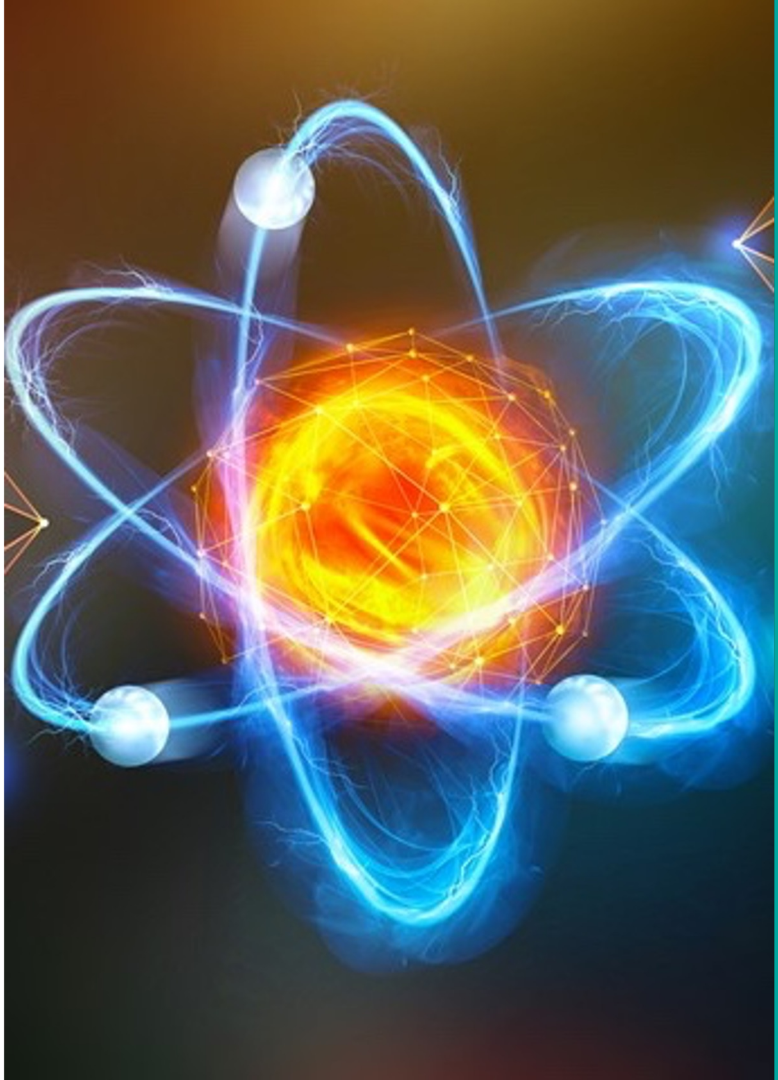

Conversion

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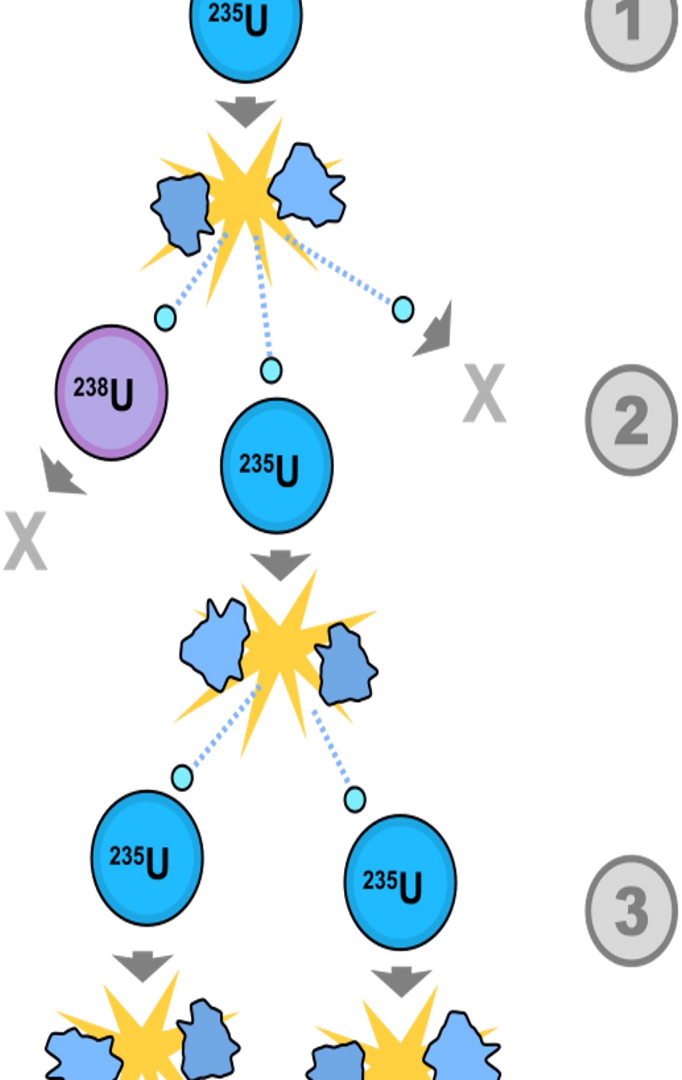

Nuclear physics :
how can we cause nuclear fission?

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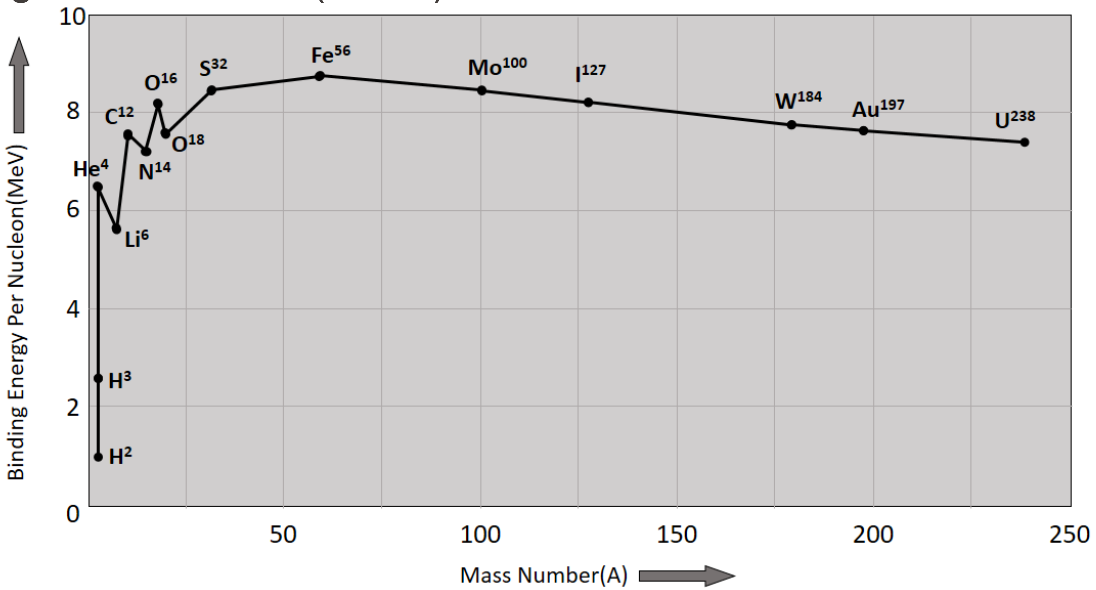
Nuclear physics
Nuclear material

- **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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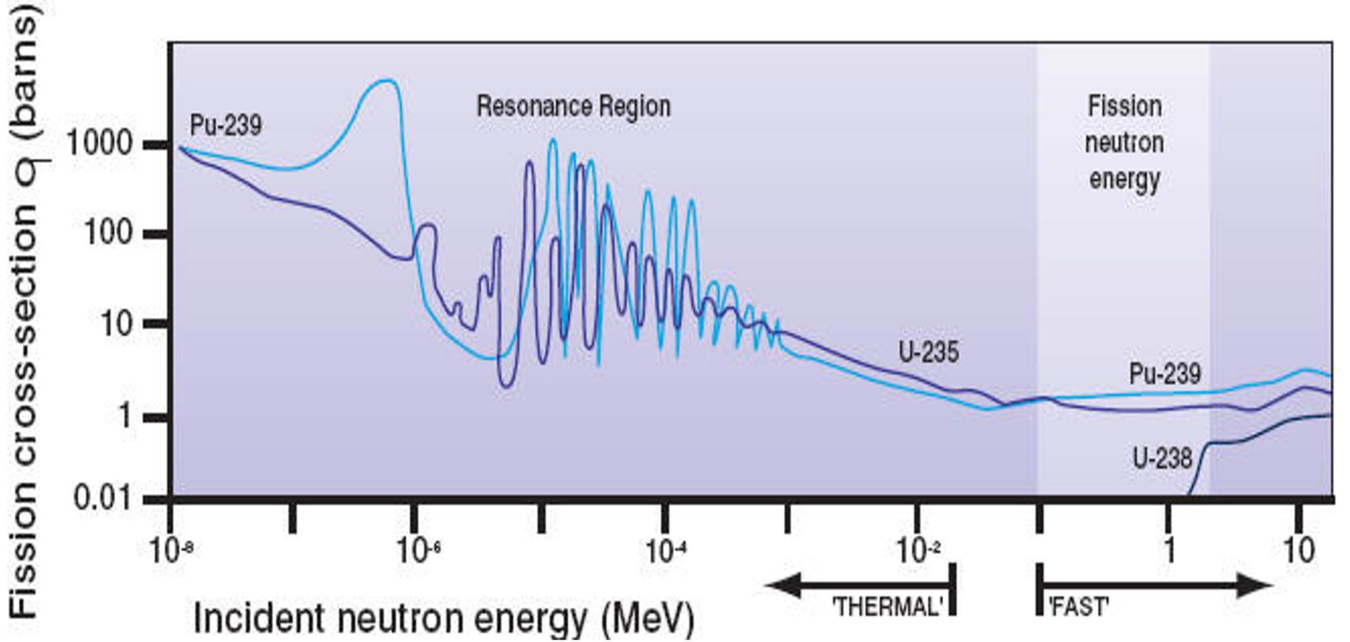
Nuclear physics
Nuclear material

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



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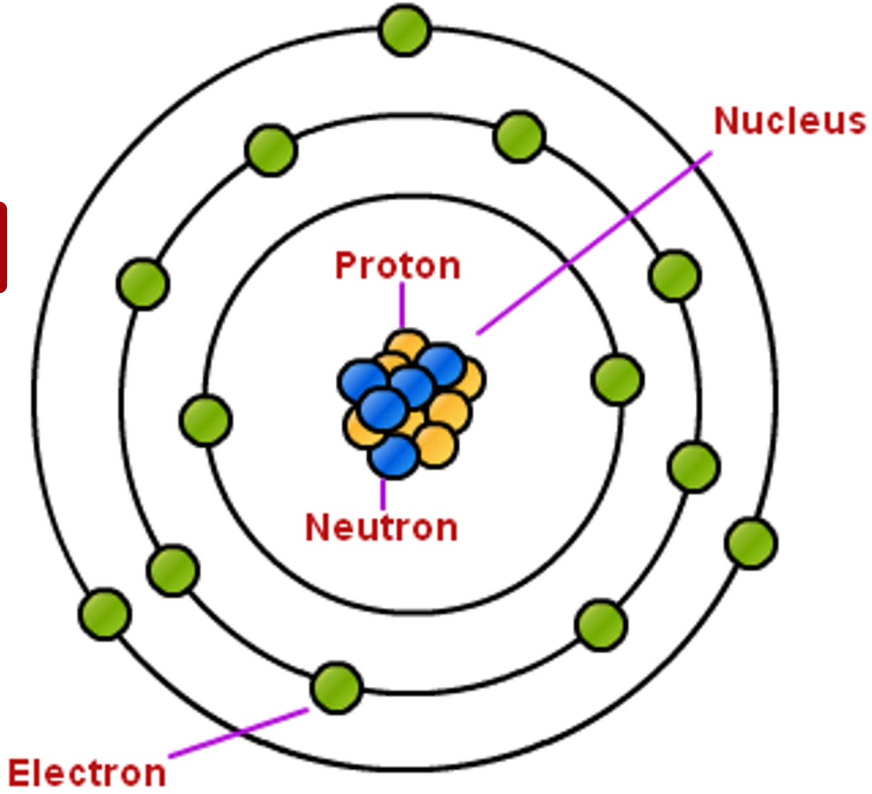
Nuclear physics
Standard Uranium

Uranium **238**: 99.3%

Uranium 235: 0.7%

Others: <0.1%



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Nuclear physics
Collision

- 1 neutron colliding 1 nucleus

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

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Nuclear physics
1st possibility – Scattering

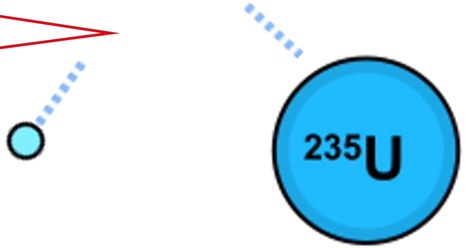
Loss of kinetic energy
= SCATTERING

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

- 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

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

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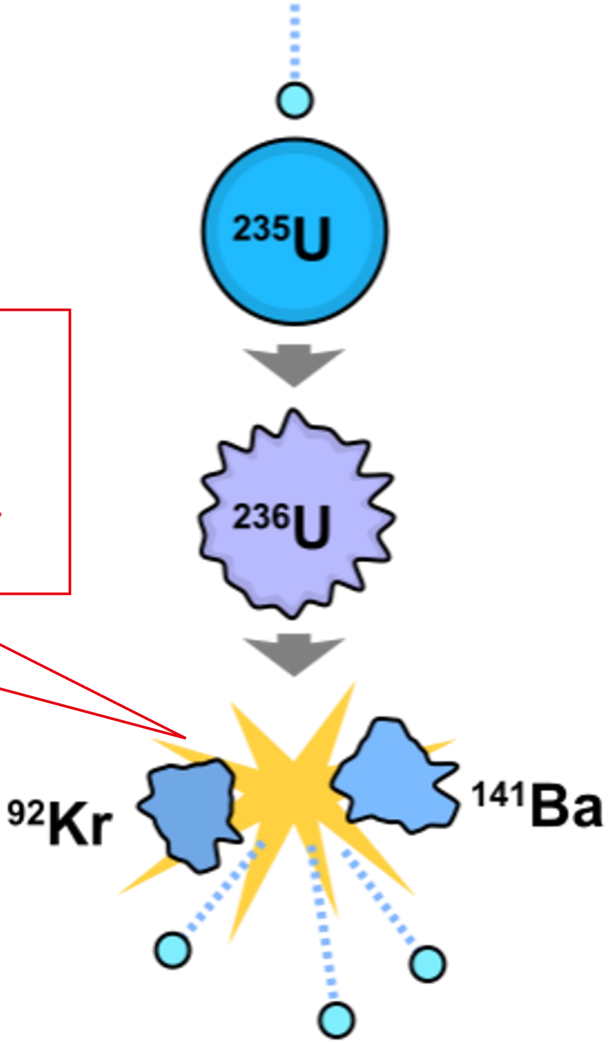
Nuclear physics

3rd possibility – Fission

The new nucleus breaks down

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



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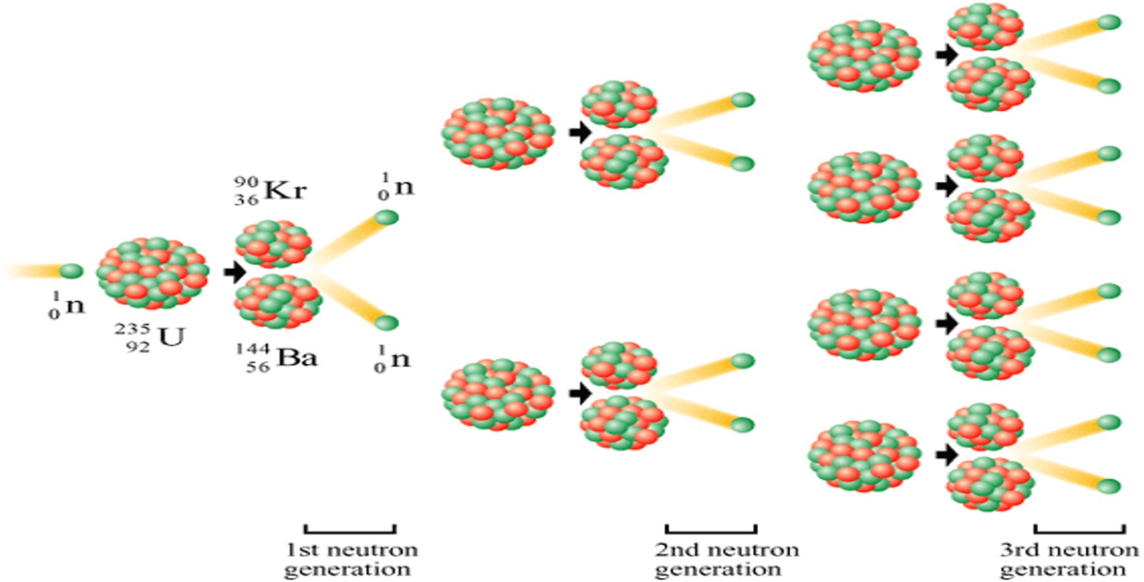
Nuclear physics

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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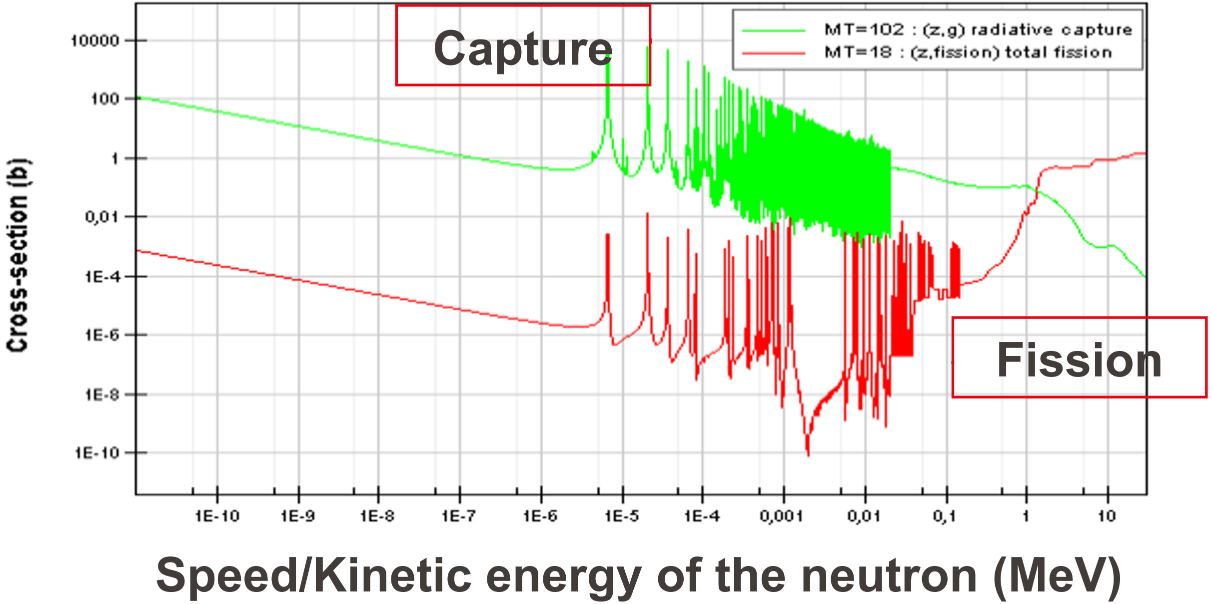
Nuclear reactivity
The concept of cross-sections

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



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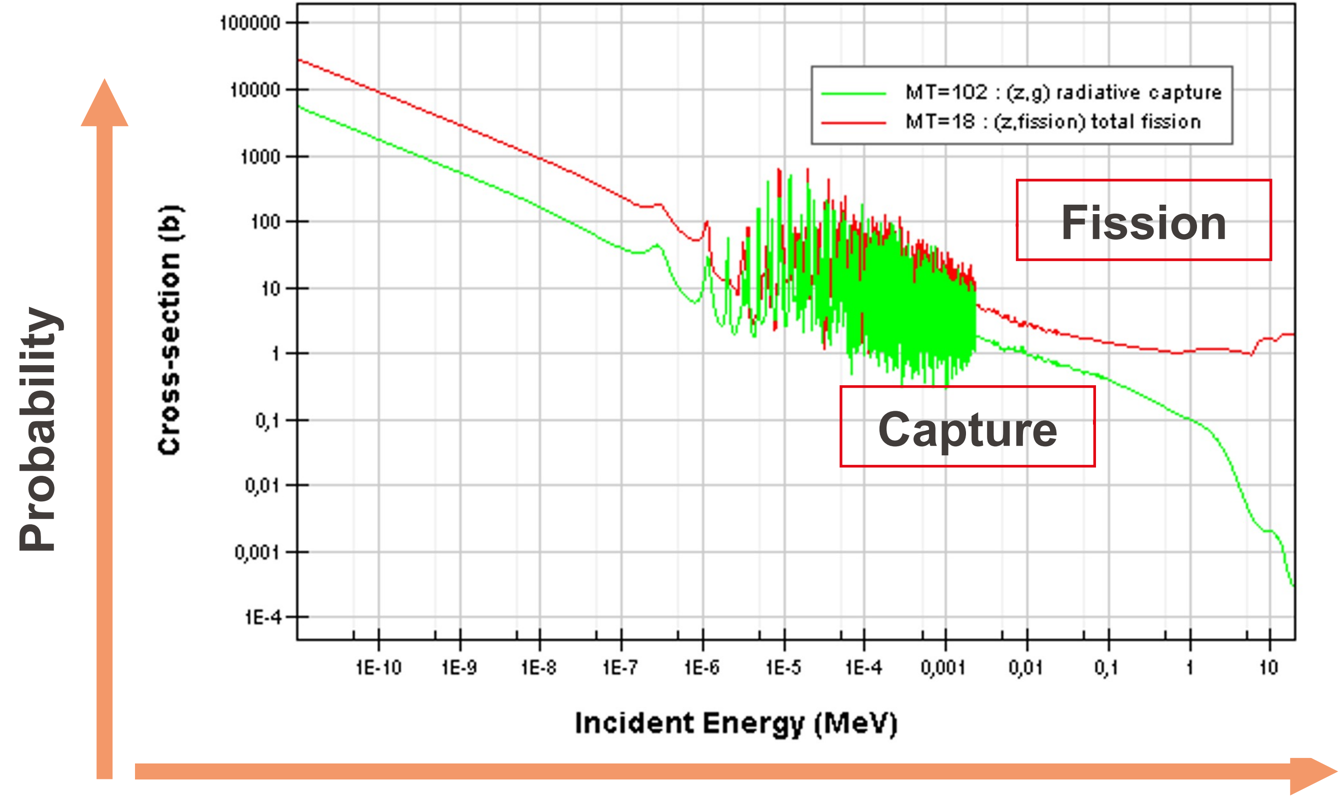
Nuclear reactivity
Case of ^{235}U



Speed/Kinetic energy of the neutron

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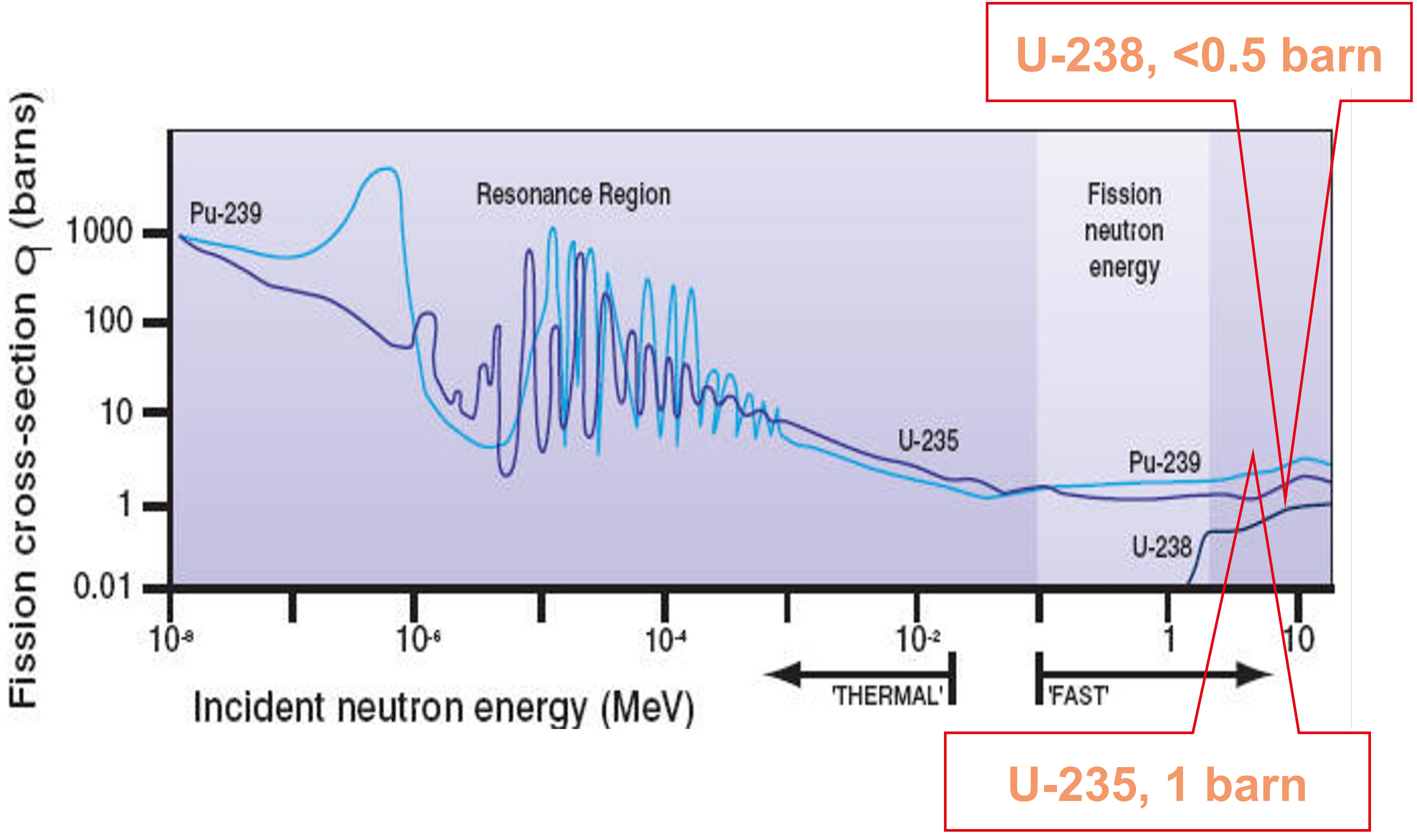
Nuclear reactivity
Fission cross-section



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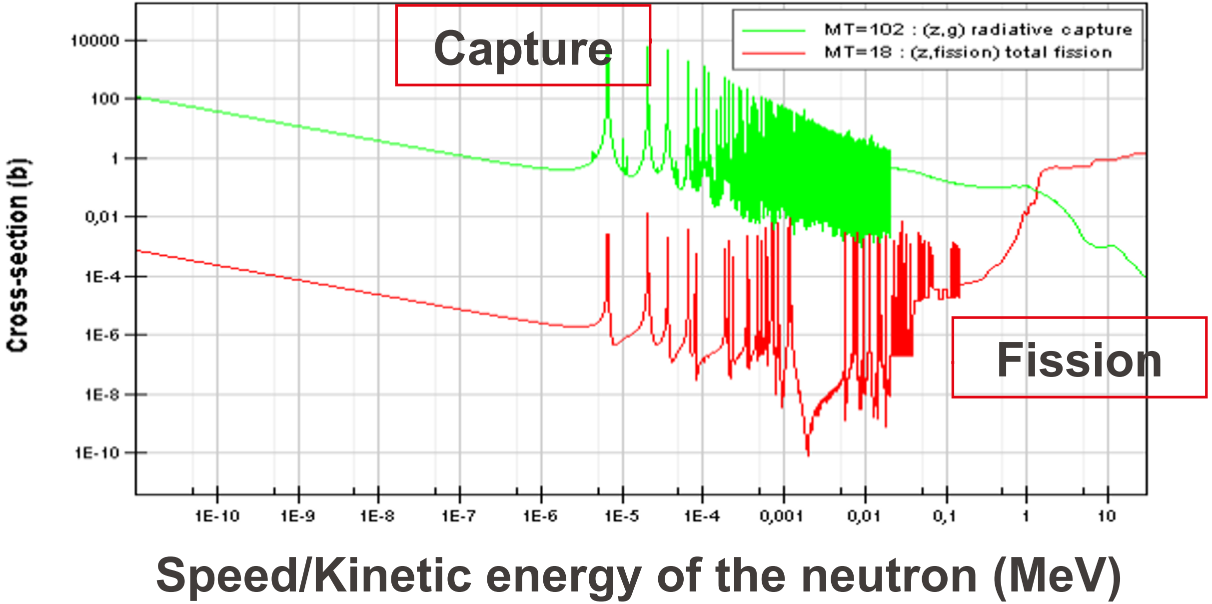
Group question – are these statements correct/false? (5-10 mins)

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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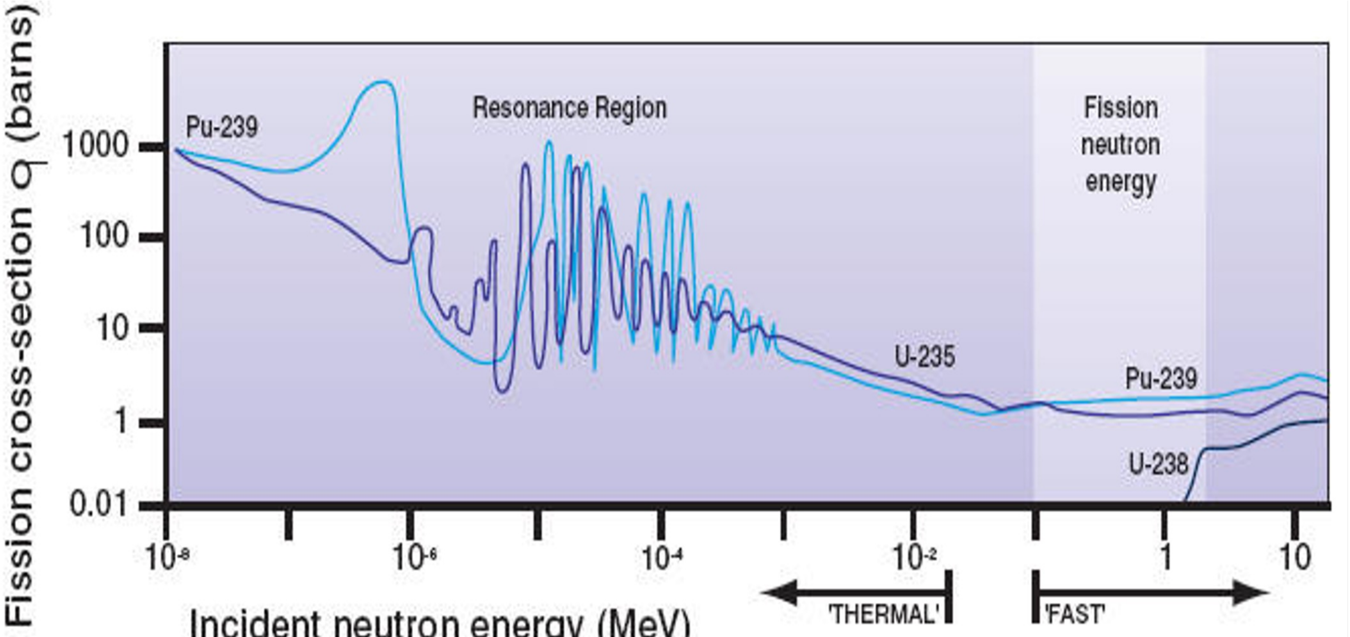
Group question – are these statements correct/false? (5-10 mins)

A) There is a higher chance to have fission of U-235 than of U-238.
B) Fission of U-235 occurs best at **low** neutron speeds
C) Fission of U-238 occurs best with **fast** neutrons
D) Fission of Pu-239 occurs best at high neutron speeds



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Enrichment, moderation and absorption

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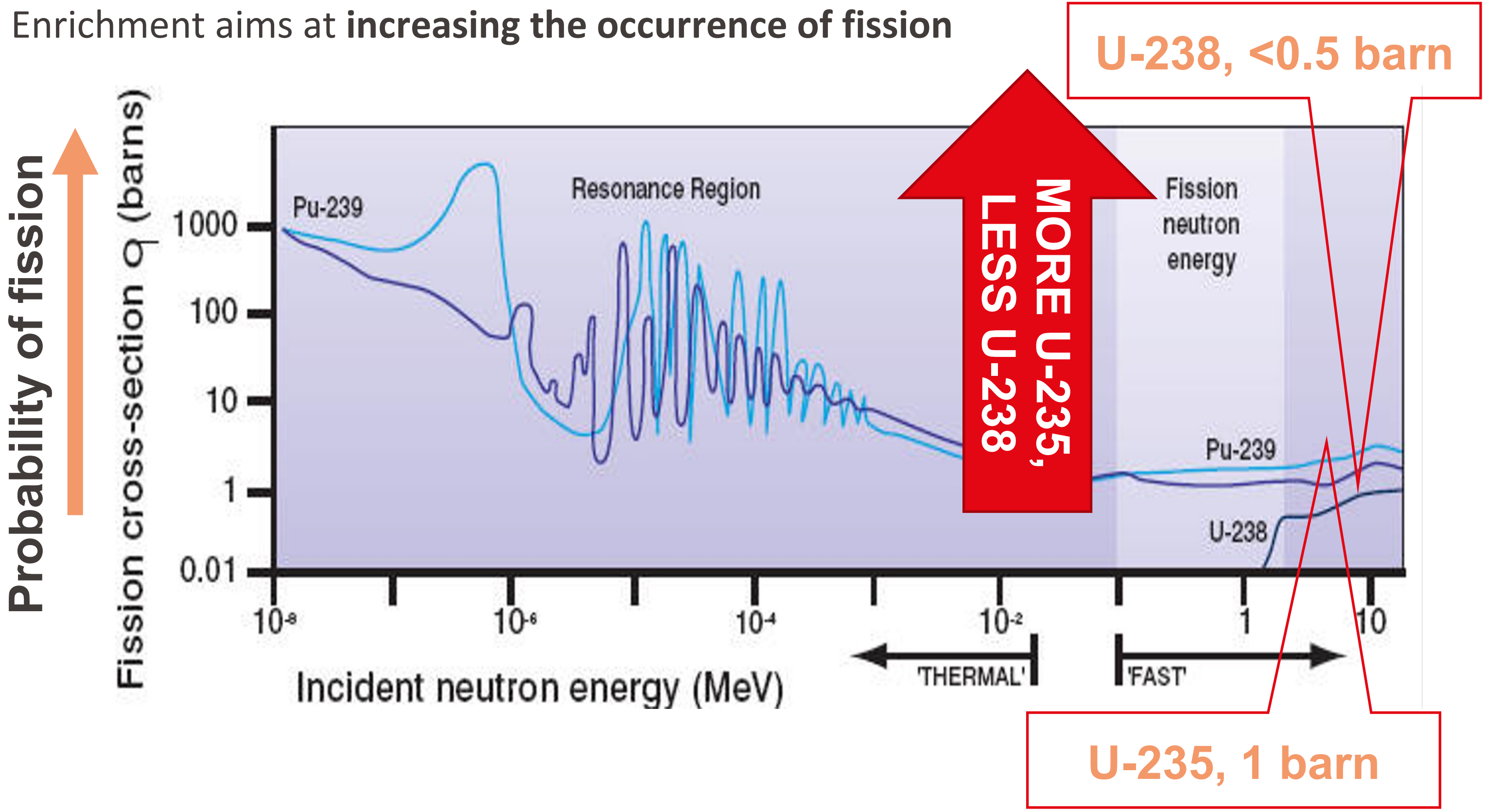
Nuclear reactivity
Enrichment (↑)

- Enrichment aims at **increasing the occurrence of fission**



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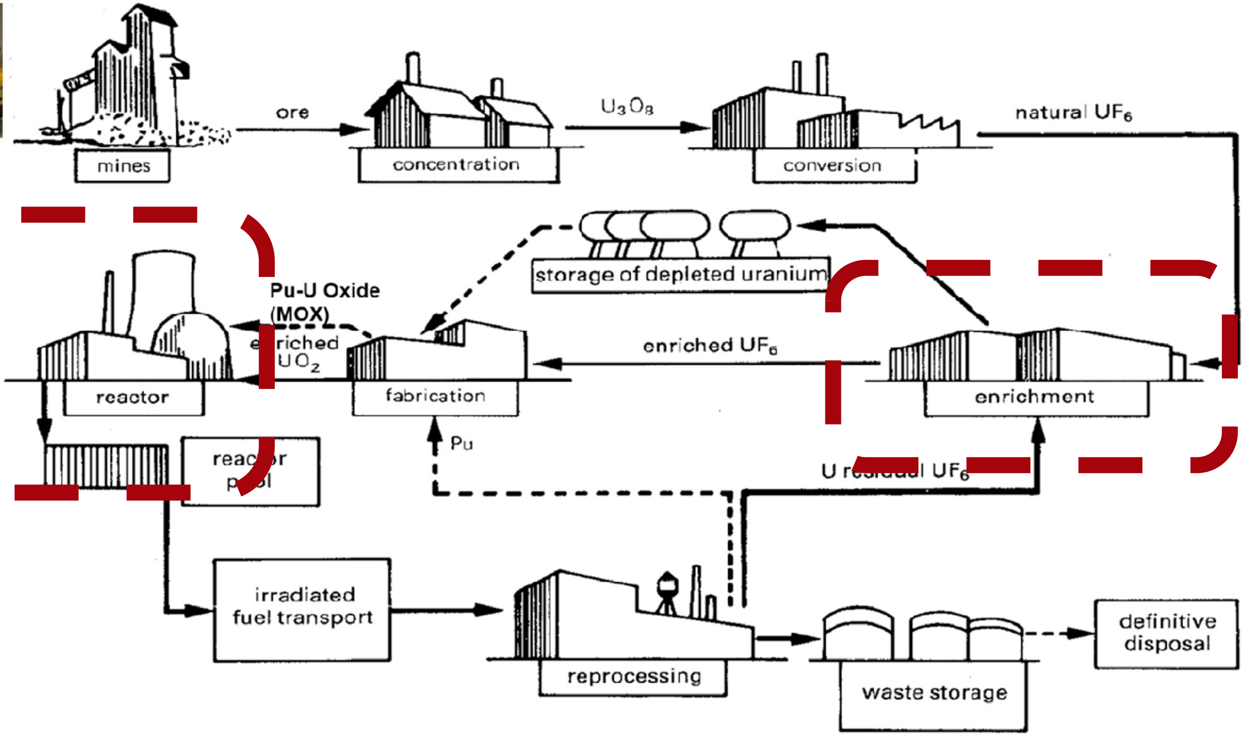
Nuclear reactivity

Enrichment (↑)

- The process increases the fraction of ^{235}U, which is essential for most reactor types



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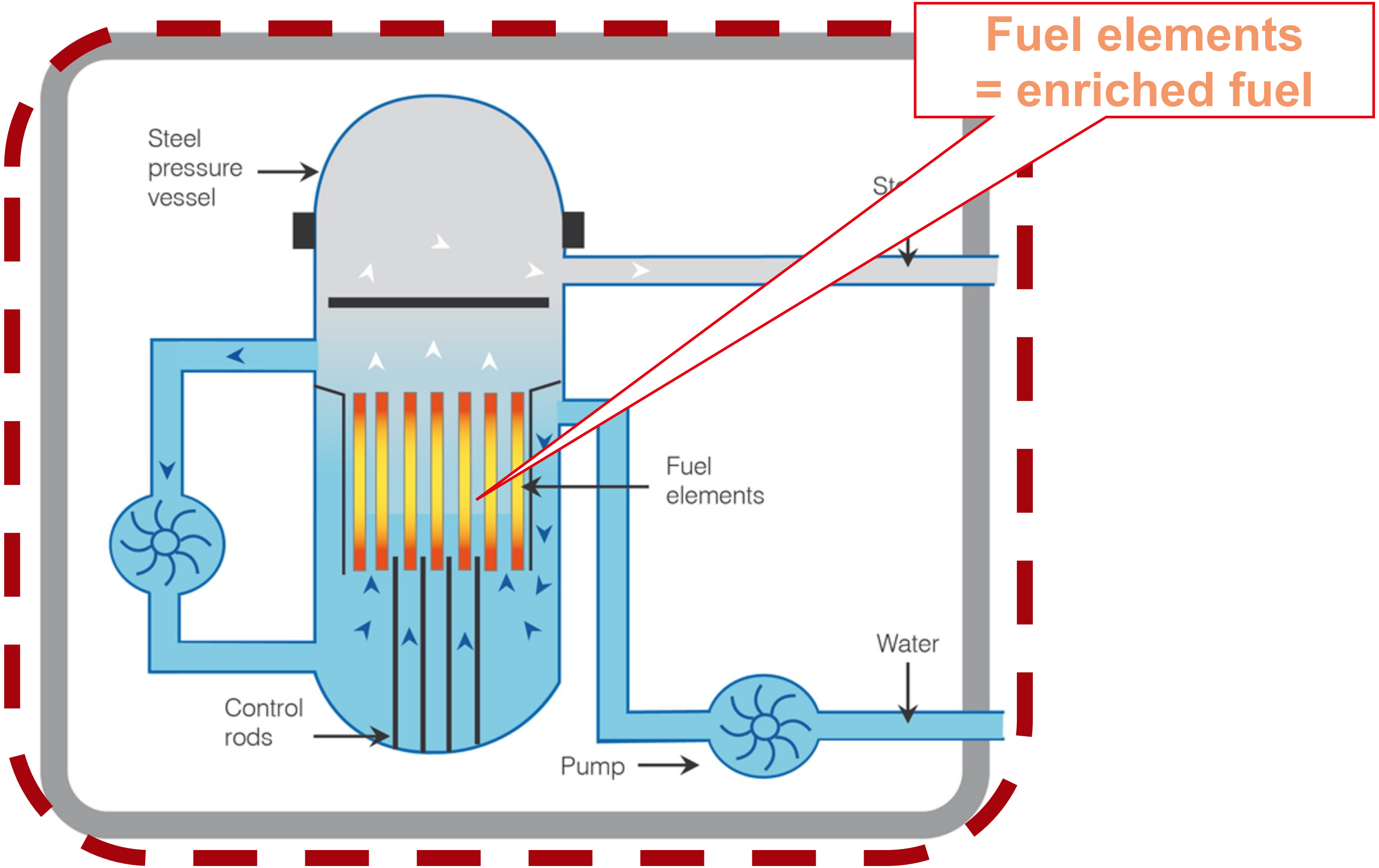
Nuclear reactivity

Enrichment (↑)



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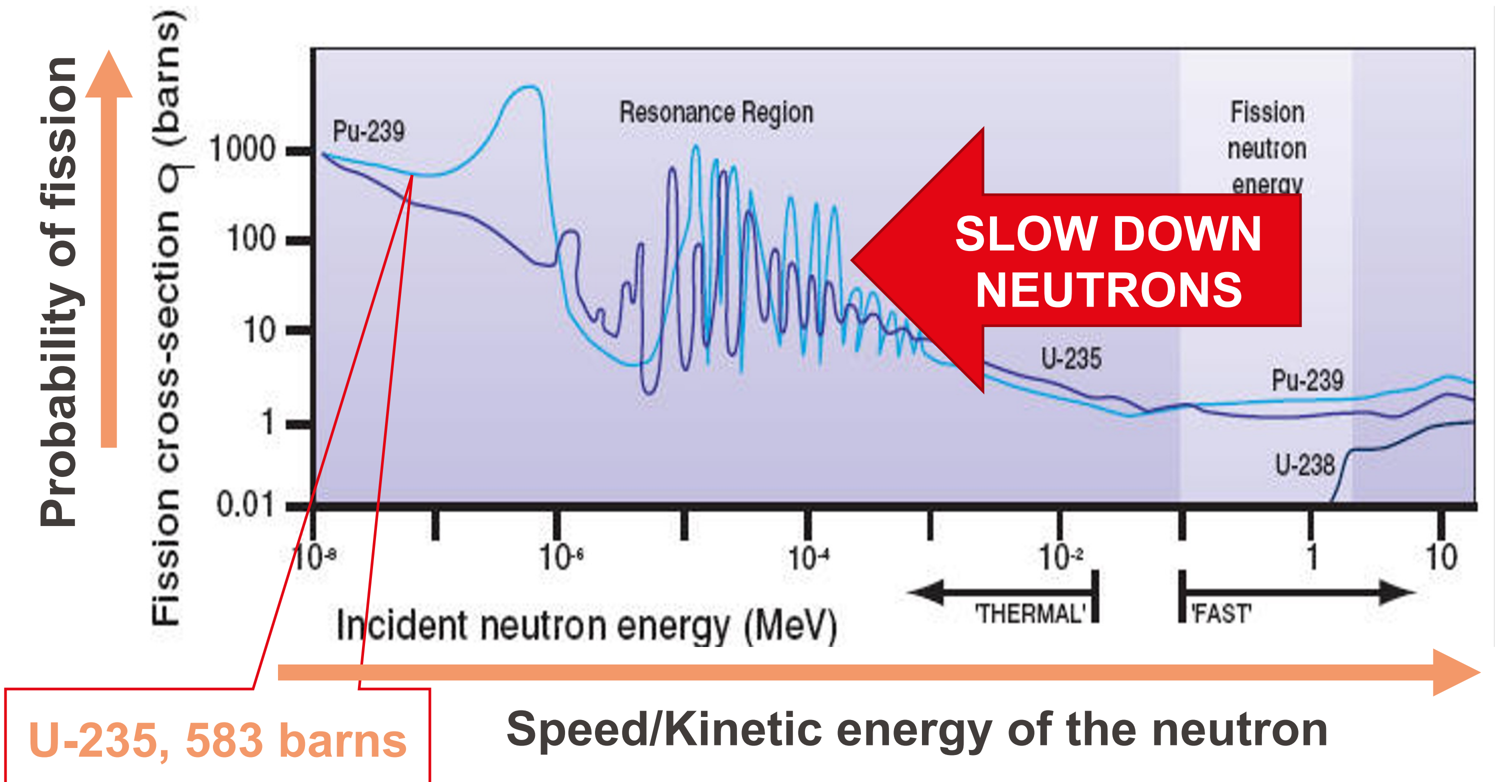
Nuclear reactivity
Moderation (↑)

- Neutrons generated through fission are « fast » - we need to slow them down



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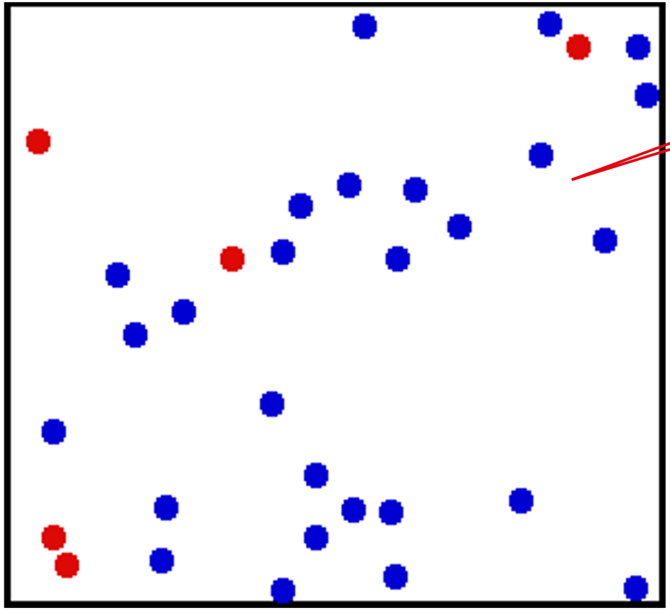
Nuclear reactivity

Moderation (↑)

- Moderation = slowing down neutrons through collisions

Red = neutron
Blue = moderator



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

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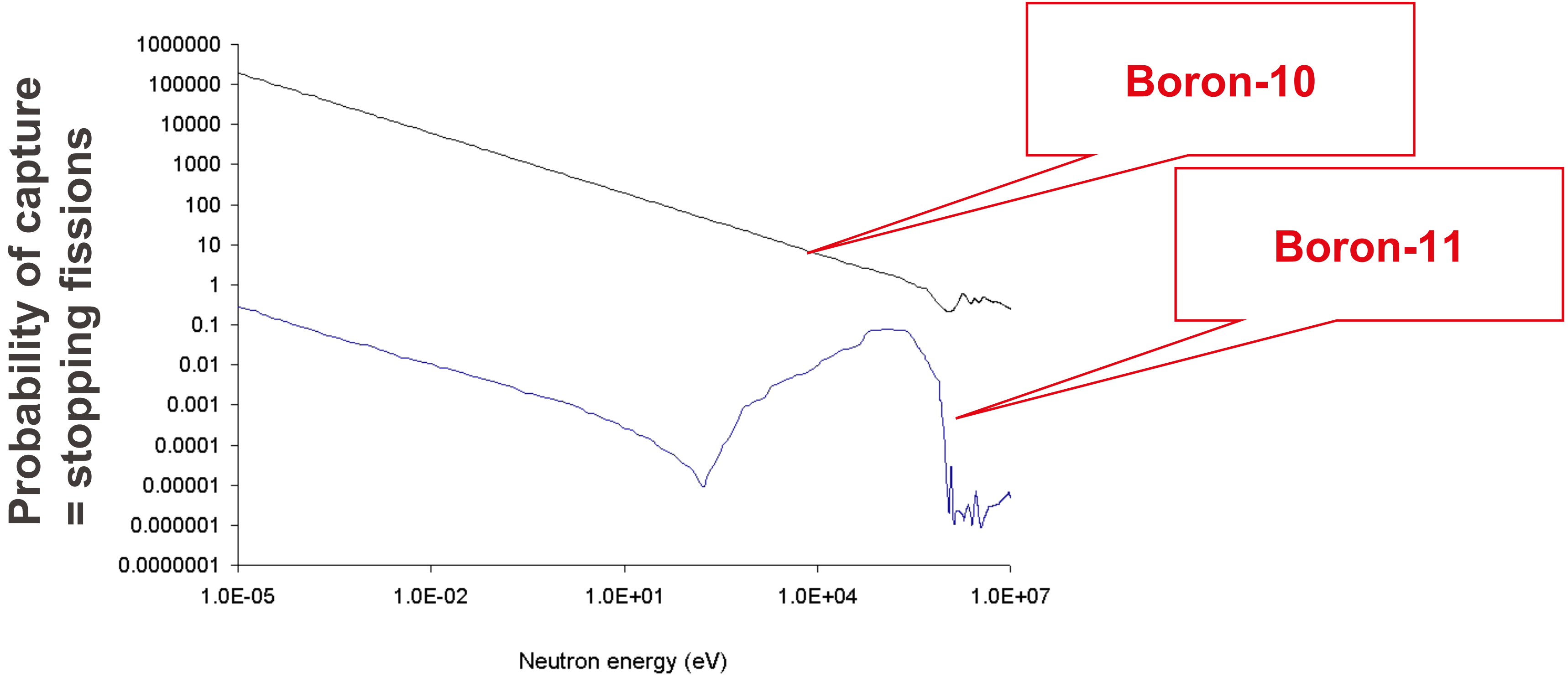
Nuclear reactivity
Absorption in control rods

- Absorption = absorbing neutrons to prevent too many fissions



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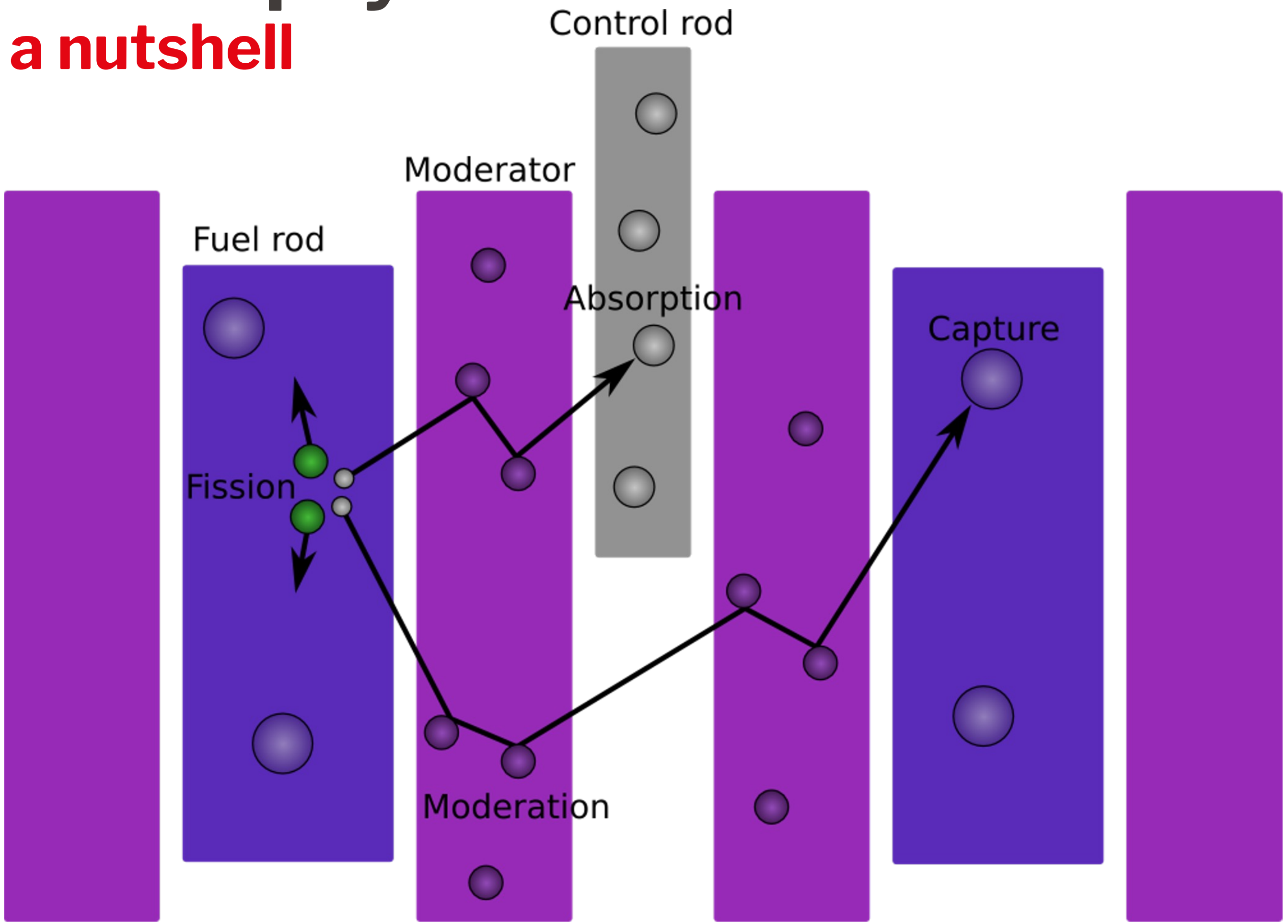
Nuclear physics
In a nutshell



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Nuclear conversion

a question of balance

- Moderation (water, graphite, etc.)

- Absorption (control rods)
- Poisoning

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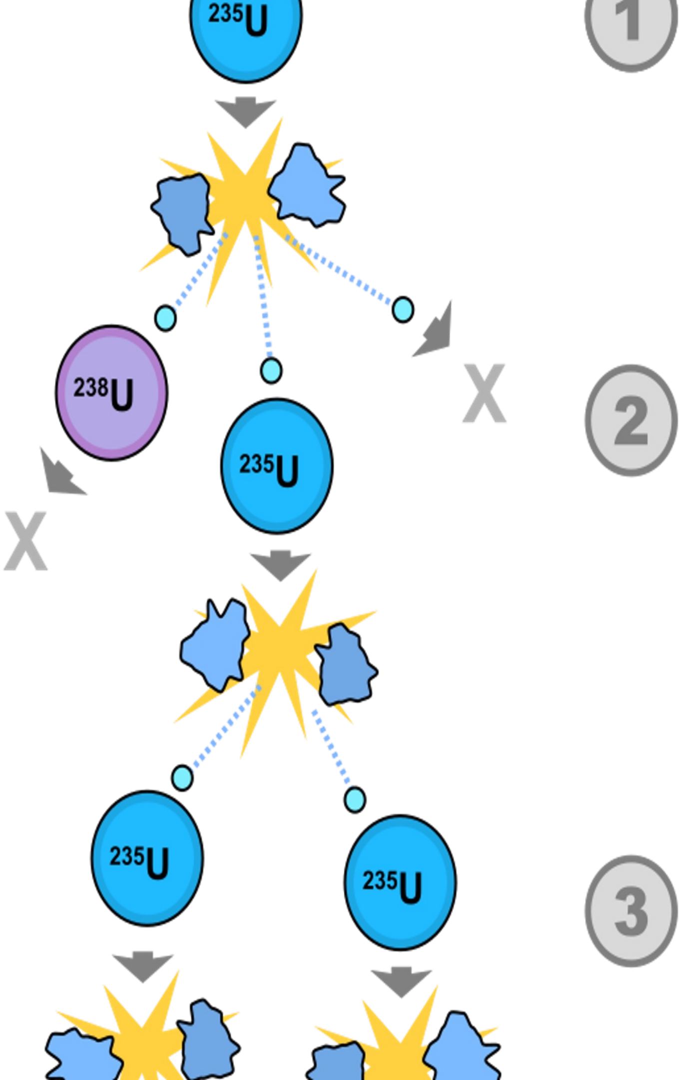

Nuclear power plants

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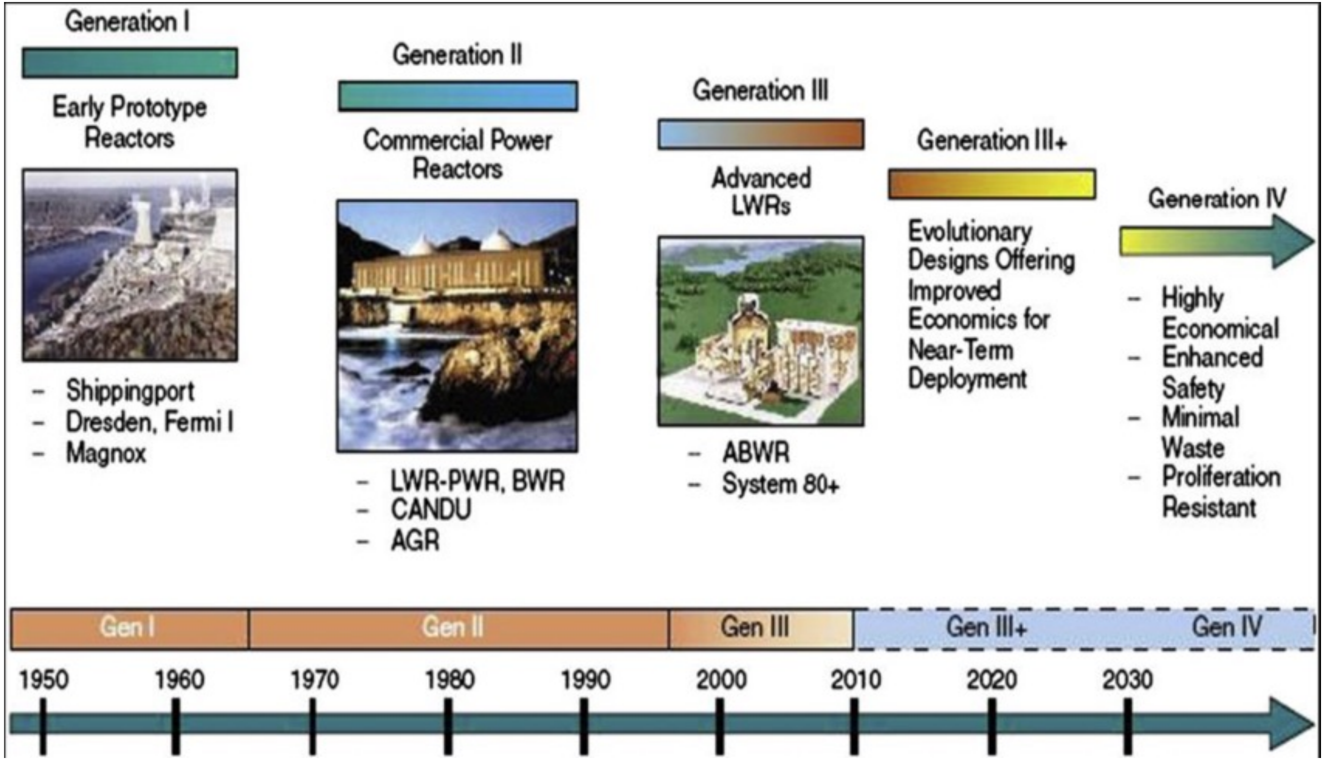
Nuclear power plants



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

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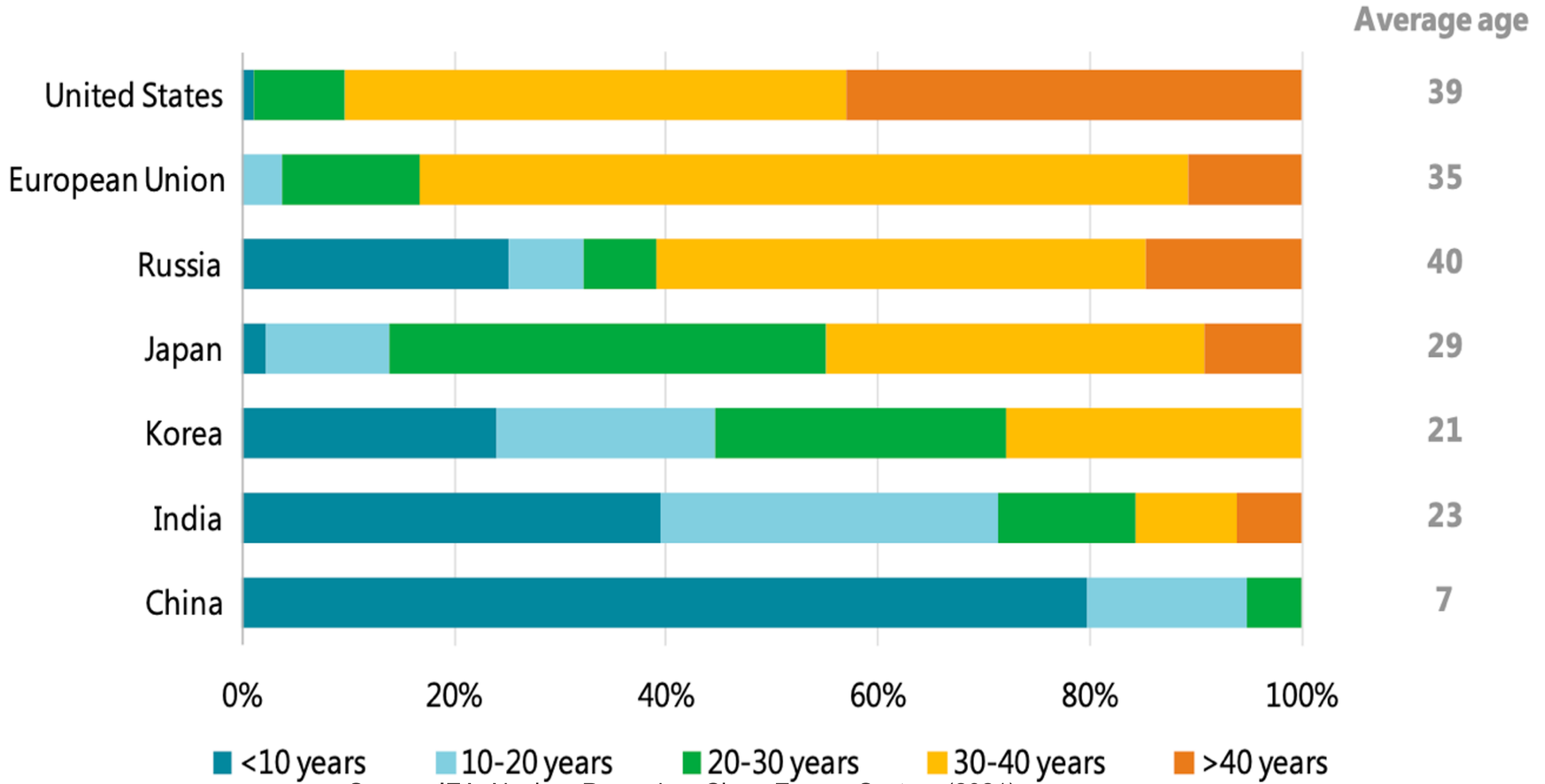
Nuclear power plants
– Age profile



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

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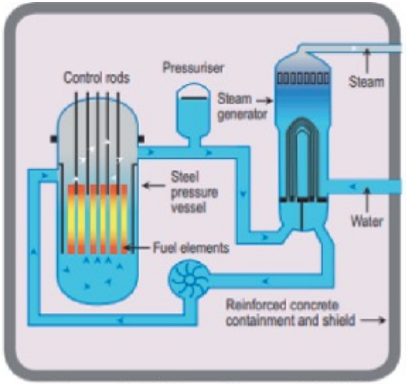
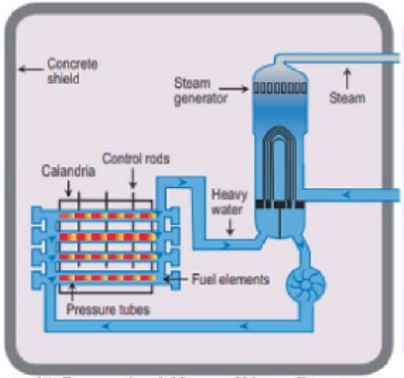
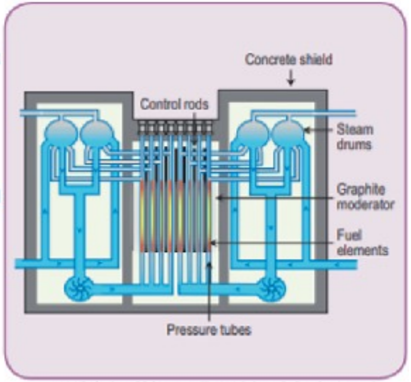
Nuclear power plants
Quick overview



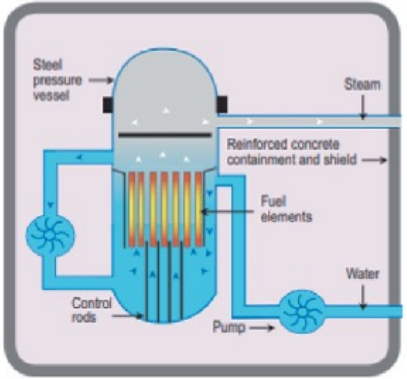
a) Pressurised Water Reactor (PWR)



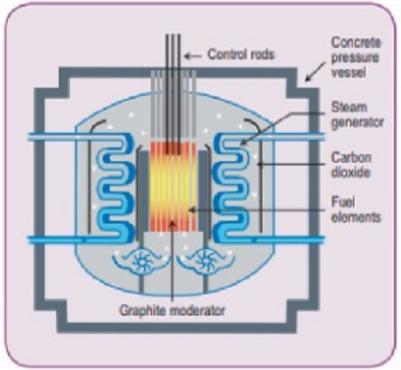
b) Pressurised Heavy Water Reactor (PHWR/Candu)



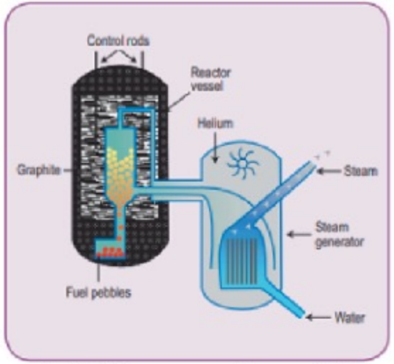
c) Light Water Graphite Moderated Reactor (LWGR/RBMK)



d) Boiling Water Reactor (BWR)



e) Advanced Gas-cooled Reactor (AGR)



f) High Temperature Reactor (HTR)

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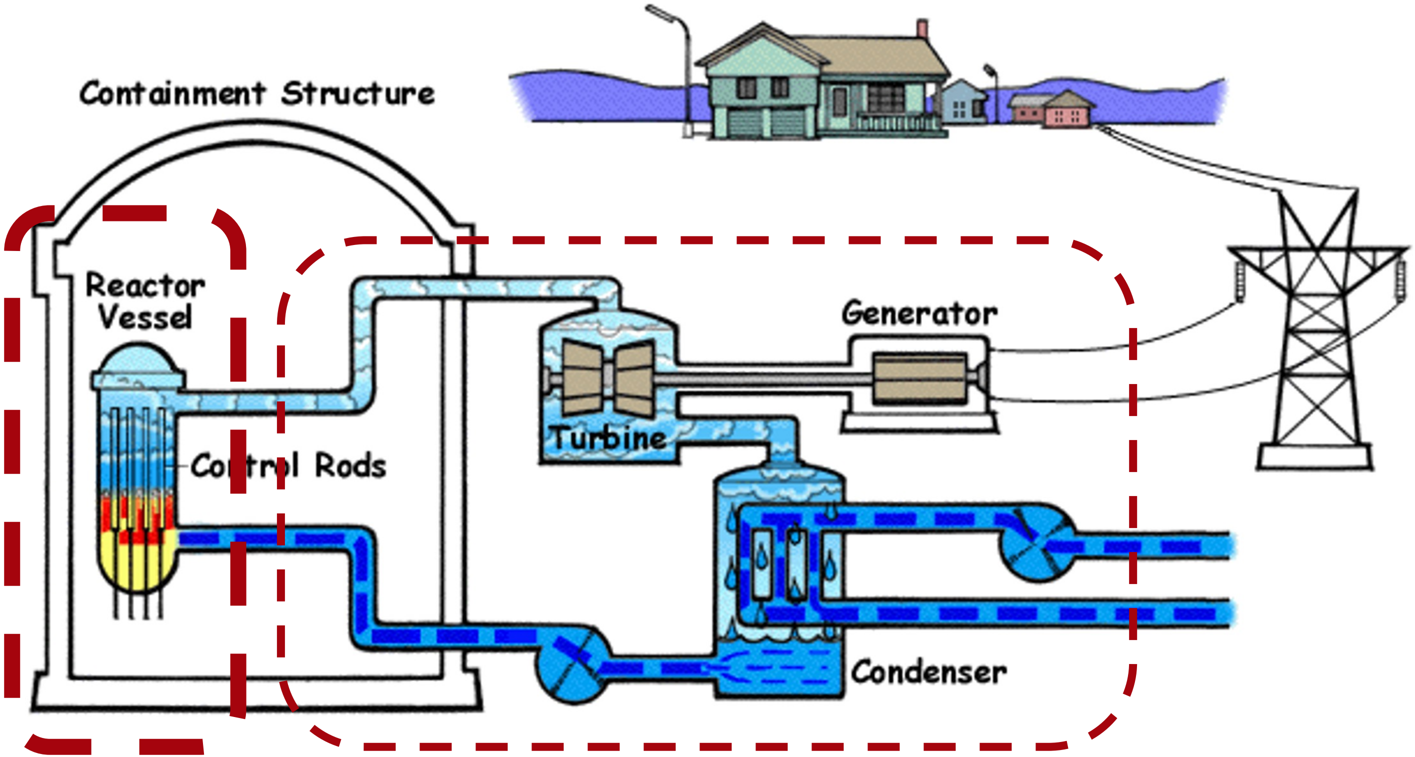
Nuclear power plants

BWR = Boiling water reactor (20% of reactors)



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Nuclear power plants BWR = Boiling water reactor (20% of reactors)

Typical conditions

- Water as a coolant and moderator
- Water at about 7.5 MPa
- Water boils at 285°C, generates steam, and is then expanded

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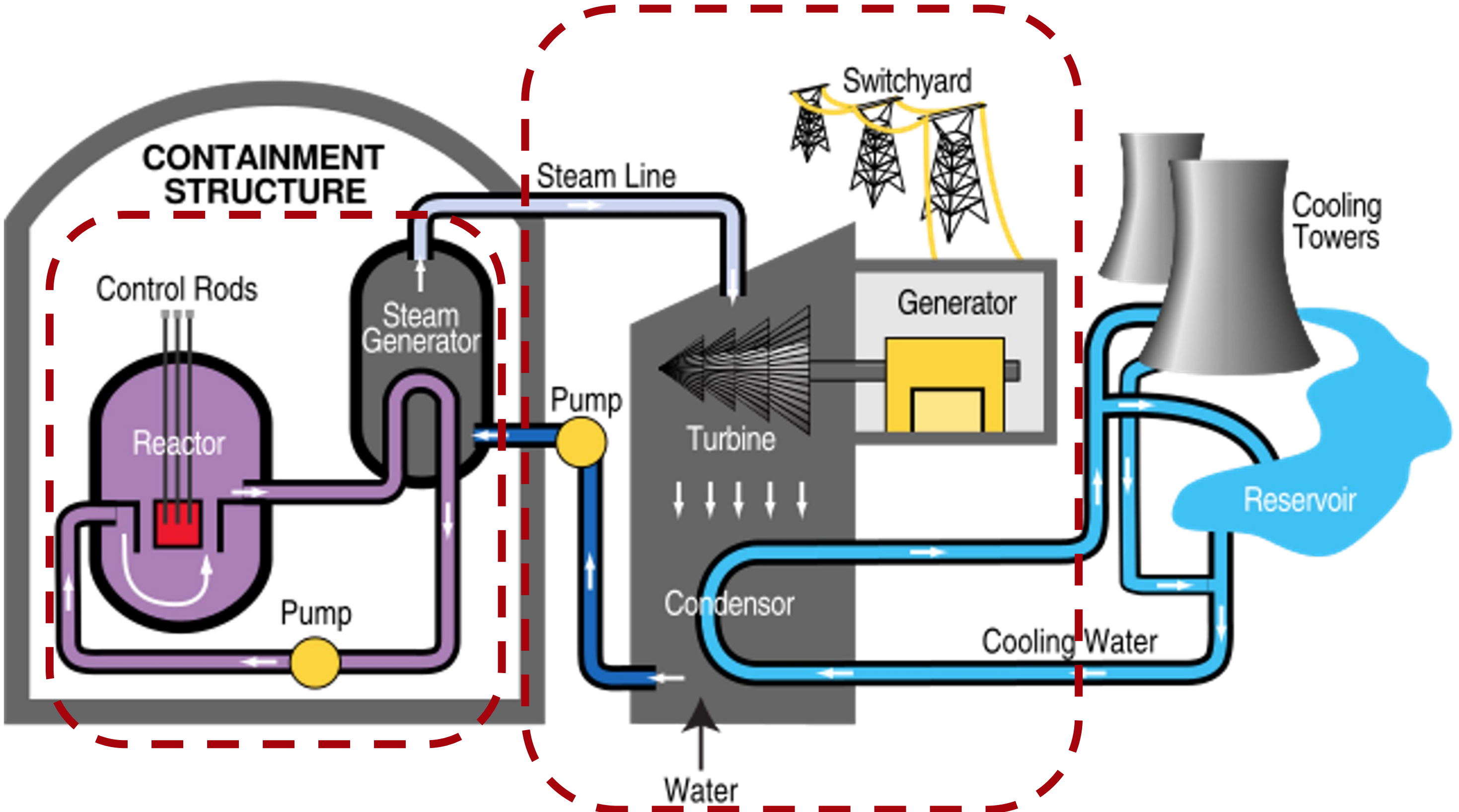
Nuclear power plants

PWR = Pressurized water reactor (70%)



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Nuclear power plants PWR = Boiling water reactor (70% of reactors)

Typical conditions

- Water as a coolant and moderator
- 2 separate circuits
- Water at about 15 MPa
- Water in the primary circuit (moderator) does **not** boil

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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?

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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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EPFL

Cogeneration

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EPFL – IPESE

Lausanne, 27/10/2025

École
polytechnique
fédérale
de Lausanne

Goals

- ***Describe*** the working principle of *cogeneration*
- ***Explain*** how cogeneration can replace conventional technologies
- ***Estimate*** the potential savings (energy, costs and environmental)

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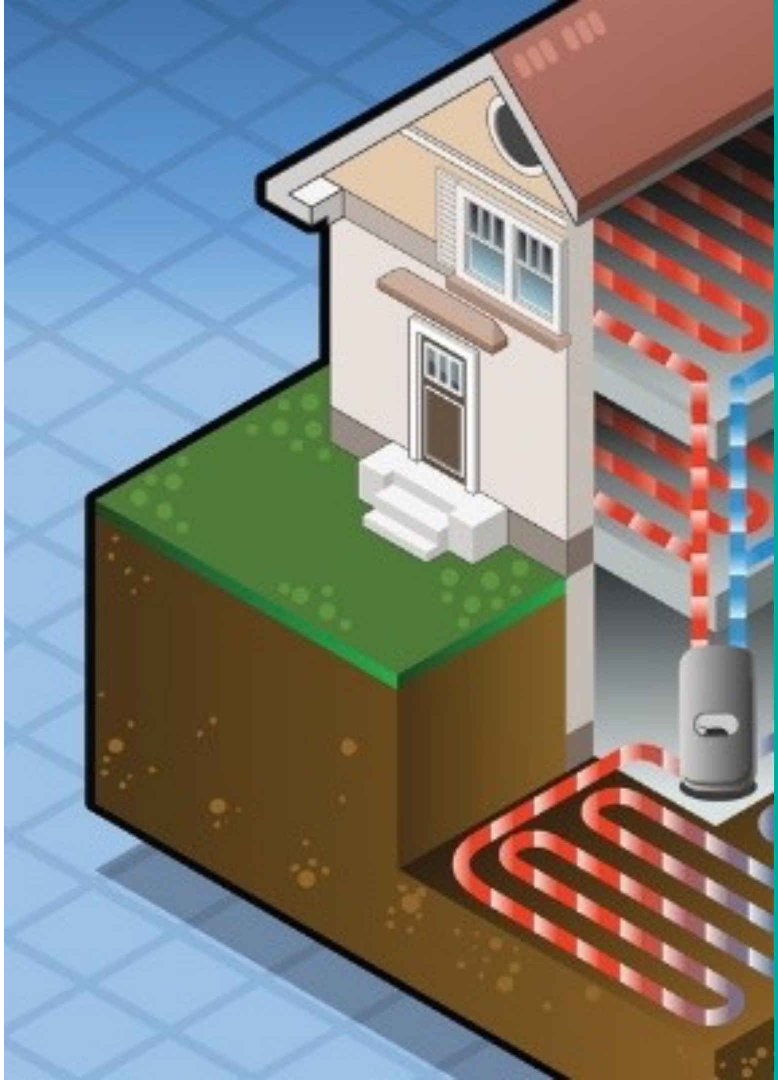

Principle

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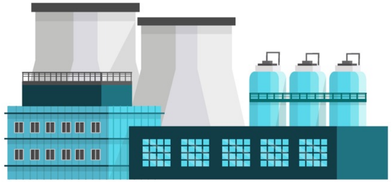
Principle



HEAT → Heat engine → ELECTRICITY

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

HEAT → Furnace, boiler → HEAT

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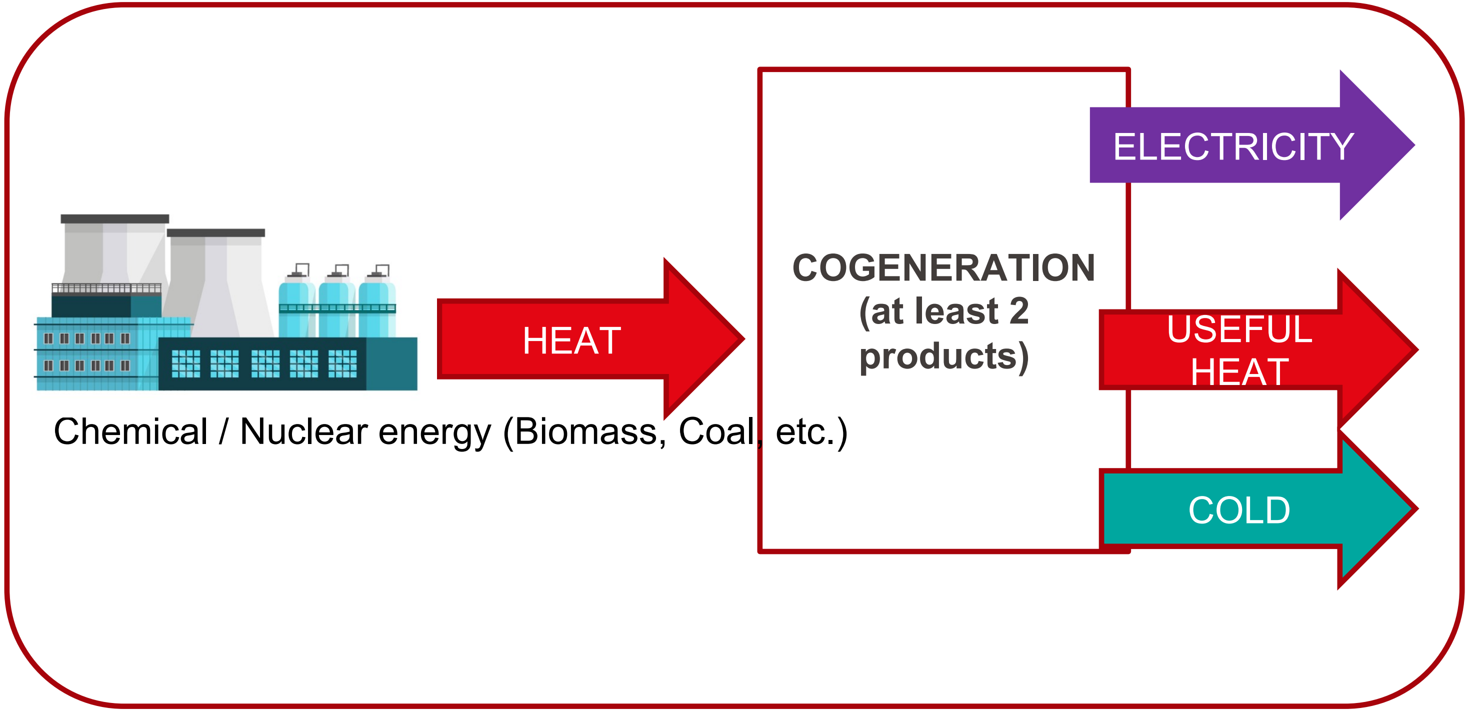
Principle

- Cogeneration : production of two useful energy outputs instead of one



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Principle

A standard power plant

- Power generation

η = 40%

FUEL
(Coal, uranium…)

100%

ELECTRICITY
40%

WASTE HEAT
60% (40°C)

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EPFL

Principle

A power plant with cogeneration

- Combined heat and power generation

FUEL
(Coal, uranium…)

100%

ELECTRICITY
35%

USEFUL HEAT
45% (150°C)

WASTE HEAT
20% (40°C)

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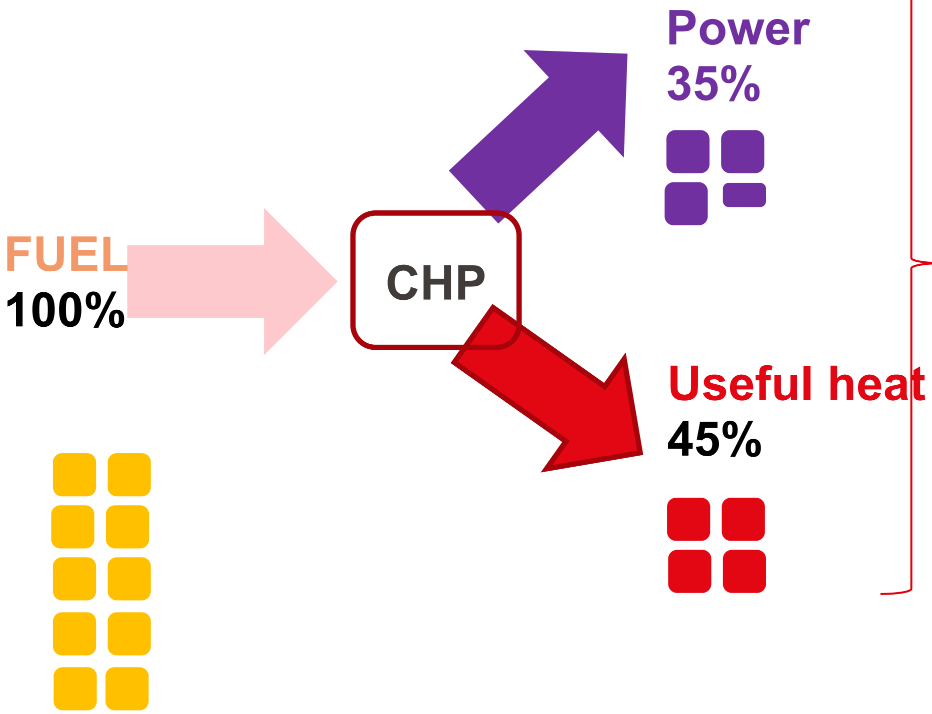
Principle

Performance indicators

- <u>Combined heat and power generation</u>



- $\eta_{\text{el}} = \frac{W^-}{Q^+}$ — Work output
- $\eta_{\text{th}} = \frac{Q^-_{\text{useful}}}{Q^+}$ — Useful heat output
- $\varepsilon = \eta_{\text{th}} + \eta_{\text{el}}$

Electrical efficiency: 35-60%

Heat production efficiency: 35-45%

Utilization factor

ε = 80%

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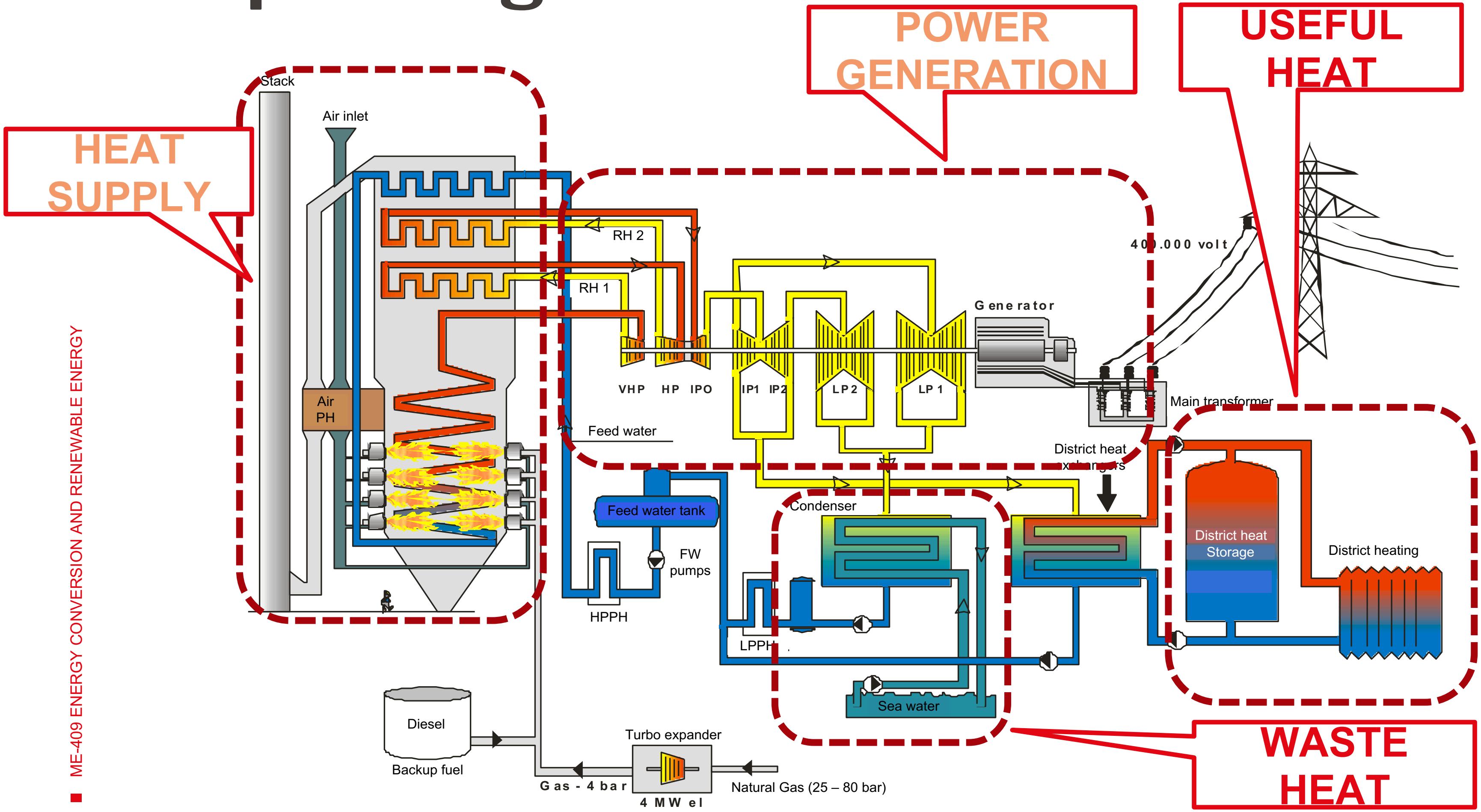
Operating modes



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Benefits

Substitution

Marginal efficiencies

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Substitution : how much *primary* energy do we save?

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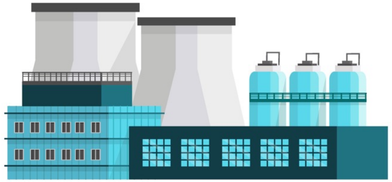


HEAT

Heat engine
40% efficiency

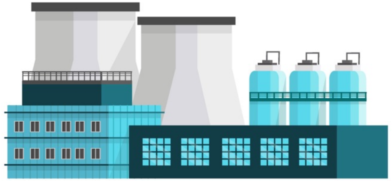
ELECTRICIT
Y

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

HEAT

Furnace, boiler
90% efficiency

HEAT



HEAT

**COGENERATI
ON
35% electrical
45% thermal**

ELECTRICITY

USEFUL
HEAT

Substitution : how much *primary* energy do we save?

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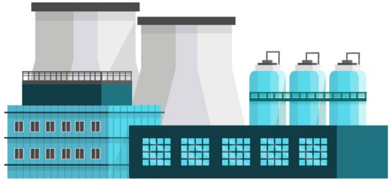
- How much extra primary energy do we spend with a cogeneration unit, compared to a boiler, for the benefit of **producing electricity** ?

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

HEAT → Furnace, boiler 90% efficiency → HEAT



HEAT → **COGENERATION 35% electrical 45% thermal** → ELECTRICITY, USEFUL HEAT

GROUP QUESTION (2 ppl., 10 mins)

A typical Swiss family living in an old building needs, per year, 4’000 kWh electricity and 18’000 kWh heat. It uses a gas boiler for heating with 90% efficiency and consumes electricity from the grid, produced with an average efficiency of 40%.

- *How much primary energy is required to satisfy the energy demand of the house?*

A small cogeneration unit with 35% electrical efficiency and 45% heat production efficiency is implemented in the building. It is designed to fully satisfy the heating needs (same heat production as the boiler).

- *How much electricity is produced in excess?*
- *How much primary energy is needed for the house?*
- *Considering that the produced electricity replaces some electricity on the grid, how much primary energy is saved in total?*

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Types of plants

Applications

Uses

Types

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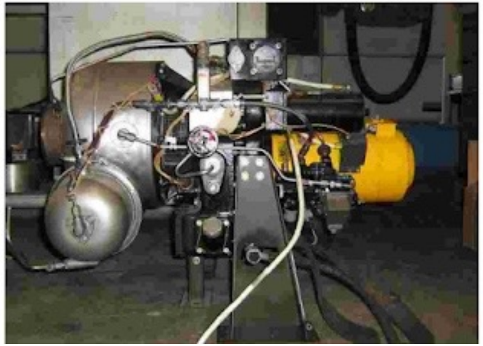
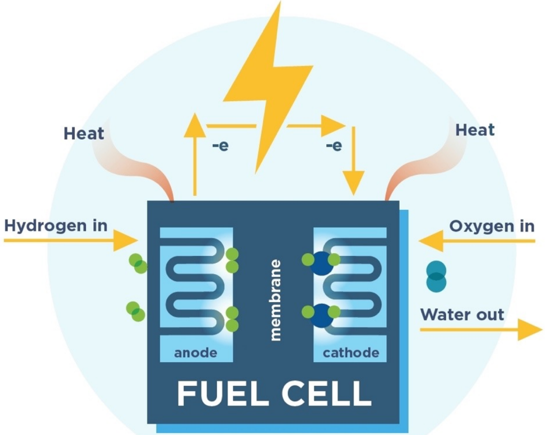
Technologies

- Gas turbines/engines
- Biofuel engines
- Advanced steam cycl
- Combined cycles (ga
- Fuel cell systems





	Typical electrical capacity	Suitable fuel types	Electrical efficiency (%)	CHP efficiency (%)	Power to heat ratio
Mature technologies					
ICE	5 kWe – 1 MWe	Natural gas, oil, biogas, bio-oil	25 – 45	80 – 95	1:1.1
Emerging technologies					
Fuel cells	1 kWe – 1 MWe	Natural gas, biogas	30 – 40	90 – 95	1:1
Micro gas engine	<5 kWe	Natural gas, oil, biogas, bio-oil	20 – 30	85 – 90	0.3 – 0.5
Micro gas turbine	1 – 100s kWe	Natural gas, oil, biogas, bio-oil	10 – 25	80 – 90	0.1 – 0.5
Stirling engines	1 – 100 kWe	Any	15 – 30	80 - 90	0.2 – 0.5

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Applications

- **Large-scale applications**

Large-scale units and power plants (> 10 MW) for cities and industries

- **Small-scale applications**

Internal combustion engines (5 kWe – 1 MW) for households

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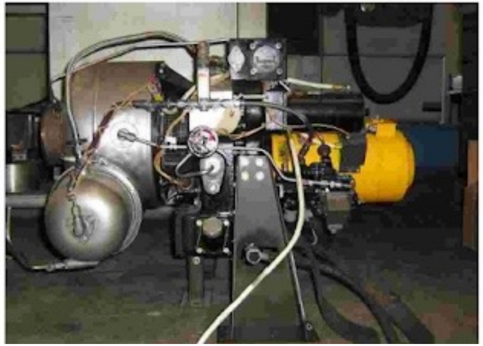
Applications

- Electricity + heat for **district heating/industrial heat**

Nuclear and biomass power plants (CH, DE, DK…)

- Electricity + heat for **small households**



Micro gas turbines, fuel cells, etc. (research)

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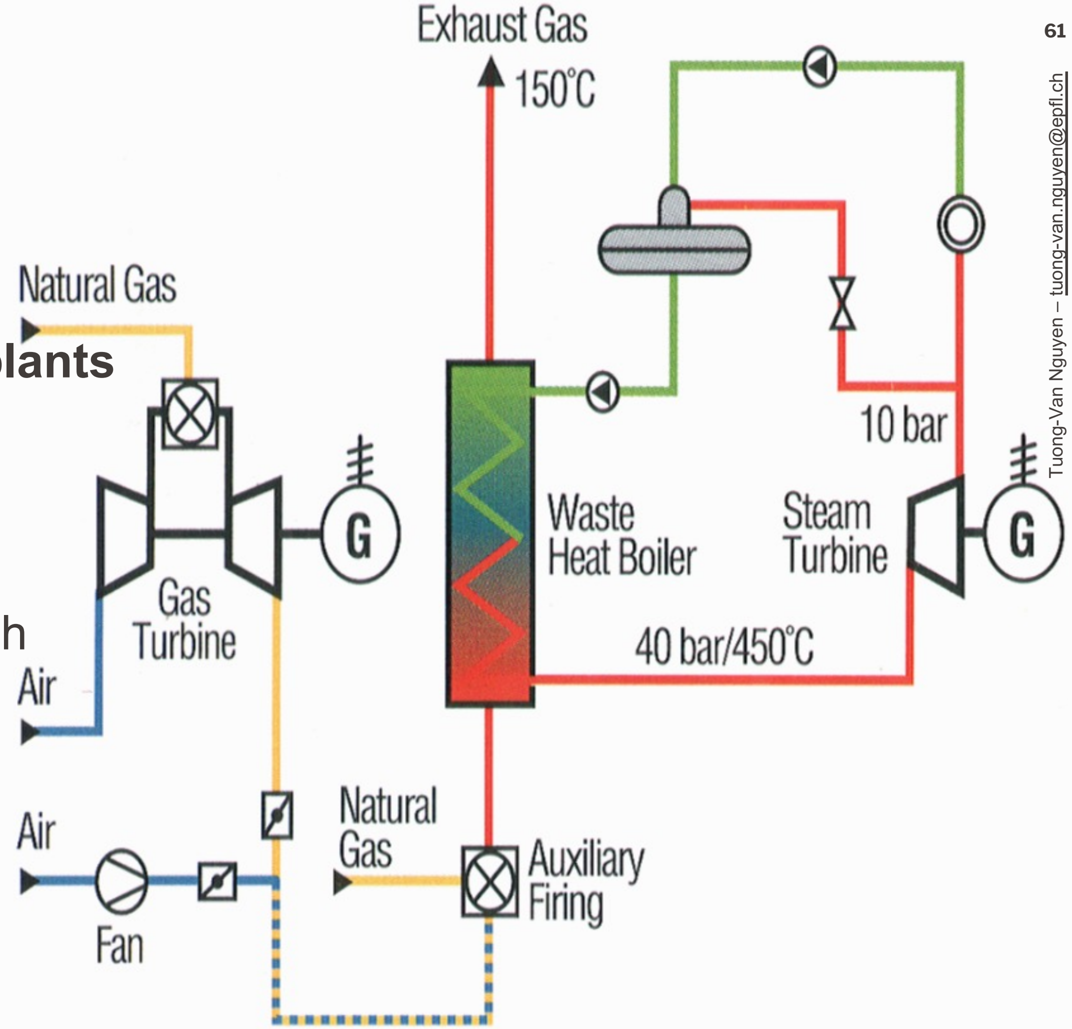
Applications

- **Gas turbines/power plants**
- Mostly large-scale applications

(cities/regions)

- Proven technology, high efficiencies
- High operational costs



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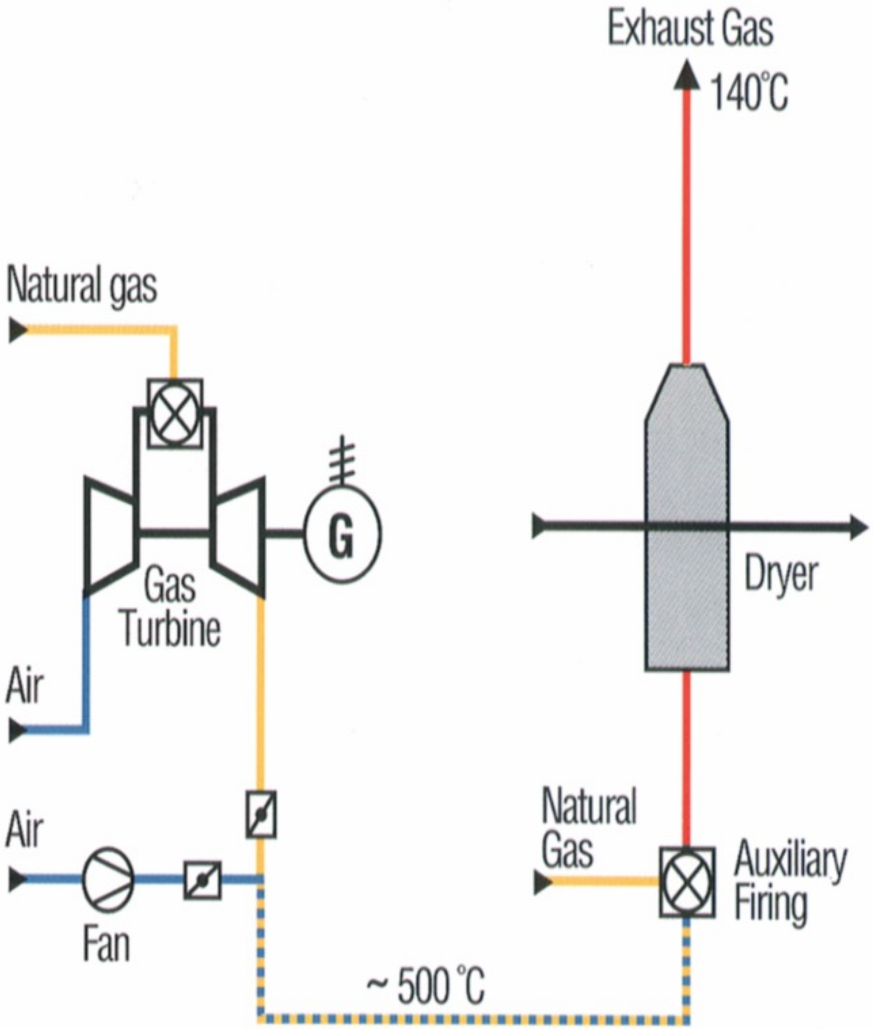
Applications

- **Gas engines** (industries)
- Small-to-medium sizes
- Application to processes

(air heating/drying)



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Take-home message

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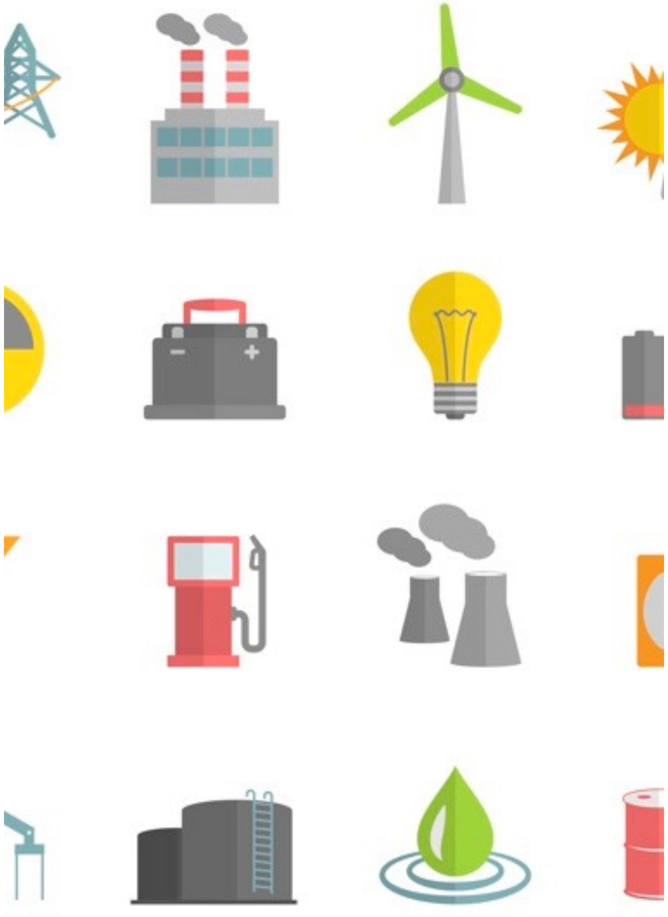
Take-home message

- **Cogeneration**
  - Electricity and heat
  - Utilization factors > 90%

- **Substitution**
  - Which systems does it replace?
  - Energy, cost and CO_2 savings



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Questions?

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