Quick Introduction to Nuclear Physics and Engineering

by two nuclear enthusiasts ☺:

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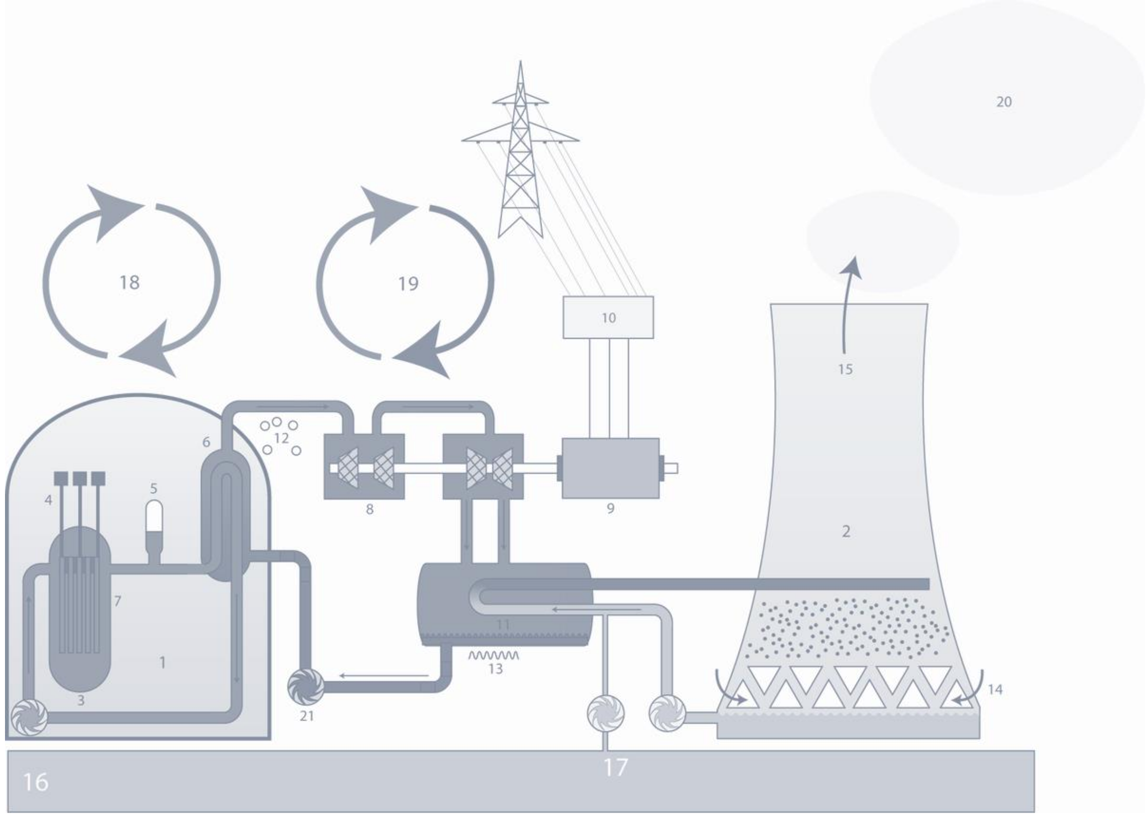
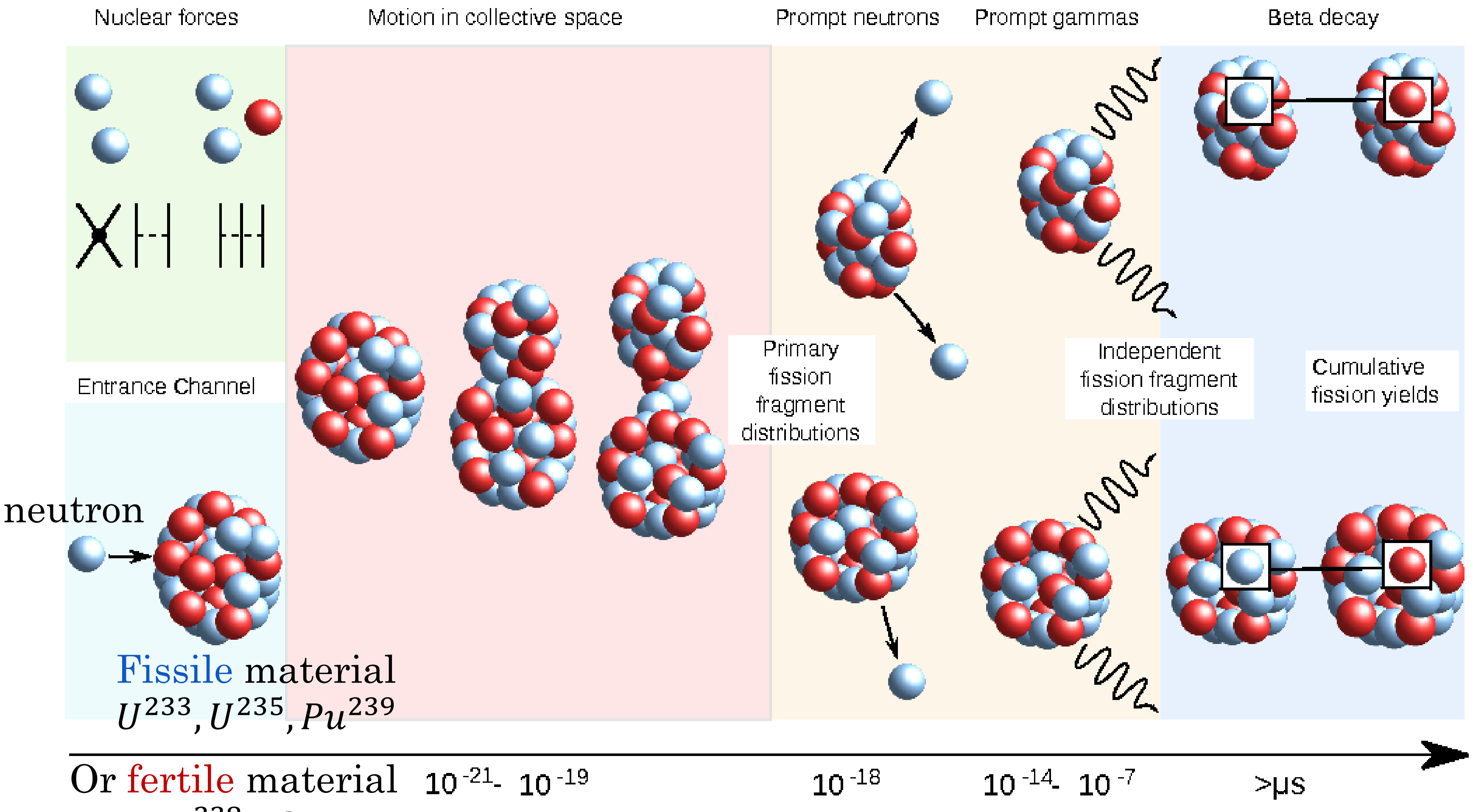
Big thanks to: G. Jiménez and S. Larriba from Universidad Politécnica de Madrid (UPM)



1. Reactor Block
2. Cooling Tower
3. Reactor
4. Control Rod
5. Support For Pressure
6. Steam Generator
7. Fuel Element
8. Turbine
9. Generator
10. Transformer
11. Condenser
12. Gaseous
13. Liquid
14. Air
15. Air (Humid)
16. River
17. Cooling-water Circulation
18. Primary Circuit
19. Secondary Circuit
20. Water Vapor
21. Pump

What is nuclear fission?

Discovered in 1938 by Otto Hahn and Lise Meitner



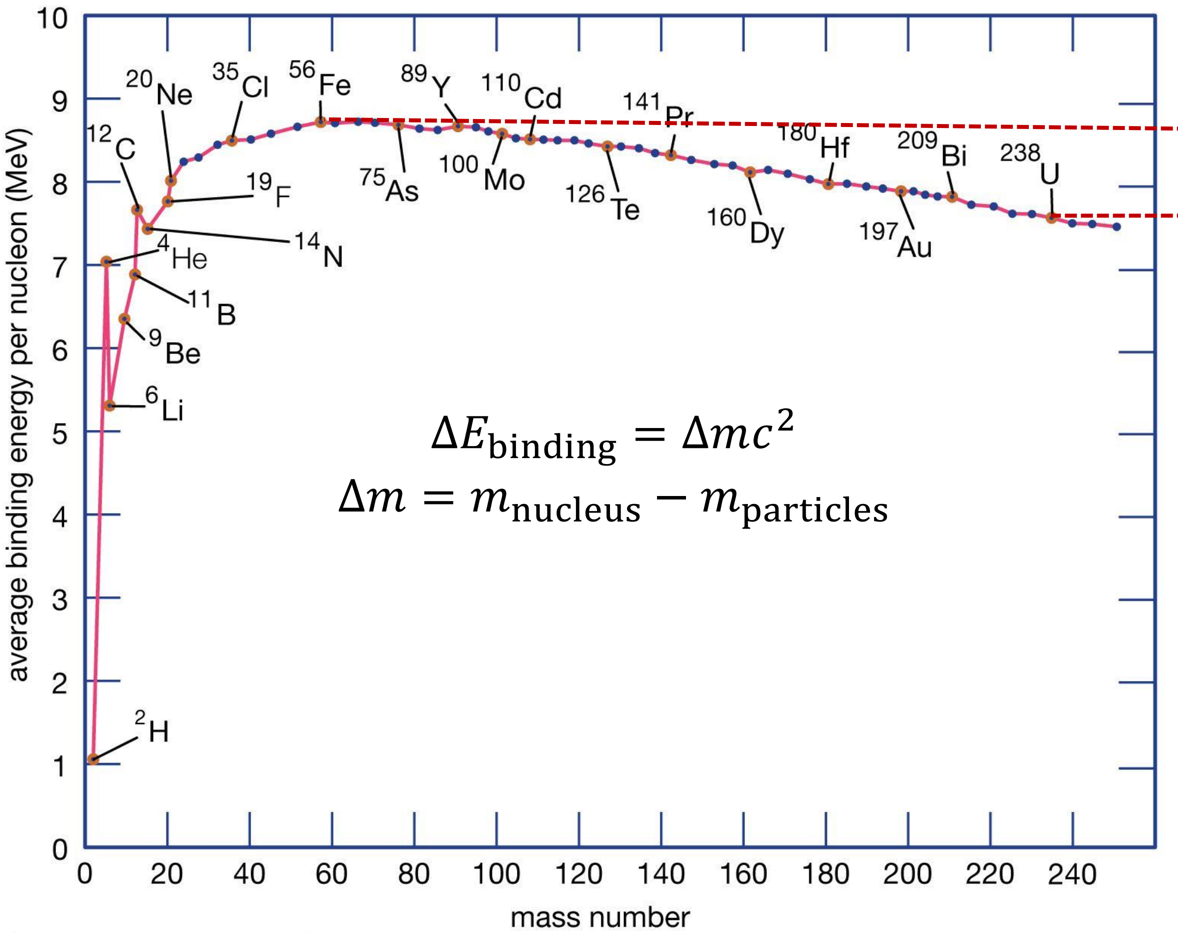
Fissile material
$U^{233}, U^{235}, Pu^{239}$

Or fertile material
U^{238}, Th

Produces 200 MeV energy per fission event

(10^7 times more than burning coal!)

What is nuclear fission?



$\Delta E_{U^{235}}$ - ΔE_{FP} = 7.6 – 8.4 = -0.8 MeV/nucleon

$\Delta H = -0.8 \times 235 \approx 200$ MeV per fission

$\Delta H < 0$: exothermic

P = 200 MeV $\times$ 1.6 10^{-19} J/eV $\times$ 10^{20} fission/s =

= 3.2 GW (10^9W) thermal power!

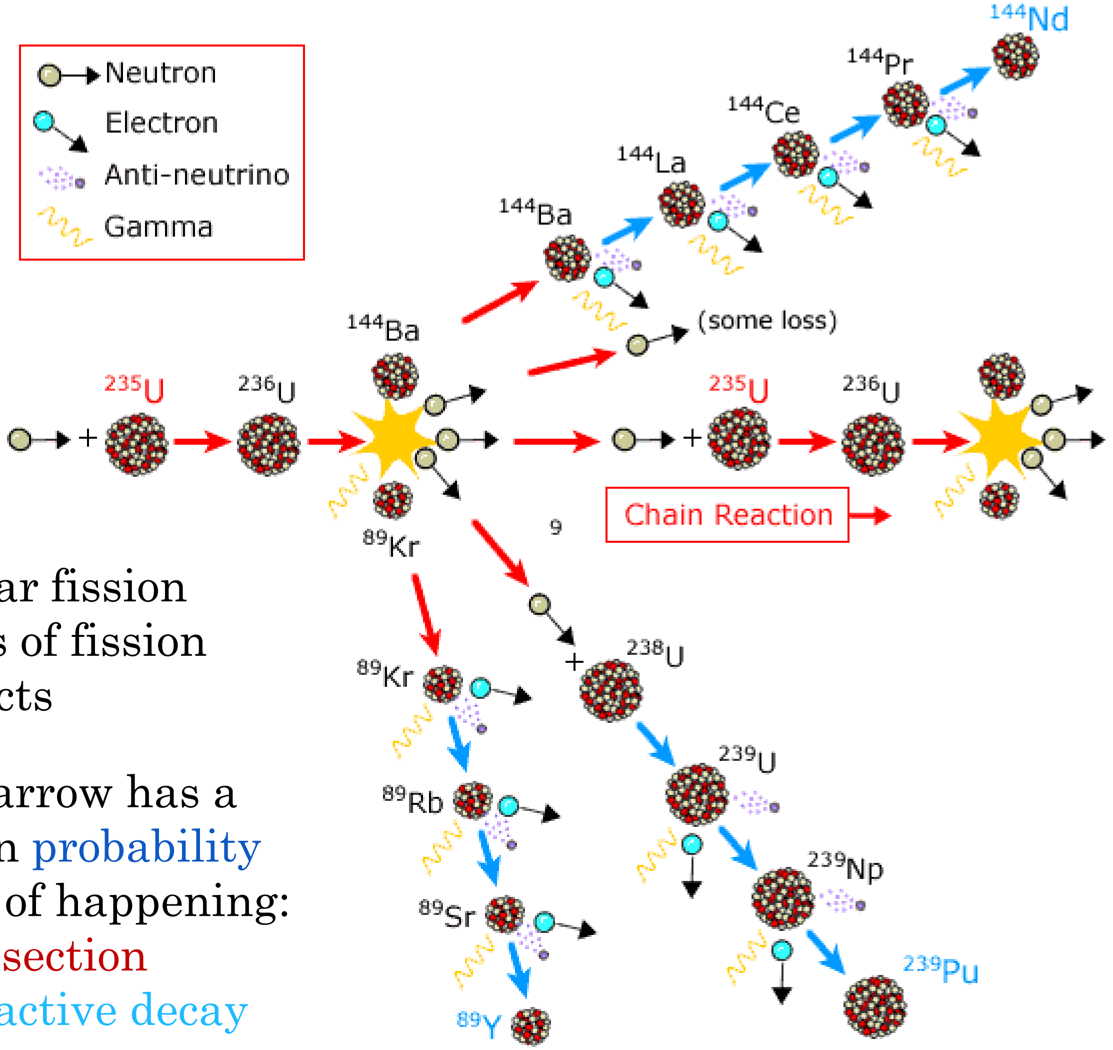
30% performance: $P_{net} = 0.3 \times P \approx 1$ GW

Typical domestic solar panel roof (16 panels):

4 kW in 25 m^2

Would need 4M panels (6250000 m^2) to produce the same energy (only when sunny ☼)

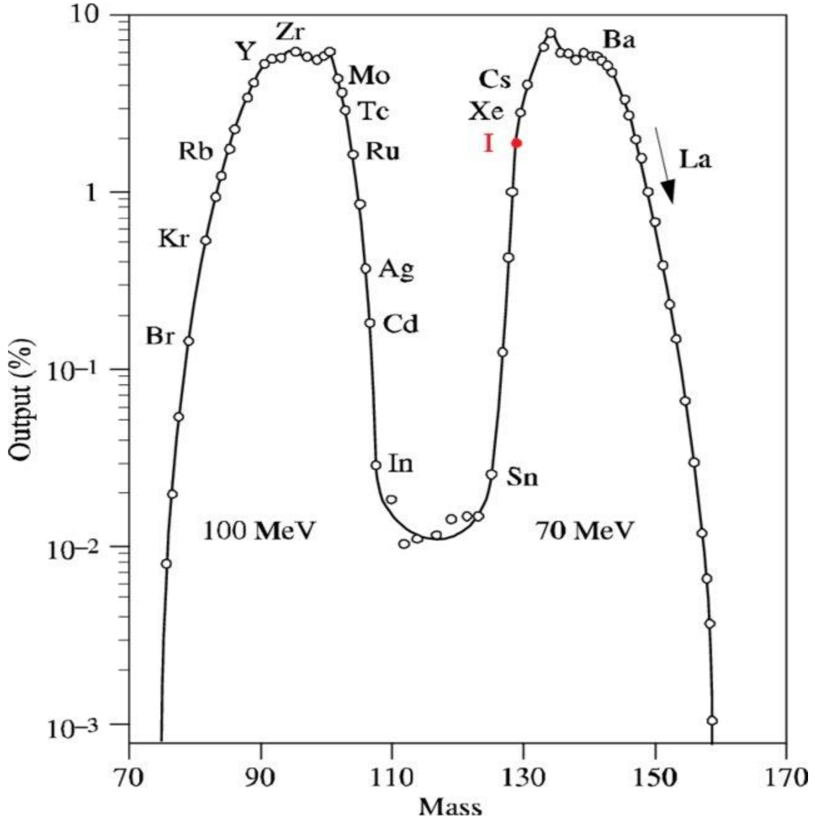
What is nuclear fission?



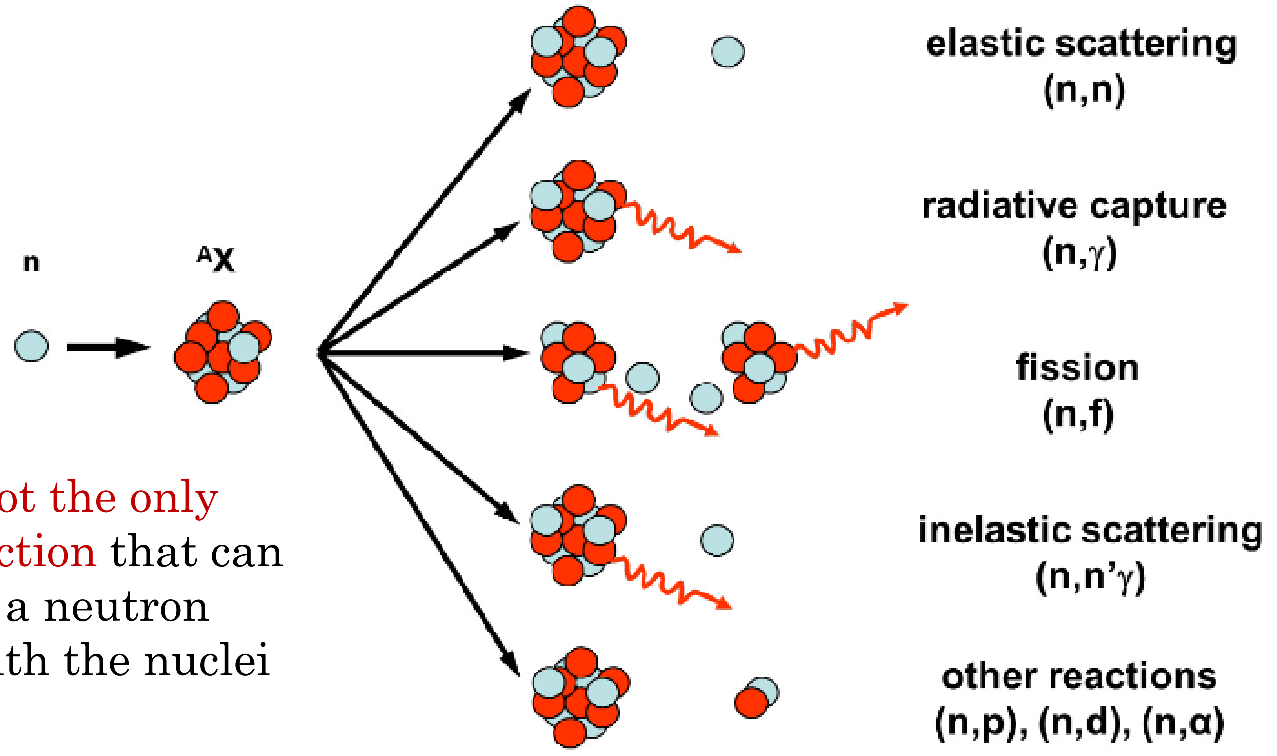
Nuclear fission chains of fission products

Each arrow has a certain probability (<1.0) of happening:
Cross section
Radioactive decay

Distribution of the nuclear fission products for U^{235}



How to achieve nuclear fission?



The probability of each reaction is defined by the cross section of the nuclei, that depends on the energy of the colliding neutron

Fission is not the only nuclear reaction that can occur when a neutron interacts with the nuclei

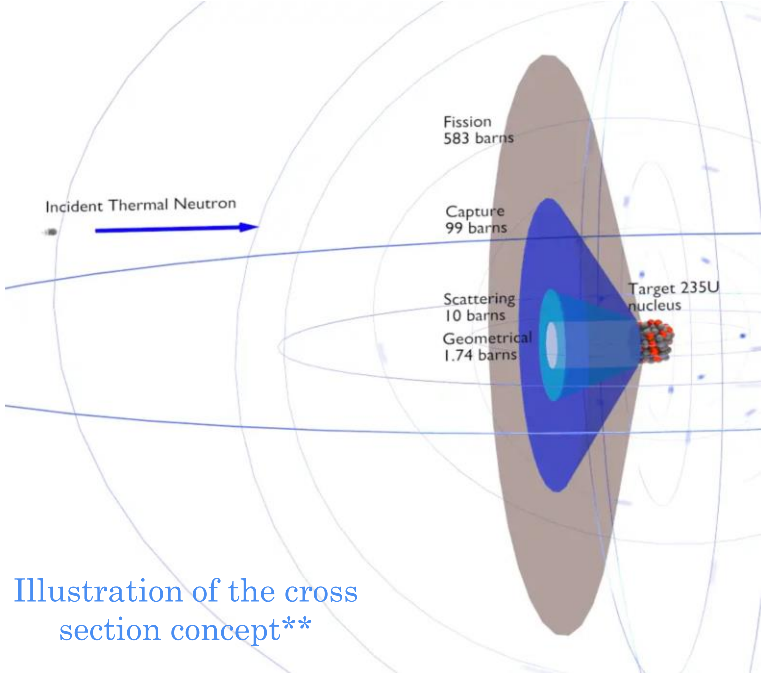
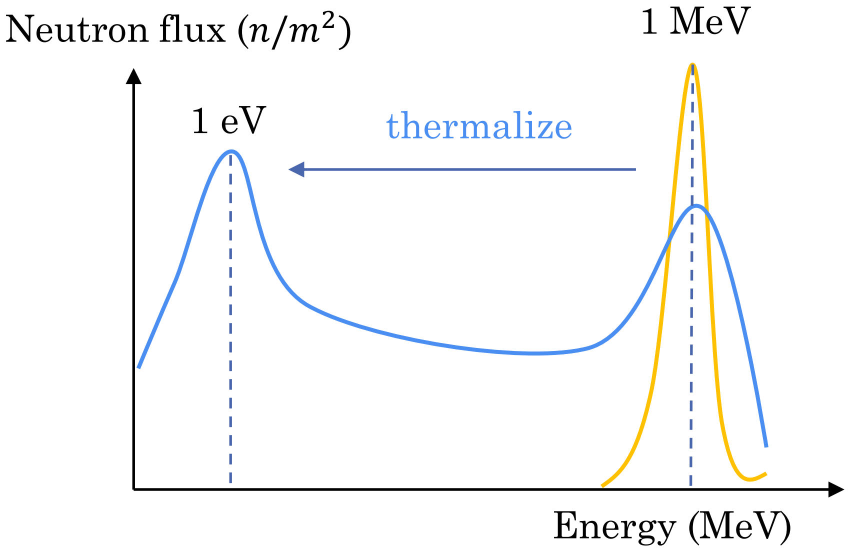


Illustration of the cross section concept**

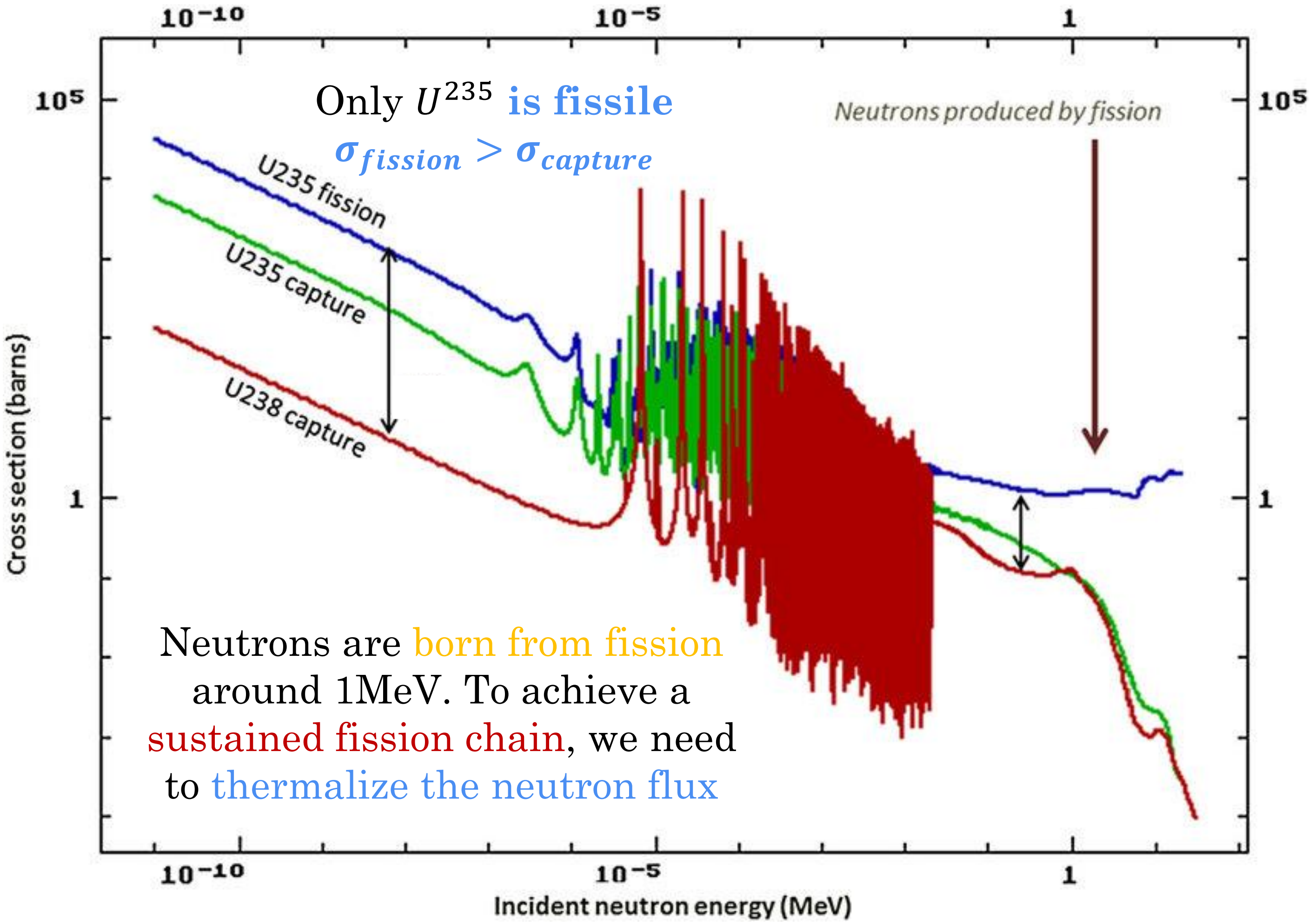
If we want a sustained fission chain reaction, we need to maximize fission and minimize capture

How to achieve nuclear fission?

Cross section σ is measured in **barns:** 10^{-28} m^2



Fission and capture cross section of nuclear fuel



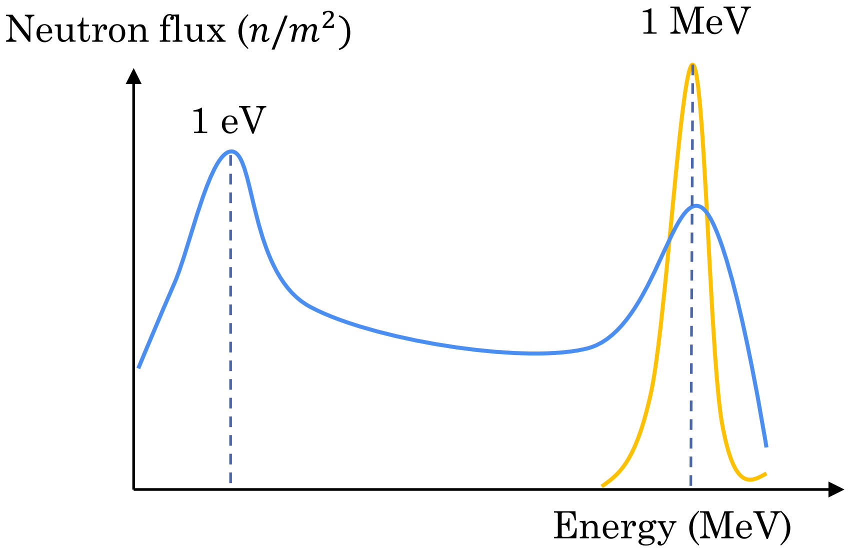
Neutrons are born from fission around 1MeV. To achieve a sustained fission chain, we need to thermalize the neutron flux

How to achieve nuclear fission?

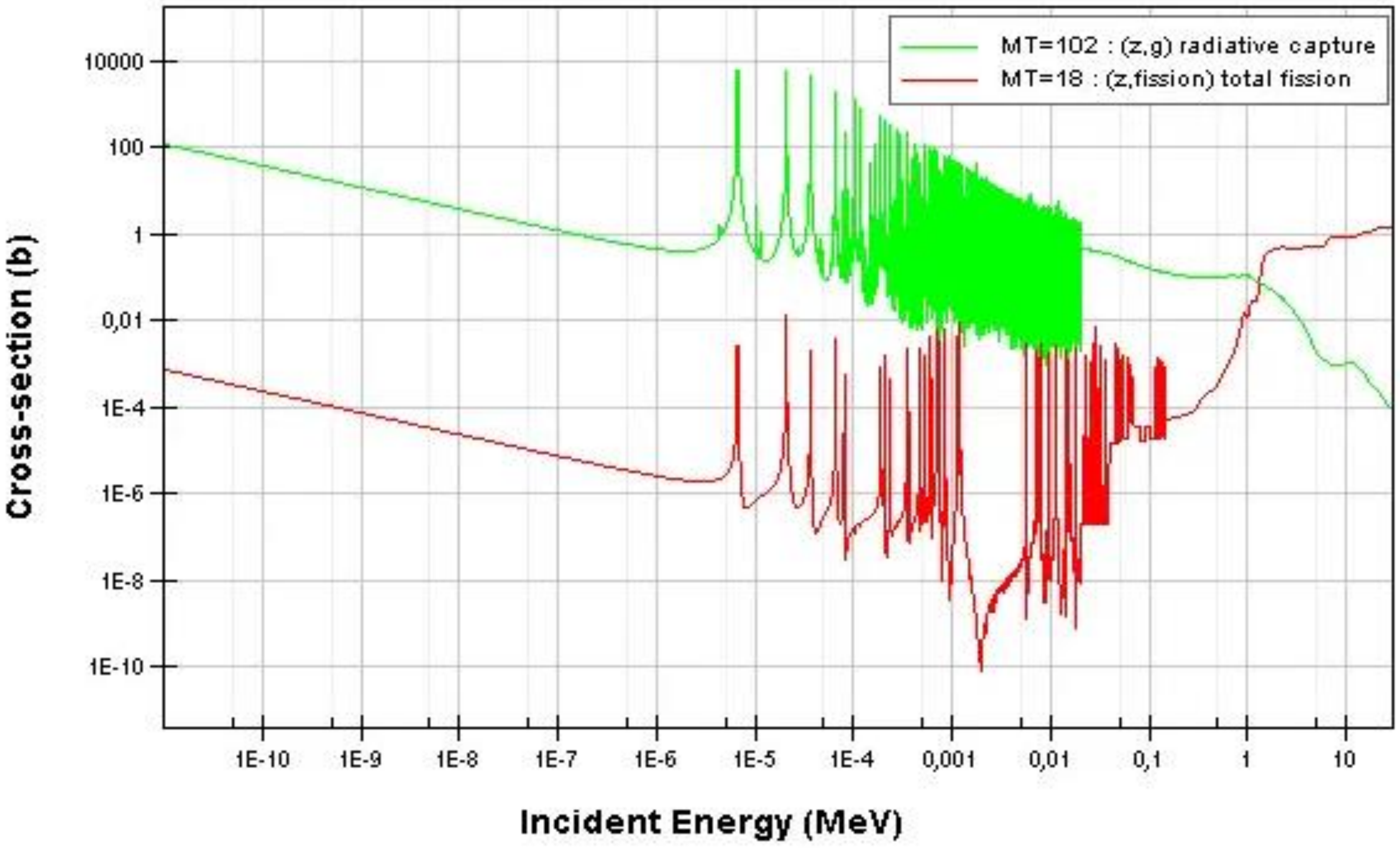
U^{238} **is fertile**
$\sigma_{fission} > \sigma_{capture}$
after 1MeV

In natural Uranium:
99.3% U^{238}, **0.7%** U^{235}

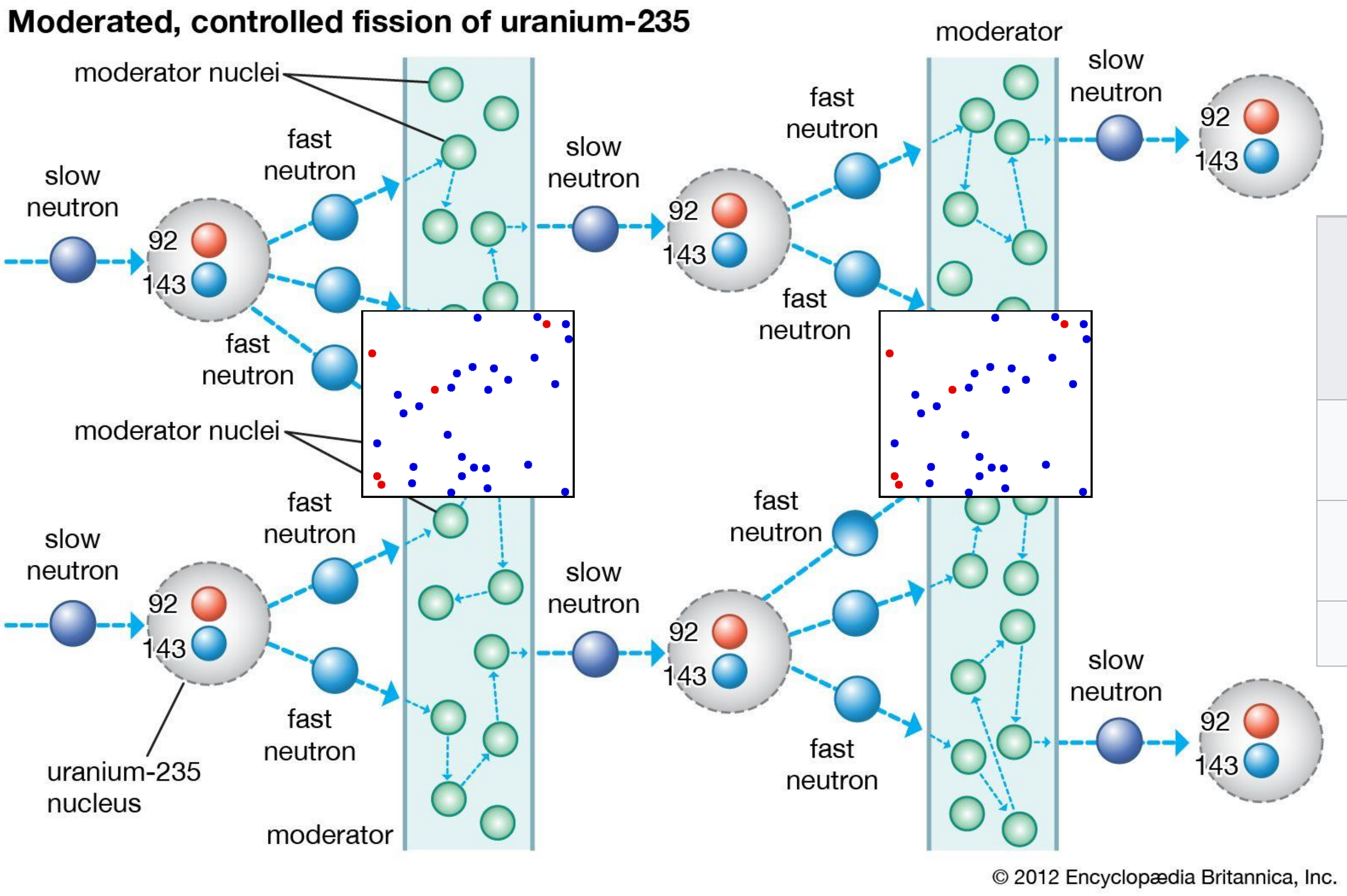
Commonly, for nuclear reactors, we need **3%-5%** U^{235} → enrichment



Fission and capture cross section of U238



How to achieve nuclear fission?



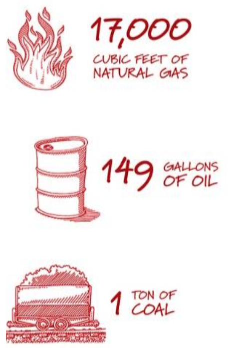
To thermalize the neutron flux, we need to use a **moderator**. Neutrons will lose their energy through scattering: elastic collisions

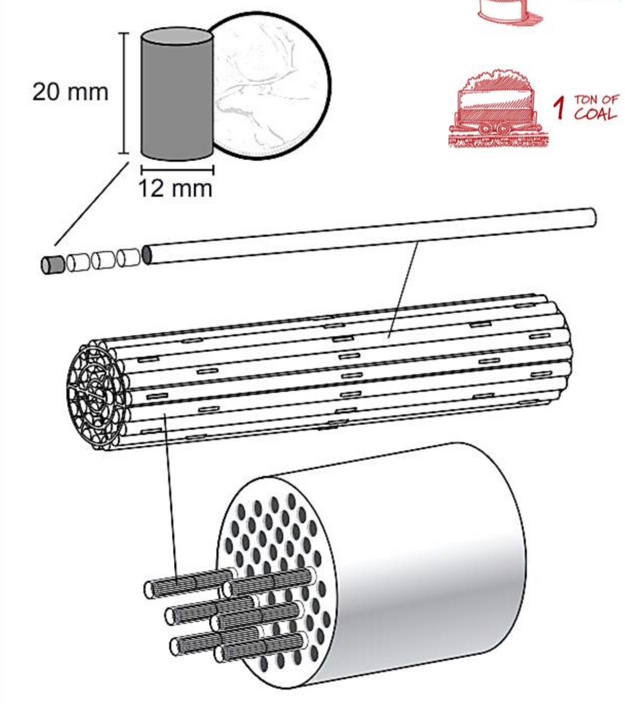
Moderator Type	Neutron scattering cross section (σ_s) in barns	Neutron absorption cross section (σ_s) in barns
Light water (H_2O)	49	0.66
Heavy water (D_2O)	10.6	0.0013
Graphite (C)	4.7	0.0035

↑ high scattering ↓ low capture

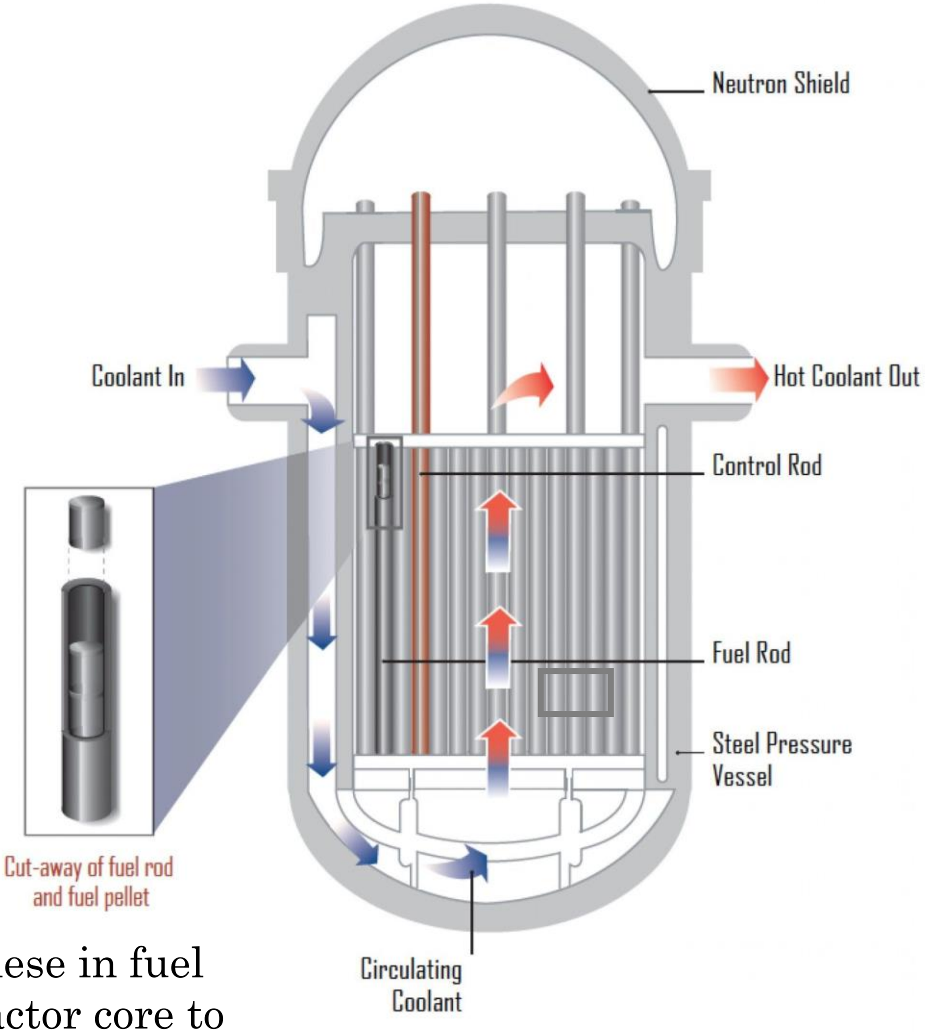
Inside the nuclear reactor core: Fuel

As much energy as:

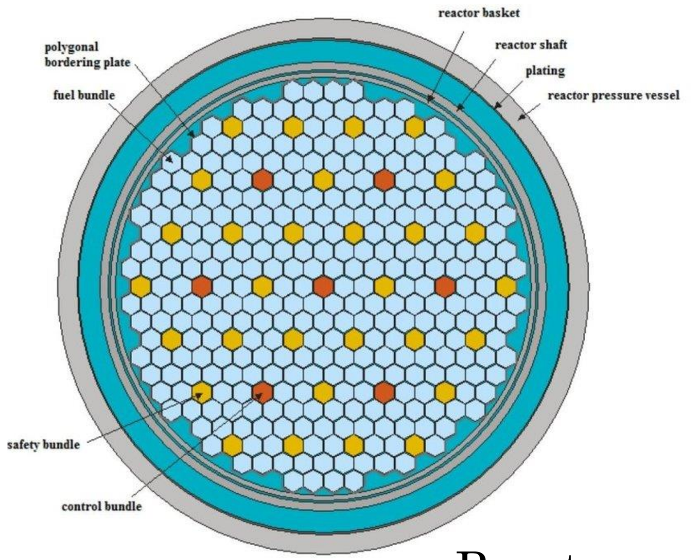




Fuel is assembled in fuel rods, these in fuel bundles and distributed in the reactor core to have a uniform neutron flux distribution



In a nuclear reactor, the fuel and the moderator are assembled inside of the reactor pressure vessel, forming the reactor core

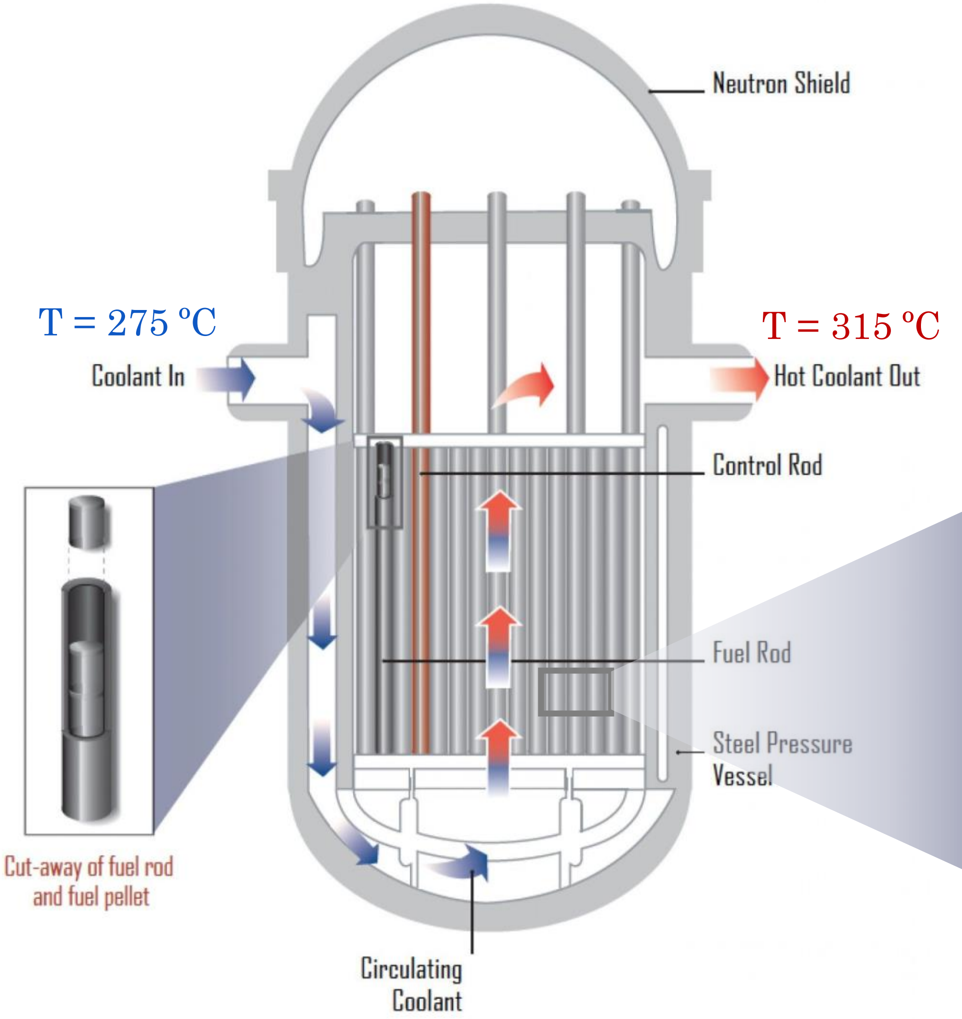


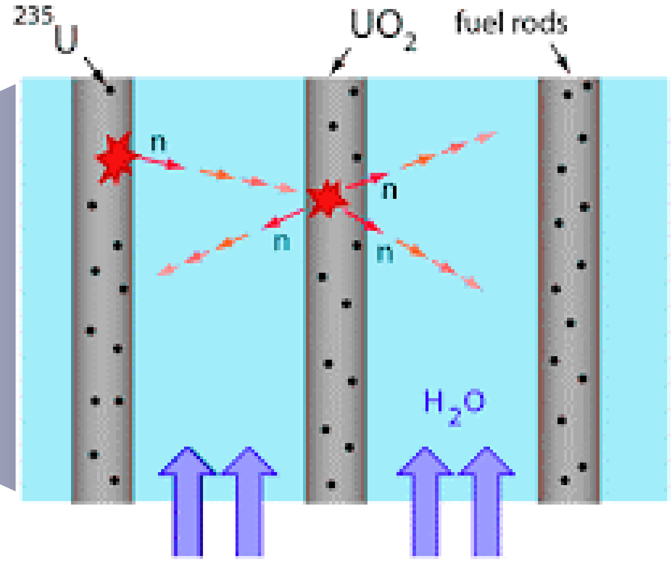
Reactor core example

Inside the nuclear reactor core: Fuel assembly

In Presurized Water Reactors (**PWR**), the moderator, water, is also the coolant.

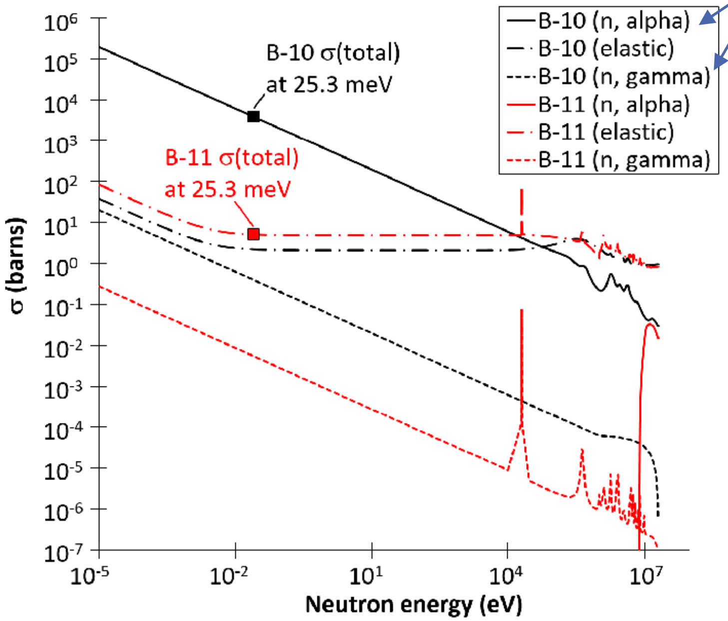
It flows between the fuel bundles, extracting the heat from the core and moderating the fission-born neutrons with a pressure of P = 155 bar



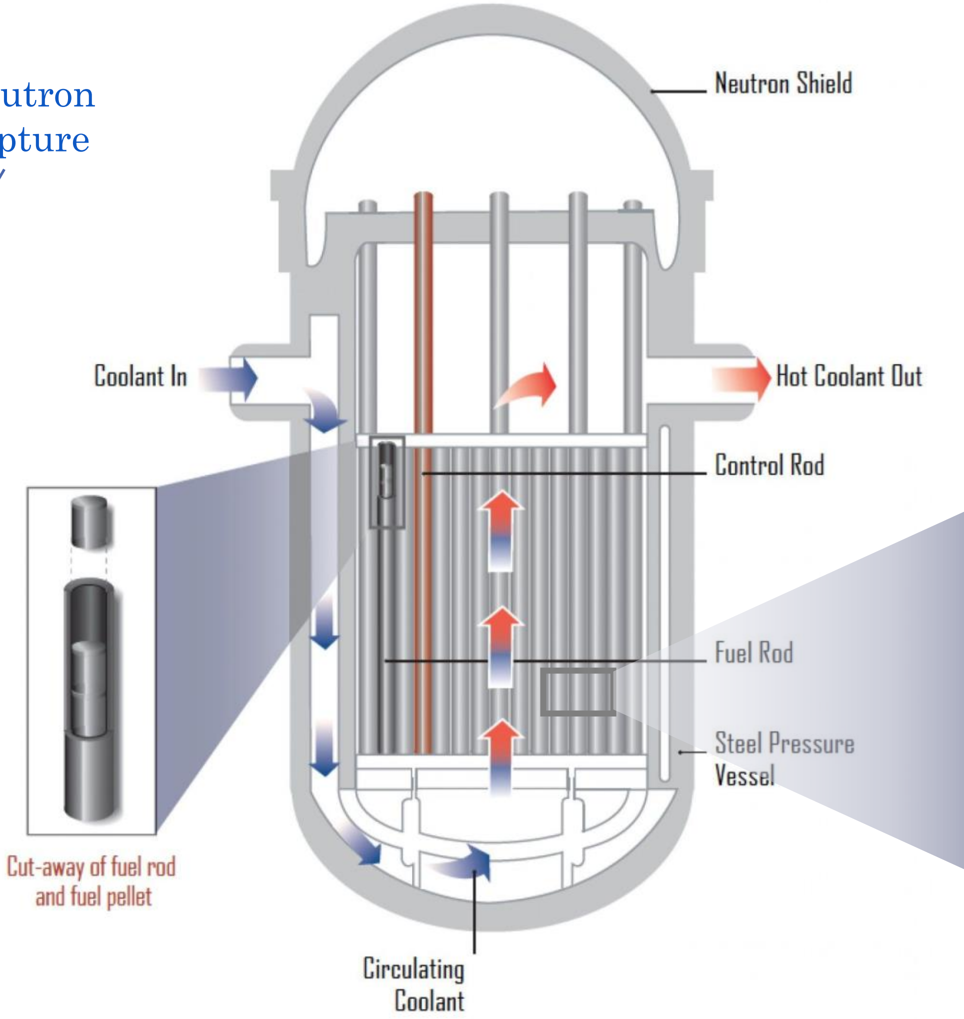


Inside the nuclear reactor core: Control rods

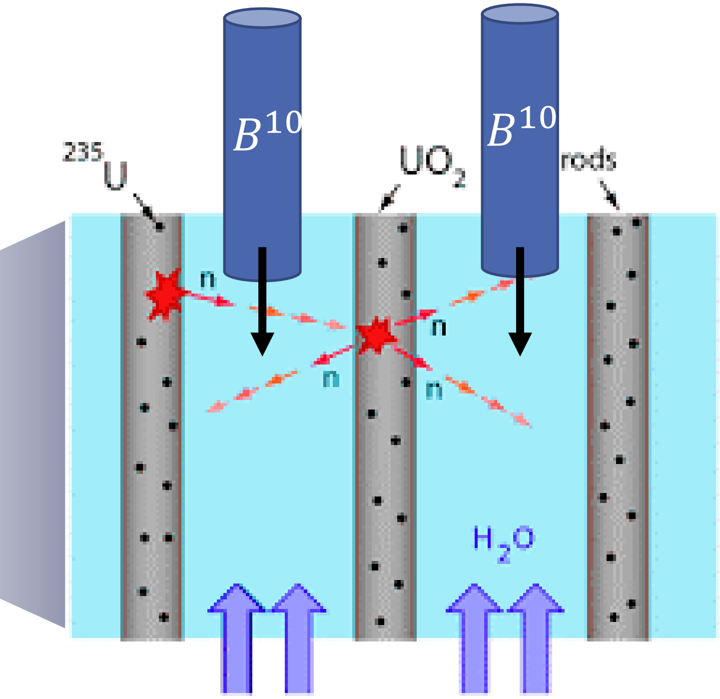
neutron capture



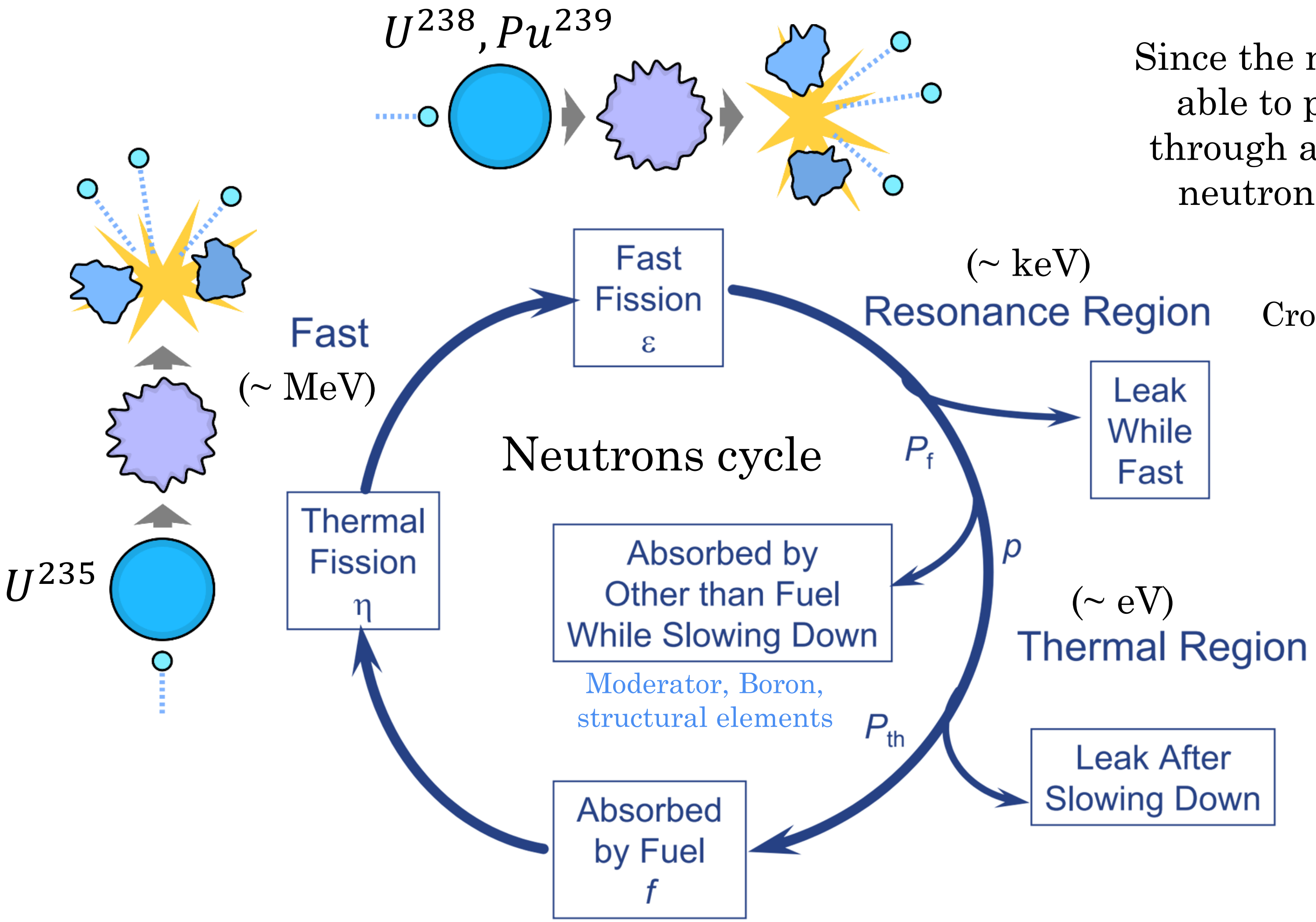
Boron B^{10} cross sections (σ) for neutron capture are very high!



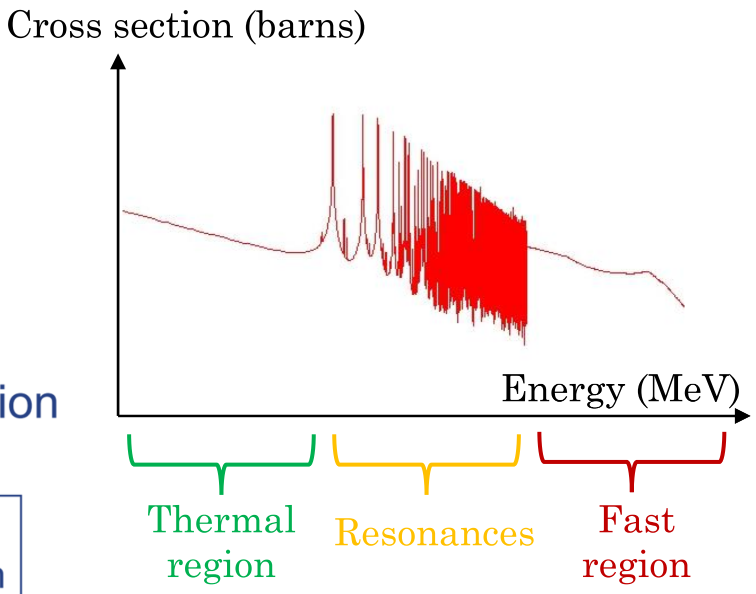
Moderation can be adjusted by control rods that can absorb many neutrons



How to maintain a controlled fission chain?

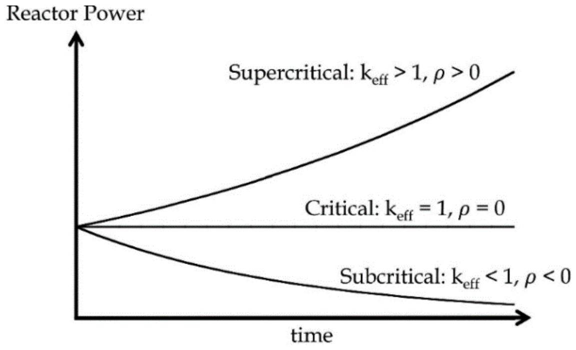


Since the neutrons are born until they are able to produce a new fission, they go through a life cycle that accounts for the neutron losses before the next fission



How to maintain a controlled fission chain?

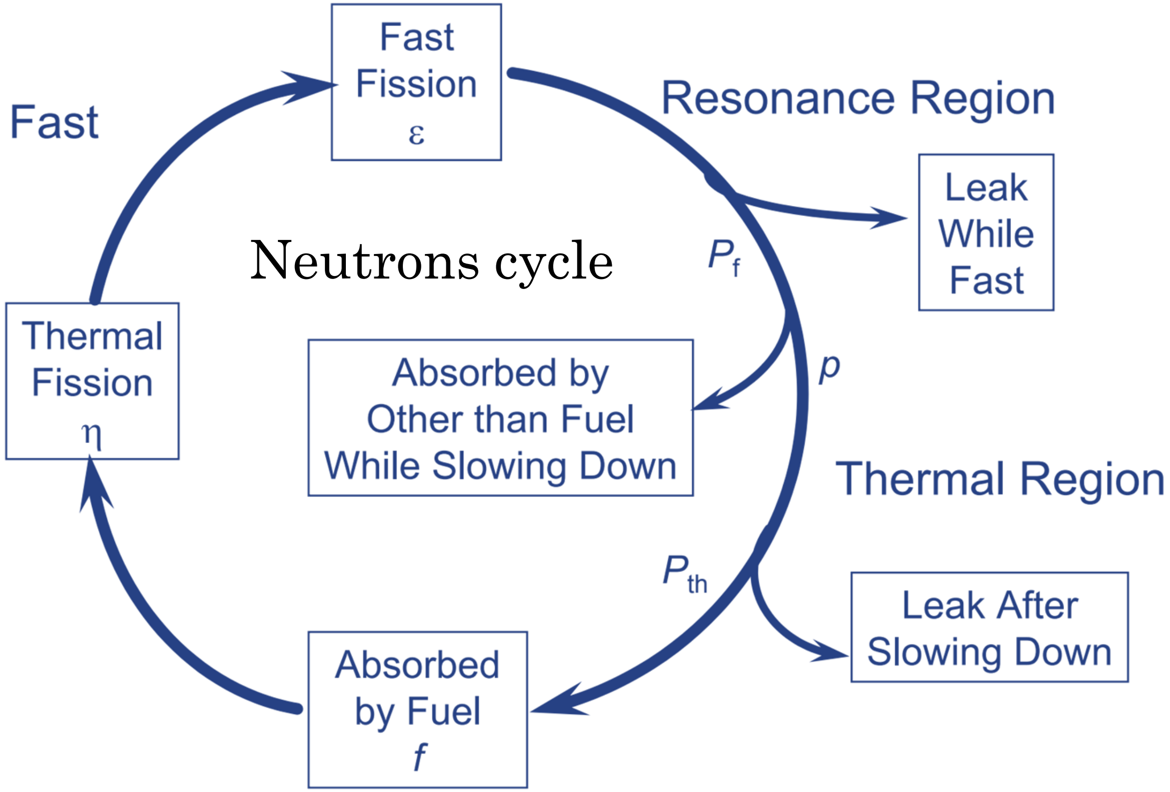
$$k_{eff} = \eta \varepsilon P_f p P_{th} f \begin{cases} < 1 \text{ sub-critical} \downarrow n \\ = 1 \text{ critical} \\ > 1 \text{ super-critical} \uparrow n \end{cases}$$



Subcriticality

The chain reaction is not maintained and will stop (intrinsically safe)

The reactor will shut down and the power produced by the core will be only the decay heat



Supercriticality

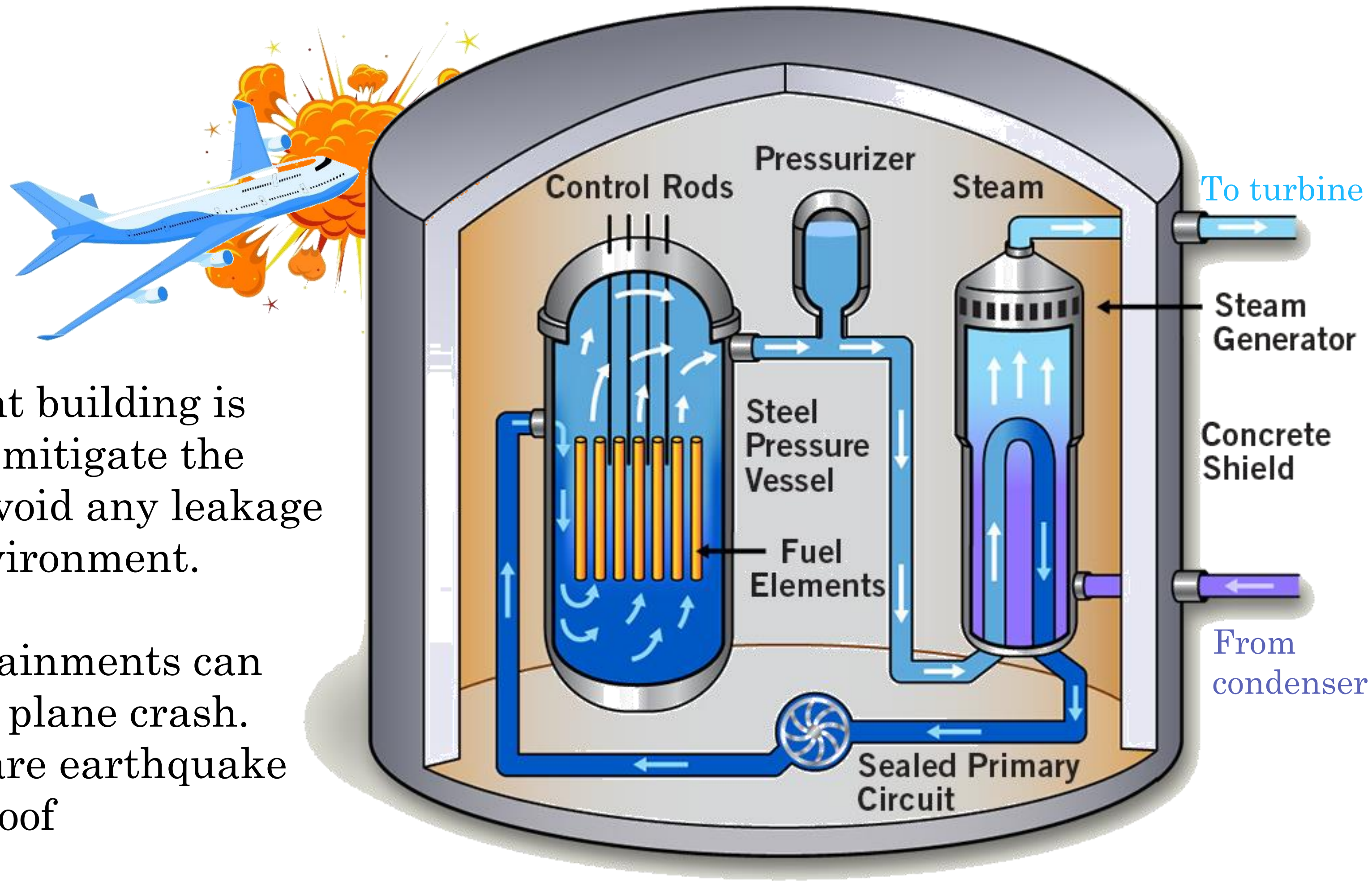
The chain reaction will lead to an exponential growth of the reactor power. If the safety system is not able to stop it, the core will melt

This is not possible in current reactors by design (void coefficient)

Inside a nuclear power plant: Containment

Containment building is designed to mitigate the radiation and avoid any leakage to the environment.

Modern containments can withstand a plane crash. Foundations are earthquake proof

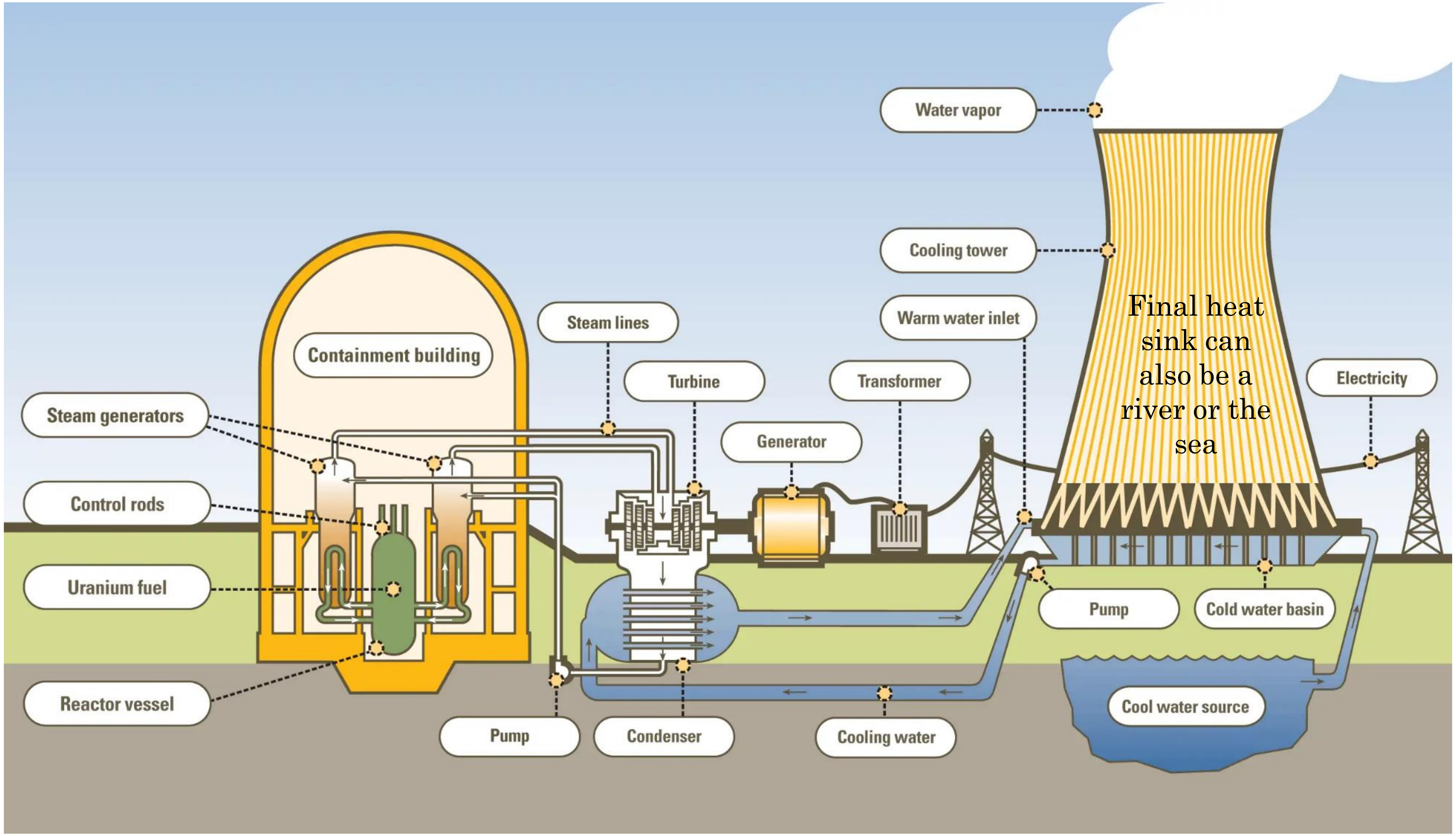


Inside, we find the reactor pressure vessel the primary coolant loop and the steam generators

For PWR design (image), the primary loop contains:

- Primary pumps: maintain loop pressure
- RPV: remove heat from core
- Pressurizer: absorbs temperature (density) changes and aids in controlling the pressure during accident
- U-tubes in steam generator: transfer heat to secondary loop

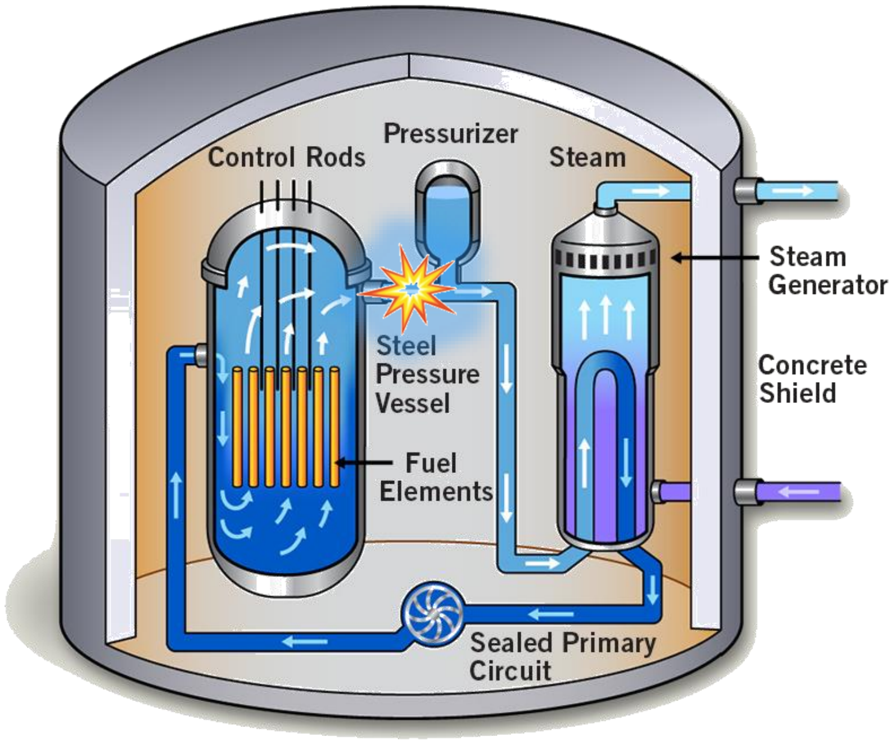
Inside a nuclear power plant: Electricity



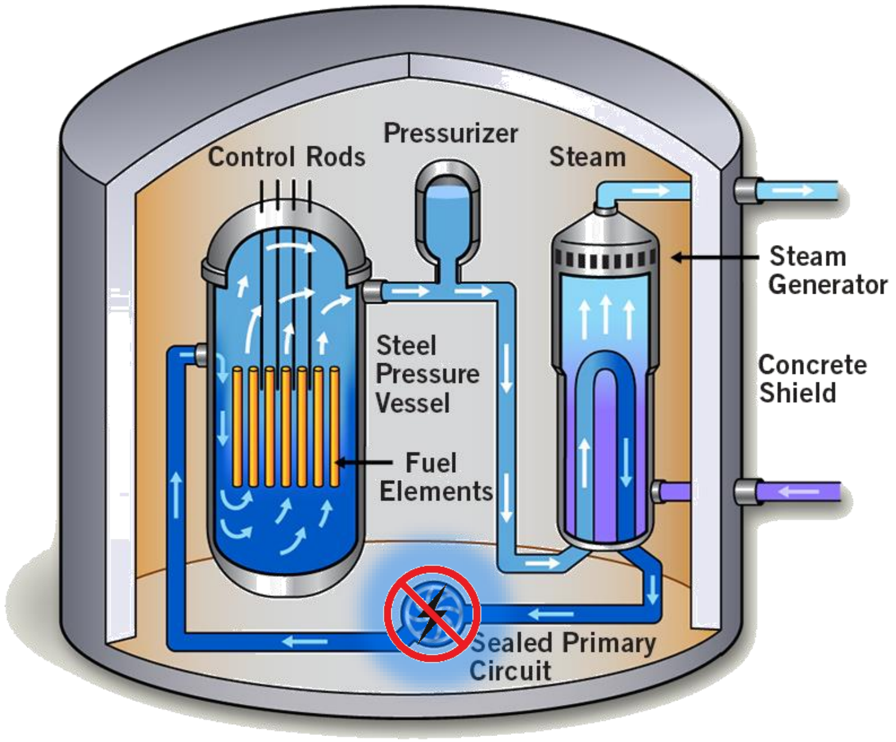
Final heat sink can also be a river or the sea

Safety in nuclear power plants: Accidents

Loss of coolant accident (LOCA)



Station Black Out (SBO)



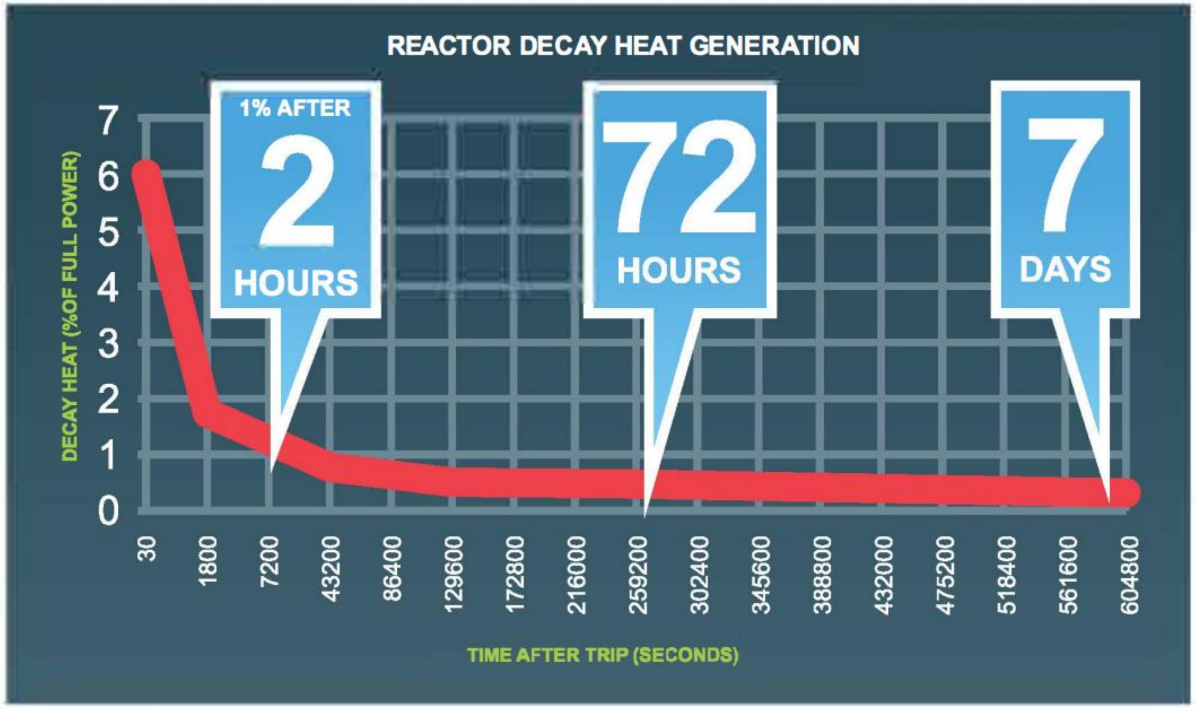
Need a full presentation to cover them properly ☺

Safety in nuclear power plants: Decay Heat

The important concept is how to remove the decay heat from the reactor core once it is shut down (SCRAM), done automatically by the reactor when an anomaly is detected

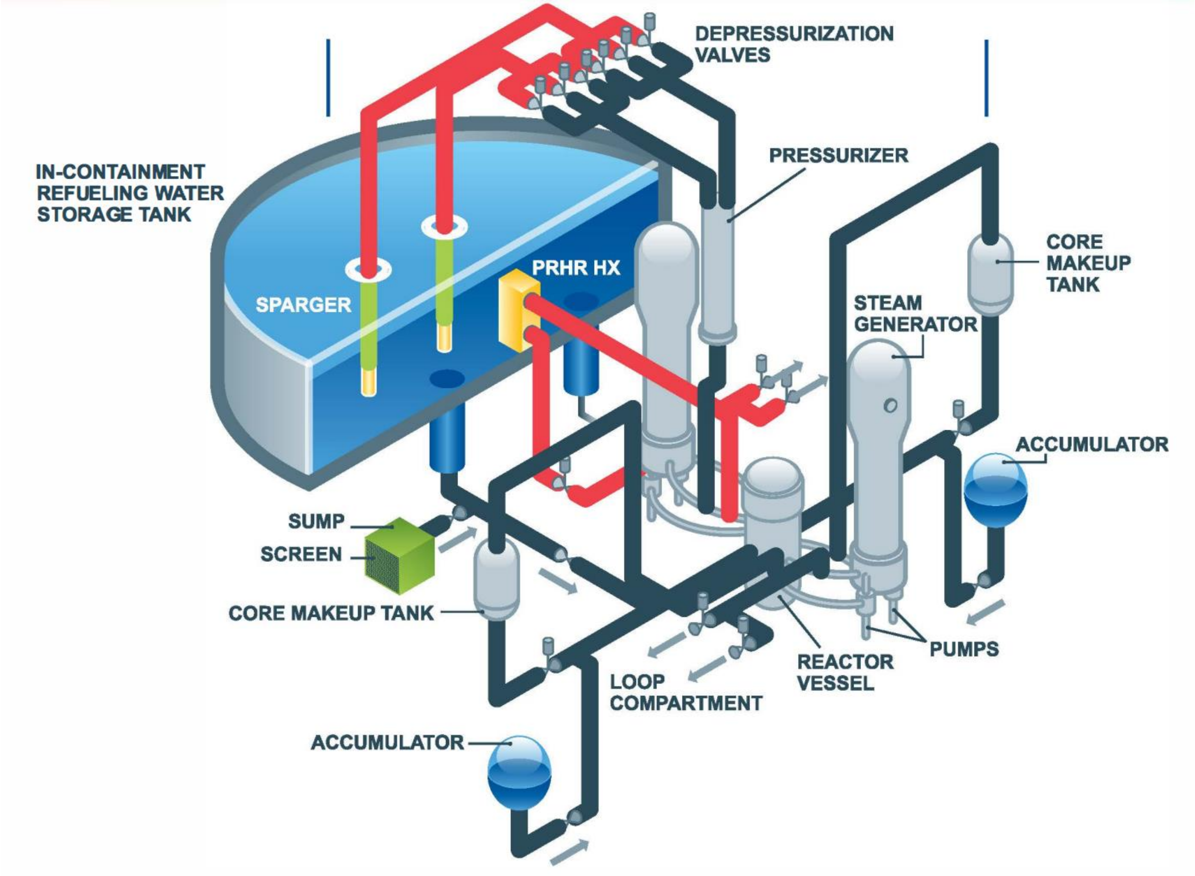
For decay heat removal (DHR), we have active systems (powered by the grid or emergency diesel generators) and in Gen III+, passive systems driven by natural forces

After Fukushima, new safety measurements don't require any human action the first 72h (This topic also requires a full presentation ☺)

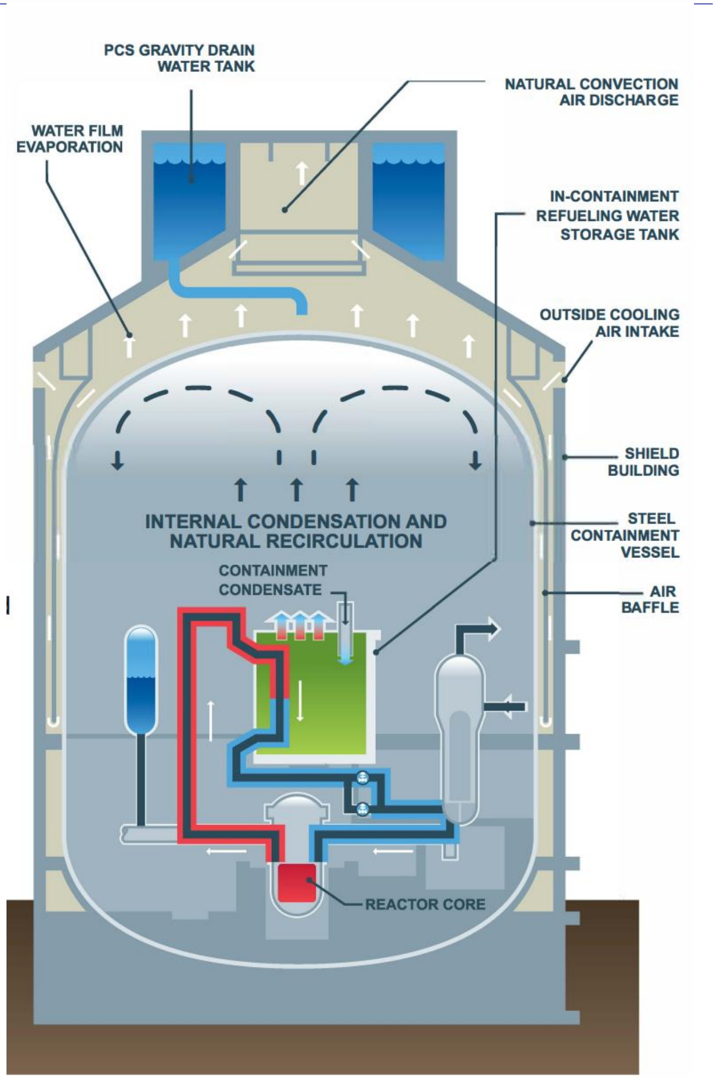


Safety in nuclear power plants: Safety systems

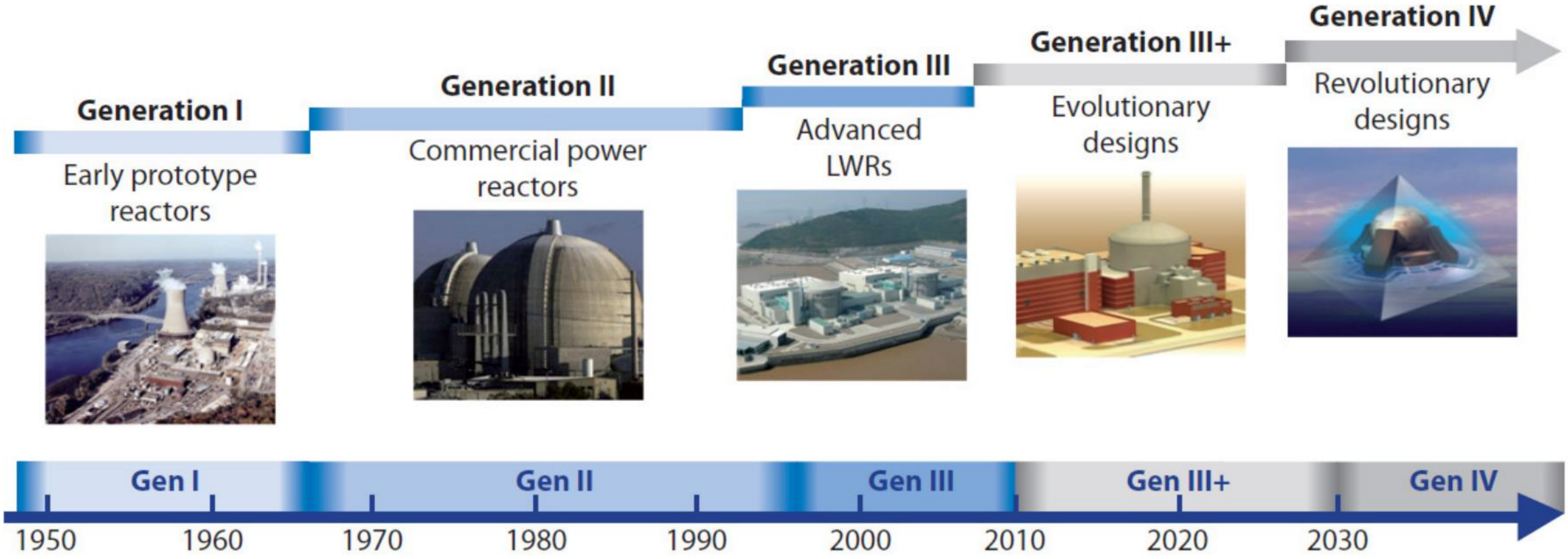
Active and passive safety systems for DHR (each system has redundancy in case one train fails)



Long term, passive cooling through containment walls condensation (just requires to refill the PCS after 72h)

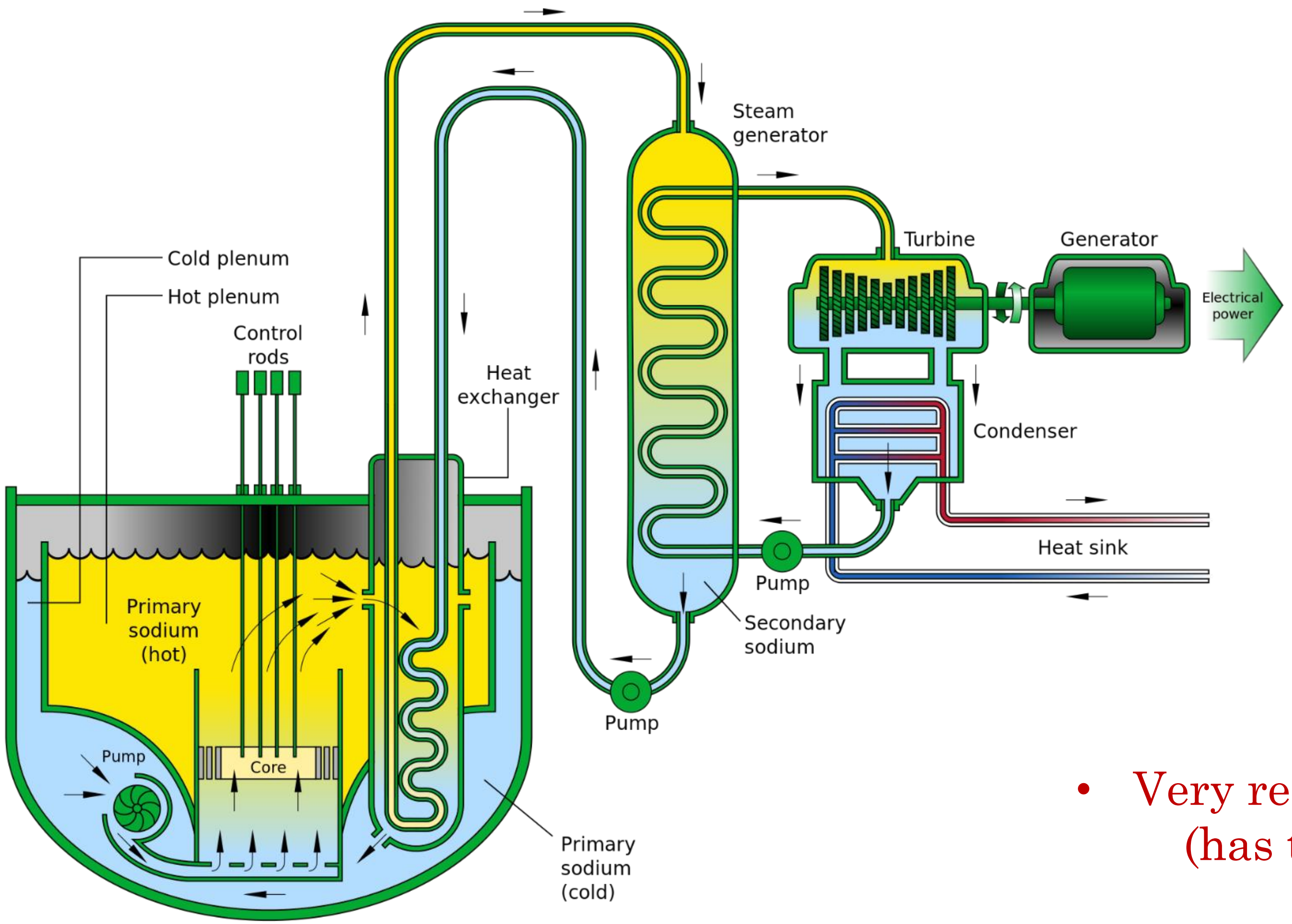


Gen IV nuclear reactors



Gen IV Designs: SFR

Sodium Fast Reactor (SFR) has an innovative design, but introduced in the 50s as a proof of concept



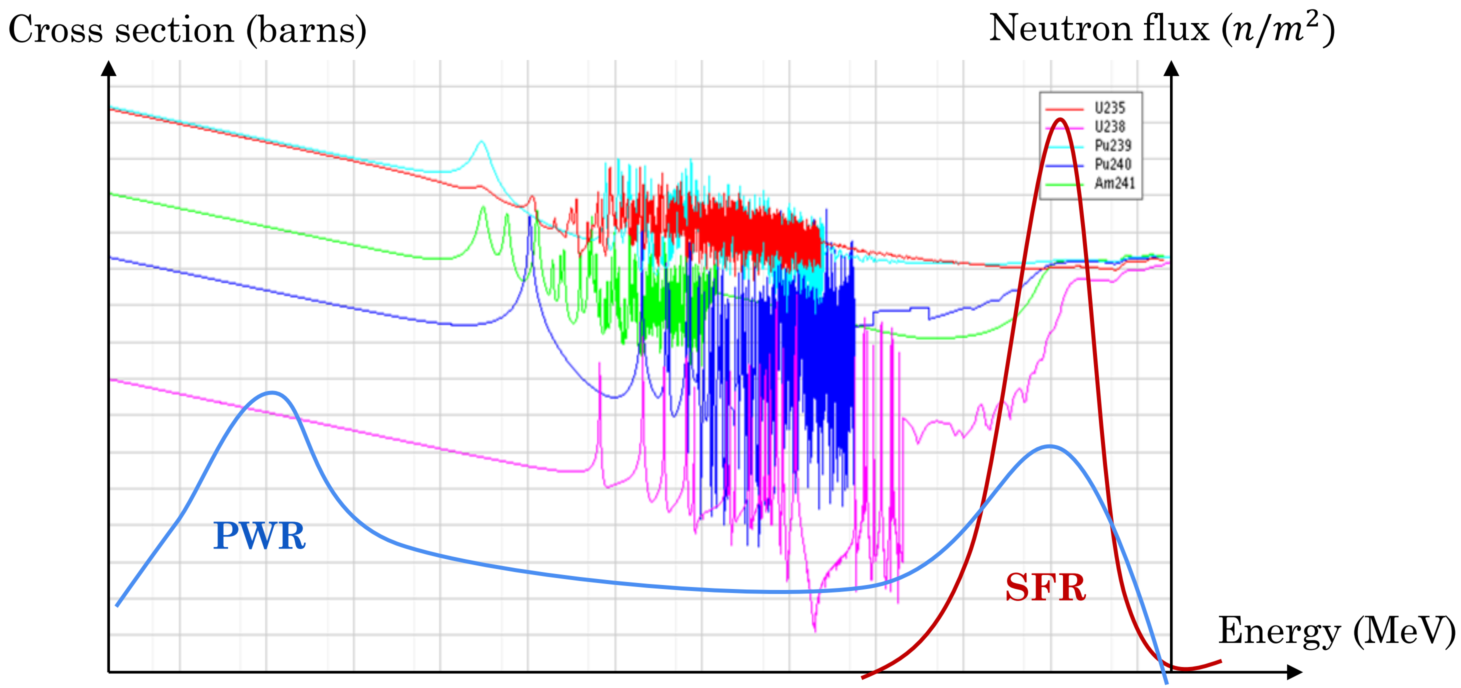
Is cooled by sodium:

- High thermal conductivity
- Does not moderate: fast neutron spectrum

- Very reactive to water and air (has to be leackage proof)
- Corrosion

Advantages of SFR

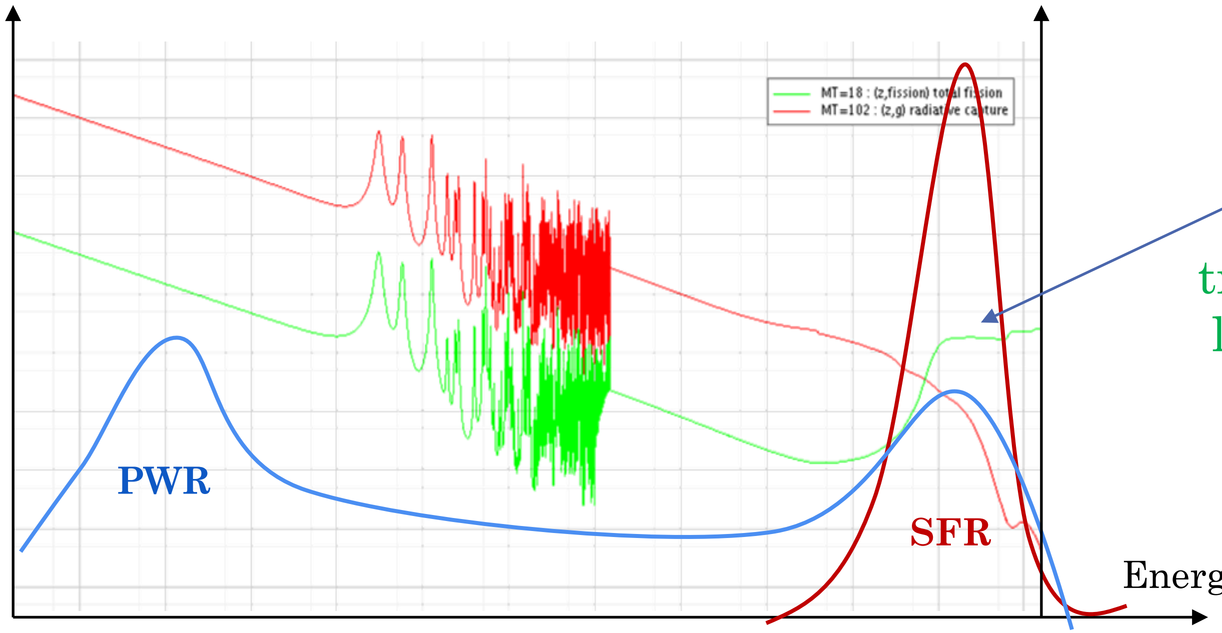
Fission cross section of $U^{235}, U^{238}, Pu^{239}, Pu^{240}, Am^{241}$



With a special design of the core, it uses natural uranium U^{238} fissions and breeding (to Pu): no need for enrichment!

Advantages of SFR

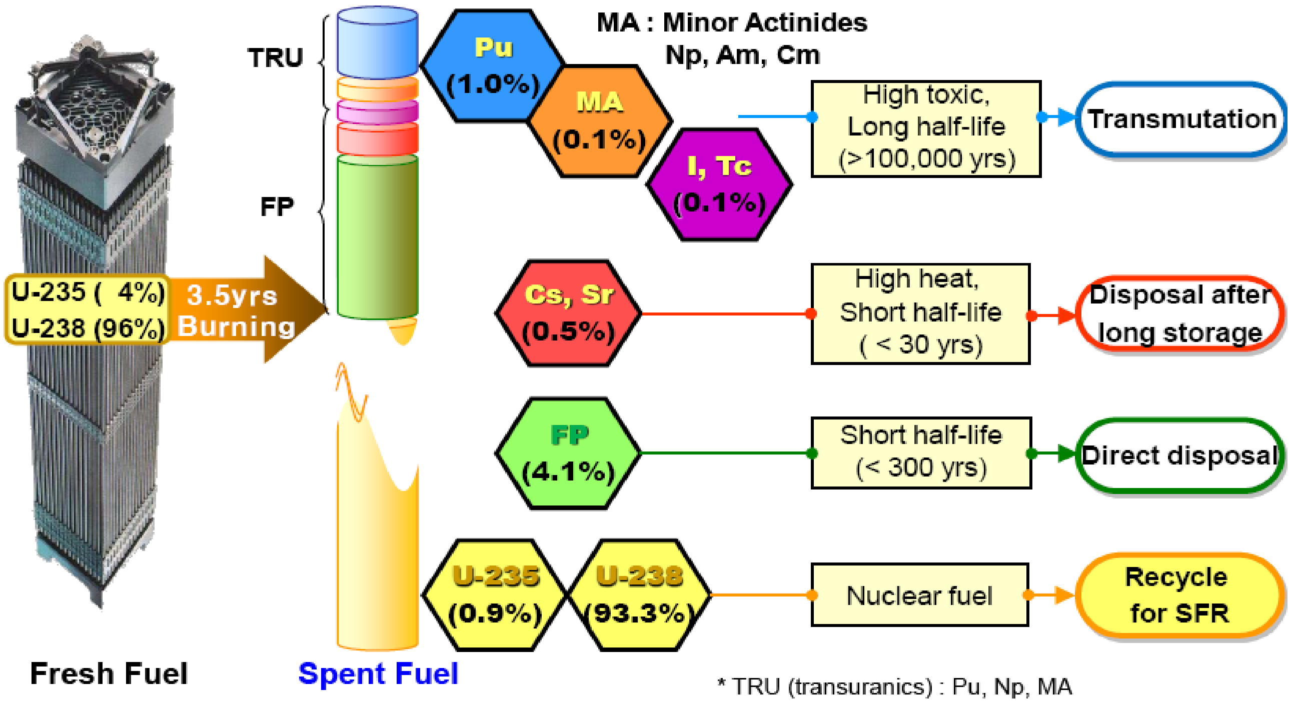
Fission and capture cross section of Am^{241}



The worrisome elements in the spent fuel that have a long-term radioactivity are the Minor Actinides, like Am^{241}

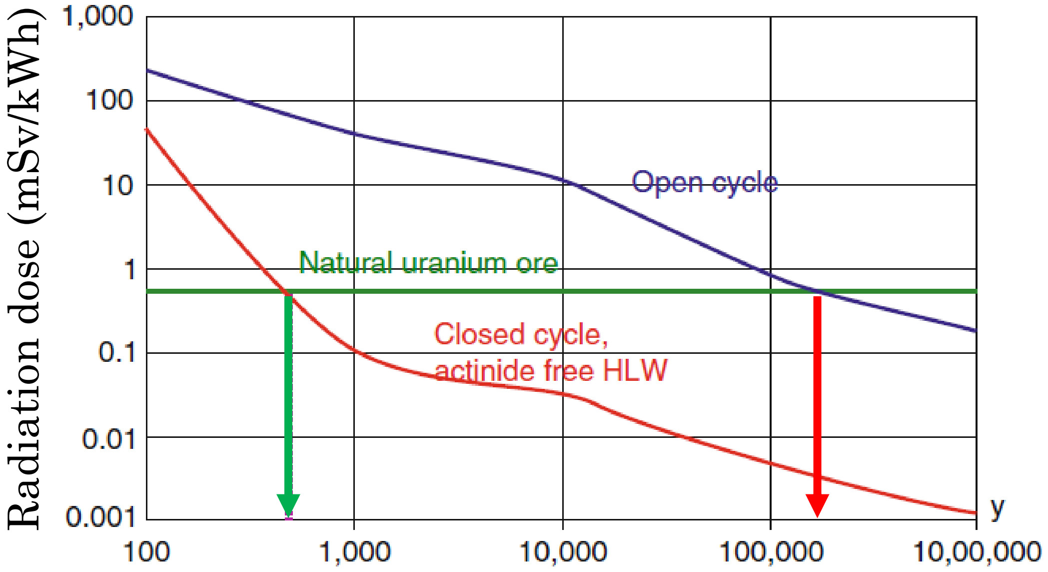
With a fast spectrum reactor, we can do transmutation of long half-life radioactive waste into fissile fuel

Advantages of SFR



Burn long half-lived Minor Actinides

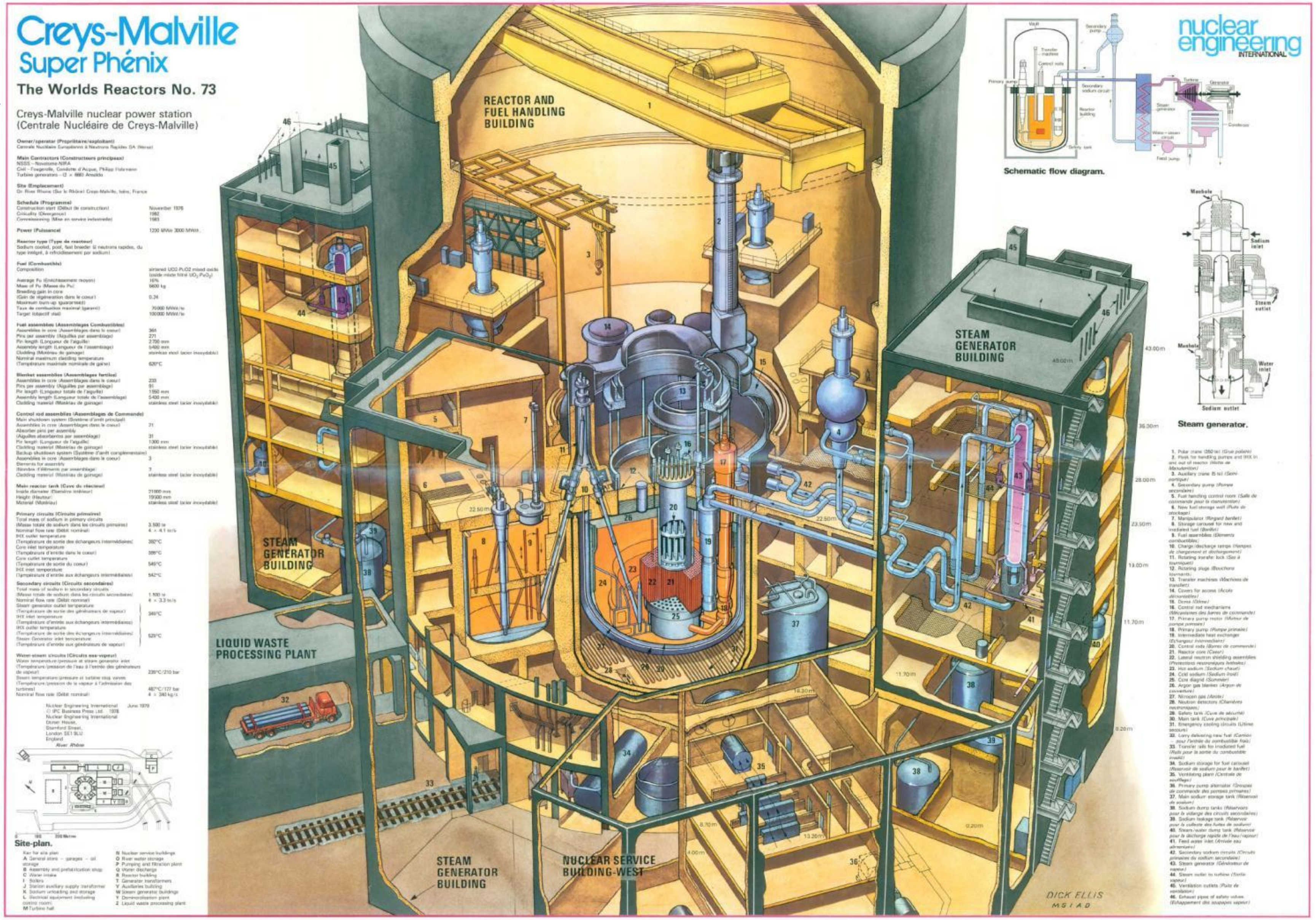
Spent fuel storage needs



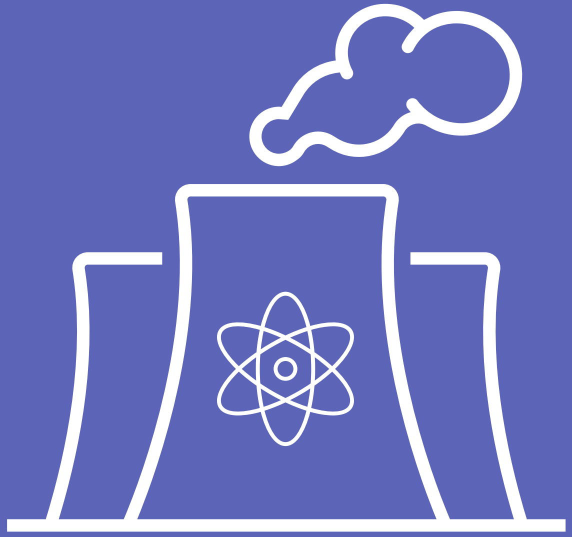
~800 ↔ ~110,000

93% of unburnt U^{238}!!!!! → recycling spent fuel ☺

Superphenix



Thank you ☺



Quick Introduction to Nuclear Physics and Engineering

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Outline