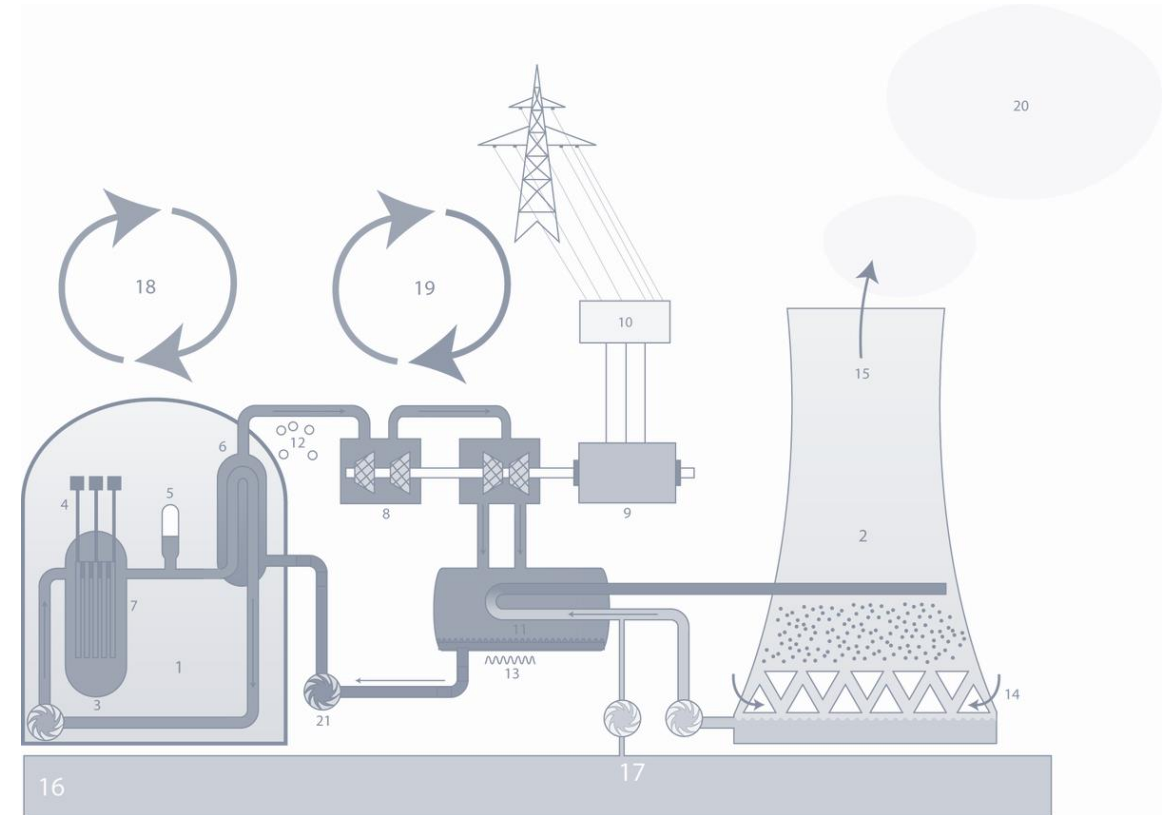


Quick Introduction to Nuclear Physics and Engineering

by two nuclear enthusiasts ☺:
E. de la Fuente, D. Amorim

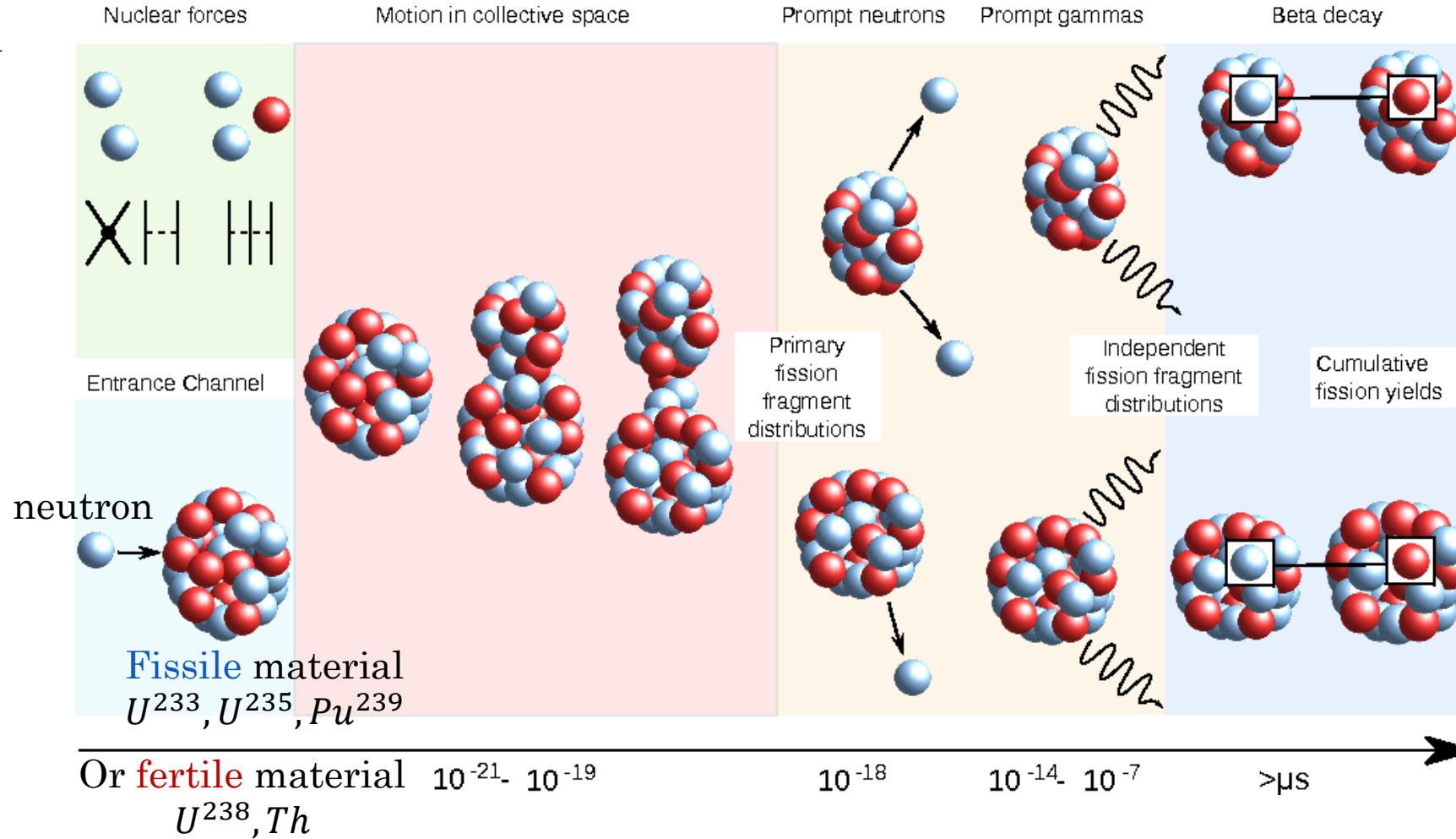
Big thanks to: G. Jiménez and S. Larriba from Universidad Politécnica de Madrid (UPM)



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

What is nuclear fission?

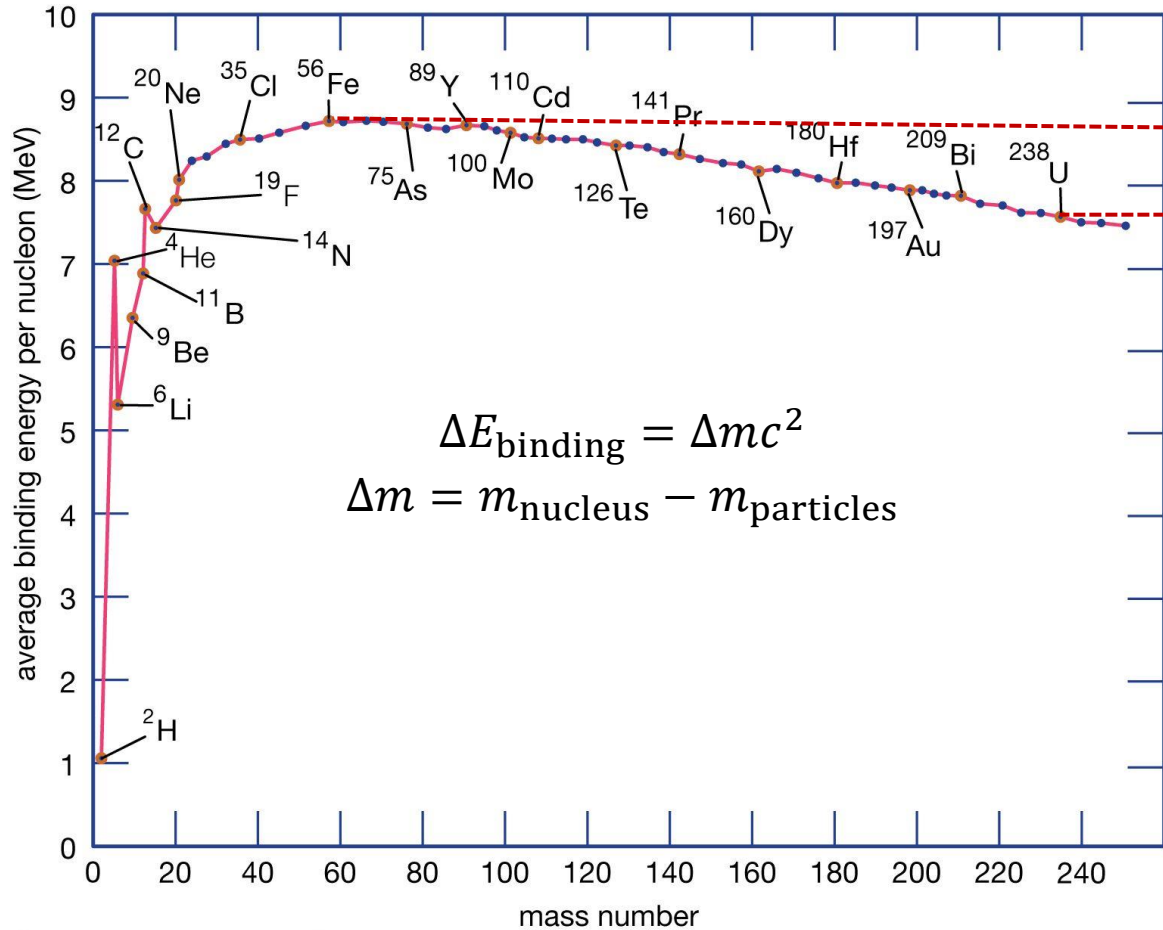
Discovered in 1938 by Otto Hahn and Lise Meitner



Produces 200 MeV energy per fission event

(10^7 times more than burning coal!)

What is nuclear fission?



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

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

$\Delta H < 0$: exothermic

$$P = 200 \text{ MeV} \times 1.6 \cdot 10^{-19} \text{ J/eV} \times 10^{20} \text{ fission/s} = 3.2 \text{ GW (} 10^9 \text{W) thermal power!}$$

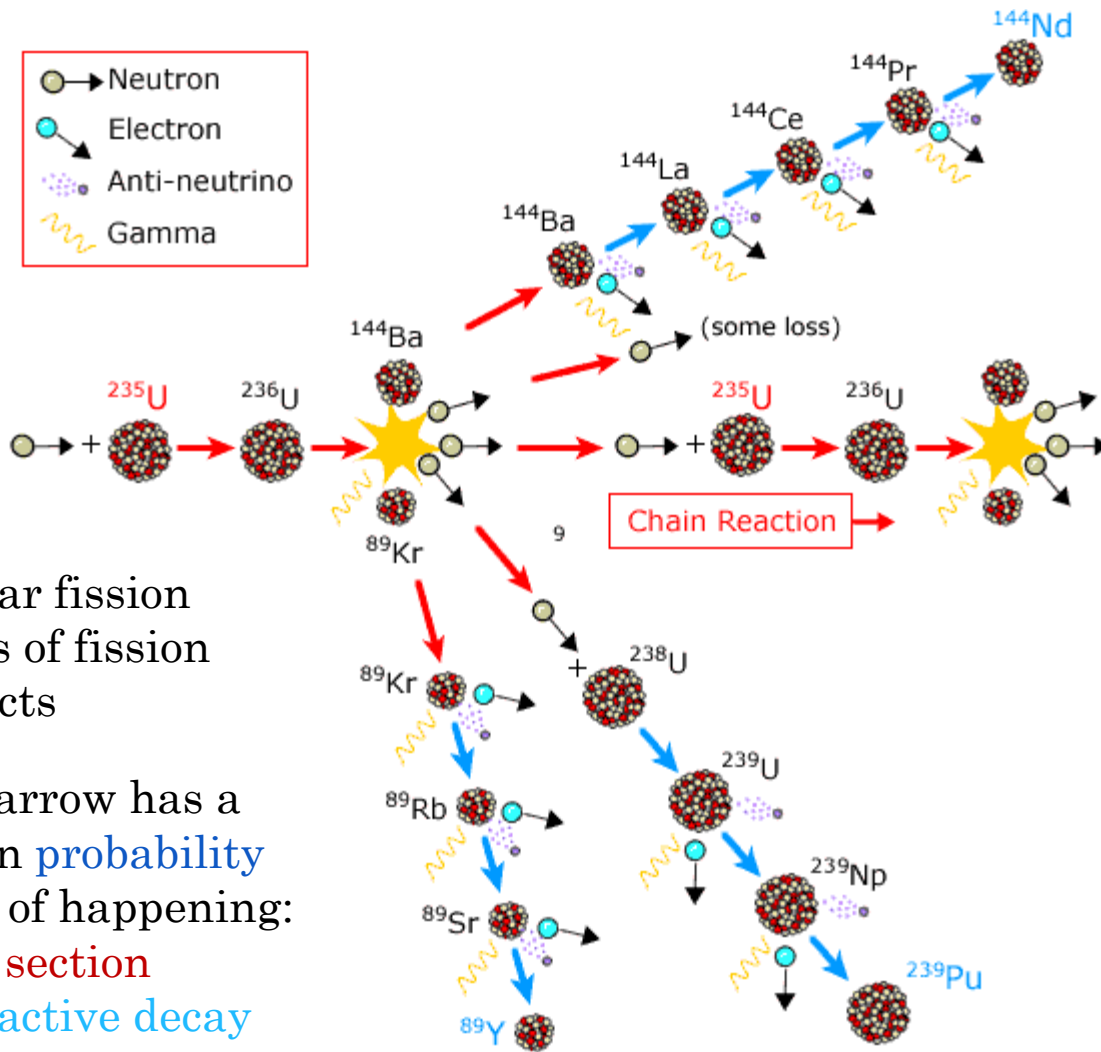
$$30\% \text{ performance: } P_{\text{net}} = 0.3 \times P \approx 1 \text{ GW}$$

Typical domestic solar panel roof (16 panels):
4 kW in 25 m²

Would need 4M panels (6250000 m²) to produce the same energy (only when sunny ☀)



What is nuclear fission?



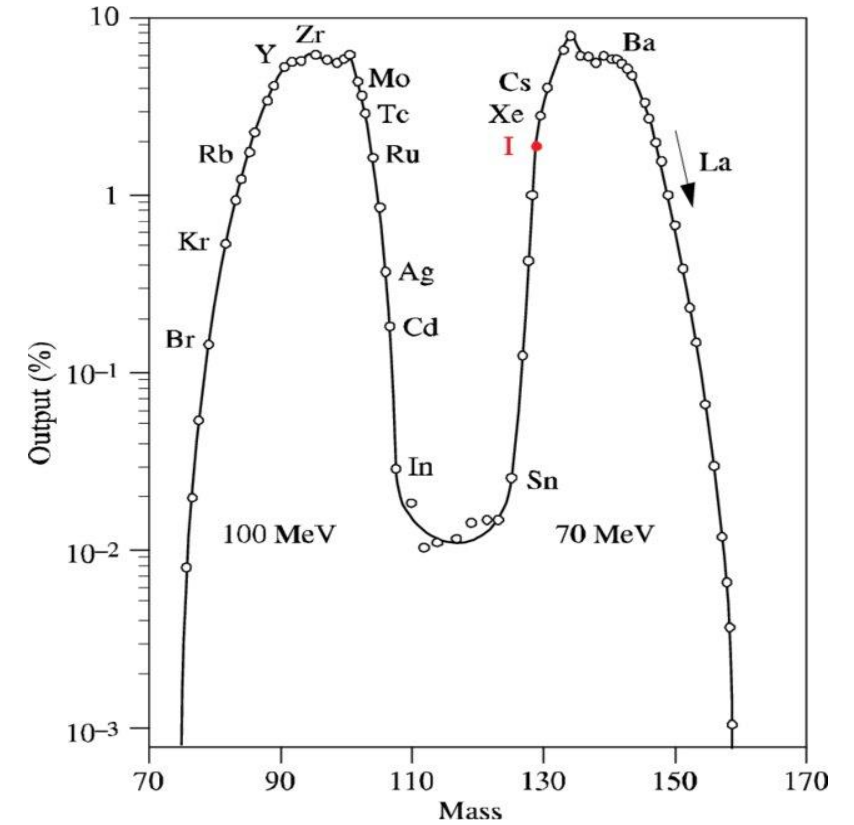
Nuclear fission chains of fission products

Each arrow has a certain **probability** (<1.0) of happening:

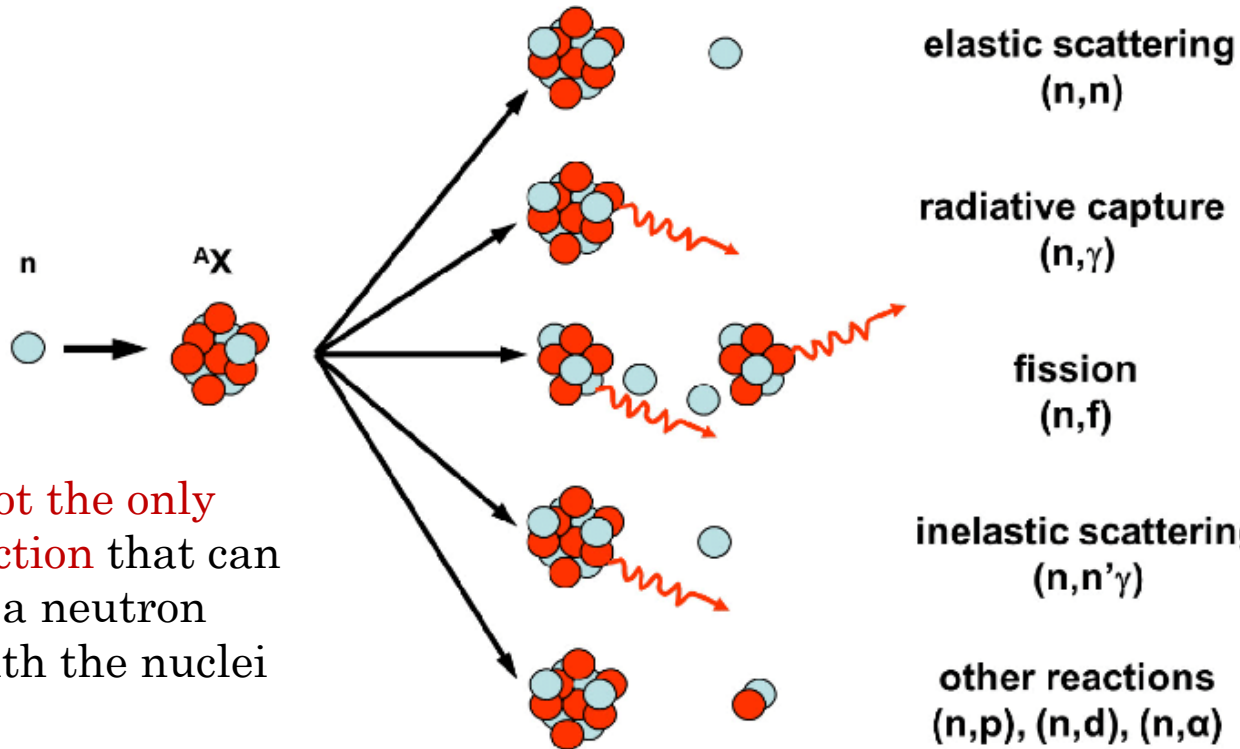
Cross section

Radioactive decay

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



How to achieve nuclear fission?



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

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

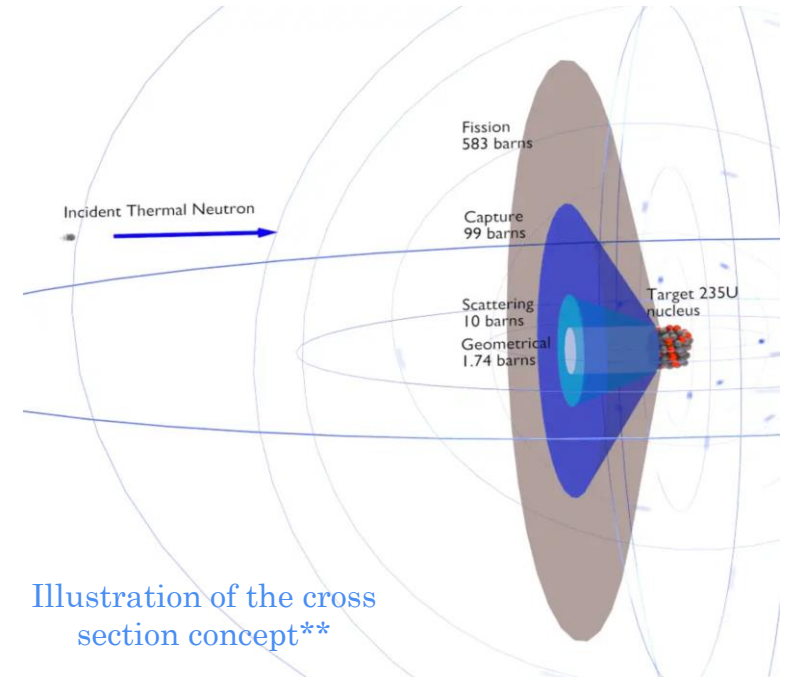
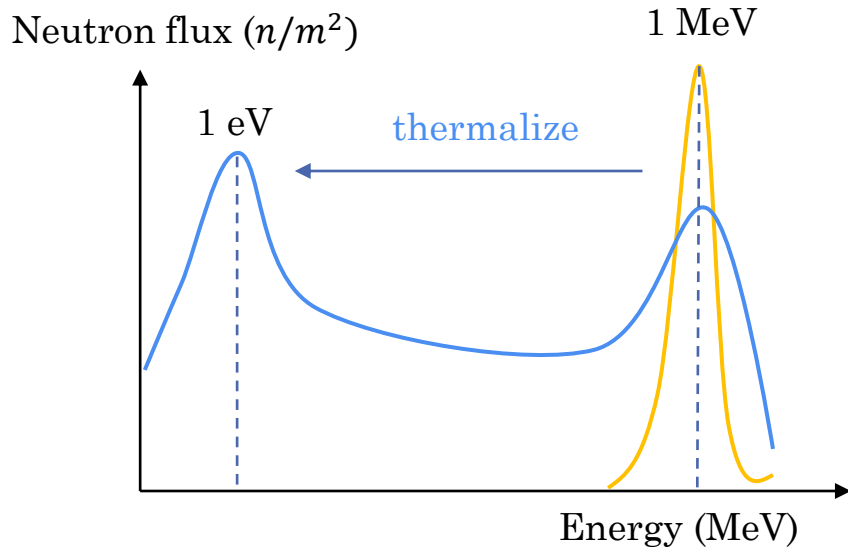


Illustration of the cross section concept**

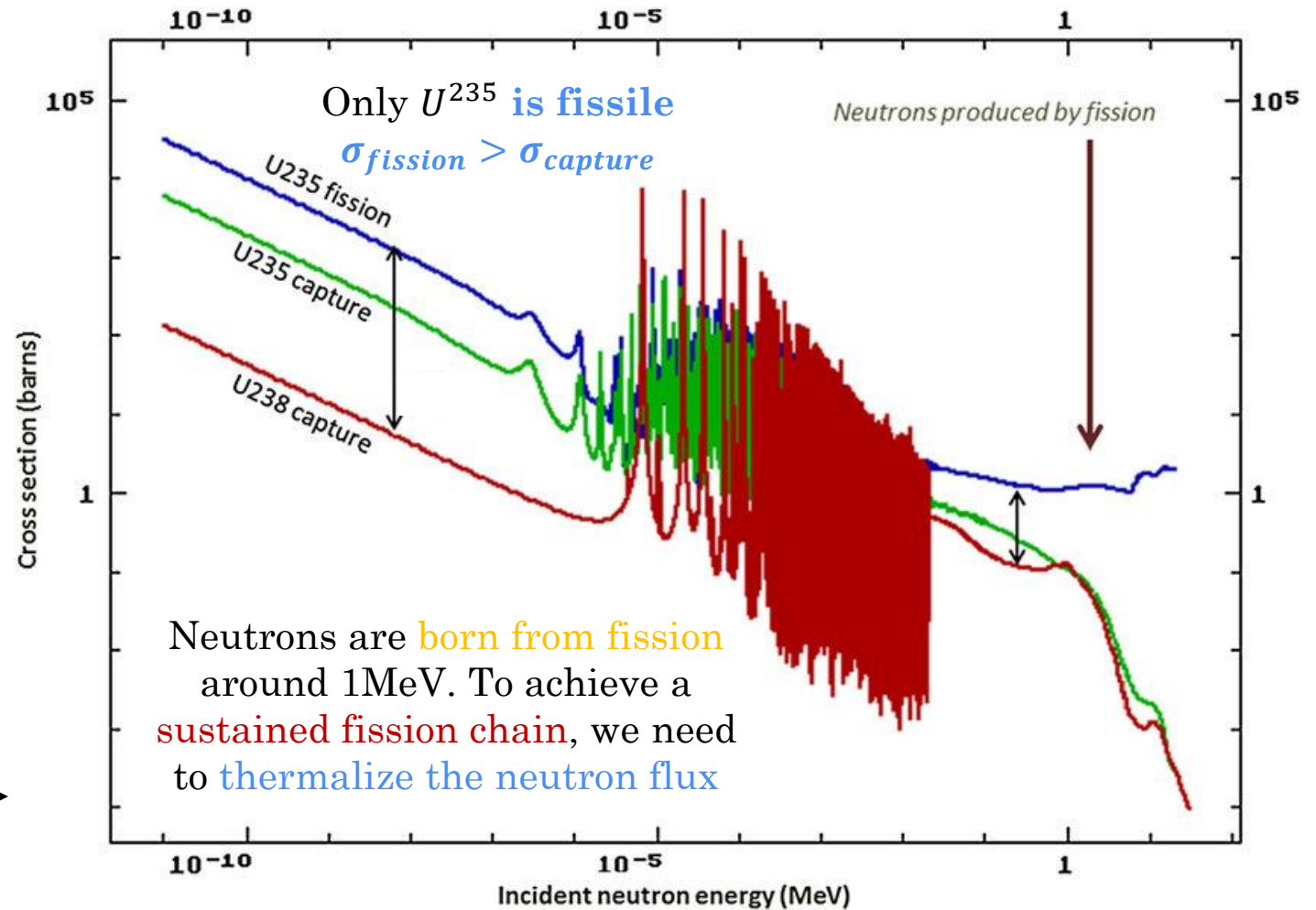
If we want a sustained fission chain reaction, we need to maximize fission and minimize capture

How to achieve nuclear fission?

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



Fission and capture cross section of nuclear fuel

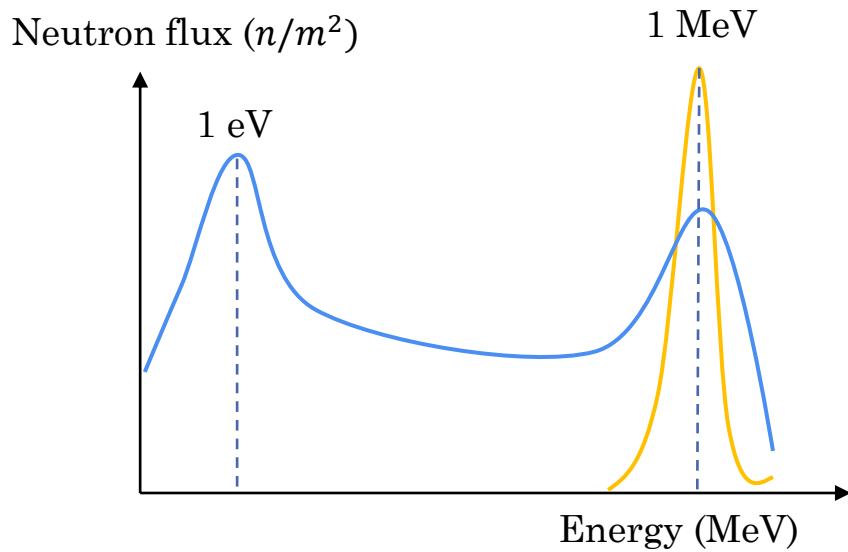


How to achieve nuclear fission?

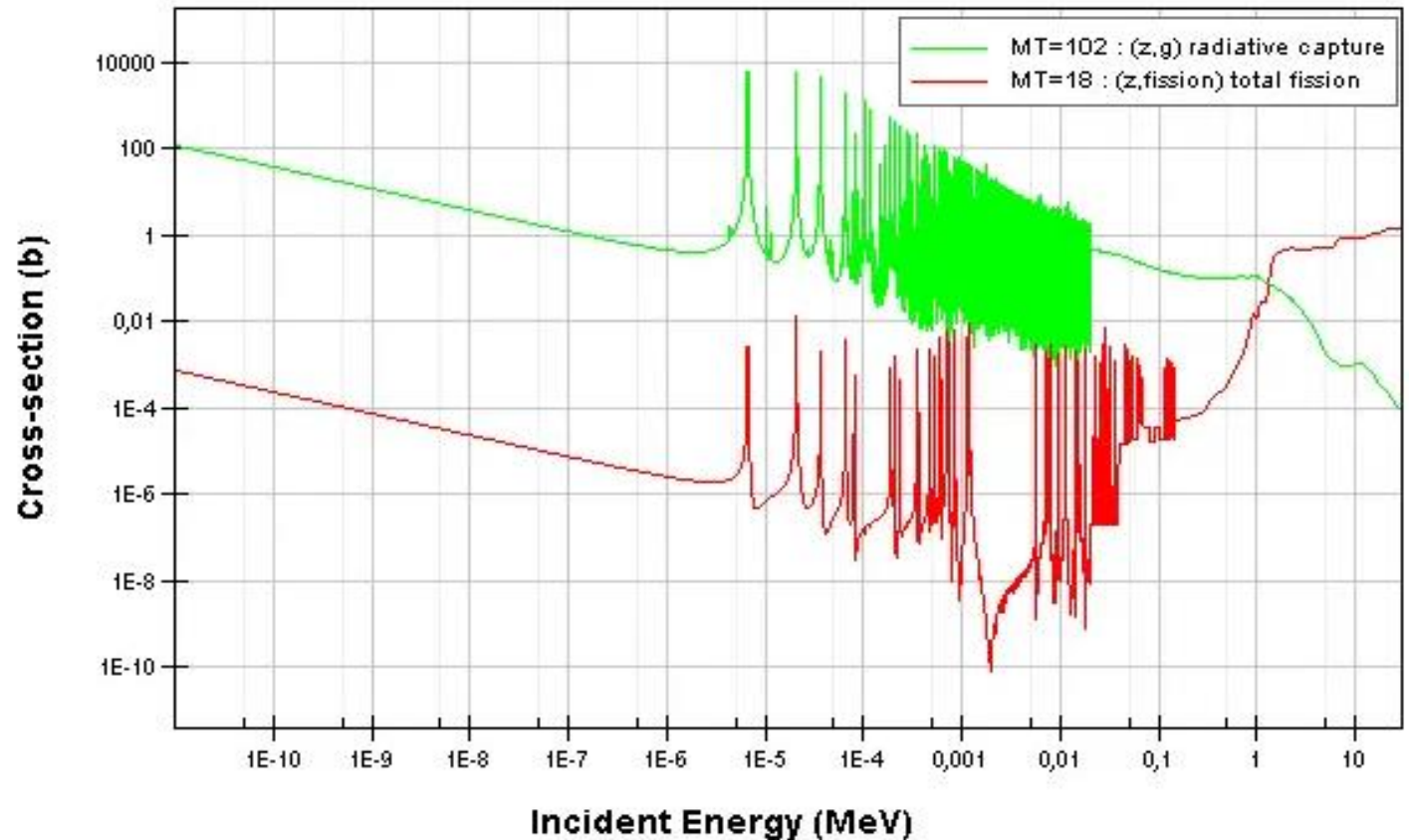
U^{238} is fertile
 $\sigma_{fission} > \sigma_{capture}$ after 1MeV

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

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

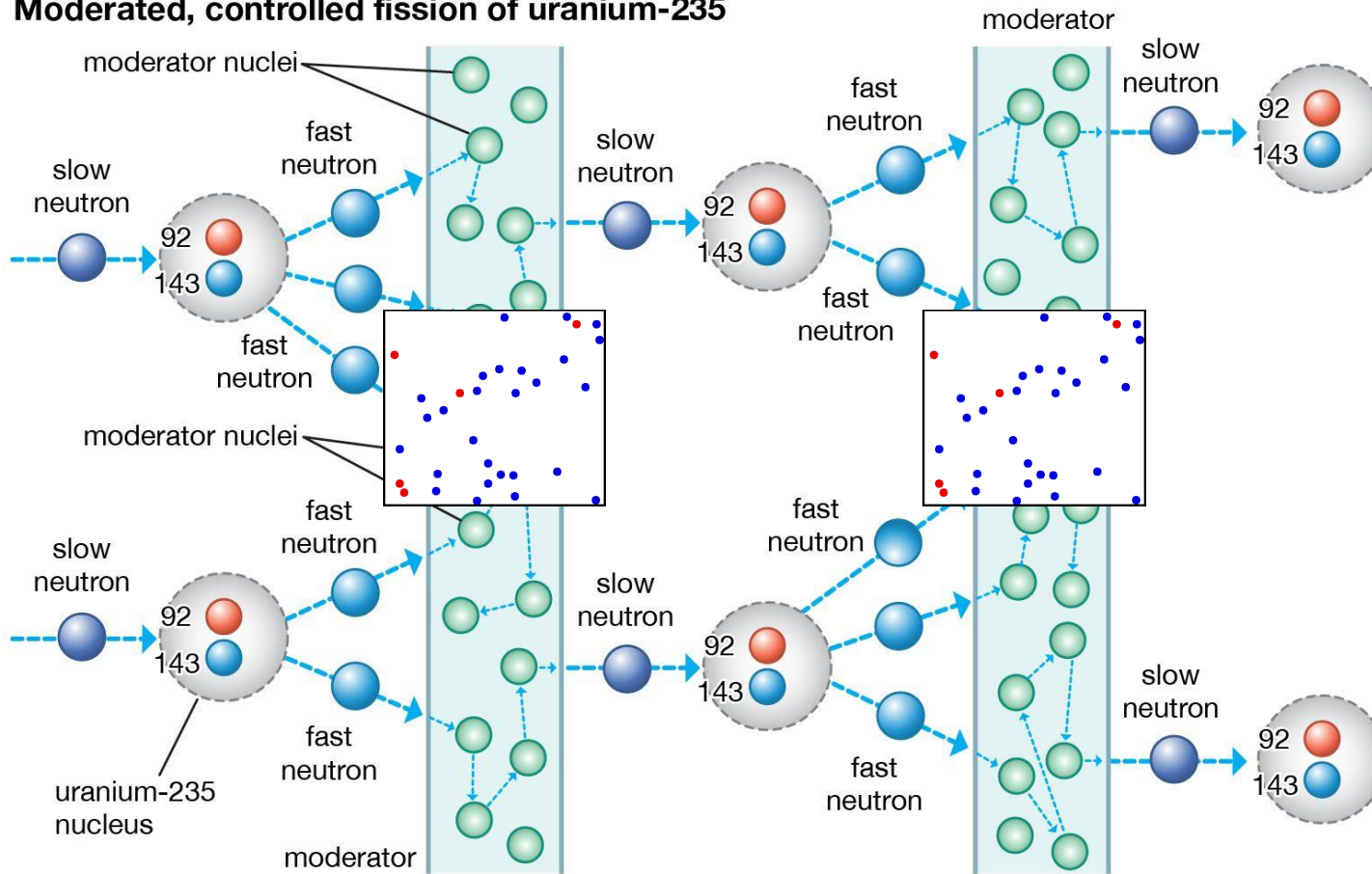


Fission and capture cross section of U238



How to achieve nuclear fission?

Moderated, controlled fission of uranium-235



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

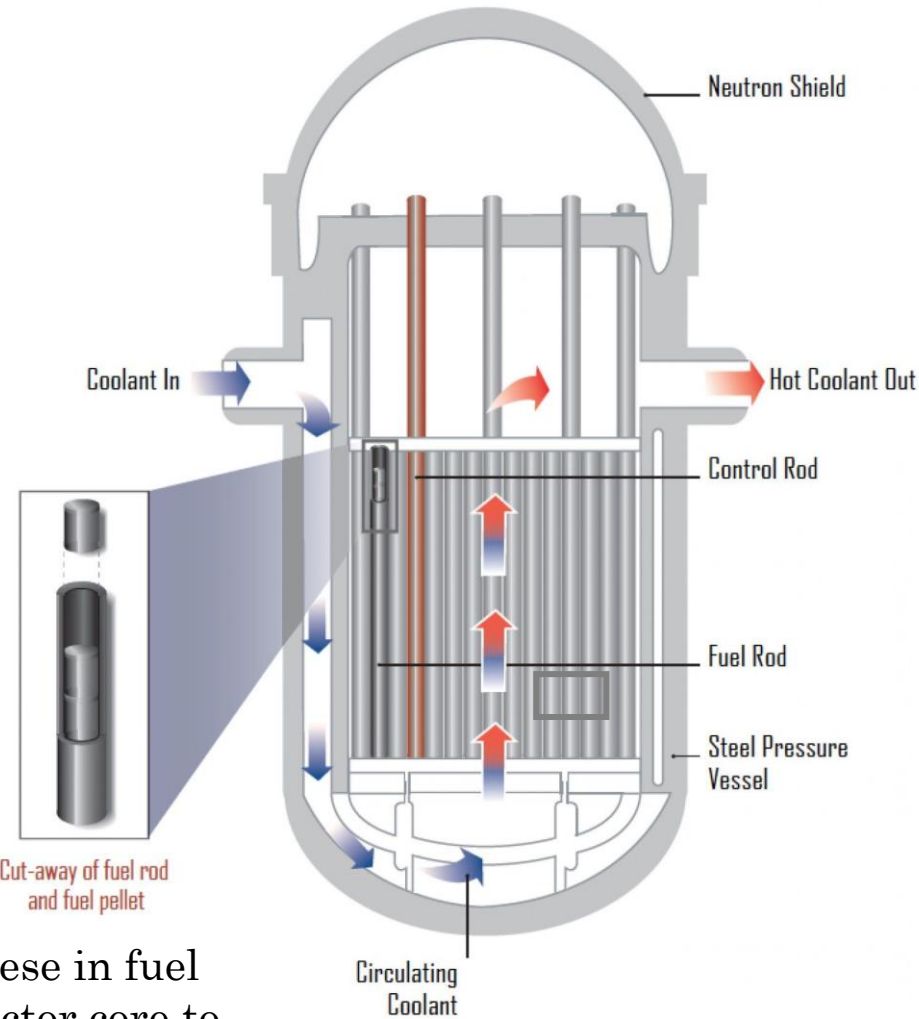
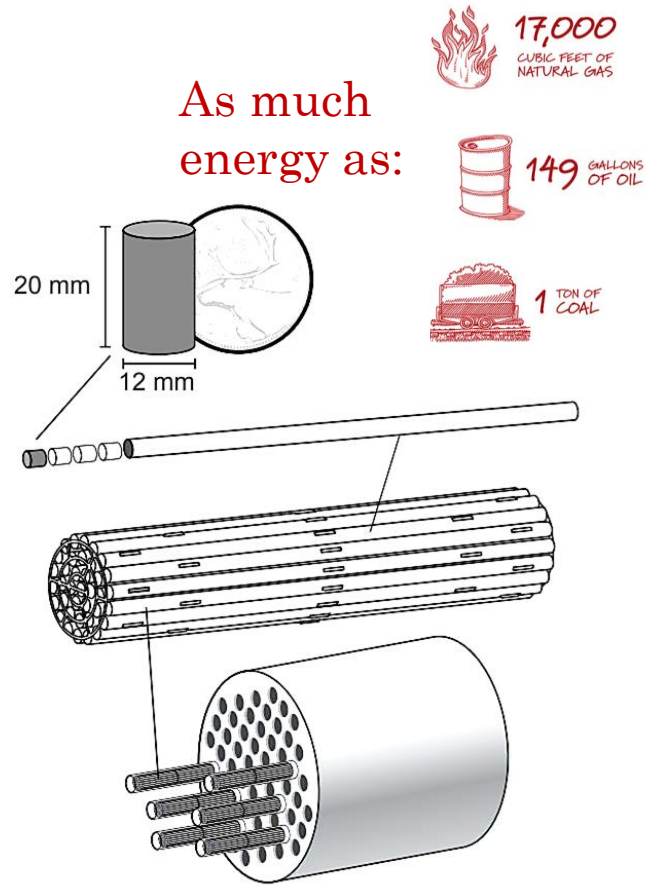
Moderator Type	Neutron scattering cross section (σ_s) in barns	Neutron absorption cross section (σ_a) in barns
Light water (H ₂ O)	49	0.66
Heavy water (D ₂ O)	10.6	0.0013
Graphite (C)	4.7	0.0035

↑ high scattering ↓ low capture

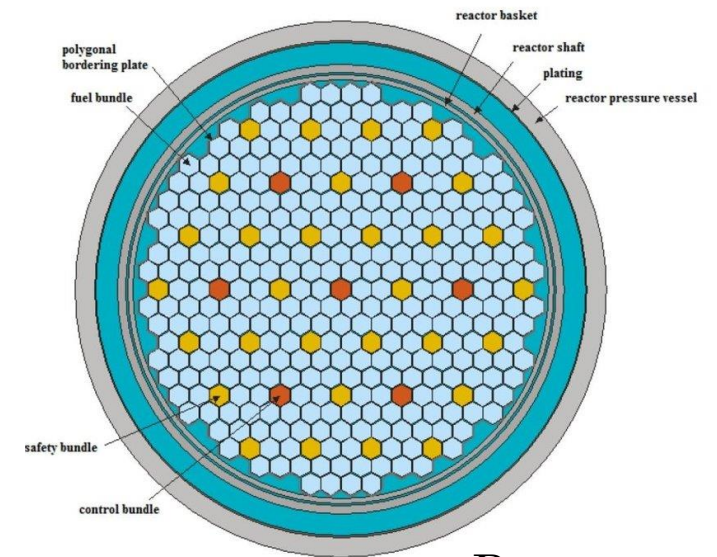
© 2012 Encyclopædia Britannica, Inc.



Inside the nuclear reactor core: Fuel



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



Reactor core example

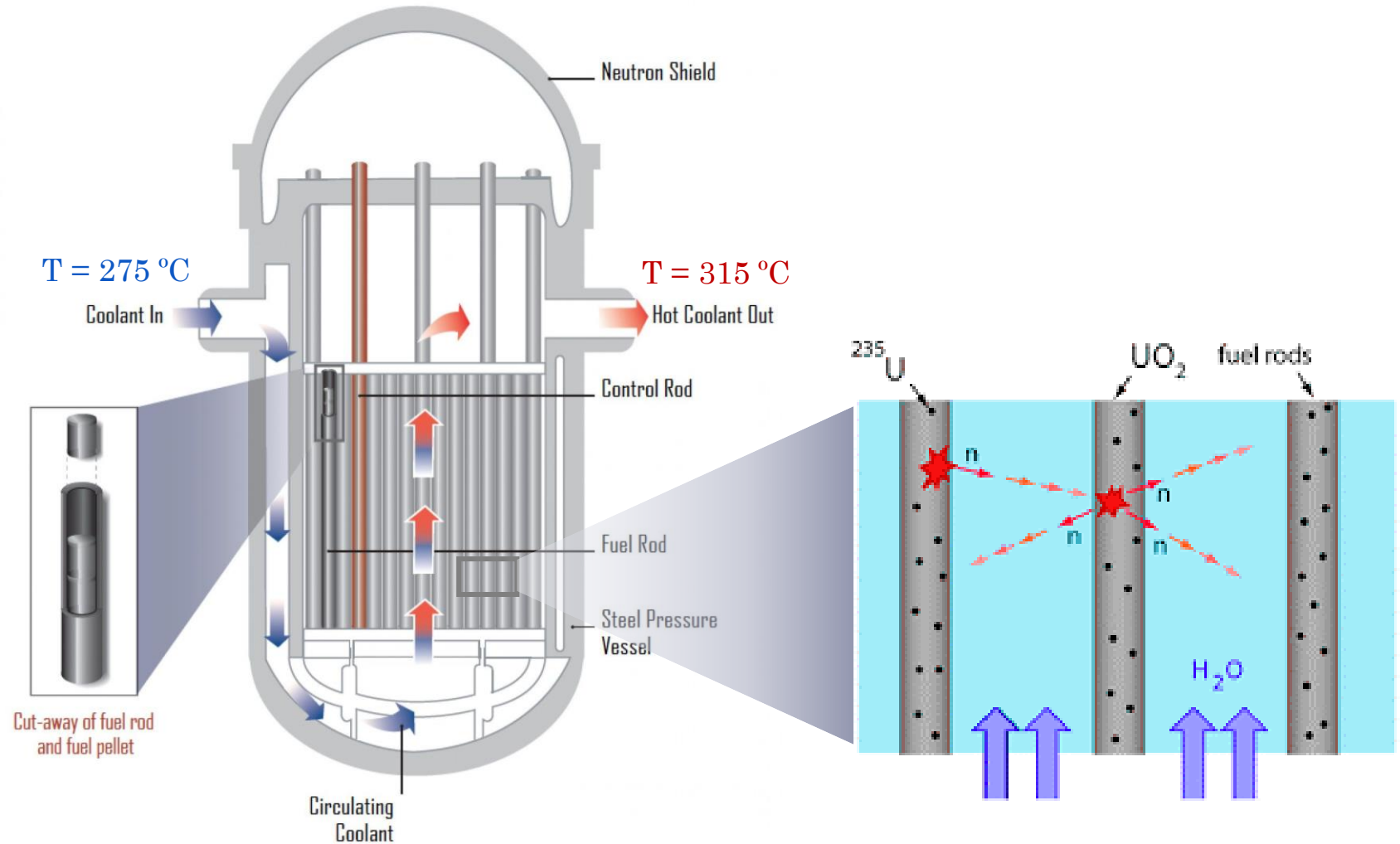
Fuel is assembled in fuel rods, these in fuel bundles and distributed in the reactor core to have a uniform neutron flux distribution



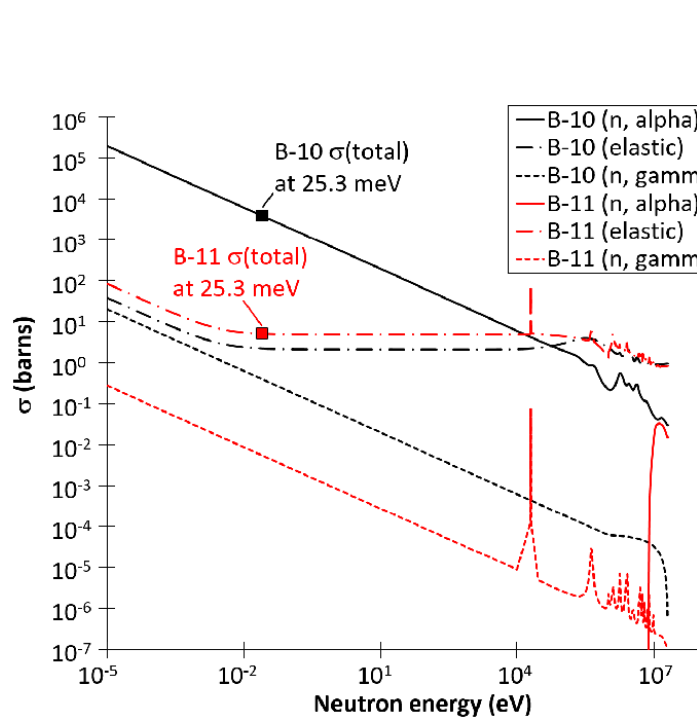
Inside the nuclear reactor core: Fuel assembly

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

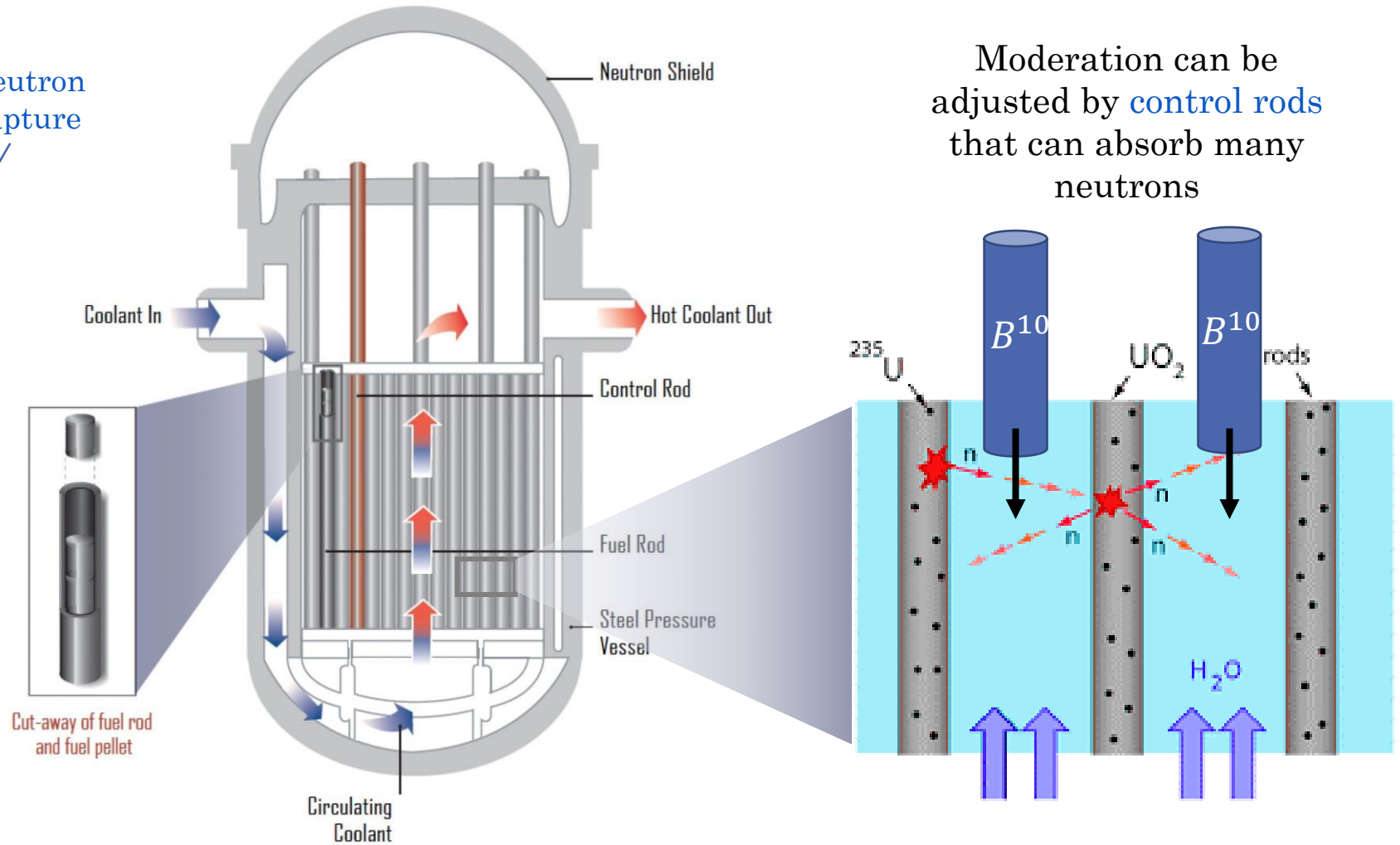
It flows between the fuel bundles, extracting the heat from the core and moderating the fission-born neutrons with a pressure of $P = 155 \text{ bar}$



Inside the nuclear reactor core: Control rods

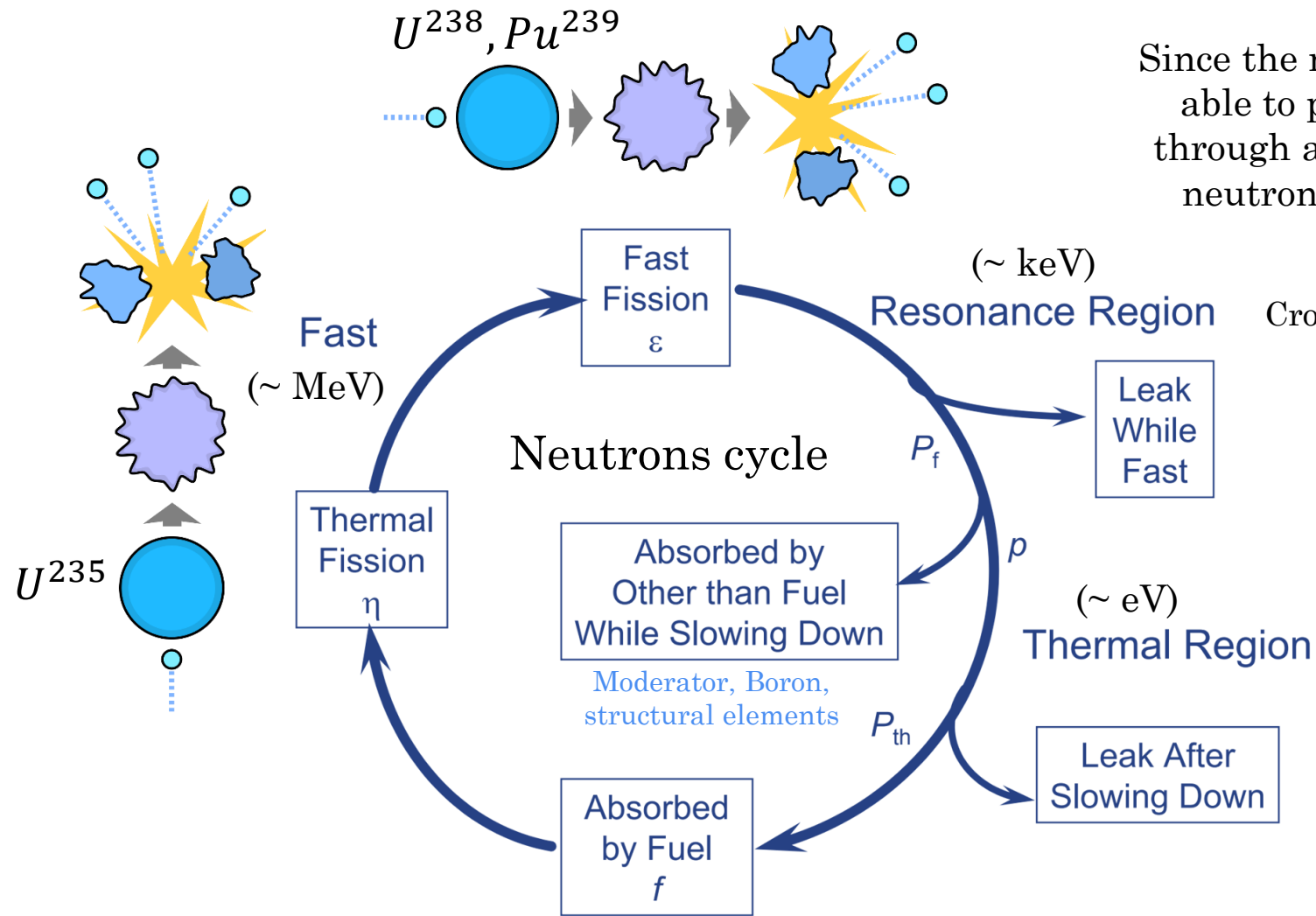


Boron B^{10} cross sections (σ) for neutron capture are very high!

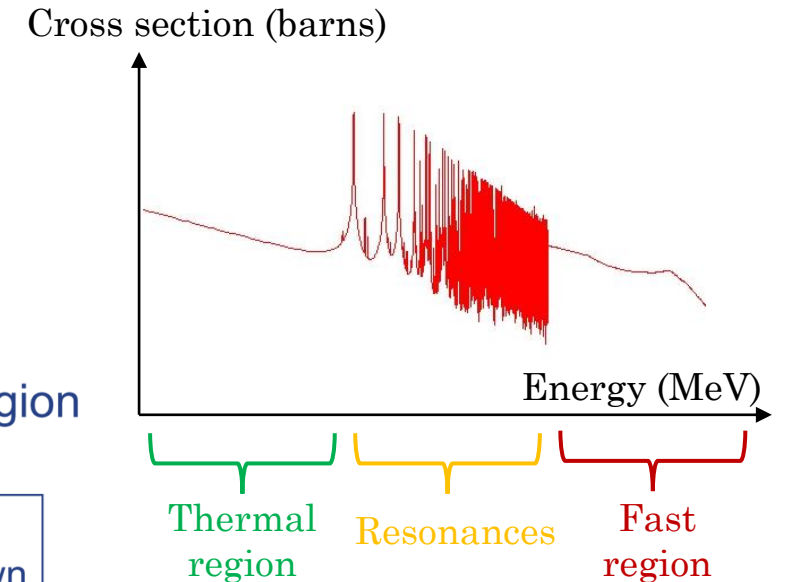


Moderation can be adjusted by control rods that can absorb many neutrons

How to maintain a controlled fission chain?

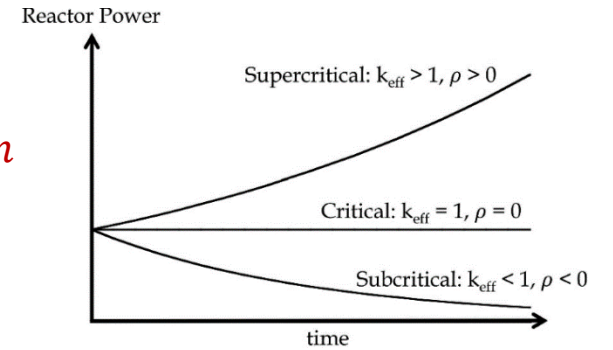


Since the neutrons are born until they are able to produce a new fission, they go through a **life cycle** that accounts for the neutron losses before the next fission



How to maintain a controlled fission chain?

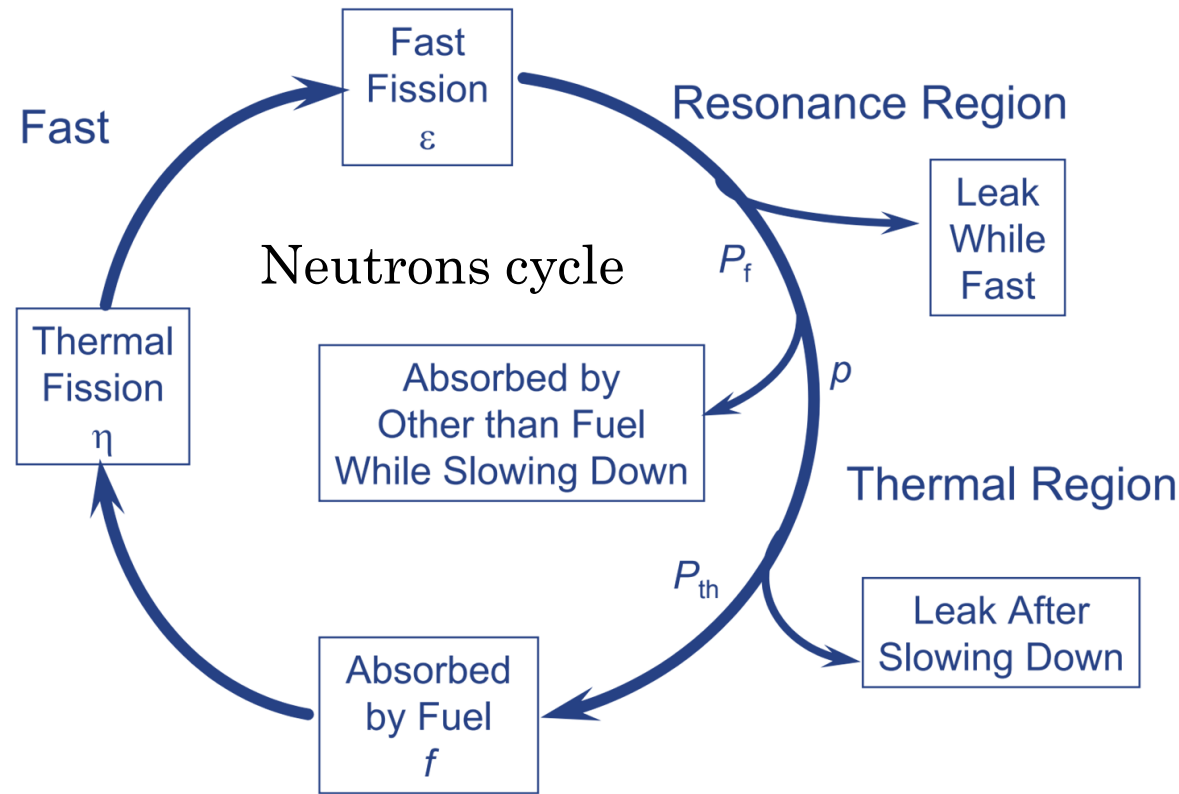
$$k_{eff} = \eta \epsilon P_f p P_{th} f \quad \left\{ \begin{array}{l} < 1 \text{ sub-critical } \downarrow n \\ = 1 \text{ critical} \\ > 1 \text{ super-critical } \uparrow n \end{array} \right.$$



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)

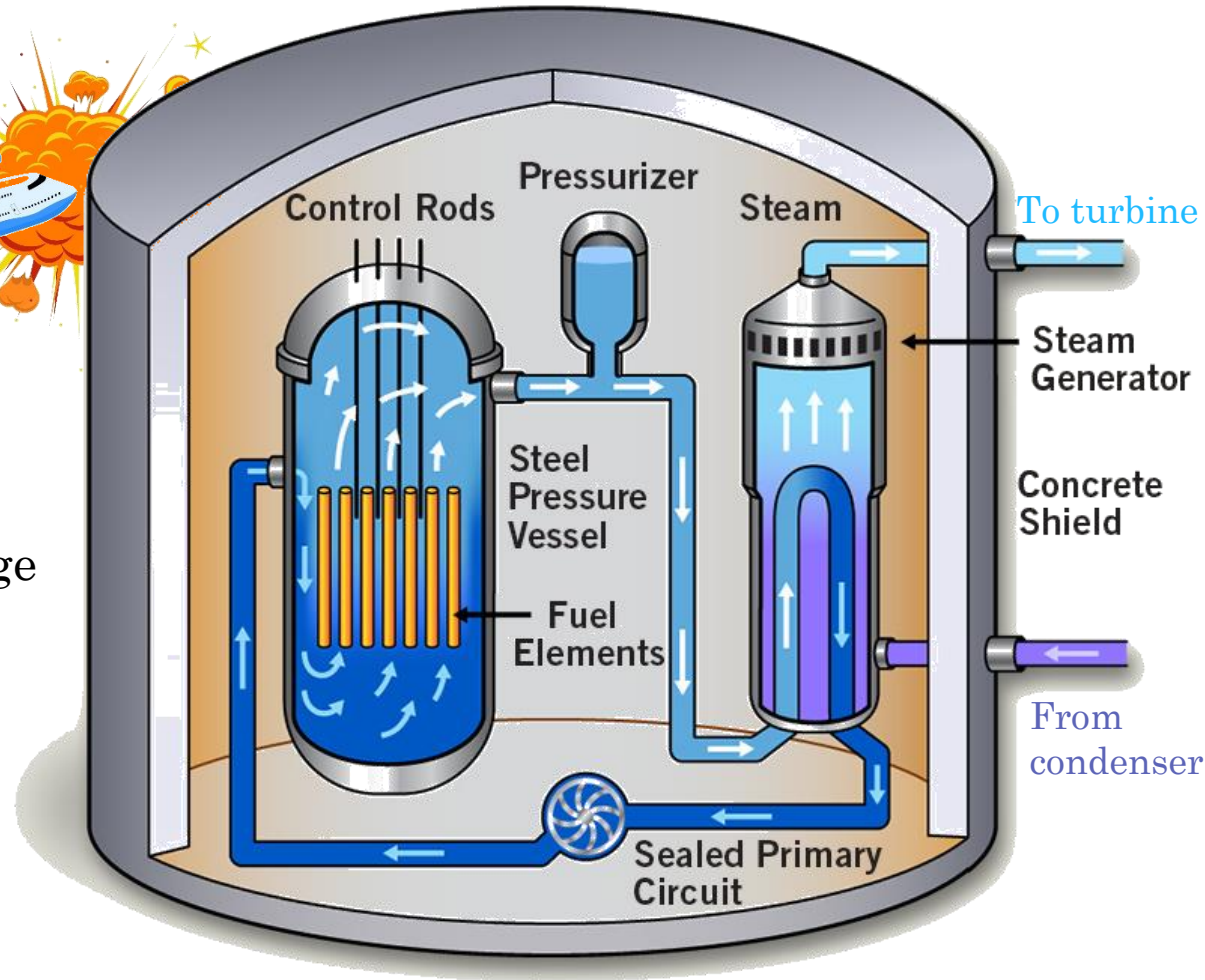


Inside a nuclear power plant: Containment



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

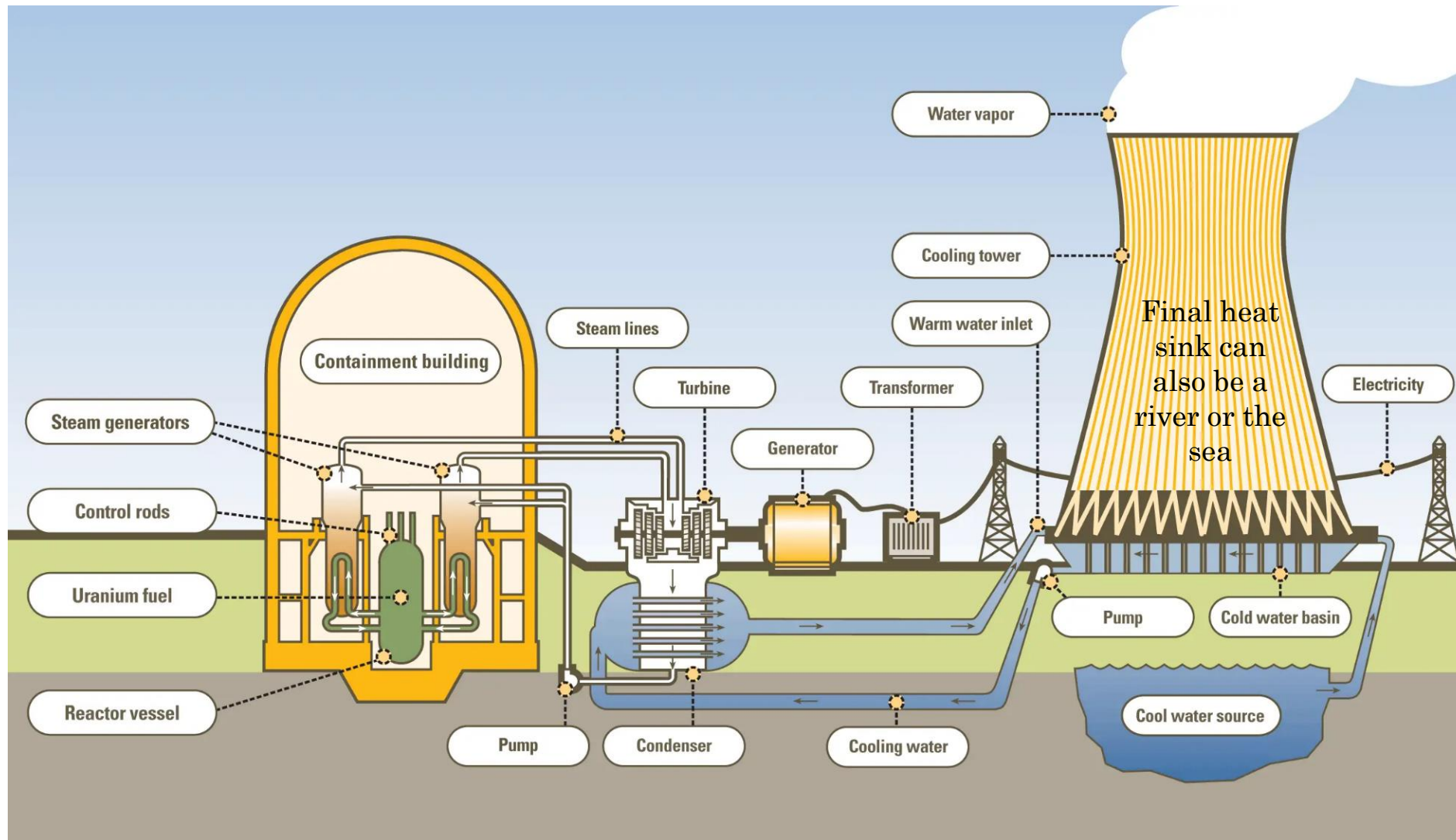


Inside, we find the reactor pressure vessel the primary coolant loop and the steam generators

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

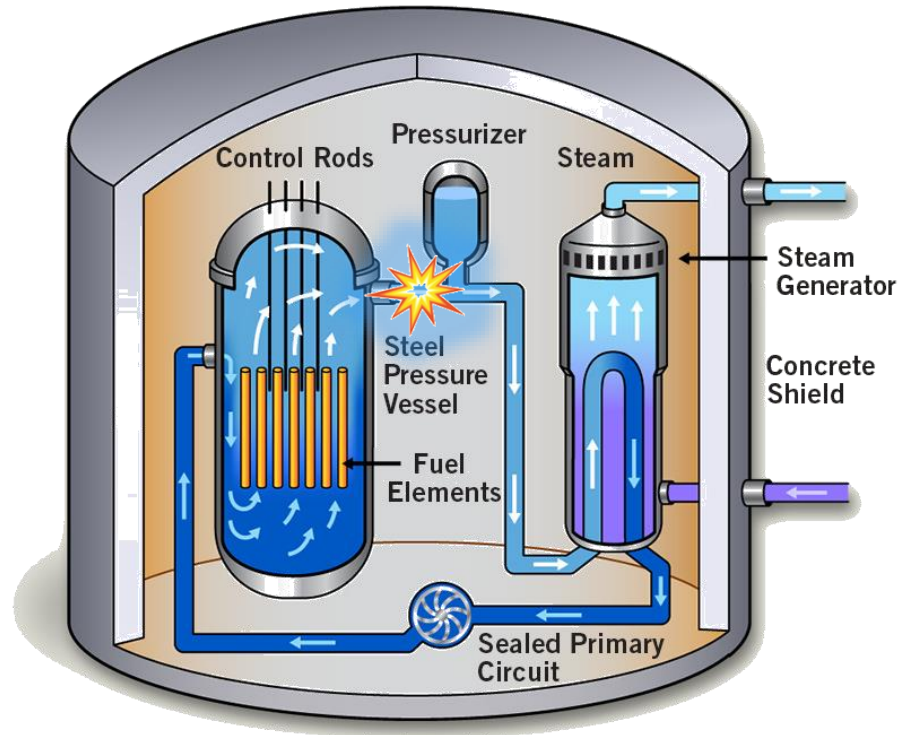
- Primary pumps: maintain loop pressure
- RPV: remove heat from core
- Pressurizer: absorbs temperature (density) changes and aids in controlling the pressure during accident
- U-tubes in steam generator: transfer heat to secondary loop

Inside a nuclear power plant: Electricity

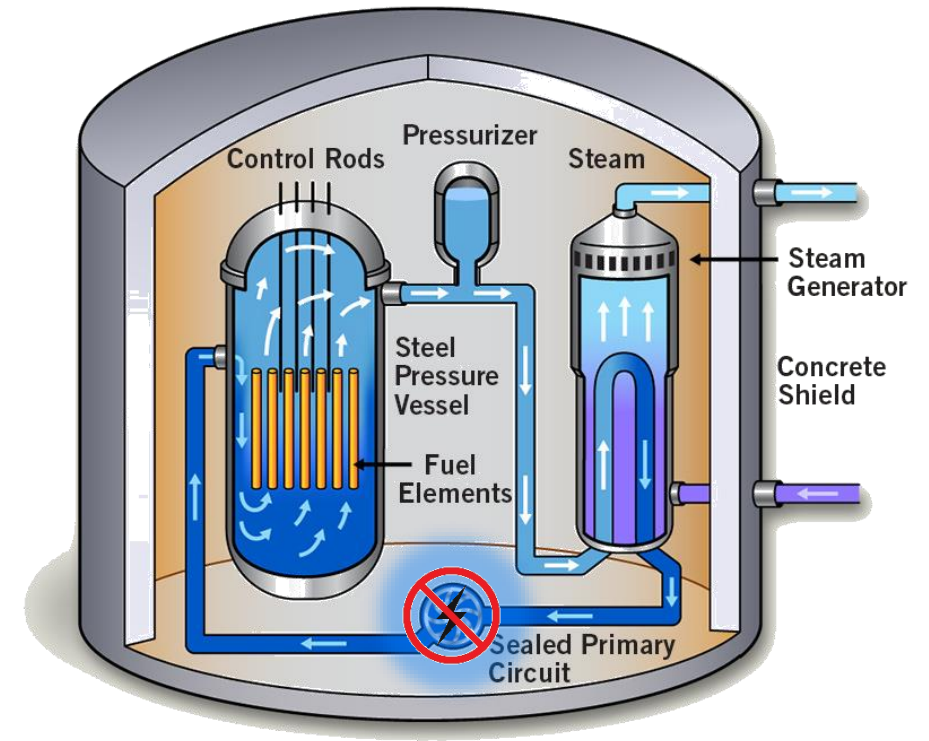


Safety in nuclear power plants: Accidents

Loss of coolant accident (LOCA)



Station Black Out (SBO)



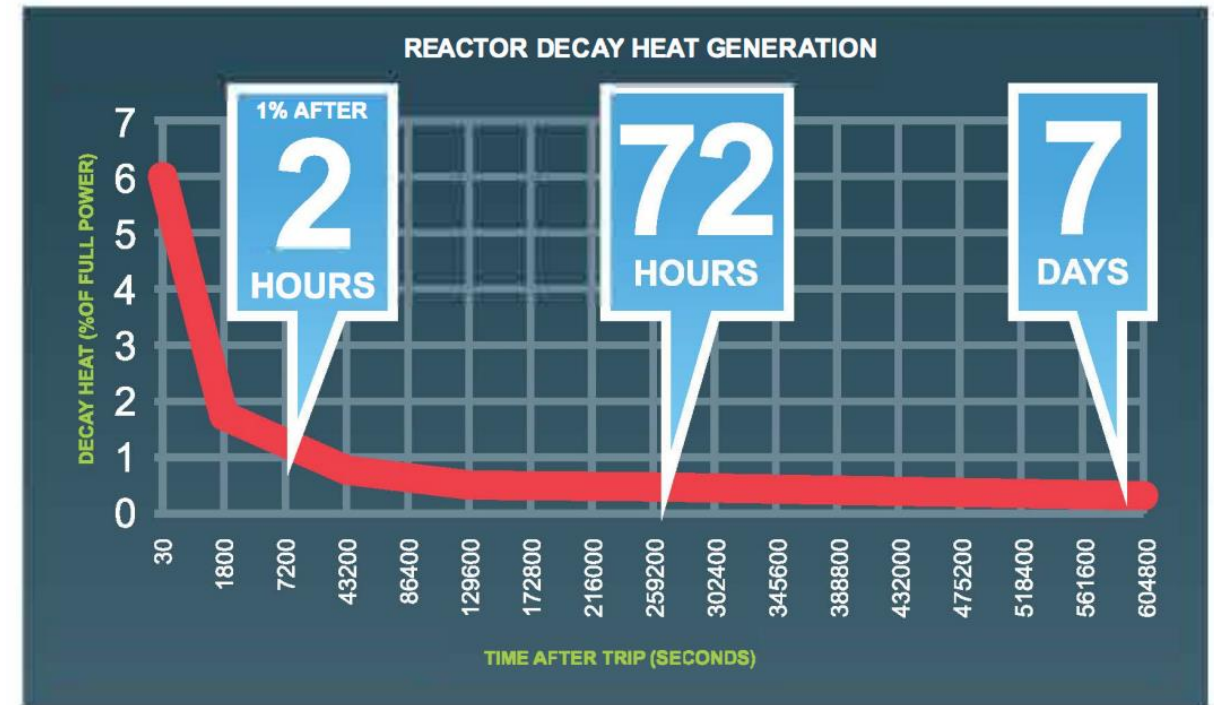
Need a full presentation to cover them properly 😊

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

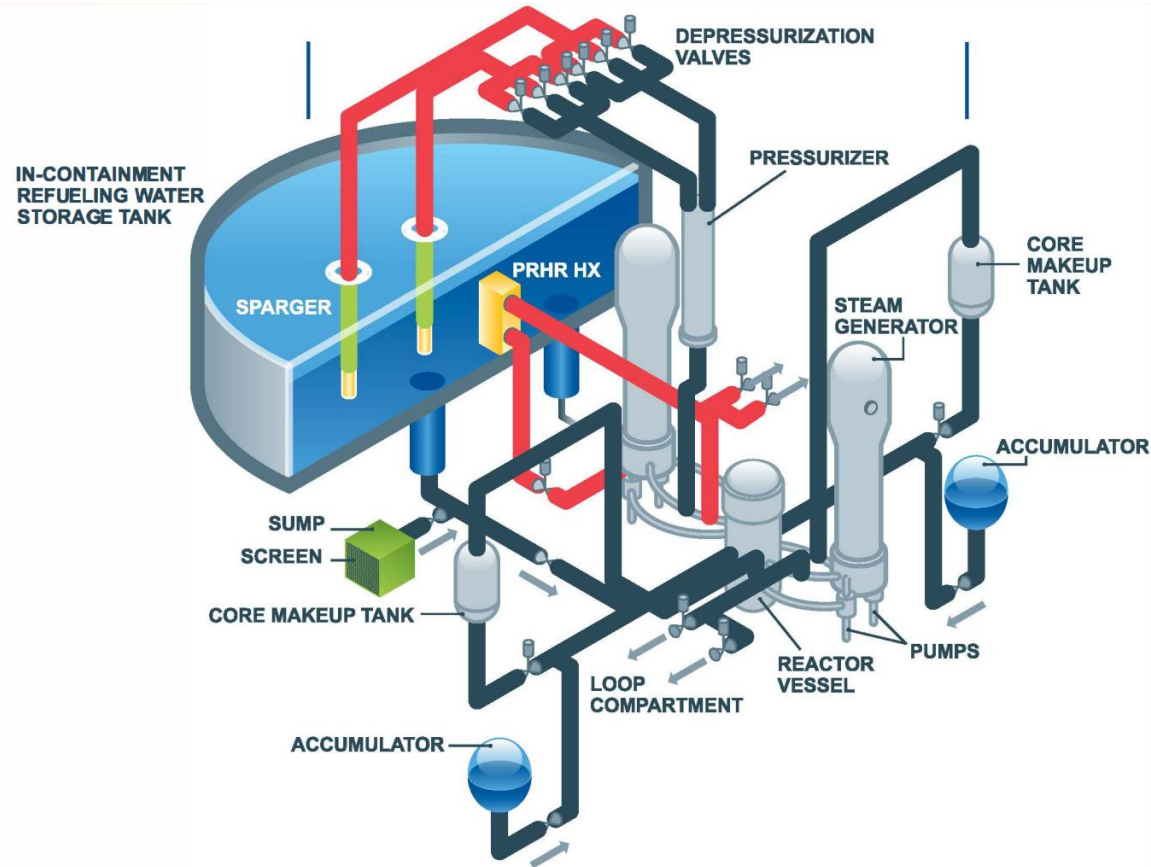
For decay heat removal (DHR), we have **active systems** (powered by the grid or emergency diesel generators) and in Gen III+, **passive systems** driven by natural forces

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

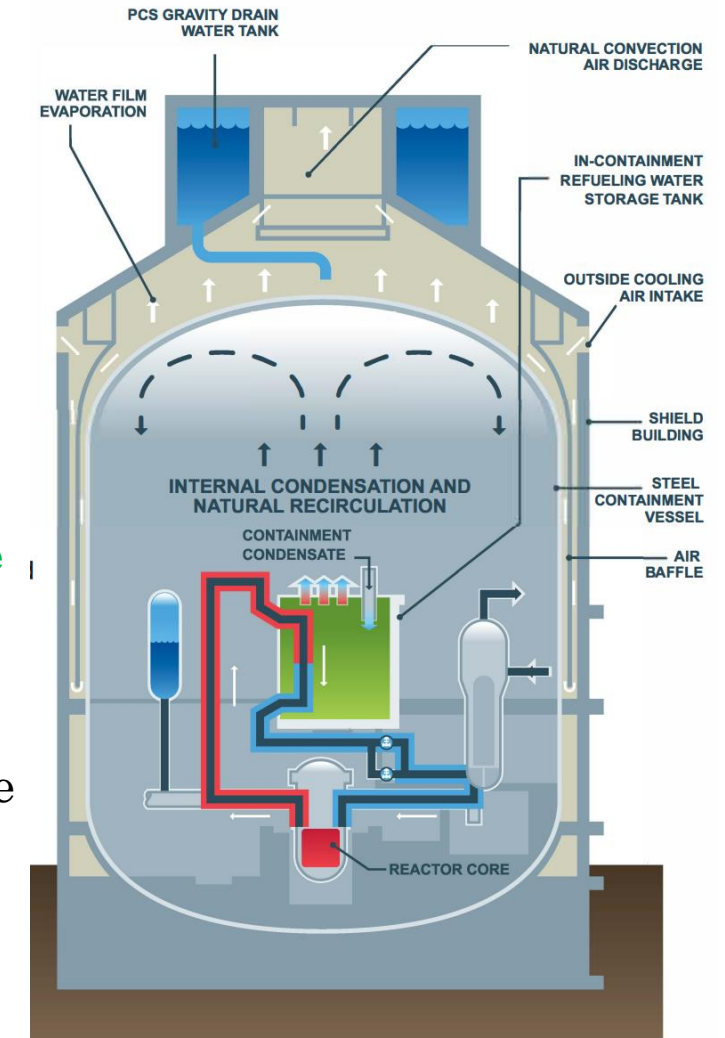


Safety in nuclear power plants: Safety systems

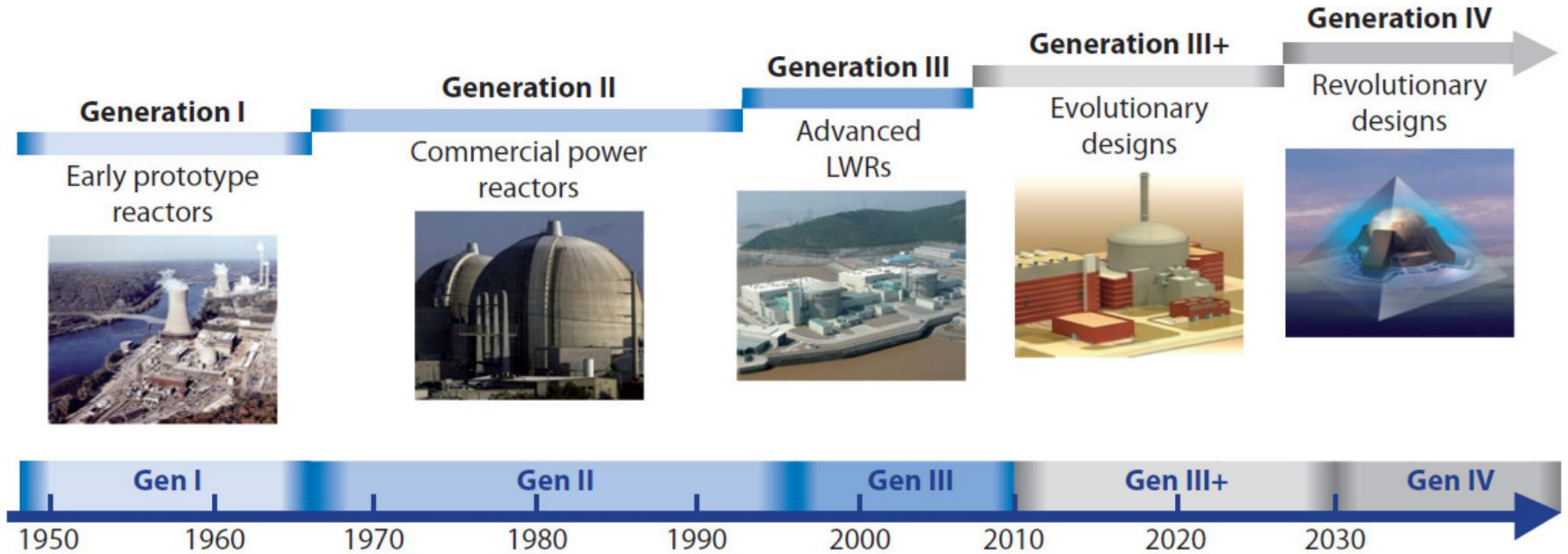
Active and passive safety systems for DHR
(each system has redundancy in case one train fails)



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



Gen IV nuclear reactors

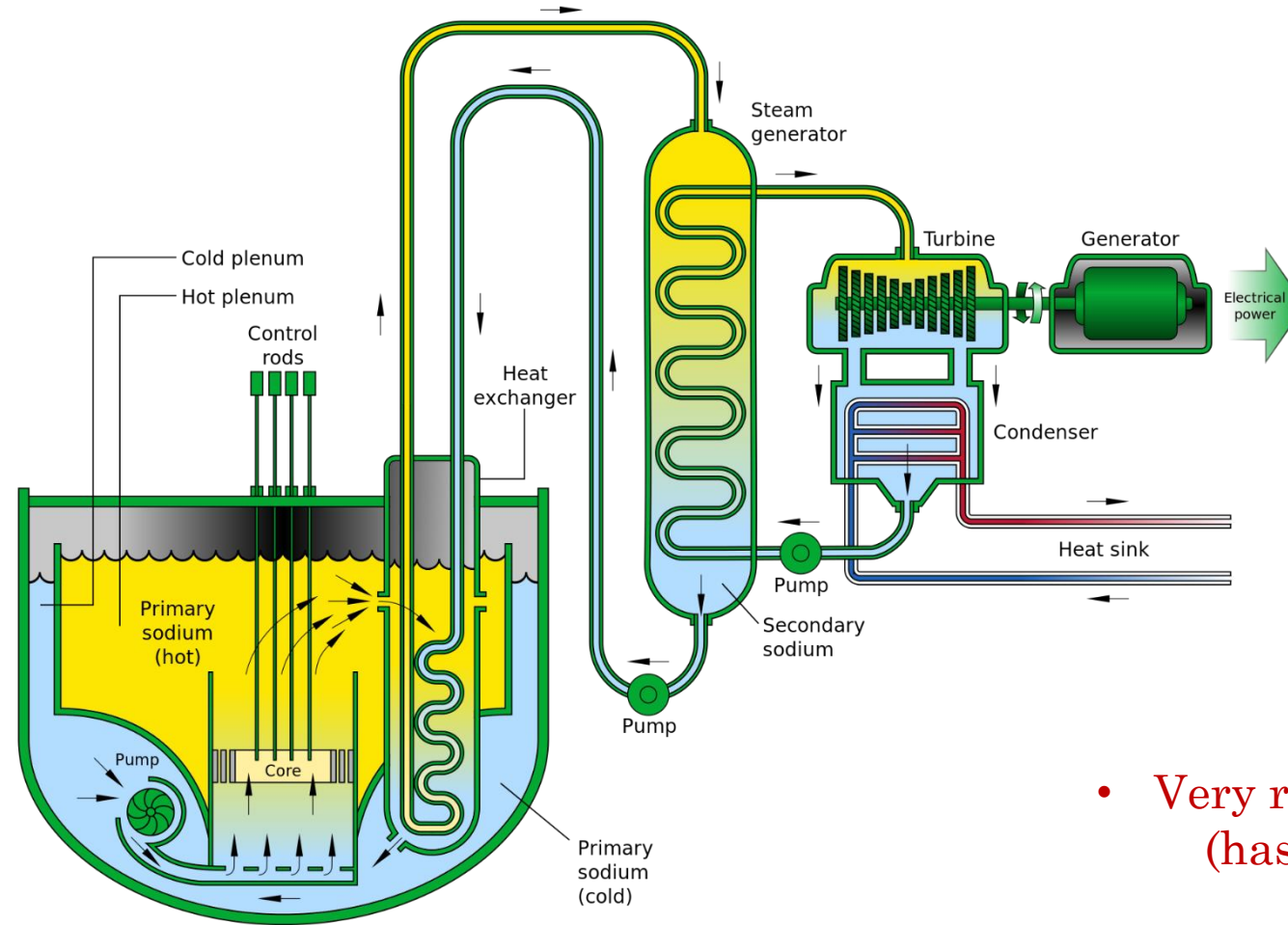


Gen IV Designs: SFR

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

Is cooled by sodium:

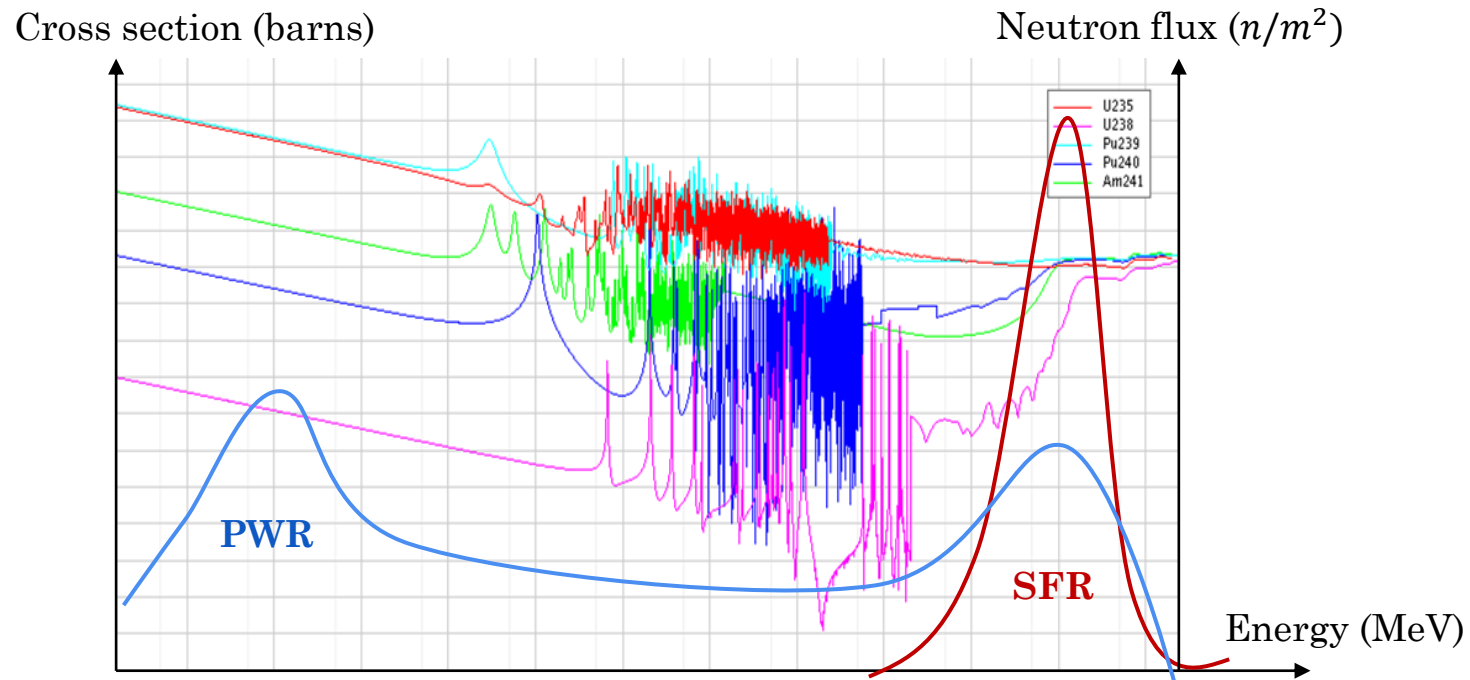
- High thermal conductivity
- Does not moderate: fast neutron spectrum



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

Advantages of SFR

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

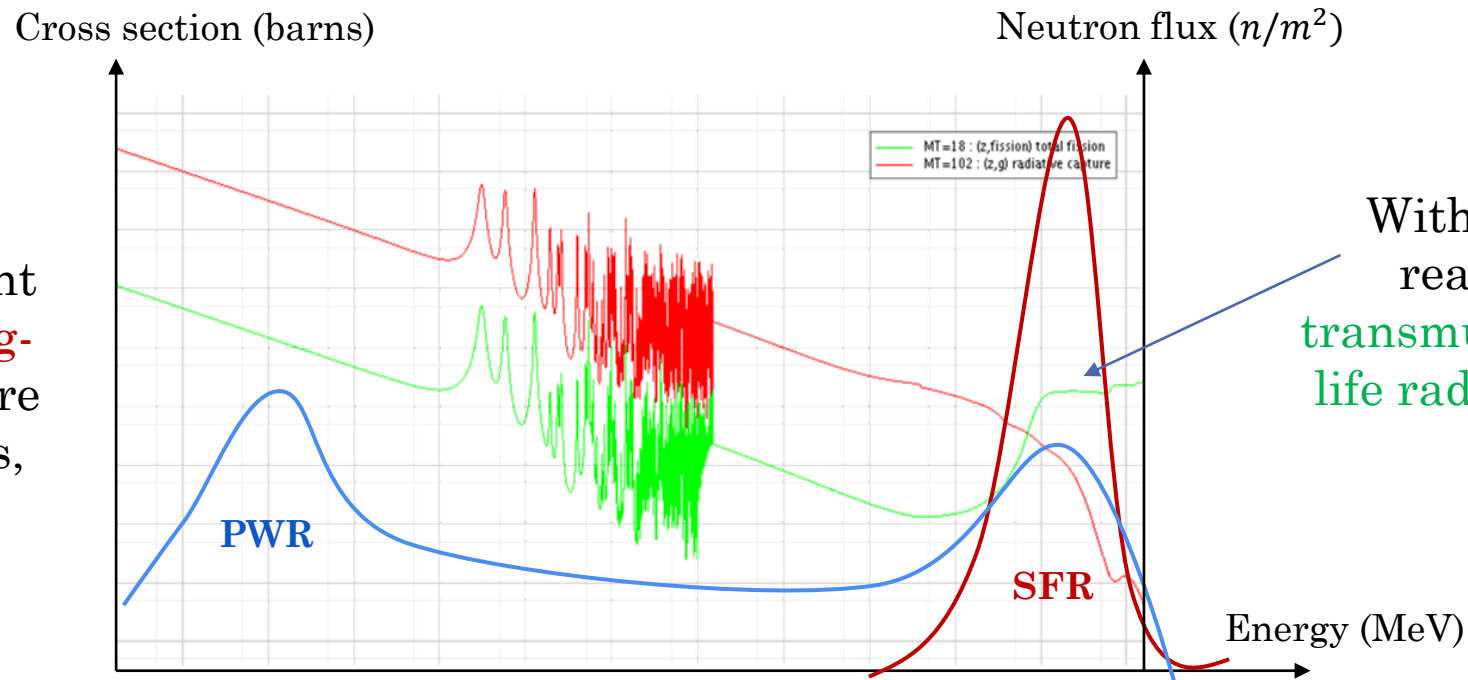


With a special design of the core, it uses natural uranium U^{238} fissions and breeding (to Pu): no need for enrichment!



Advantages of SFR

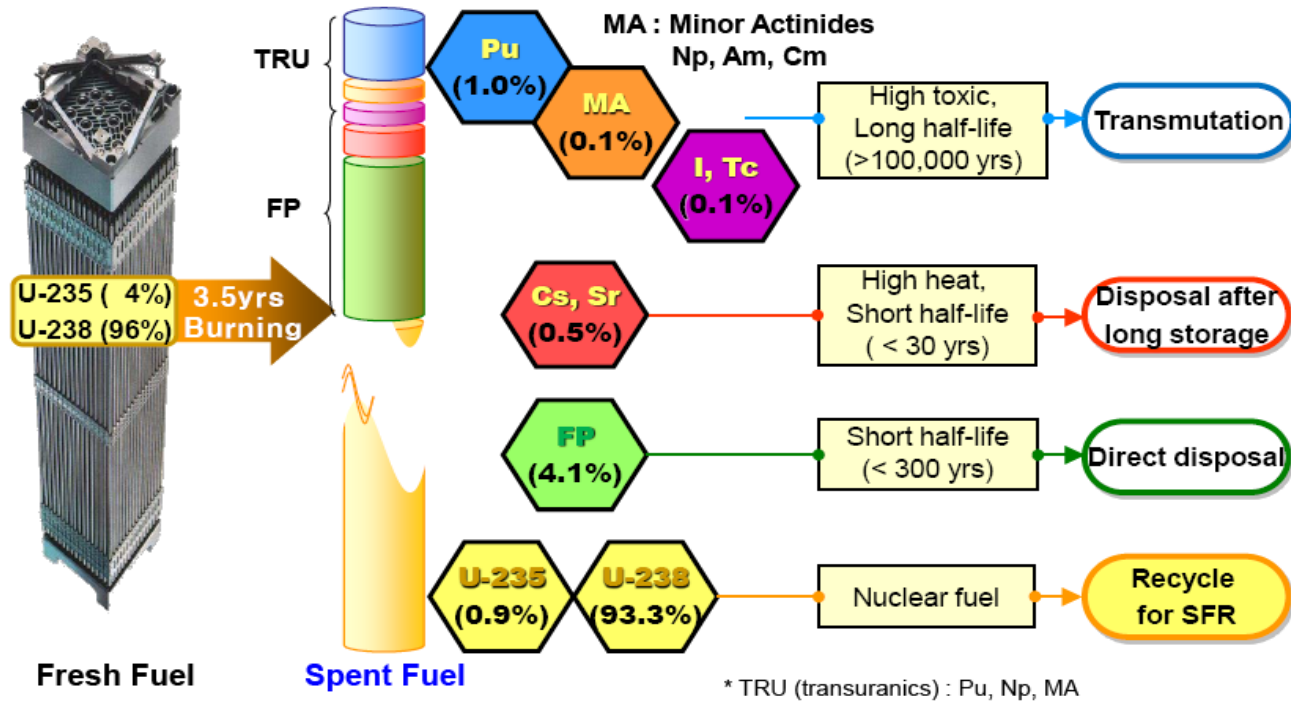
Fission and capture cross section of Am^{241}



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

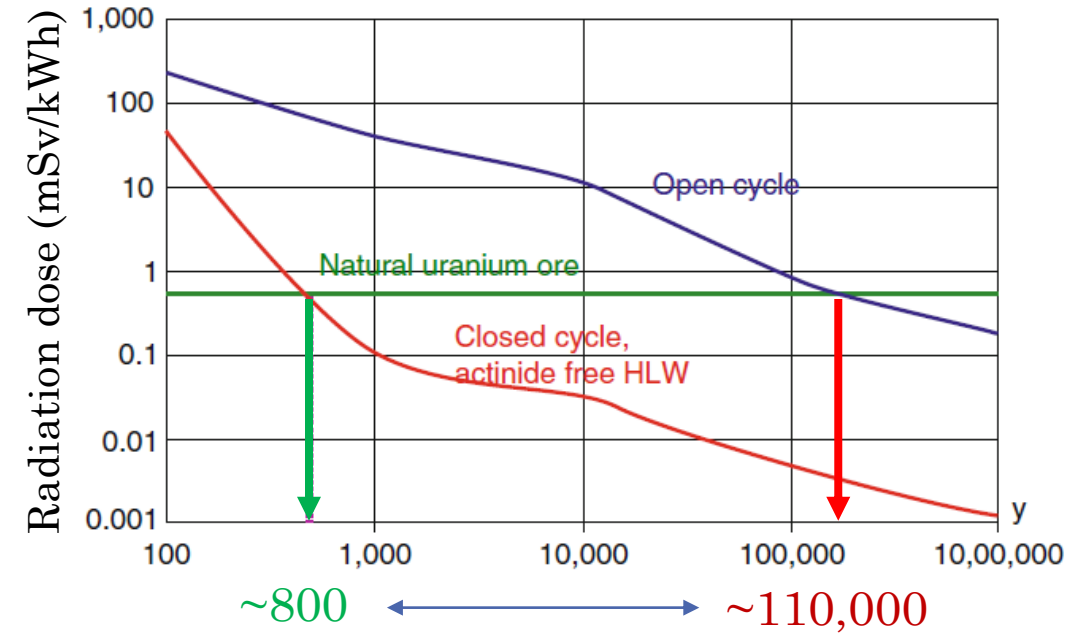
With a fast spectrum reactor, we can do **transmutation of long half-life radioactive waste into fissile fuel**

Advantages of SFR



Burn long half-lived Minor Actinides

Spent fuel storage needs



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

Superphenix

Creys-Malville Super Phénix

The Worlds Reactors No. 73

Creys-Malville nuclear power station
(Centrale Nucléaire de Creys-Malville)

Owner/operator (Propriétaire/exploitant)
Commissariat à l'Énergie Atomique (CEA) (France)

Main Contractor (Contracteur principal)
NED - Nucleon SA
Cof - Fougères, Comar et AECV, Philips Industrie
Turbine générale - 12 et 1980 Ansaldo

Site (Implantation)
Dr. River Rhone (Sur le Rhône) Creys Malville, Isère, France

Schedule (Programme)
Construction start (Début de construction)
1983
Commissioning (Mise en service industrielle)
1985

Power (Puissance)
1200 MW(e) 3000 MW(t)

Reactor type (Type de réacteur)
Sodium cooled, pool, fast breeder (à neutrons rapides, à type intégré, à refroidissement par sodium)

Fuel (Combustible)
Composition
enriched UO₂-PuO₂ mixed oxide
(oxyde mixte enrichi UO₂-PuO₂)
10%
enrichment (enrichissement)
1000 kg
burning gas (gaz de refroidissement)
0.34
burning gas inlet temperature (température d'entrée des gaz de refroidissement)
3000 MW(t) to
30000 MW(t) to
30000 MW(t) to

Fuel assemblies (Assemblages combustibles)
Assemblies in core (Assemblages dans le cœur)
365
Pin per assembly (Bâtonnets par assemblage)
277
Pin length (Longueur de l'assemblage)
2.725 m
Assembly weight (Poids de l'assemblage)
1400 kg
Cladding material (Matériau de revêtement)
Zircaloy-4
Maximum cladding temperature (Température maximale nominale du gain)
600°C

Shield assemblies (Assemblages blindés)
Assemblies in core (Assemblages dans le cœur)
220
Pin per assembly (Bâtonnets par assemblage)
170
Pin length (Longueur de l'assemblage)
1.902 m
Assembly weight (Poids de l'assemblage)
5400 kg
Cladding material (Matériau de revêtement)
zirconium metal (acier inoxydable)

Control rod assemblies (Assemblages de Commande)
Main assembly system (Système à commande principale)
Assemblies in core (Assemblages dans le cœur)
21
Assemblies per assembly (Assemblages par assemblage)
21
Pin length (Longueur de l'assemblage)
1.382 m
Cladding material (Matériau de revêtement)
Zircaloy-4
Maximum cladding temperature (Température maximale nominale du gain)
3
Assemblies in core (Assemblages dans le cœur)
3
Assemblies per assembly (Assemblages par assemblage)
3
Cladding material (Matériau de revêtement)
zirconium metal (acier inoxydable)

Main reactor tank (Cœur du réacteur)
Height (Hauteur)
10.000 m
Weight (Poids)
19000 ton
Cladding material (Matériau de revêtement)
zirconium metal (acier inoxydable)

Primary circuit (Circuit primaire)
Total mass of sodium in primary circuit
13 000 t
Mass of sodium in each loop (Masses primaires)
4 x 4 100 t
Inlet sodium temperature
300°C
Temperature of sodium in each loop (Température de sodium dans chaque boucle)
300°C
Core inlet temperature
540°C
Temperature of sodium in core (Température de sodium dans le cœur)
542°C
Inlet water temperature
342°C
Temperature of water in each loop (Température de l'eau dans chaque boucle)
342°C

Secondary circuit (Circuit secondaire)
Total mass of sodium in secondary circuit
1 500 t
Mass of sodium in each loop (Masses secondaires)
4 x 375 t
Inlet sodium temperature
340°C
Temperature of sodium in each loop (Température de sodium dans chaque boucle)
340°C
Core inlet temperature
520°C
Temperature of water in each loop (Température de l'eau dans chaque boucle)
340°C

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

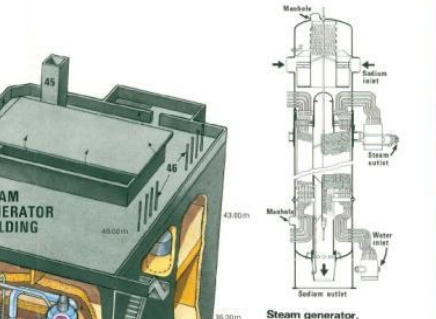
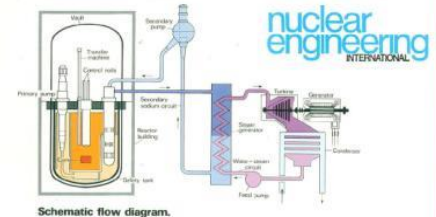
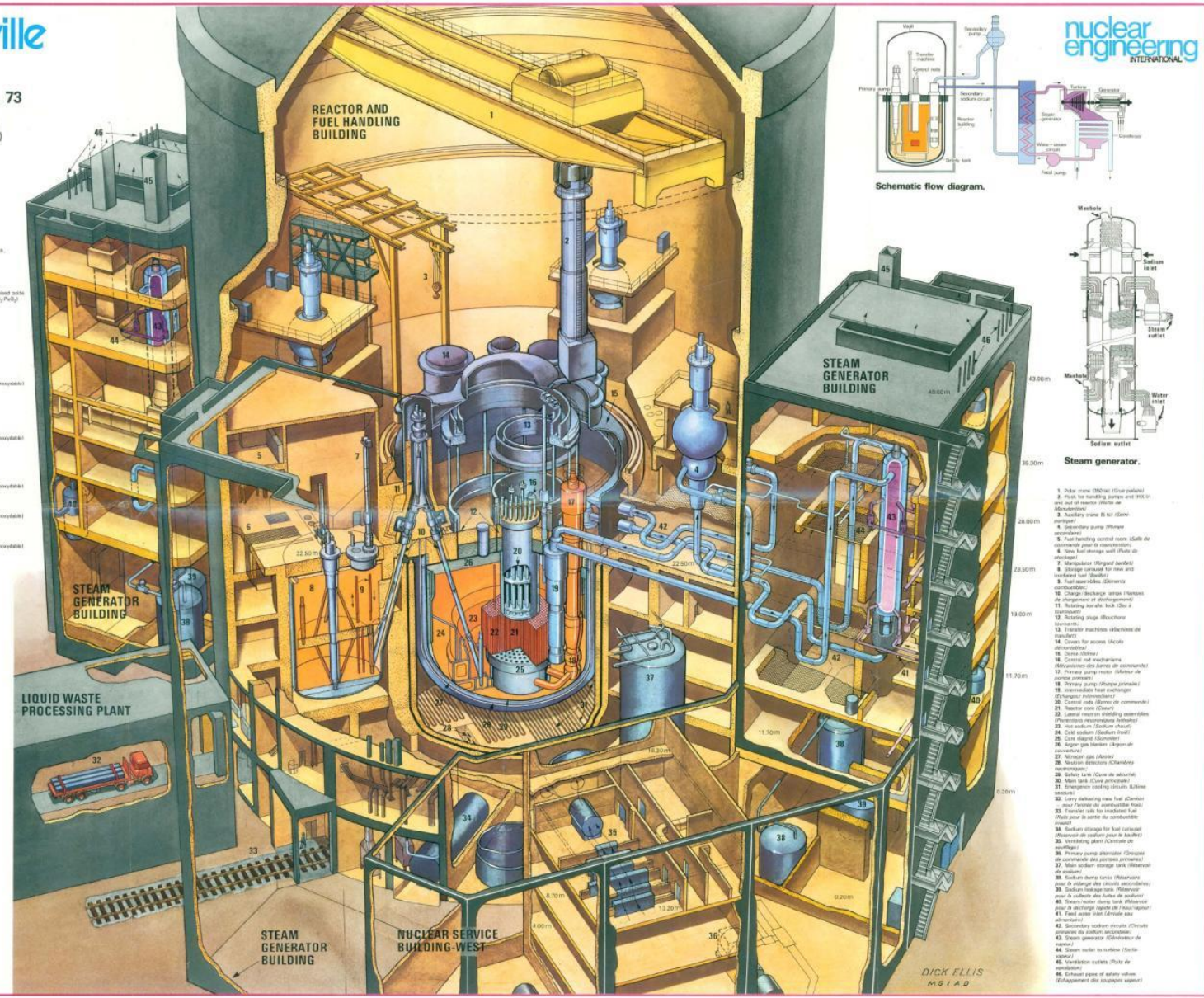
Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

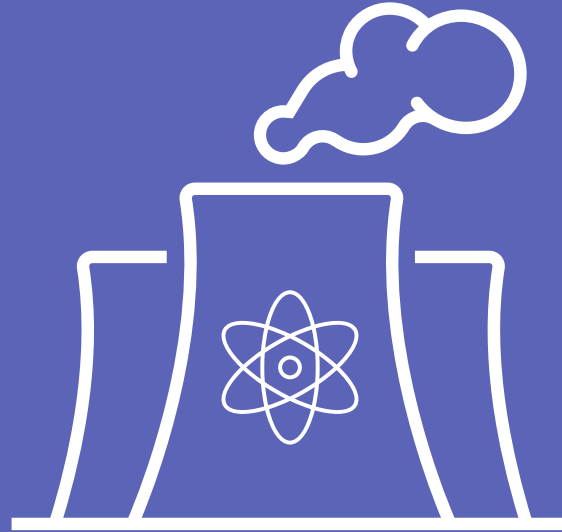
Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h

Water steam circuit (Circuit eau-vapeur)
Water temperature pressure at steam generator exit
(Température pression de l'eau à l'entrée des générateurs de vapeur)
220°C/220 bar
Steam temperature pressure at turbine inlet valve
(Température pression de la vapeur à l'entrée des turbines)
460°C/127 bar
Normal flow rate (Débit normal)
4 x 3 000 t/h



1. Pile (cœur) (Core) (pile)
2. Flux for handling current and PWR in case of reactor (Flux de commande pour la manutention)
3. Fuel handling control room (Salle de commande pour la manutention)
4. Fuel storage (Salle de stockage)
5. Fuel handling control room (Salle de commande pour la manutention)
6. Fuel storage (Salle de stockage)
7. Manutention (Manutention)
8. Storage tank for sodium (Salle de stockage pour le sodium)
9. Fuel storage (Salle de stockage)
10. Charge (charge) (charge)
11. Storage tank for sodium (Salle de commande pour la manutention)
12. Storage tank for sodium (Salle de commande pour la manutention)
13. Transfer machine (Machine de transfert)
14. Covers for access (Couvercles d'accès)
15. Control and monitoring (Contrôle et surveillance)
16. Control and monitoring (Contrôle et surveillance)
17. Primary pump (Pompe primaire)
18. Primary pump (Pompe primaire)
19. Intermediate heat exchanger (Échangeur intermédiaire)
20. Charge (charge) (charge)
21. Reactor core (Cœur du réacteur)
22. Control and monitoring (Contrôle et surveillance)
23. Fuel storage (Salle de stockage)
24. Fuel storage (Salle de stockage)
25. Fuel storage (Salle de stockage)
26. Fuel storage (Salle de stockage)
27. Fuel storage (Salle de stockage)
28. Fuel storage (Salle de stockage)
29. Fuel storage (Salle de stockage)
30. Fuel storage (Salle de stockage)
31. Fuel storage (Salle de stockage)
32. Fuel storage (Salle de stockage)
33. Fuel storage (Salle de stockage)
34. Fuel storage (Salle de stockage)
35. Fuel storage (Salle de stockage)
36. Fuel storage (Salle de stockage)
37. Fuel storage (Salle de stockage)
38. Fuel storage (Salle de stockage)
39. Fuel storage (Salle de stockage)
40. Fuel storage (Salle de stockage)
41. Fuel storage (Salle de stockage)
42. Fuel storage (Salle de stockage)
43. Fuel storage (Salle de stockage)
44. Fuel storage (Salle de stockage)
45. Fuel storage (Salle de stockage)
46. Fuel storage (Salle de stockage)

Thank you ☺



**Quick Introduction to Nuclear
Physics and Engineering**

Elena de la Fuente García (BE-ABP-CEI)

Outline

