Khemis Miliana University – Djilali BOUNAAMA
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Department of Physics

Nuclear Physics

L3 Fundamental Physics

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Content

Nuclear Physics

L3 Fundamental Physics

Chapter 04

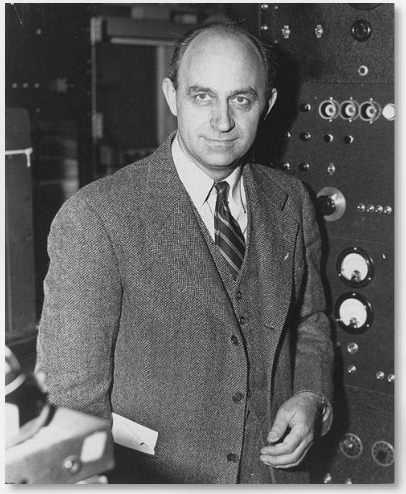
Nuclear Energy

IV Nuclear Energy

Reactions classification

In 1932, J. CHADWICK, after redoing the Joliot-Curie experiment, was able to explain that the observed highly penetrating rays was not a $\gamma -$ rays but a massive neutral particle rays (~1uma) named initially "neutrino", adjusted later as "neutron".

Fritz Strassmann, Lise Meitner, Otto Hahn, realized the first induced fission experiment in 1938 (Berlin)



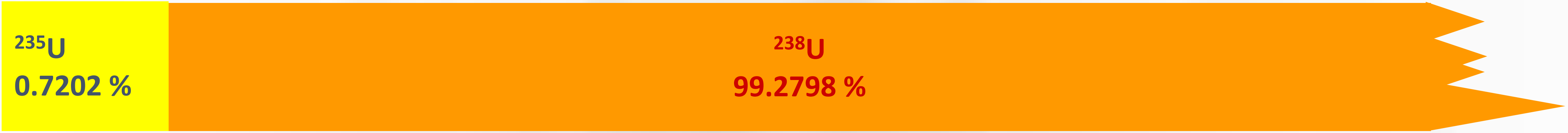
2nd of December 1942, E. Fermi conducted the first controlled fission reaction chain within Chicago-Pile1

IV Nuclear Energy

In nature, Uranium is present with two main isotopes:

- **U235 (0.720%)**
- **U238 (99.275%)**

Tiny traces of U234 (0.005%) are associated to the U238 decay.

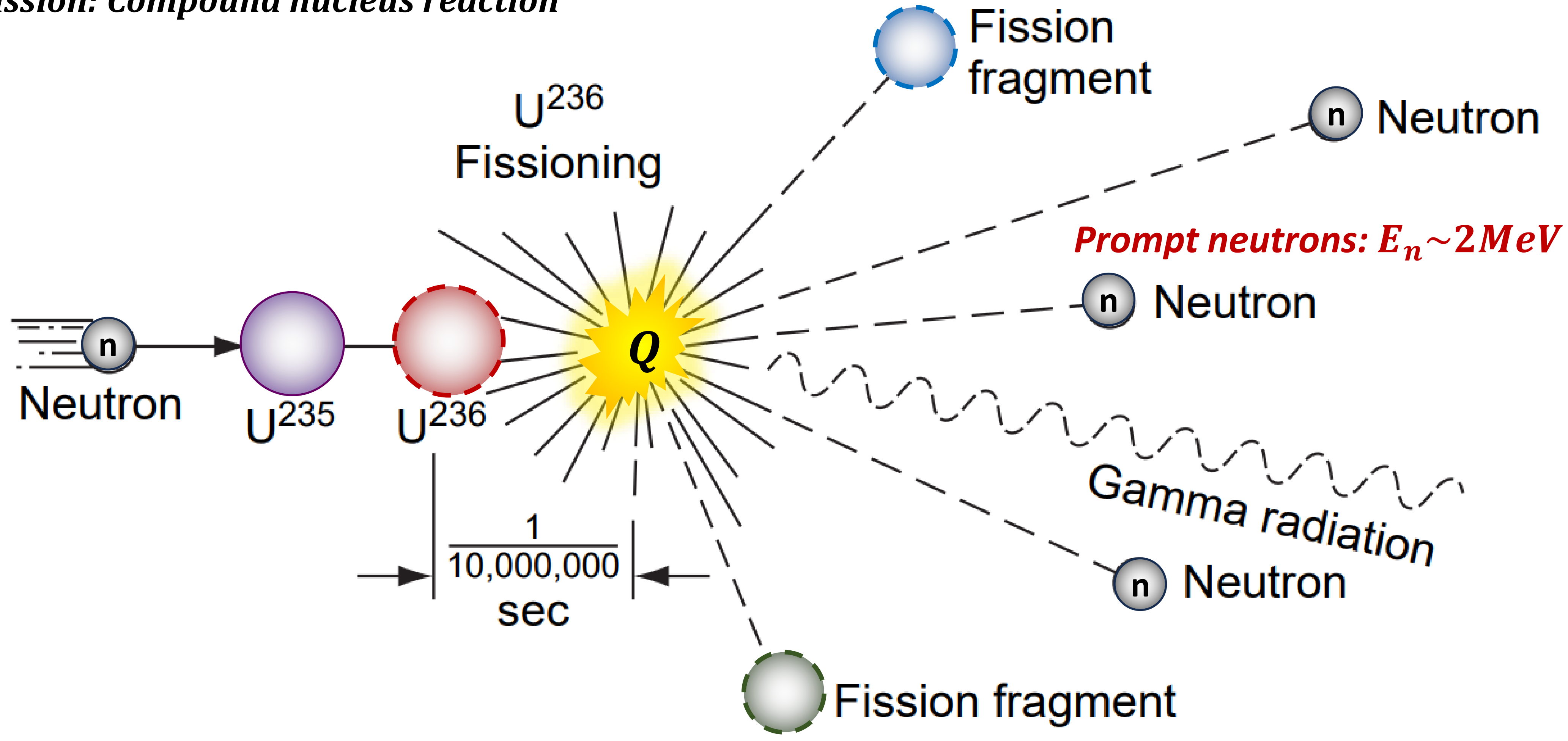


IV Nuclear Energy

U235 fission

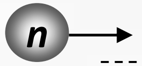
$$Q = (m_n + M_{235})c^2 - (\bar{\nu} m_n + M_{FP1} + M_{FP2})c^2 \cong 200MeV$$

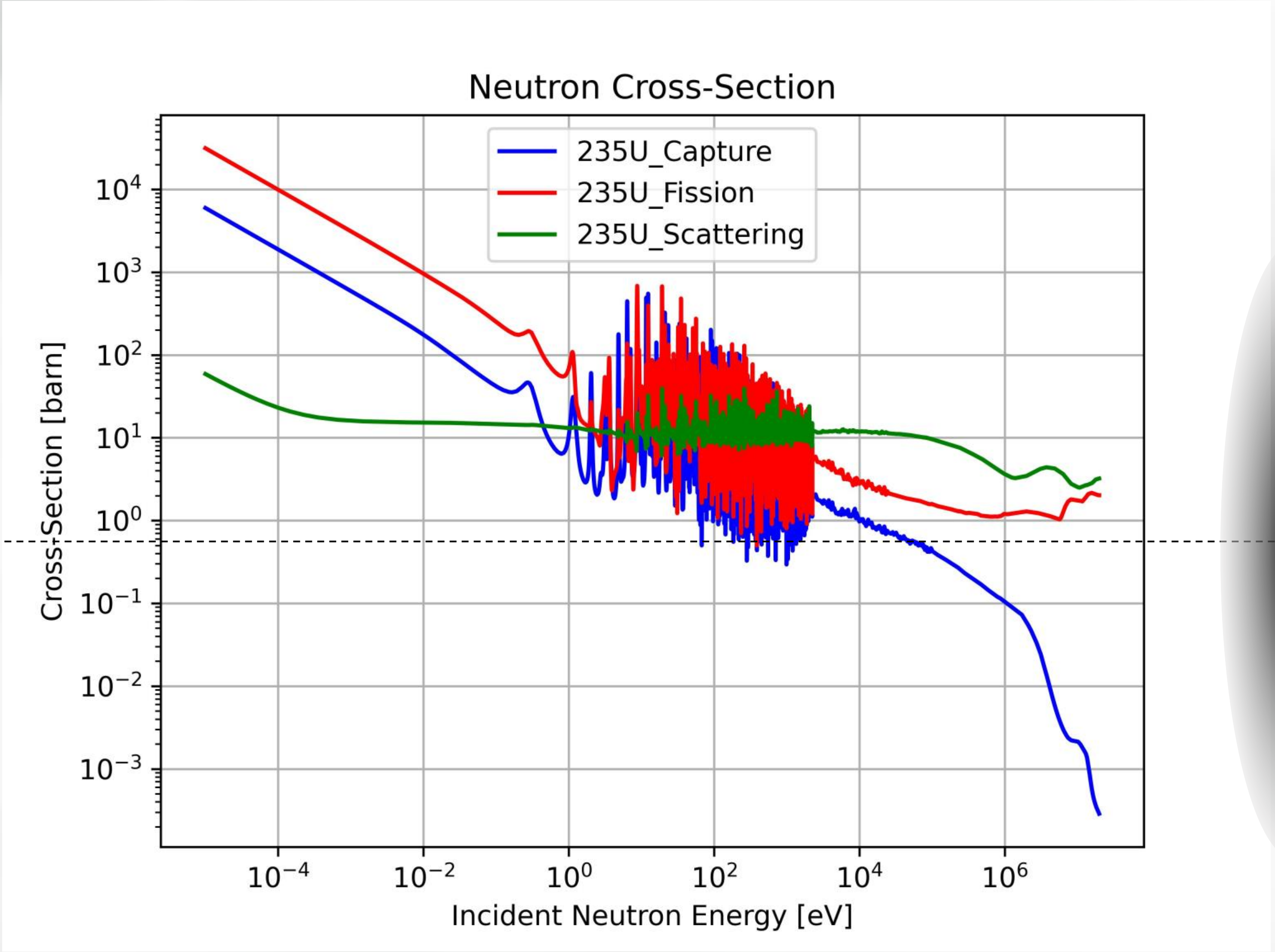
Fission: Compound nucleus reaction



IV Nuclear Energy

U235 fission





U235 fission

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U \longrightarrow ^{90}_{38}Sr + ^{144}_{54}Xe + 2\,^{1}_{0}n$$

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U \longrightarrow ^{87}_{35}Br + ^{146}_{57}La + 3\,^{1}_{0}n$$

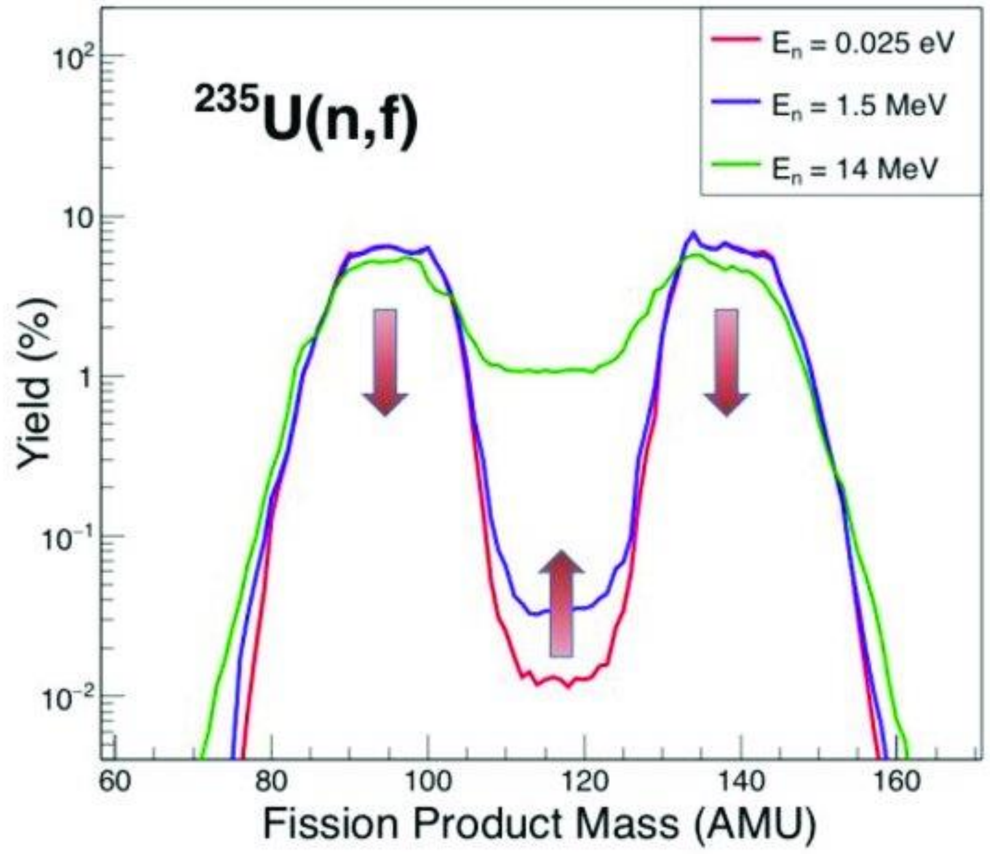
$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U \longrightarrow ^{96}_{37}Rb + ^{137}_{55}Cs + 3\,^{1}_{0}n$$

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U \longrightarrow ^{137}_{52}Te + ^{97}_{40}Zr + 2\,^{1}_{0}n$$

$$^{235}_{92}U + ^{1}_{0}n \longrightarrow ^{236}_{92}U \longrightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3\,^{1}_{0}n$$

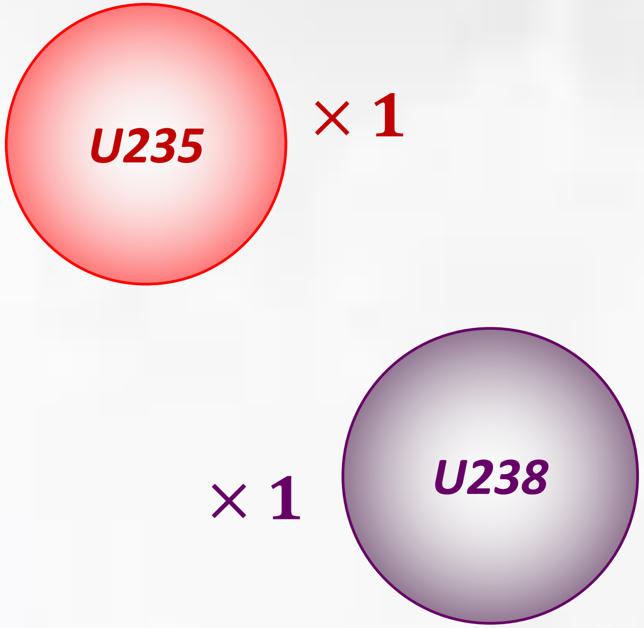
Fission yields $\bar{\nu} \sim 2.5$

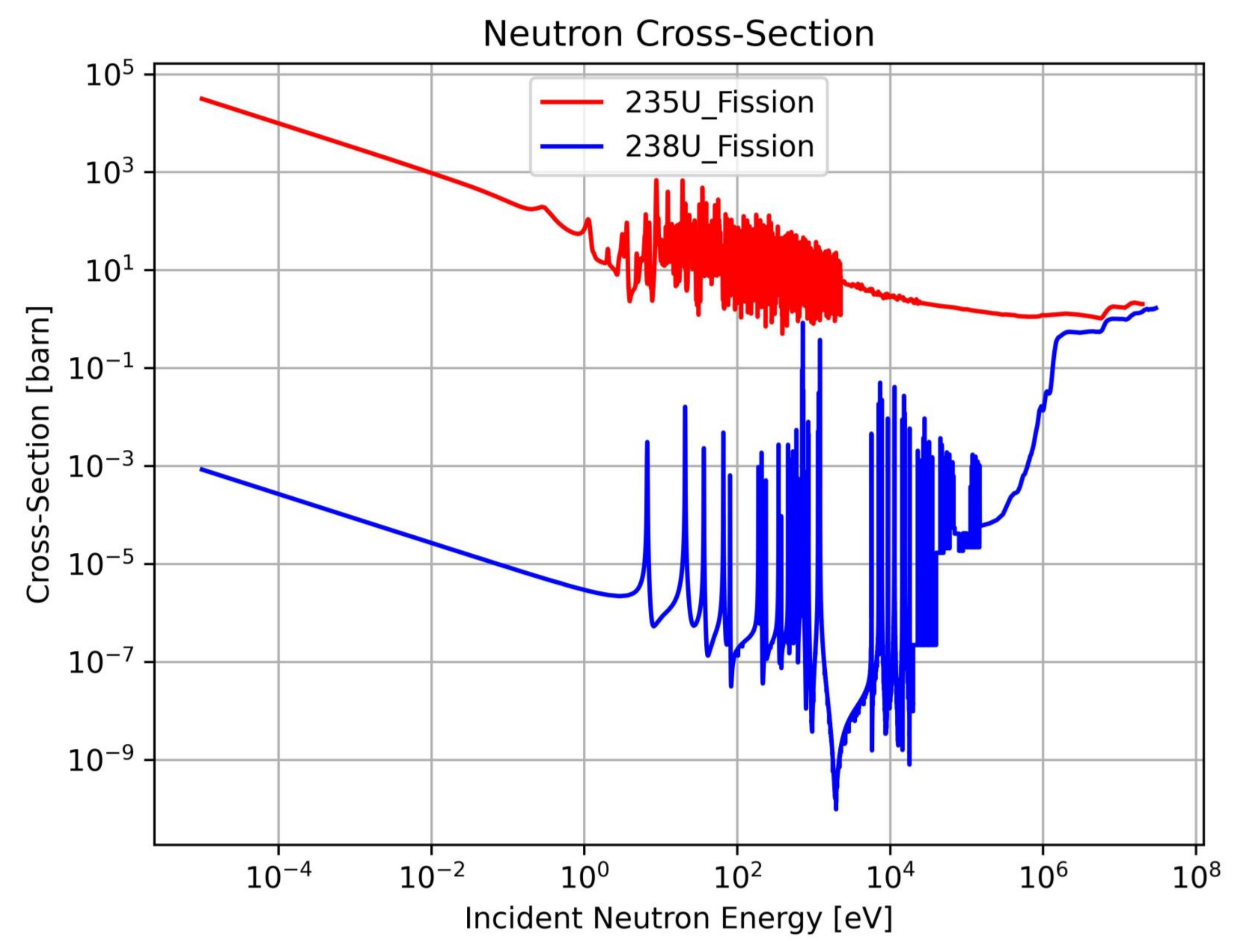
Fission products yields



IV Nuclear Energy

U8 vs U5 Cross-sections



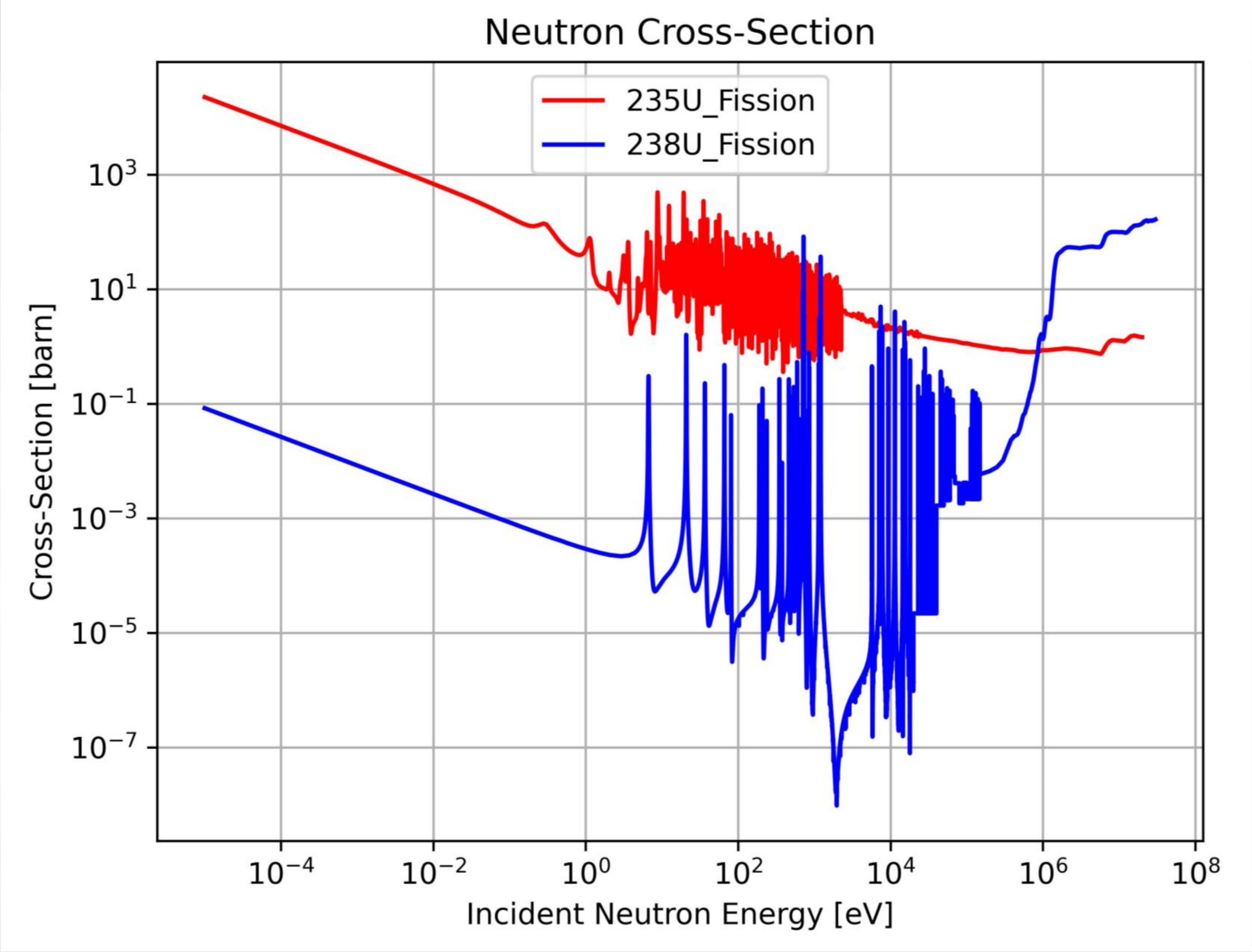


IV Nuclear Energy

U8 vs U5 Cross-sections

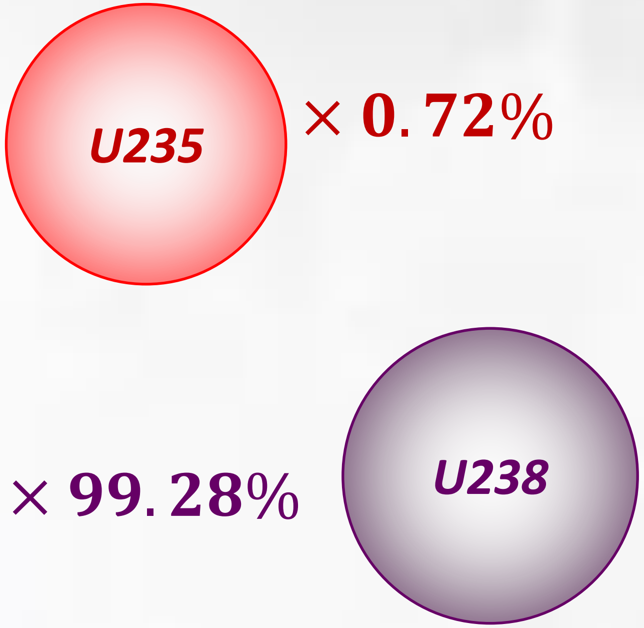
$\times$ **0.72%**

$\times$ **99.28%**



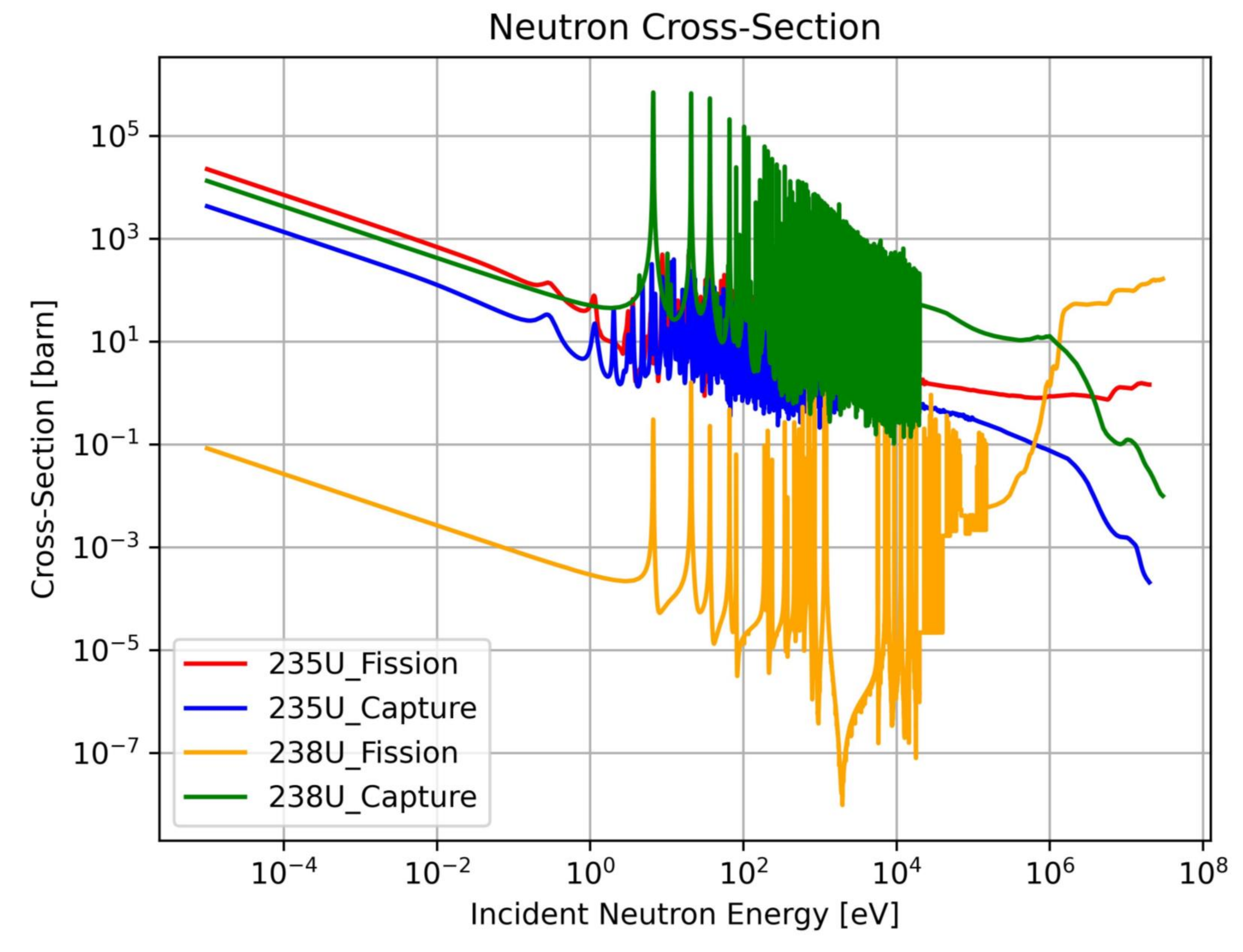
IV Nuclear Energy

U8 vs U5 Cross-sections



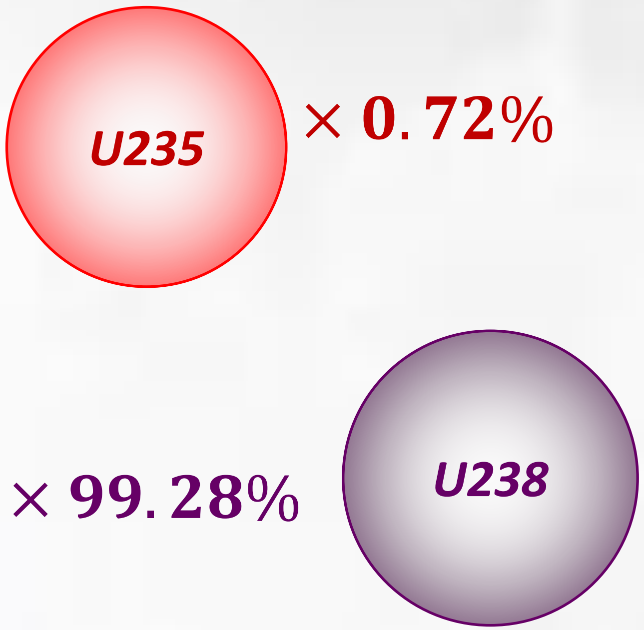
$\times$ 0.72%

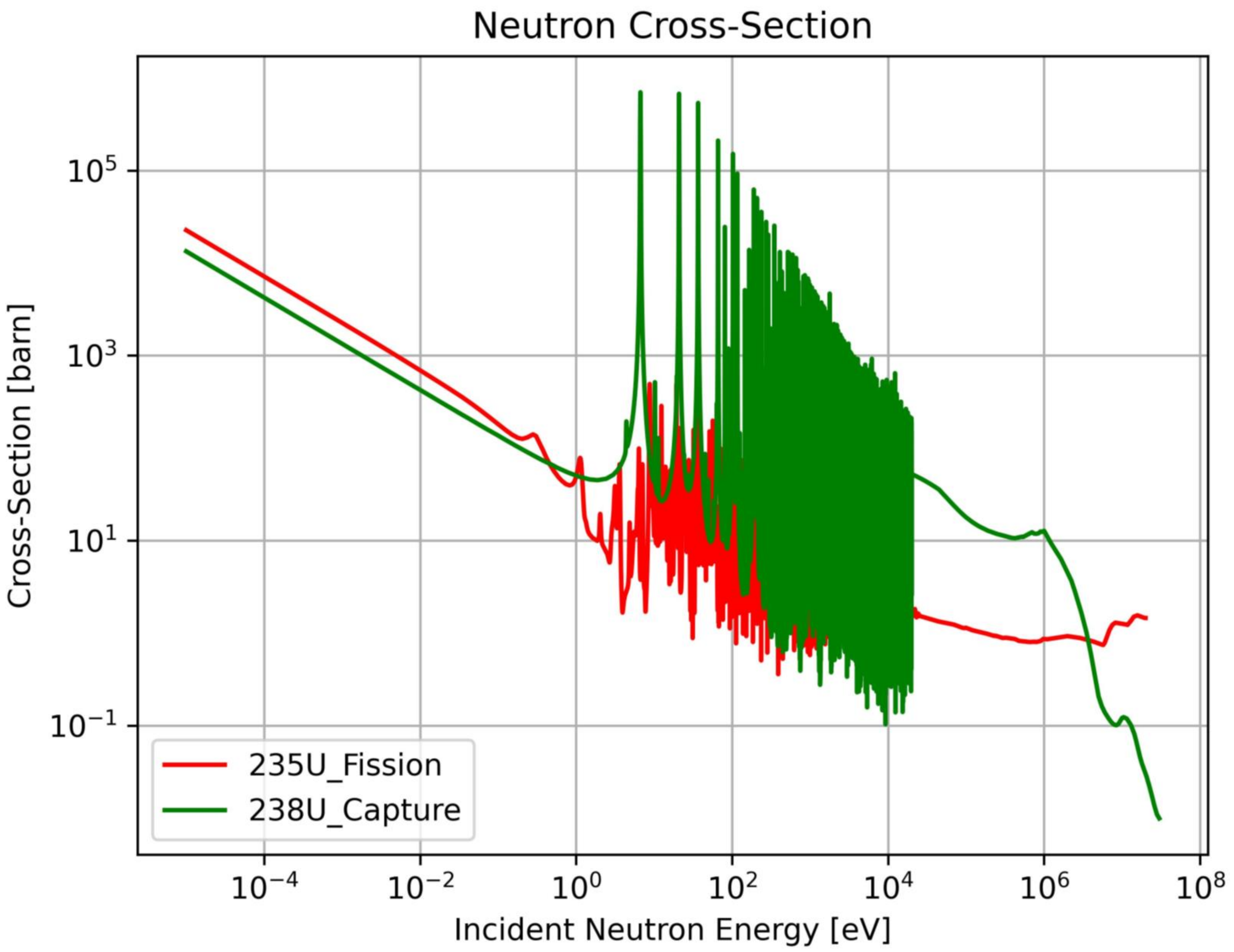
$\times$ 99.28%



IV Nuclear Energy

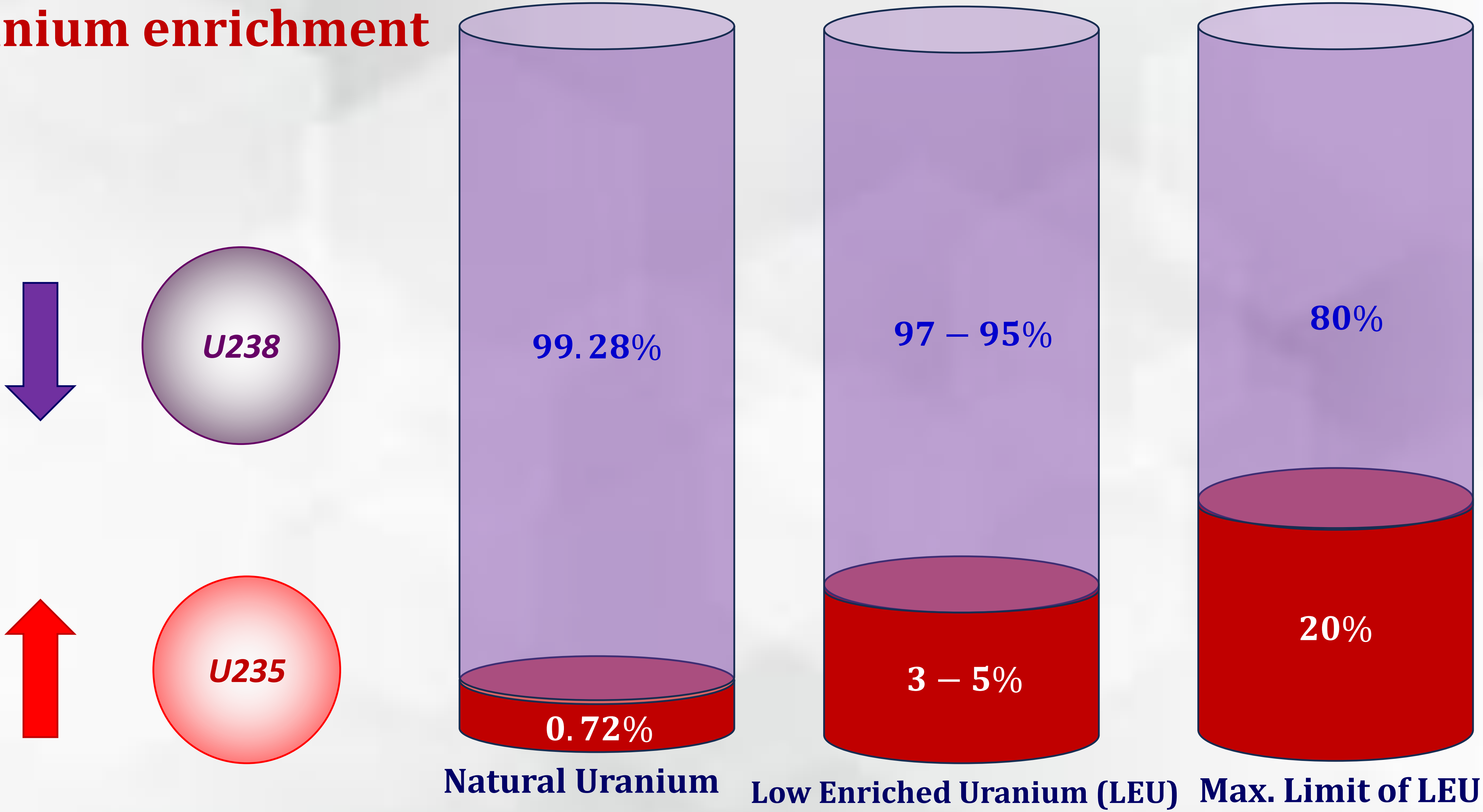
U8 vs U5 Cross-sections





IV Nuclear Energy

Uranium enrichment



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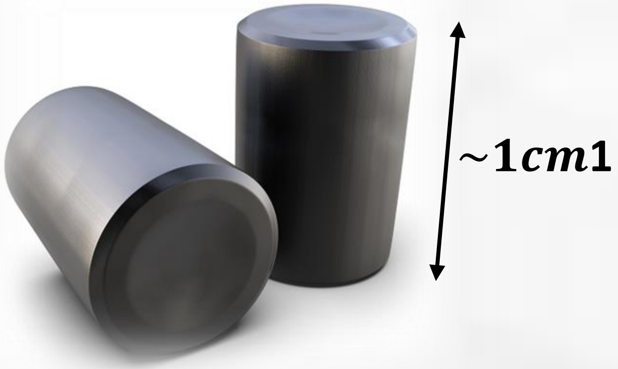
U8 vs U5 Cross-sections

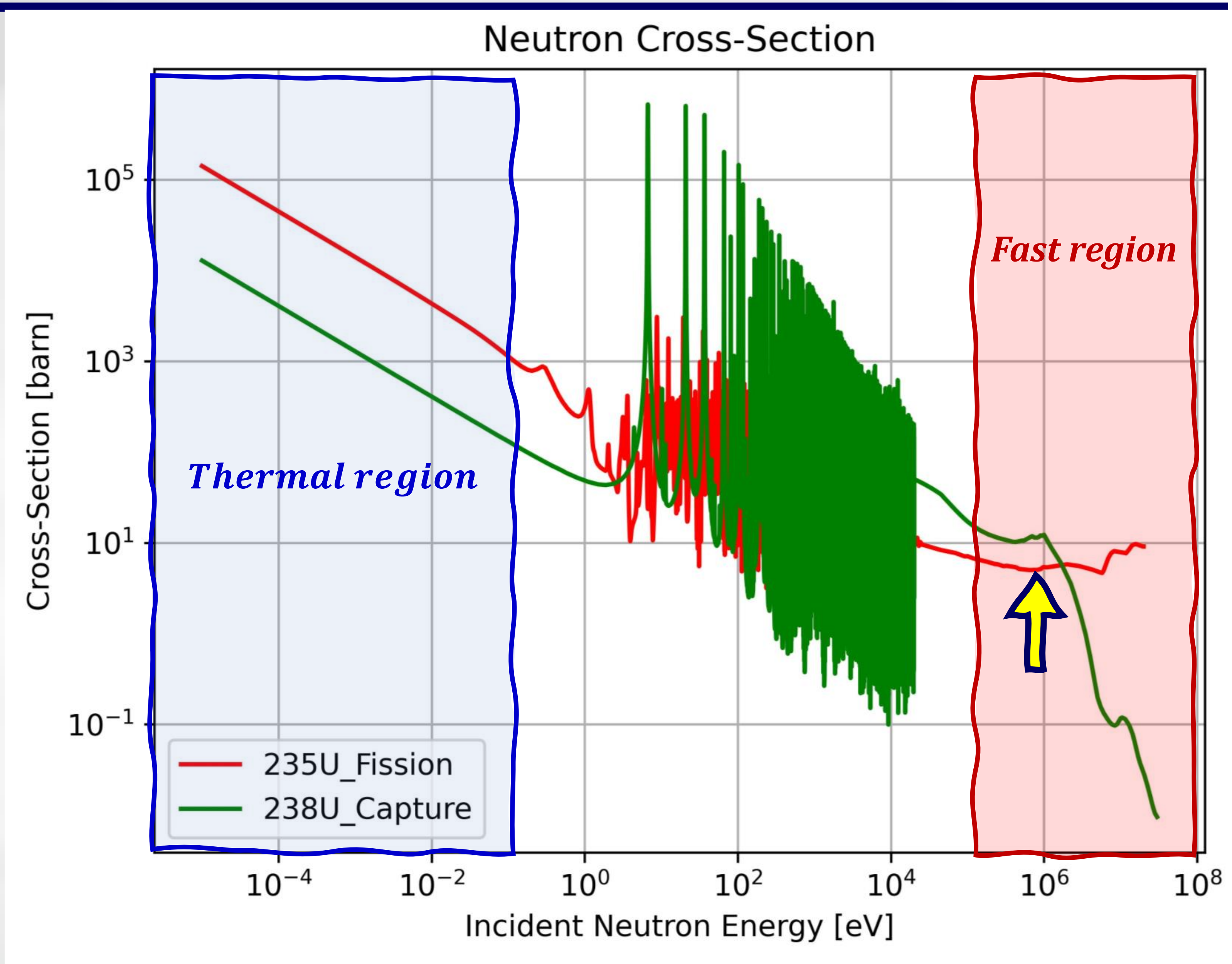
U235 × 4%

U238 × 96%



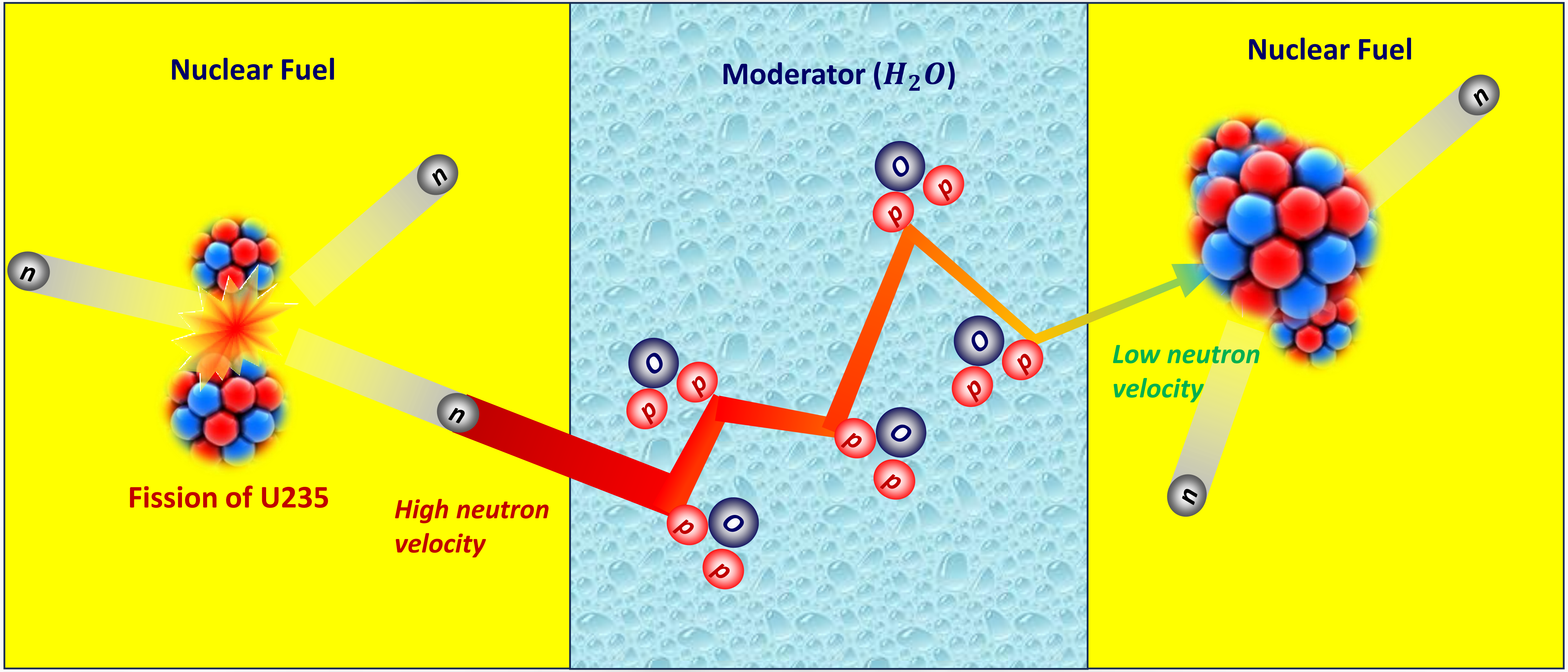
Fuel pellet : $UO_2(\rho_{fuel} \cong 10.6[g/cc])$

$n_U \cong 2 \times 10^{22}[atoms/cc]$



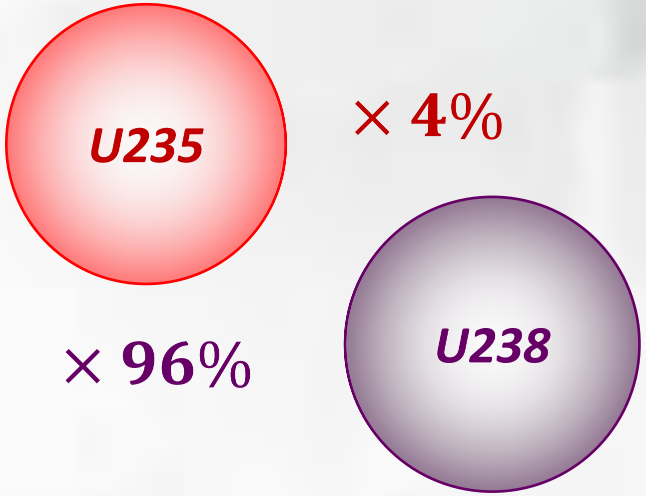
III Nuclear Reactions

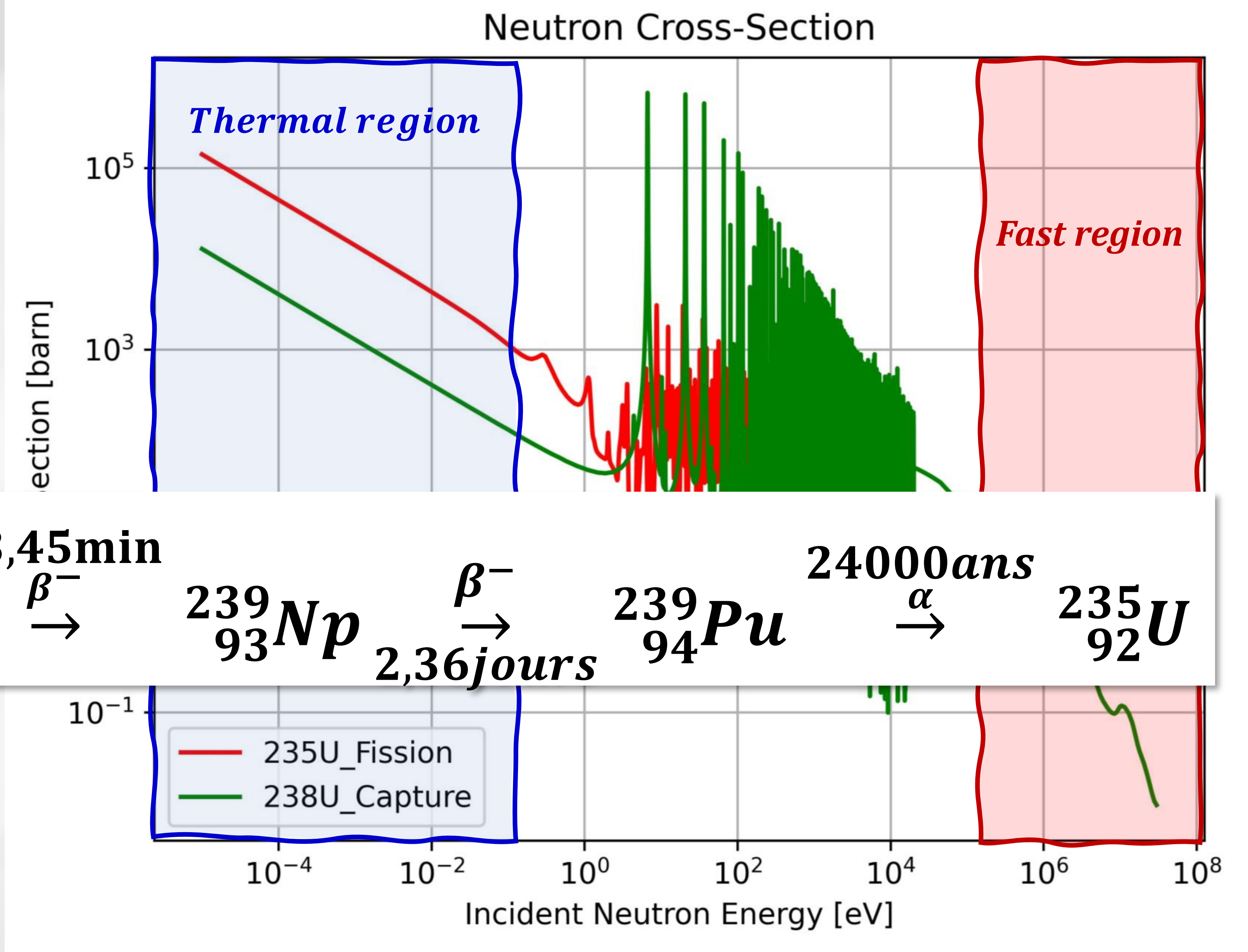
Neutron slowdown



IV Nuclear Energy

U8 vs U5 Cross-sections



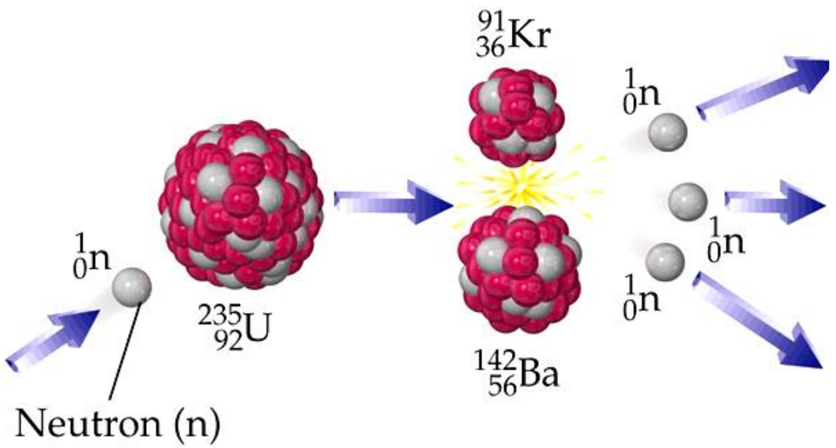


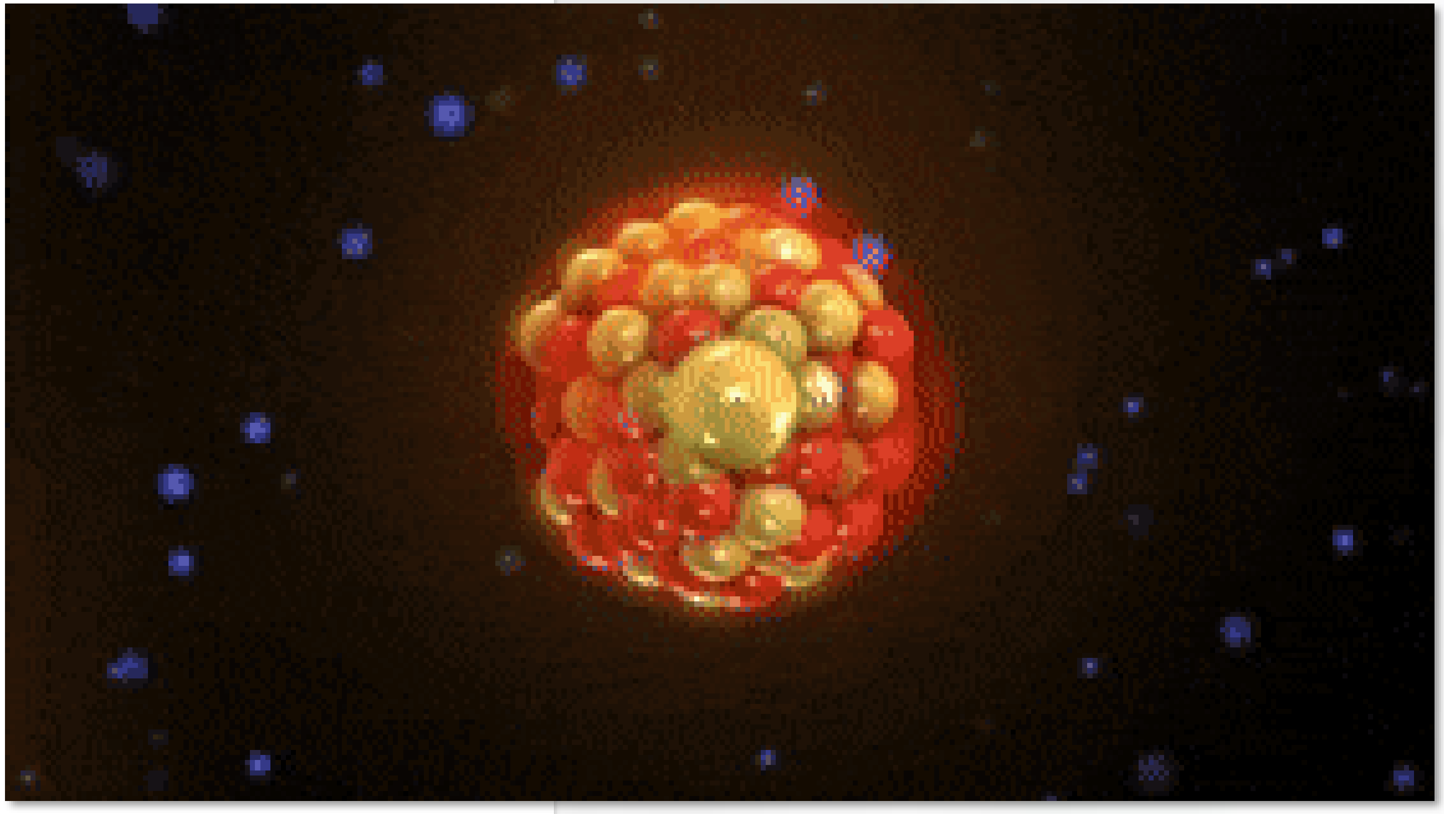
$$ {}^{1}_{0}n + {}^{238}_{92}U \rightarrow {}^{239}_{92}U^{*} \overset{23{,}45\text{min}}{\xrightarrow{\beta^-}} {}^{239}_{93}Np \xrightarrow[2{,}36 jours]{\beta^-} {}^{239}_{94}Pu \overset{24000ans}{\xrightarrow{\alpha}} {}^{235}_{92}U $$

U238 is a "fertile" isotope because it could produce another fissile isotope through neutron capture

IV Nuclear Energy

Fission chain reaction





$$RR_f = \frac{dN}{dt} = \phi\Sigma \rightarrow P[W] \propto Q \times RR_f \equiv Q\phi\Sigma = Q\phi n\sigma$$

IV Nuclear Energy

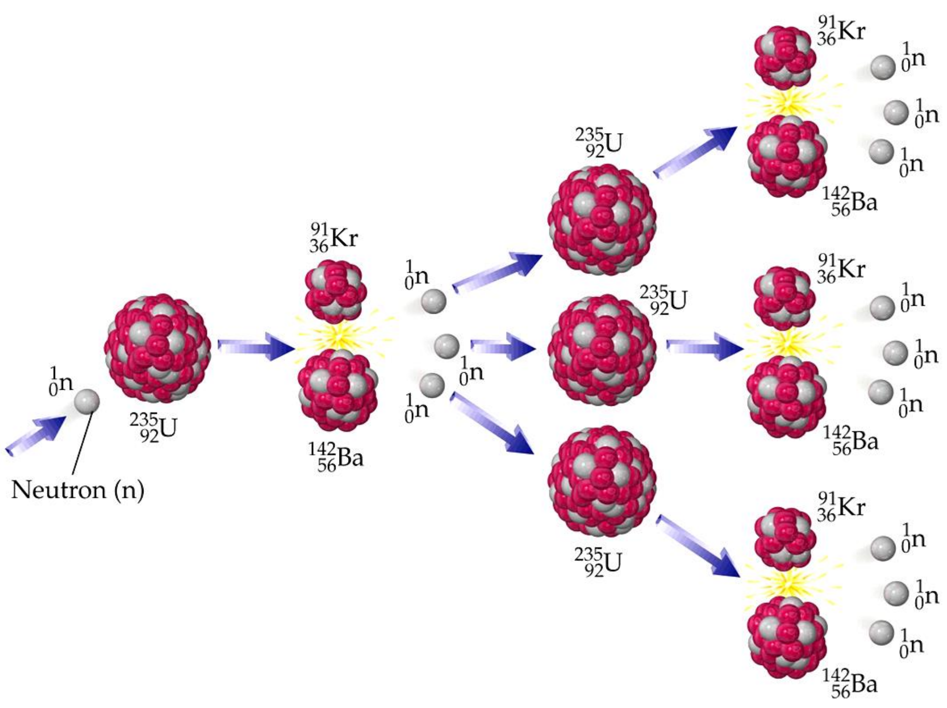
Multiplication factor

The multiplication factor describes the ratio between consecutive neutron generation (neutrons produced simultaneously) :

$$k = \frac{Generation_{m+1}}{Generation_m}$$

According to the k value (geometrical sequence), three main situations could be distinguished:

1. **Sub-critical system: $k < 1$**
2. **Critical system: $k = 1$ (Nuclear reactor)**
3. **Supercritical system: $k > 1$**



N fissions
↓
N.k fissions
↓
N.K² fissions
↓
N.k³ fissions
↓
N.k⁴ fissions
⋮
N.k^M fissions

IV Nuclear Energy

Criticality and sustained fission

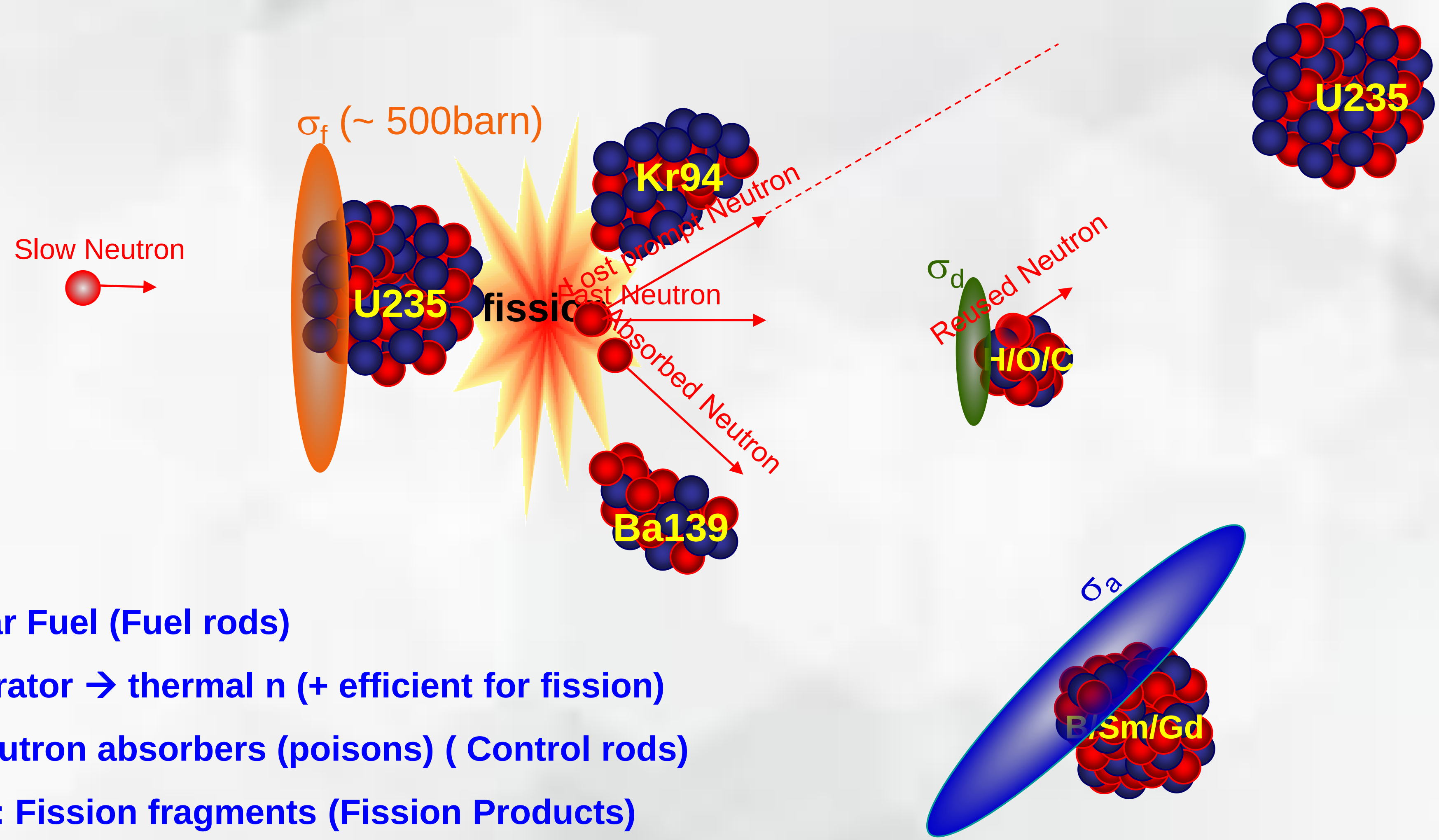
If somehow, someone could keep the k factor near 1 (critical system) we get what we call "Sustained fission reactions chain".

That what E. Fermi succeeded to do in dec. 1942 at Chicago Univ. with the first human-made nuclear fission reactor CP-1.

The excess of neutrons should be handled to avoid any over-rate of fission reactions (increase of reactor heat). In this case, some material known as neutrons absorbers are used to control fission reactions chain. Boron, Cadmium, Gadolinium, Samarium are used in the control rods conception, and inserted according the situation to reduce the neutron population amount (Neutron flux)

IV Nuclear Energy

Criticality and sustained fission



U235: Nuclear Fuel (Fuel rods)

H/O/C: Moderator → thermal n (+ efficient for fission)

B/Sm/Gd: Neutron absorbers (poisons) (Control rods)

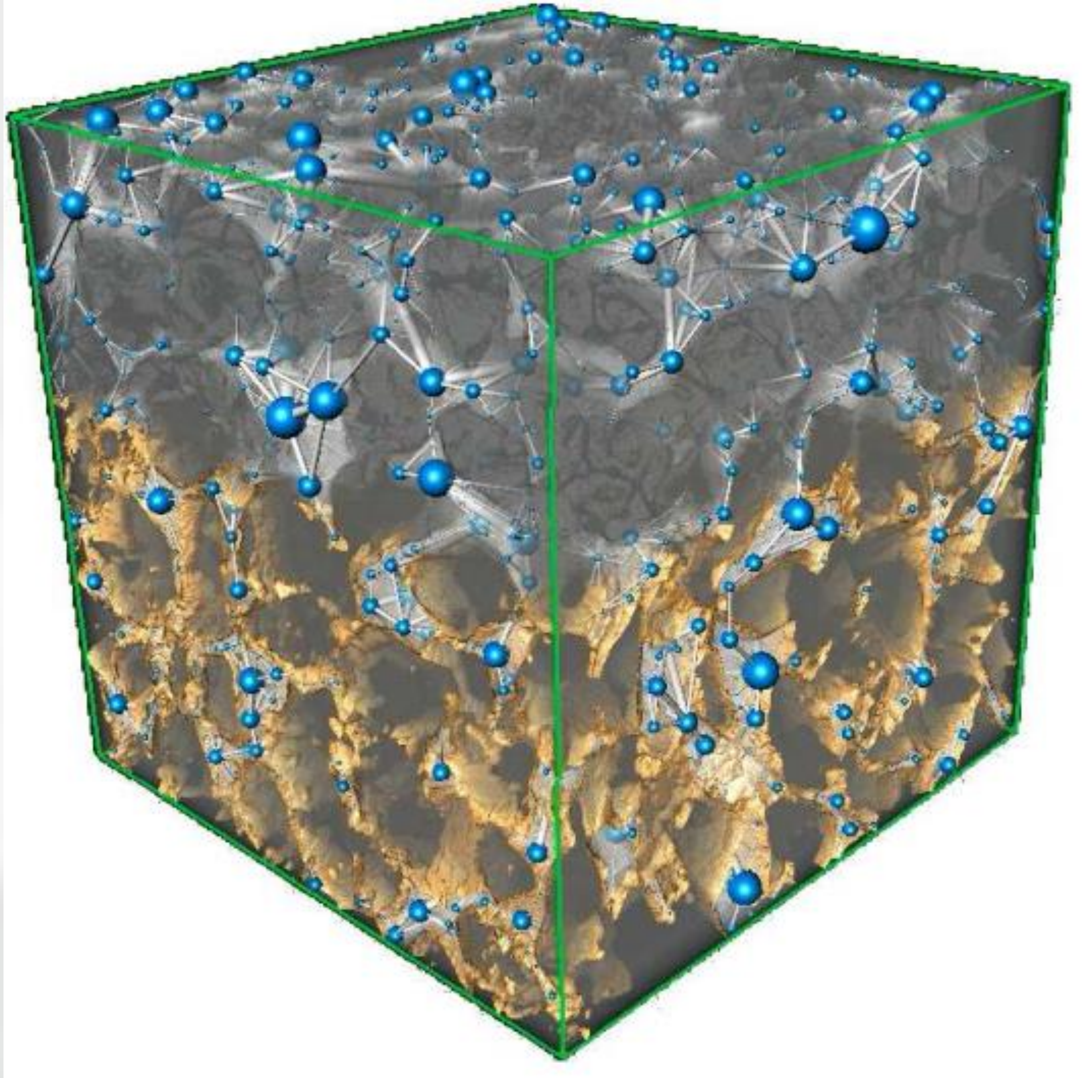
Kr94 / Ba139: Fission fragments (Fission Products)

III Nuclear Reactions

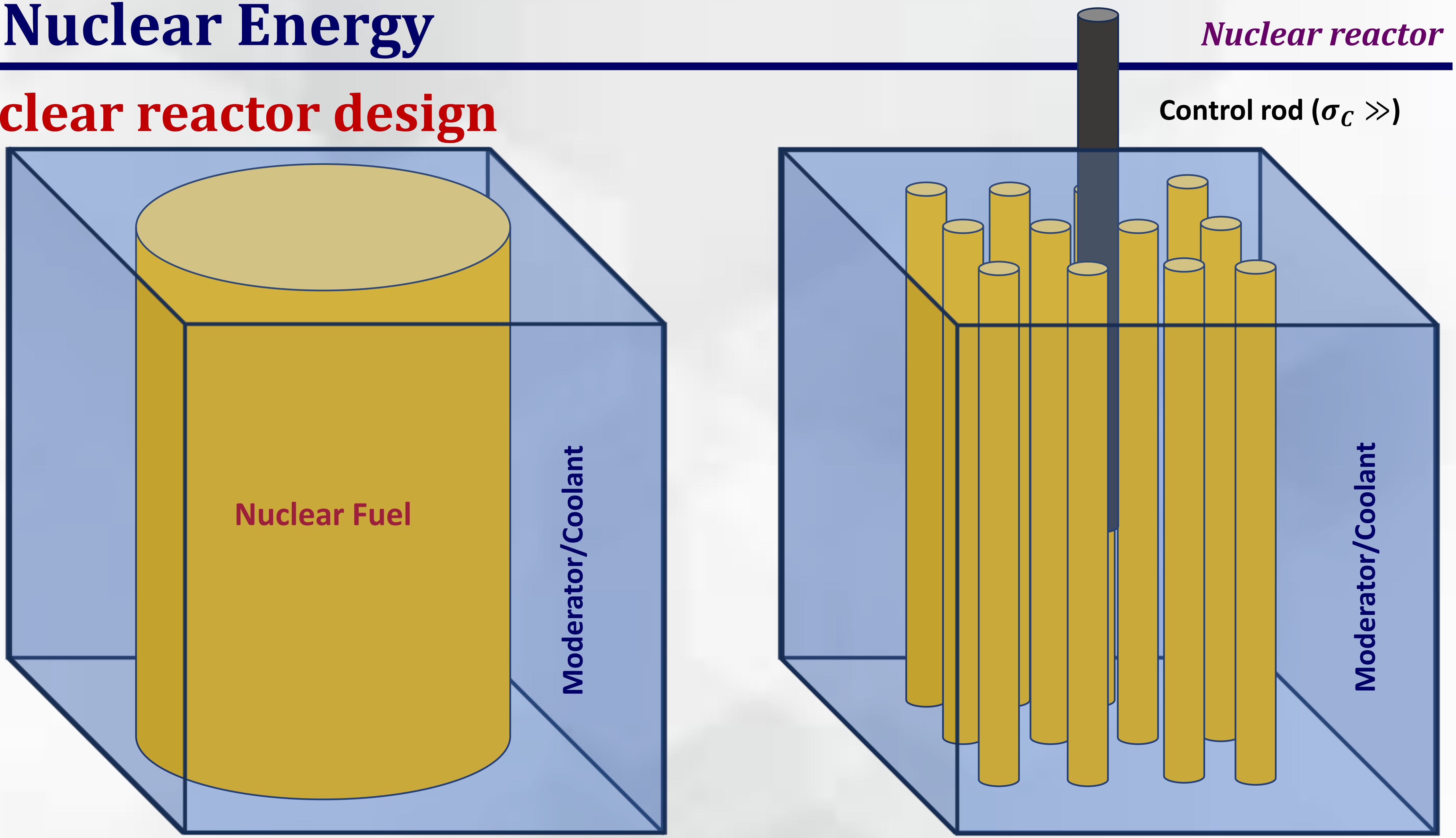
Oklo phenomenon: 2 billion years old natural nuclear reactors (Gabon)

In 1956, J.P. Kuroda predicted that if about 2 b.y old deposit of uranium existed with sufficient content of Uranium and hydrogenous material (Water/Hydrocarbons), sustained fission chain reactions may be ignited and sustained.

In 1972, fossil nuclear fission reactors were discovered in U-deposit in Oklo deposit (near Franceville, Gabon)



Nuclear reactor design



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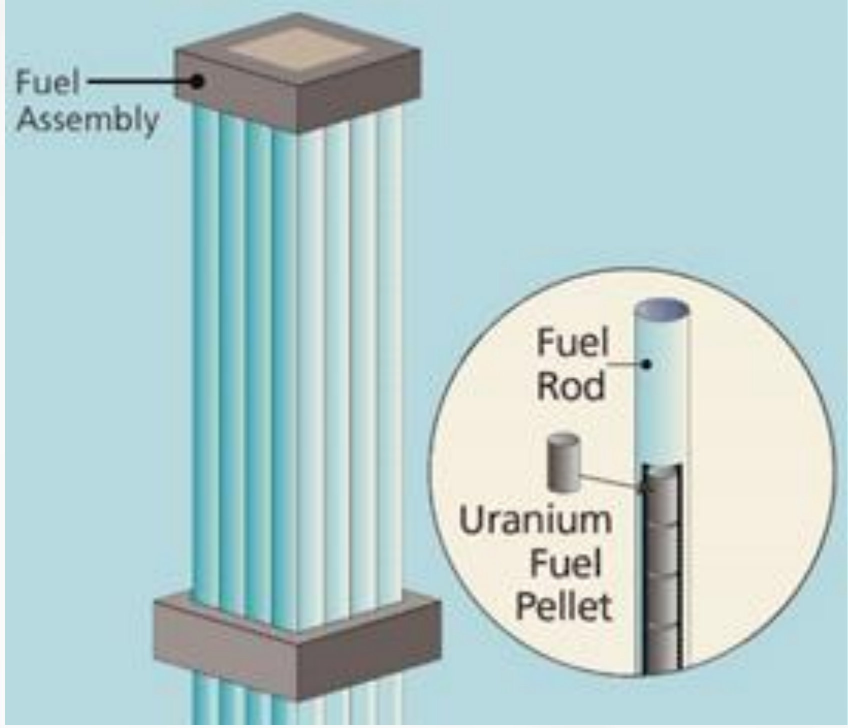
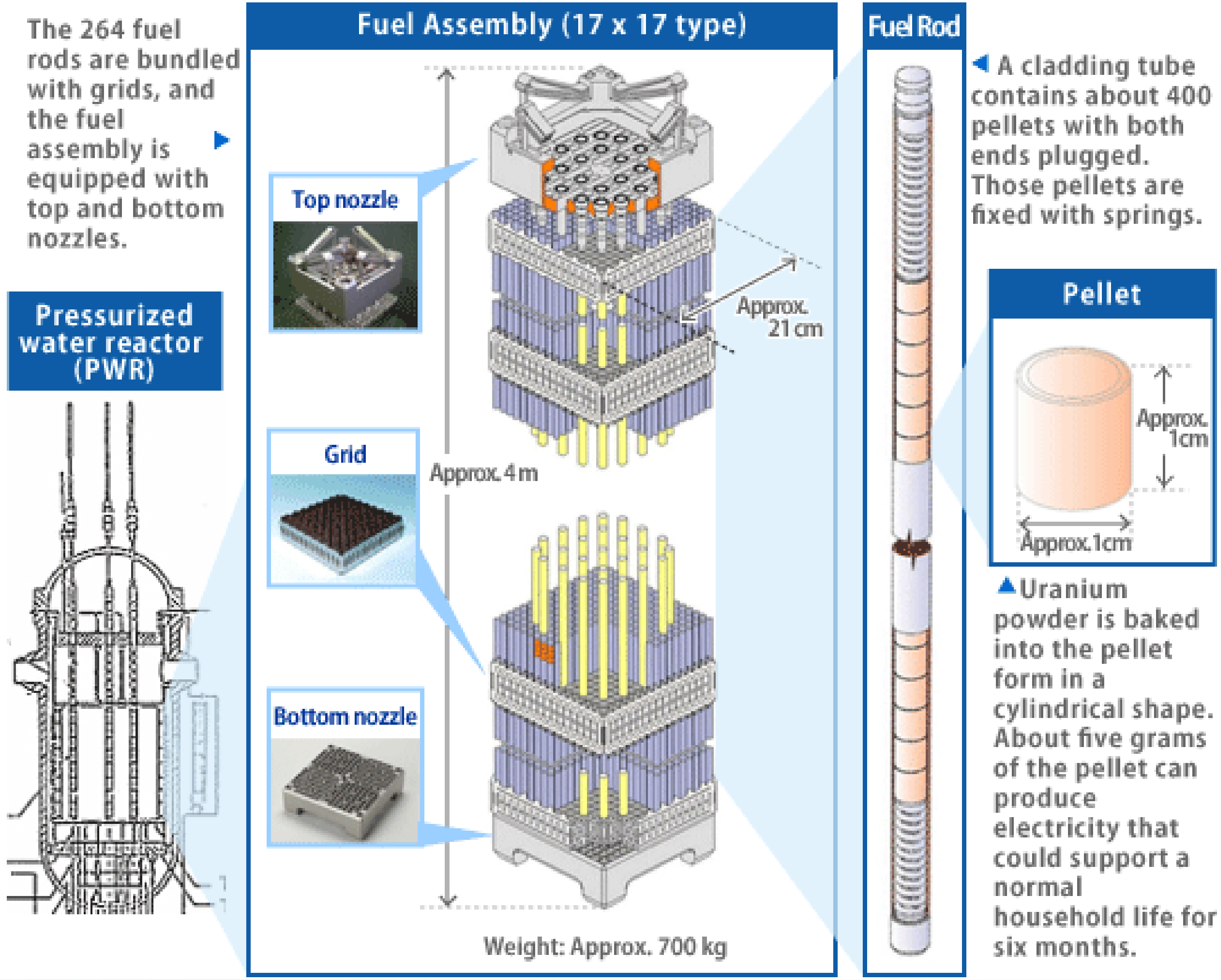
Nuclear reactor design





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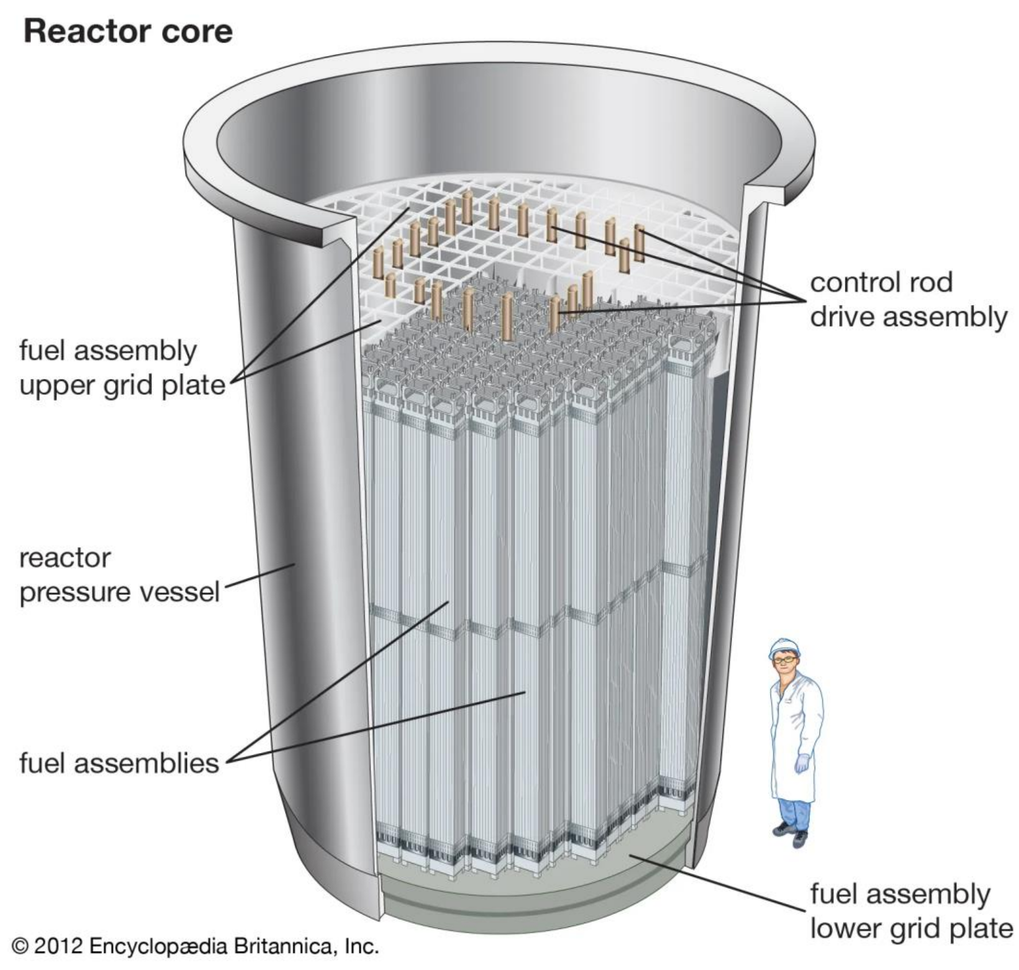
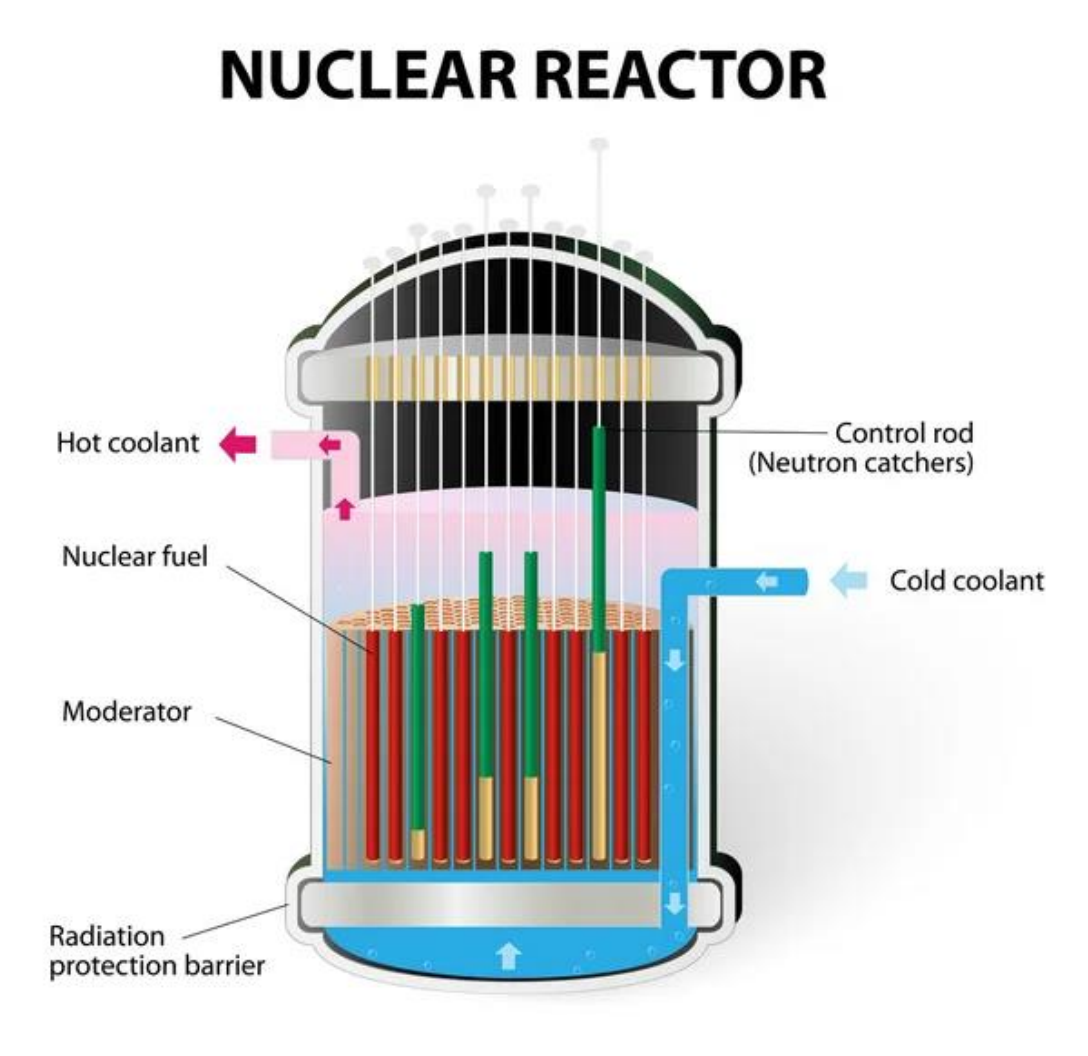
Nuclear reactor core



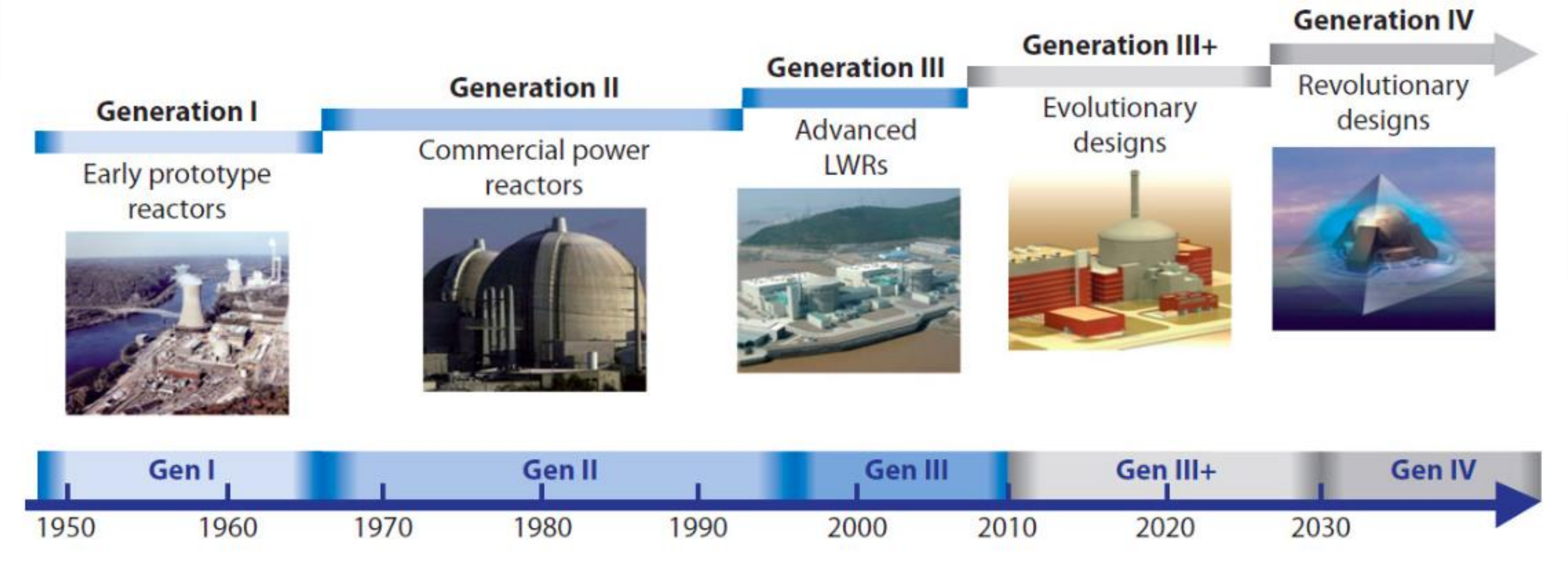
Arrangement of nuclear FAs to obtain the reactor core



Operating the nuclear reactor to obtain usable heat

IV Nuclear Energy

Nuclear reactor core



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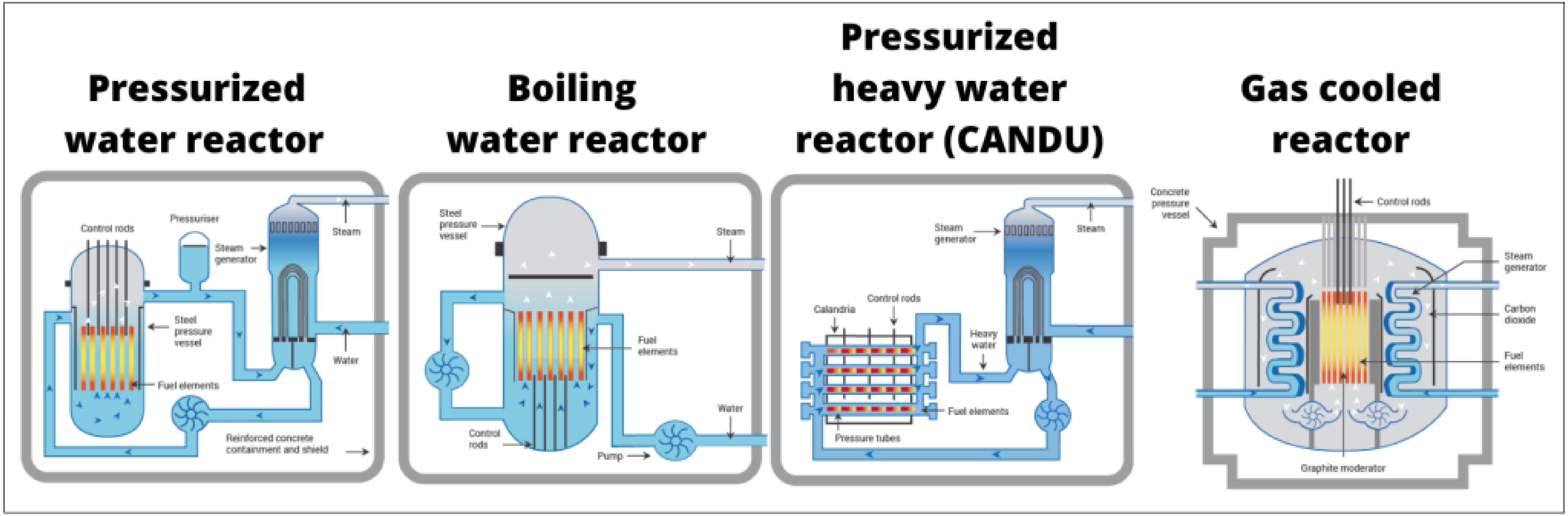
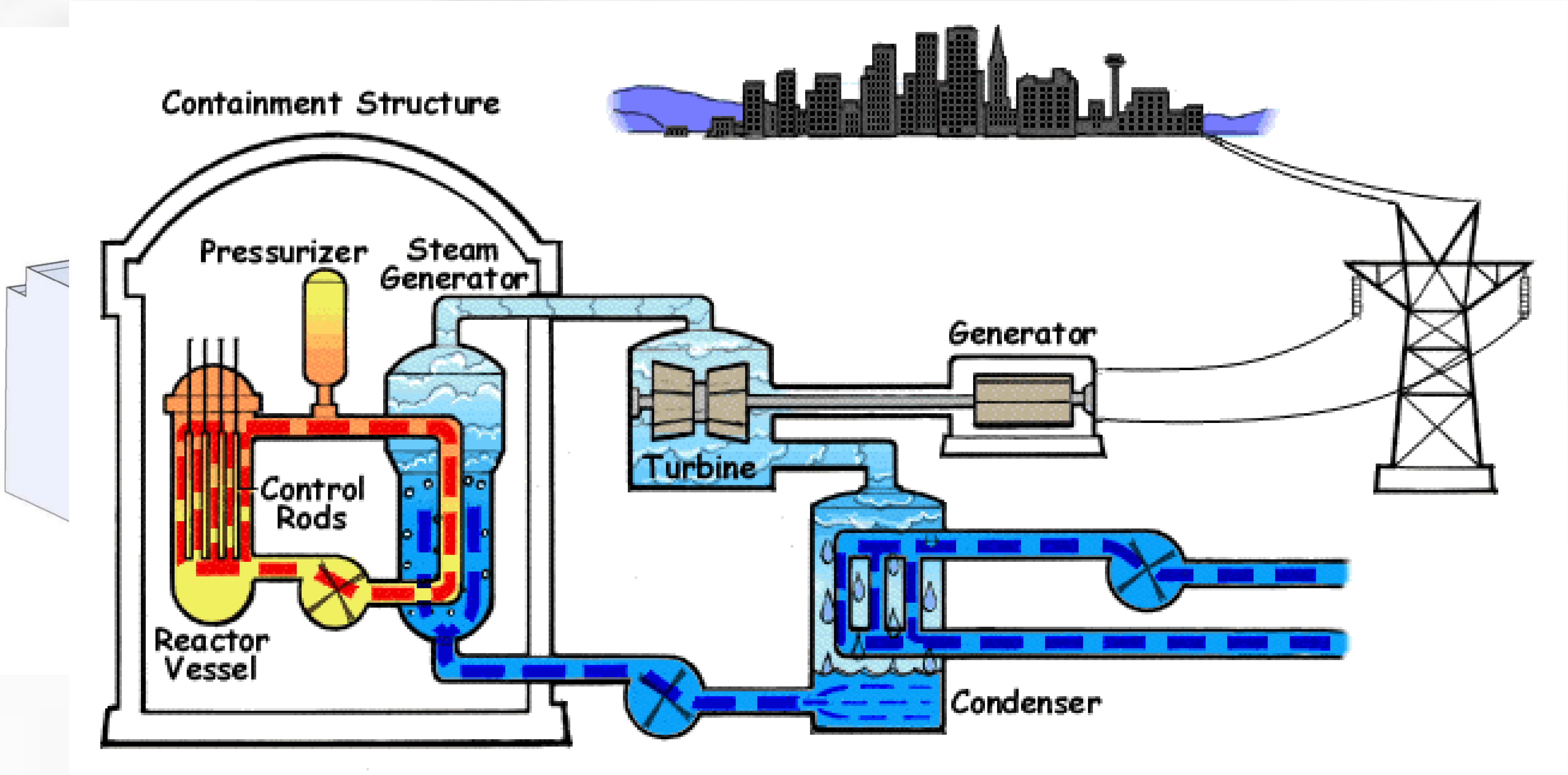
Nuclear reactor technologies

A given nuclear reactor technology is defined according: the fuel (Natural, Low enriched, Highly enriched), Moderator (Light water, Heavy Water, Graphite, Gaz) and Coolant (Water, gaz, salt)



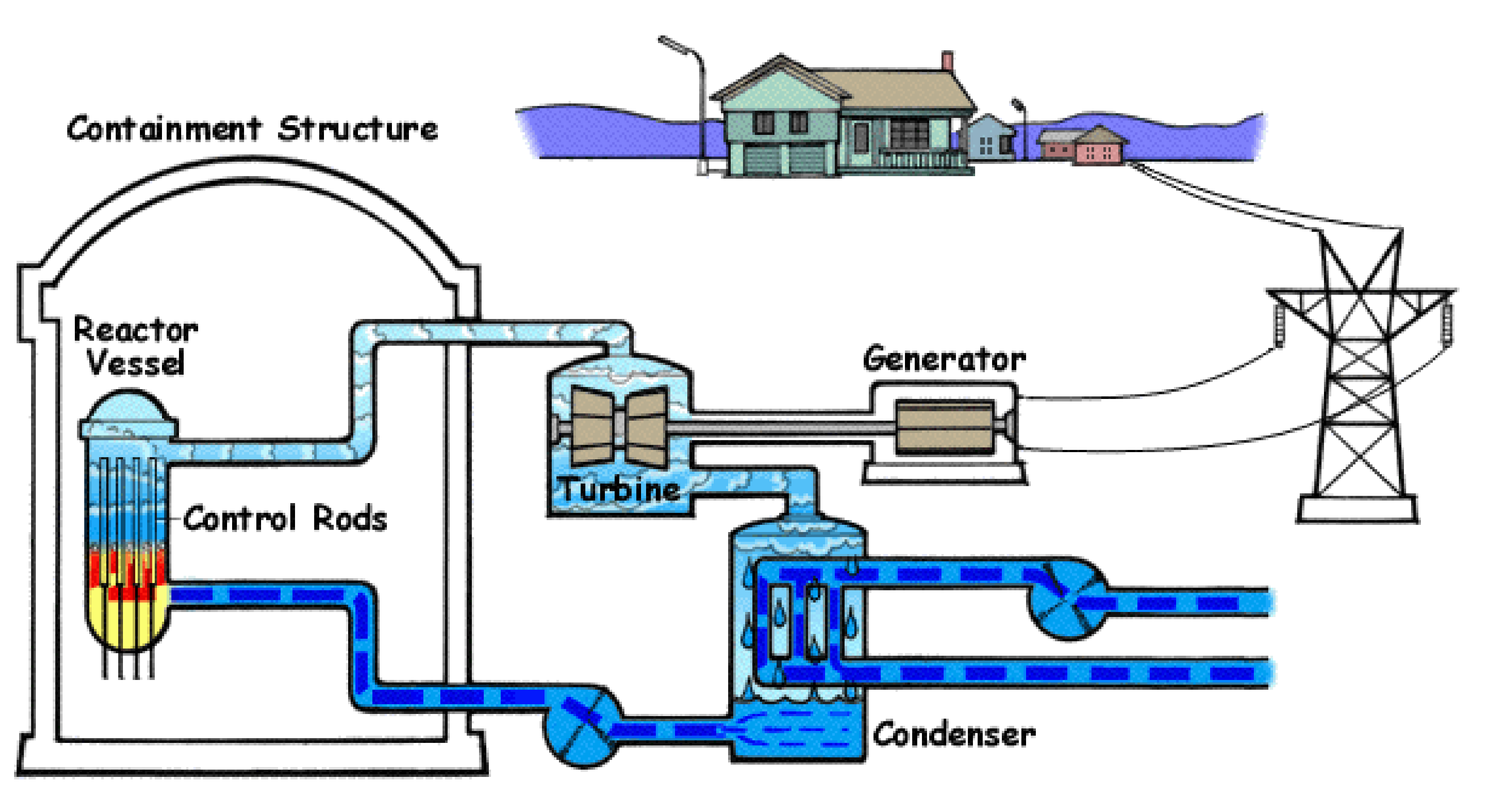
IV Nuclear Energy

Nuclear Power Plant (NPP)

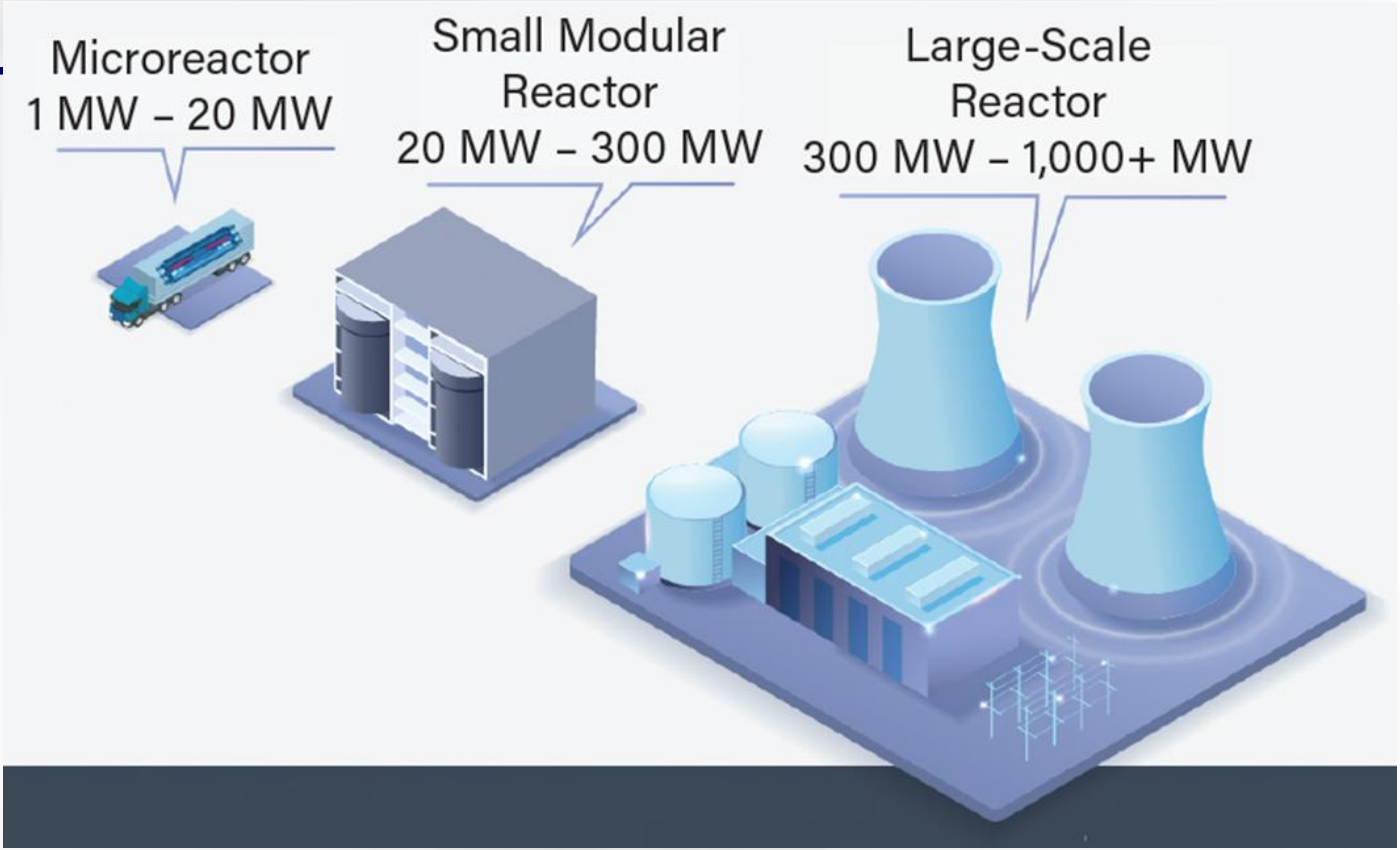


IV Nuclear Energy

Nuclear Power Plant (NPP)



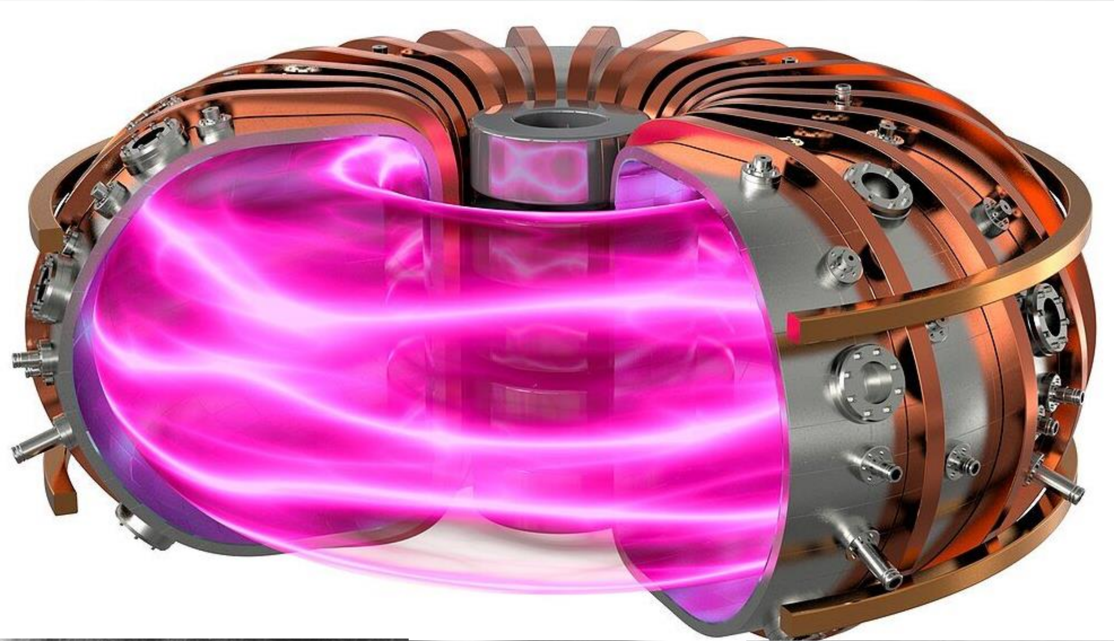
Small modular reactors and Micro-reactors



IV Nuclear Energy

Nuclear fusion

TOKAMAK



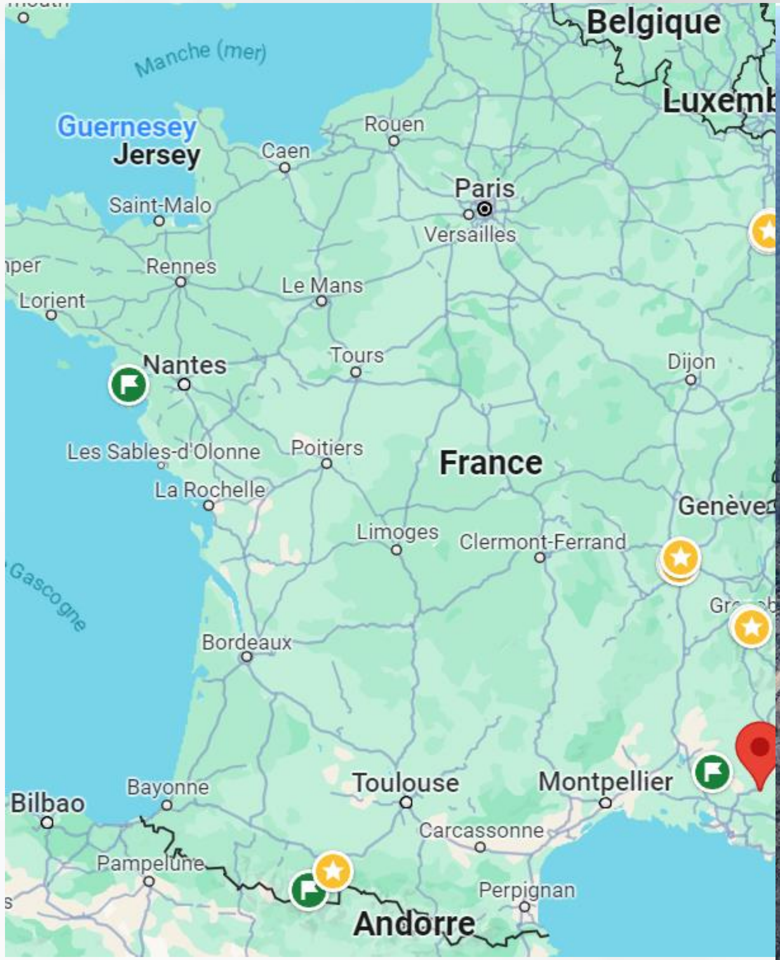
__TO__roidalnaïa __KA__amera s __MA__gnitnymi __K__atushkami :

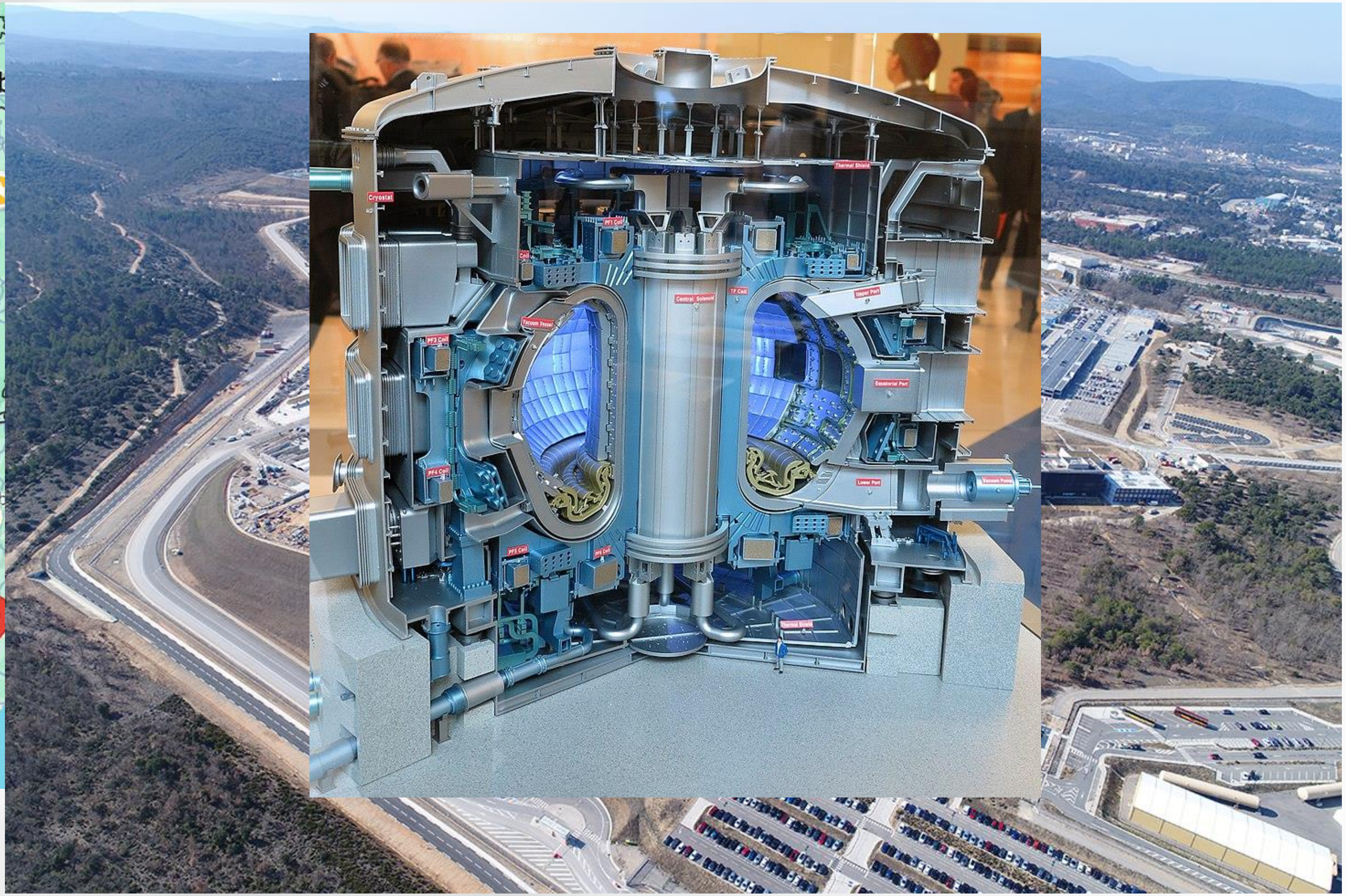
Toroidal chamber with magnetic coils

The proposal to use controlled thermonuclear fusion for industrial purposes and a specific scheme using thermal insulation of high-temperature plasma by an electric field were first formulated by the Soviet physicist Oleg Lavrentiev in a mid-1950. In 1951, Andrei Sakharov and Igor Tamm proposed to modify the scheme by proposing a theoretical basis for a thermonuclear reactor, where the plasma would have the shape of a torus and be held by a magnetic field. The first TOKAMAK or Fusion Reactor was built in 1954 in USSR.

IV Nuclear Energy

ITER (International Thermonuclear Experimental Reactor)

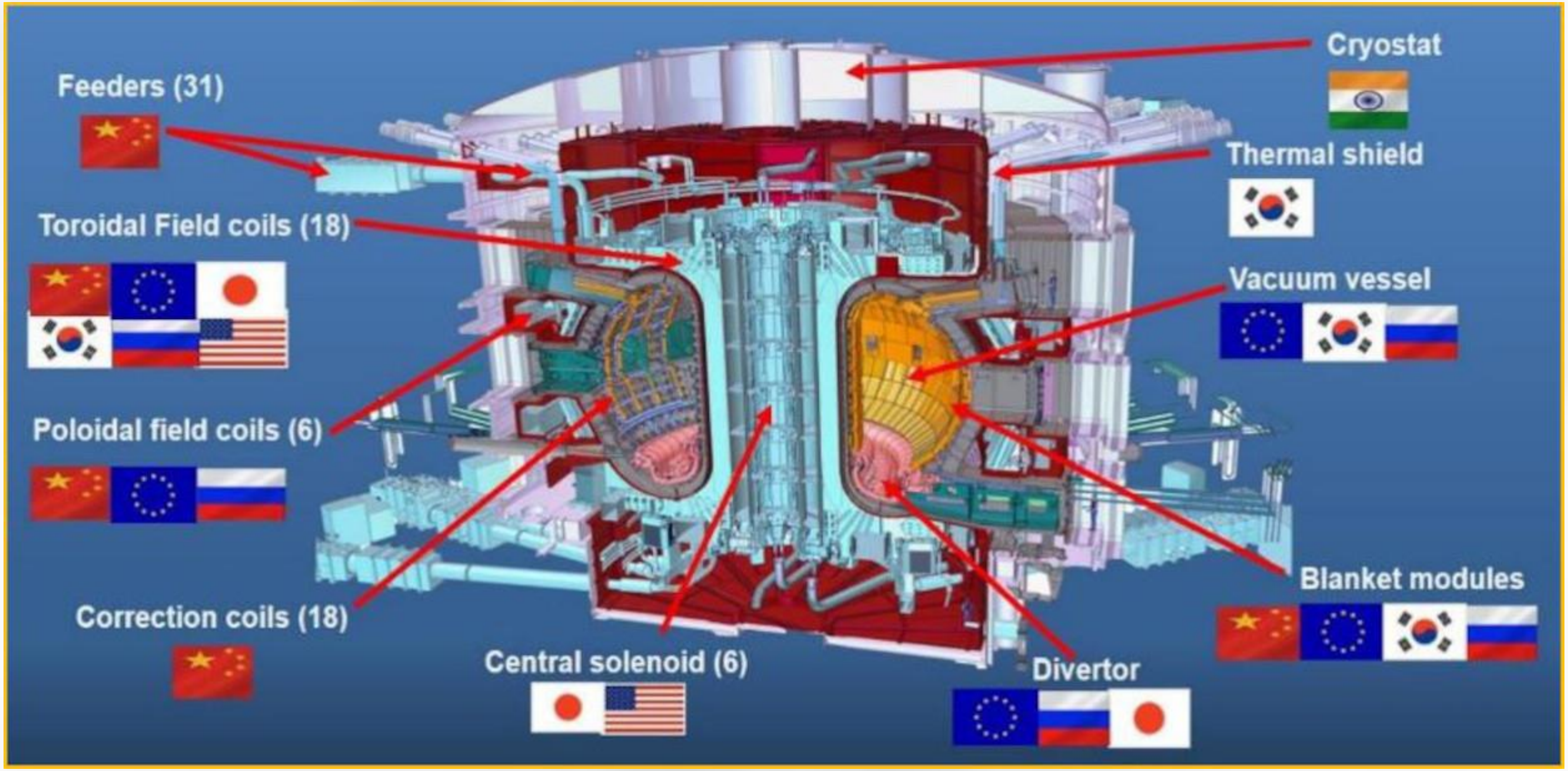




Started 2013 – 2035(planned)
300MWe input → 50MWth fusion

IV Nuclear Energy

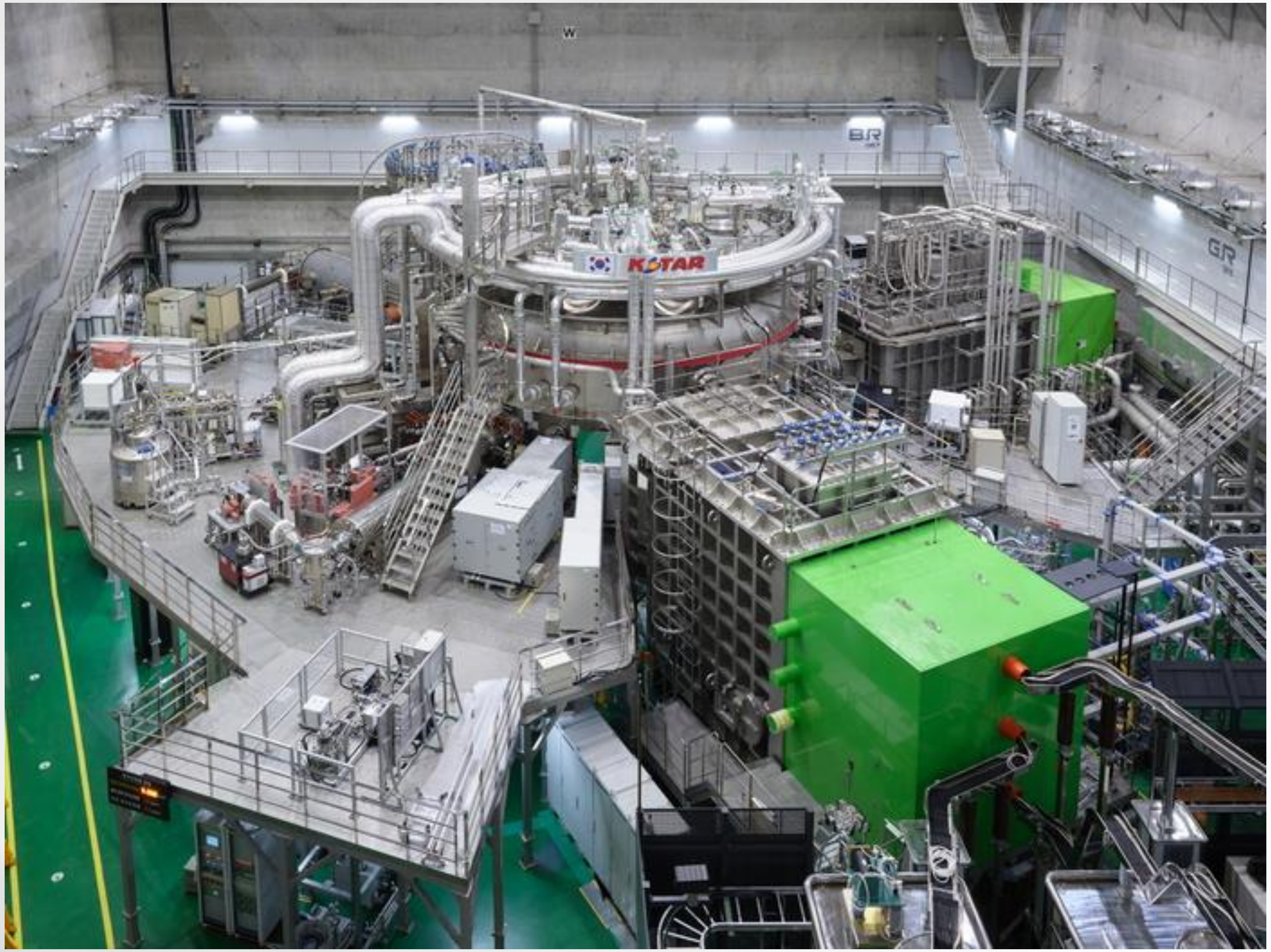
ITER (International Thermonuclear Experimental Reactor)



IV Nuclear Energy

KSTAR (Korea Superconducting Tokamak Advanced Research)

KSTAR achieved a plasma temperature higher than 100 million degrees Celsius lasting for 48 seconds, hitting a new record, in Februray 2024

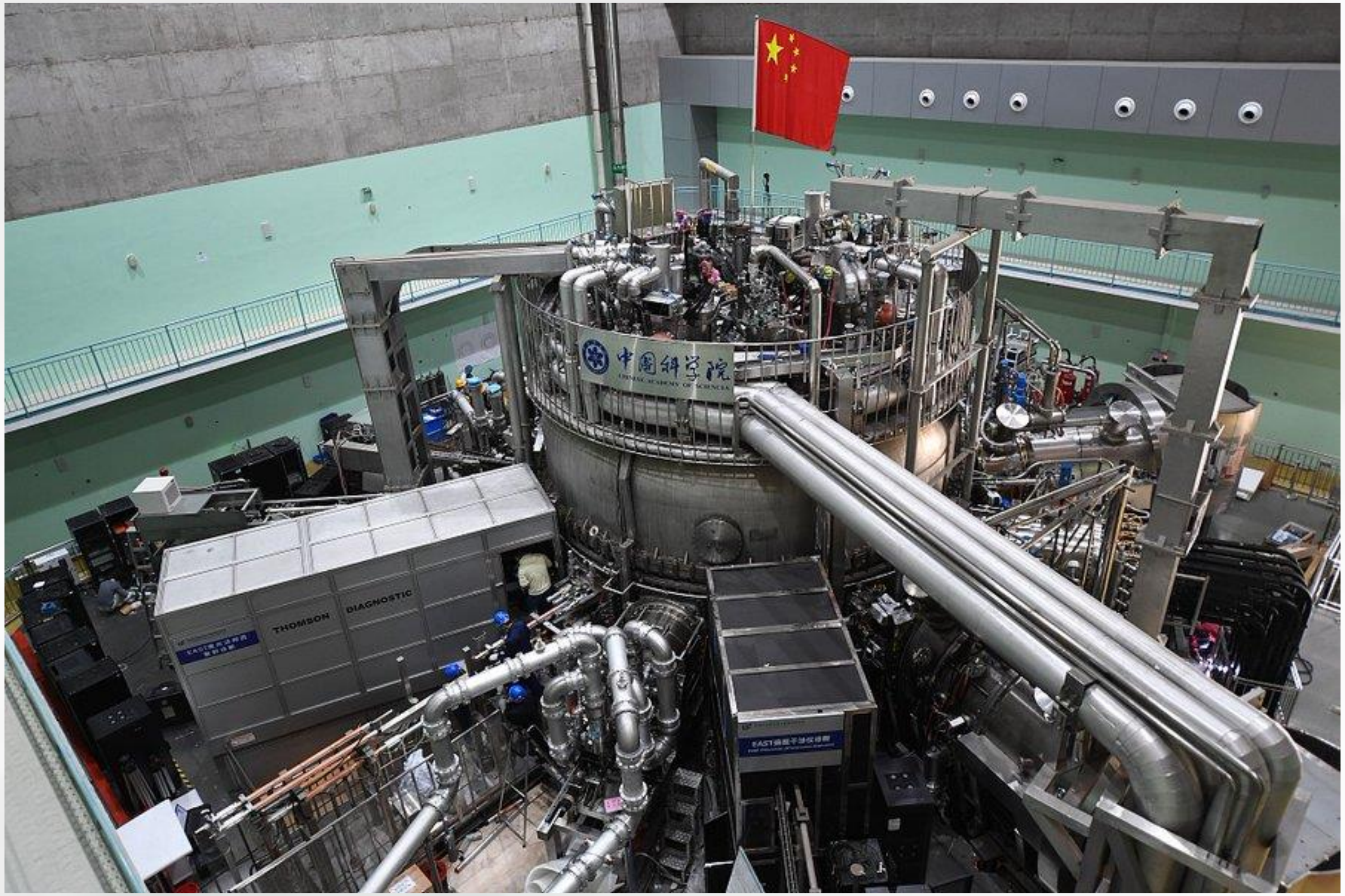


IV Nuclear Energy

EAST (Experimental Advanced Superconducting Tokamak)

In May, 2021, EAST reached a milestone of 120 million °C electron temperature for 101 seconds

On April 12, 2023, EAST achieved the world's first 403-second steady-state plasma



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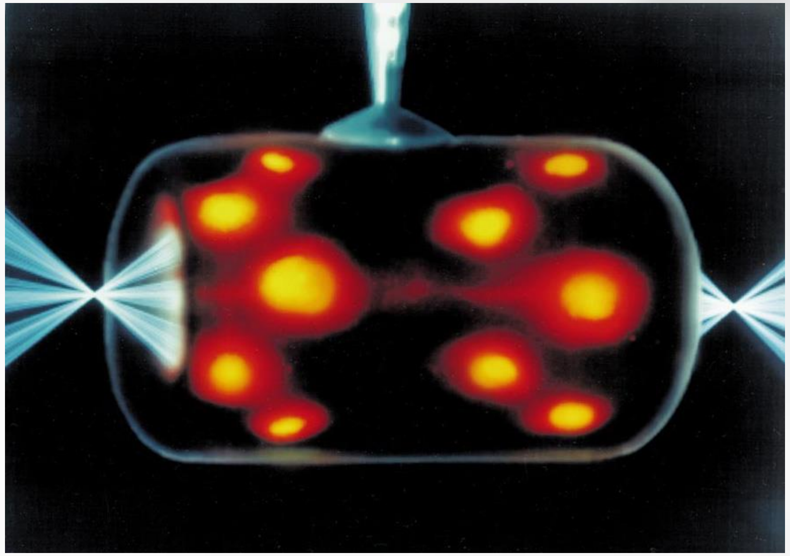
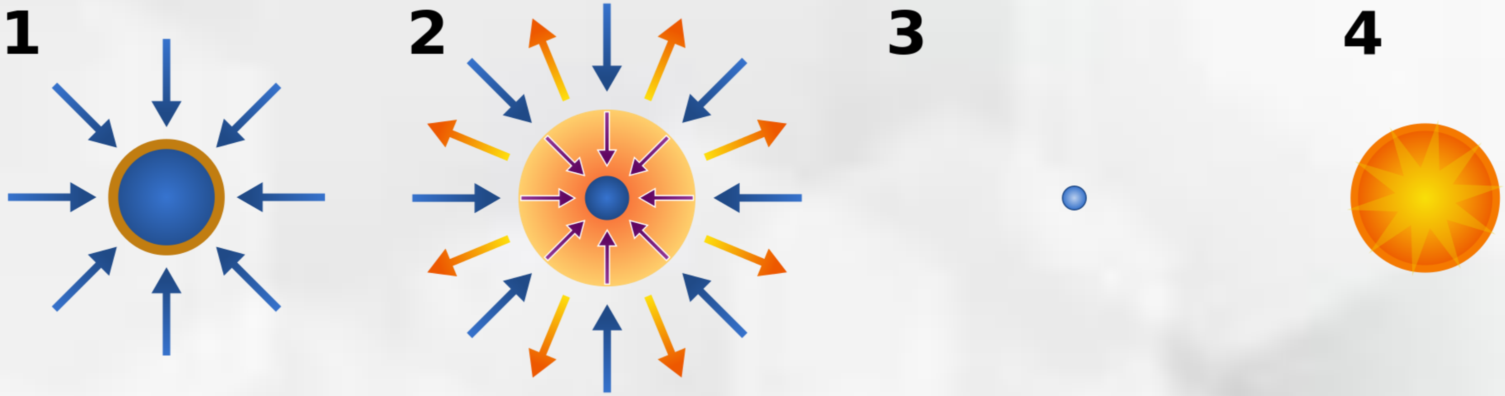
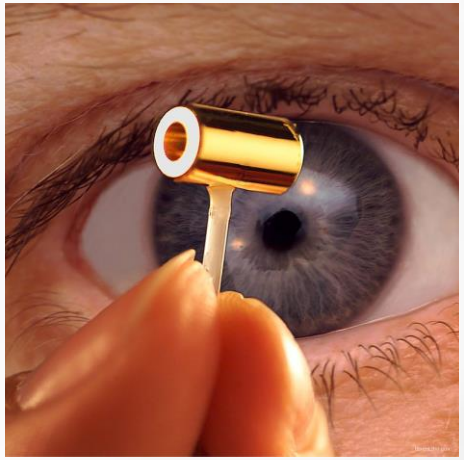
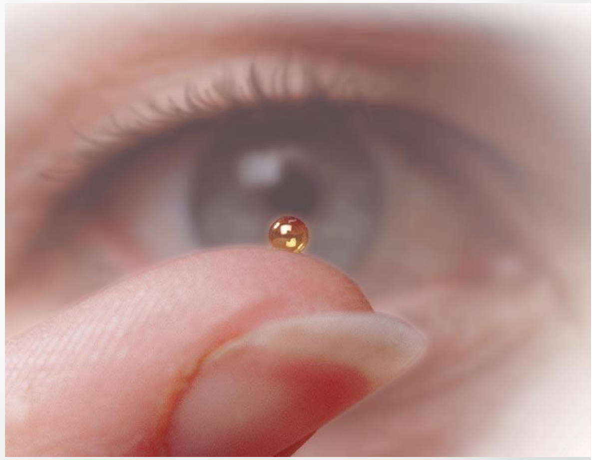
Inertial confinement fusion









1. Laser beams or laser-produced X-rays rapidly heat the surface of the fusion target, forming a surrounding plasma envelope.
2. Fuel is compressed by the rocket-like blowoff of the hot surface material.
3. During the final part of the capsule implosion, the fuel core reaches 20 times the density of lead and ignites at 100,000,000 ℃.
4. Thermonuclear burn spreads rapidly through the compressed fuel, yielding many times the input energy.