VNIVERSIDAD D SALAMANCA

Instituto Universitario de Física Fundamental y Matemáticas

IUFFyM

Nuclear Reactors: A Brief Journey Through Their Principles, History, Present, and Future

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Real Sociedad Española de Física

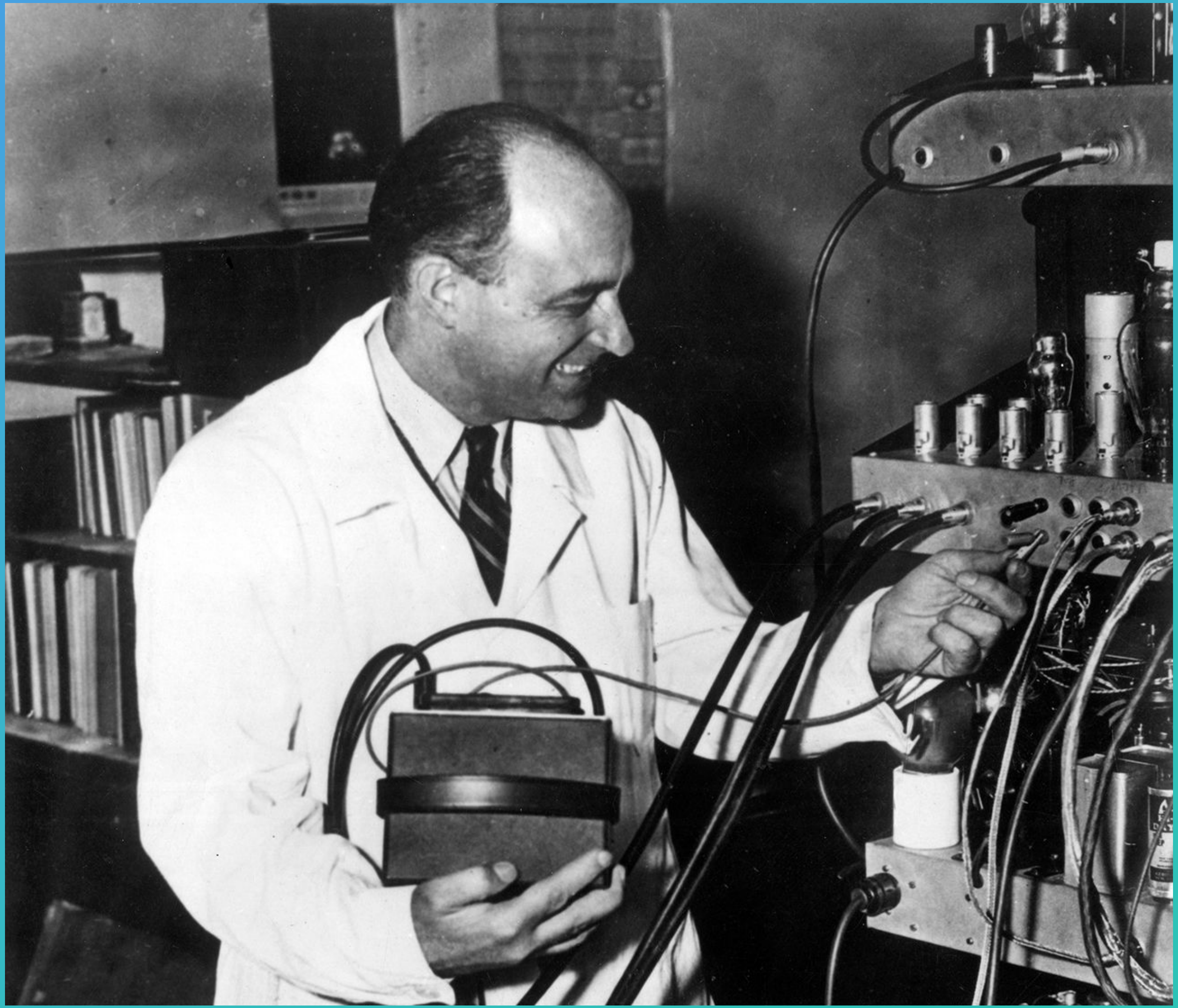
R.S.E.F.

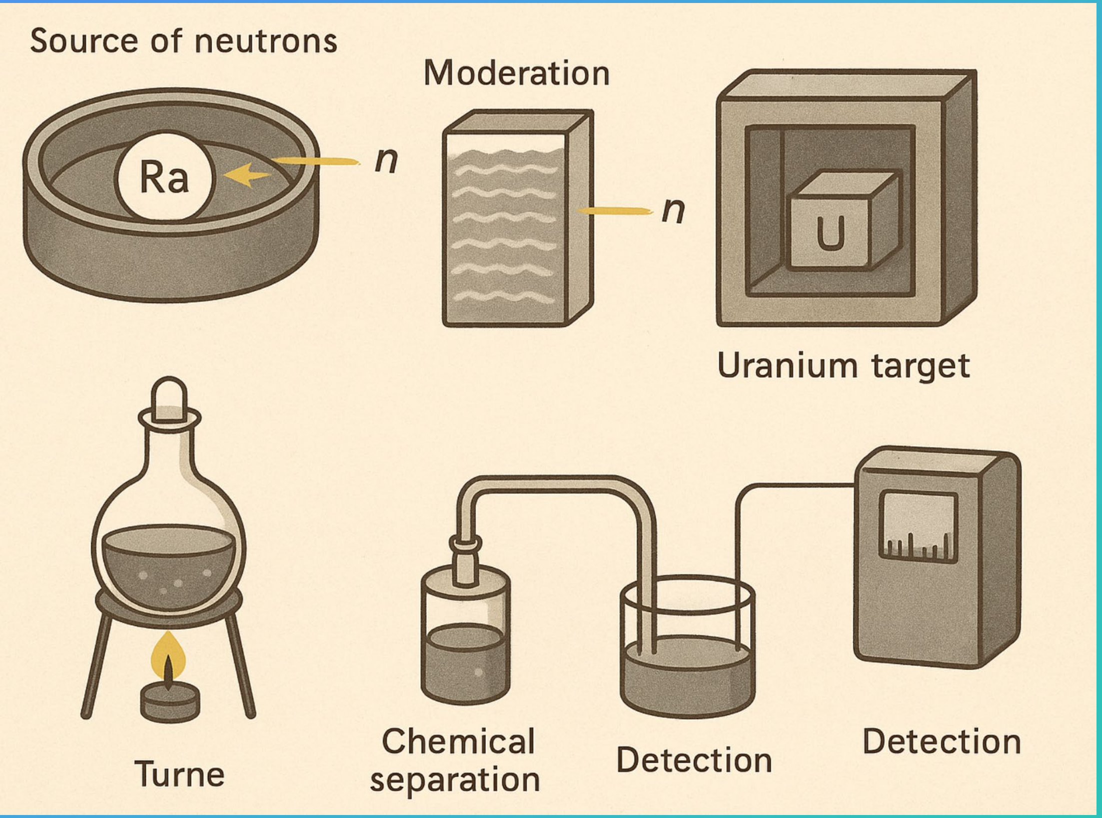
FÍSICA

DISCOVERY OF NEW RADIOACTIVE ELEMENTS BY NEUTRON BOMBARDMENT (1934)

FERMI DEVELOPED A METHOD OF BOMBARDING ATOMIC NUCLEI WITH SLOW (THERMAL) NEUTRONS, WHICH PROVED MUCH MORE EFFECTIVE AT INDUCING NUCLEAR REACTIONS THAN PREVIOUS METHODS USING ALPHA PARTICLES.

BY DOING THIS, HE PRODUCED MANY ARTIFICIAL RADIOACTIVE ISOTOPES, SOME OF WHICH WERE ELEMENTS NOT PREVIOUSLY KNOWN (LATER FOUND TO BE PRODUCTS OF NUCLEAR FISSION, THOUGH FERMI INITIALLY THOUGHT HE HAD CREATED TRANSURANIC ELEMENTS.





The Crucial Experiment (December 1938):

Hahn and Strassmann bombarded uranium with neutrons → chemical analysis → detection of barium.

L. Meitner and O. Frisch correctly interpreted the results and demonstrated that it was nuclear fission. Using $E = mc^2$,they calculated that the loss of mass (≈ 0.2 u) corresponded to an enormous release of energy (≈ 200 MeV per nucleus).

Chain reaction. Historical Context:

- In January 1939, just weeks after the discovery of fission by Hahn, Strassmann, Meitner, and Frisch, several scientists—especially in the United States and Europe—quickly realized that if each fission released a large amount of energy and also emitted more neutrons, it would be possible to initiate a chain reaction.
- Among the first to propose the idea of harnessing this as a source of energy were **Leo Szilard** and **Enrico Fermi**. In fact, Szilard had imagined the concept of a chain reaction several years earlier, in 1933, after reading about neutrons.

FISSION PROCESS IN A NUCLEAR REACTOR

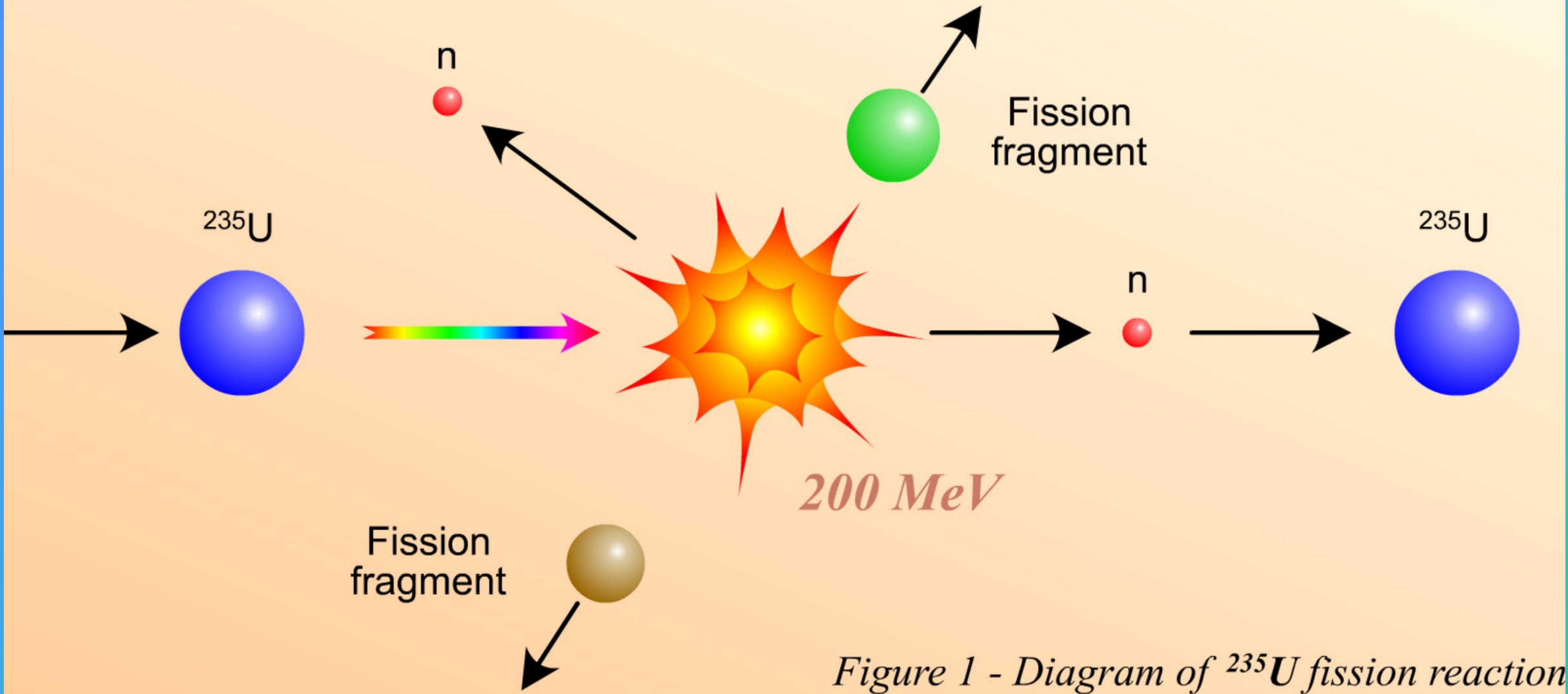


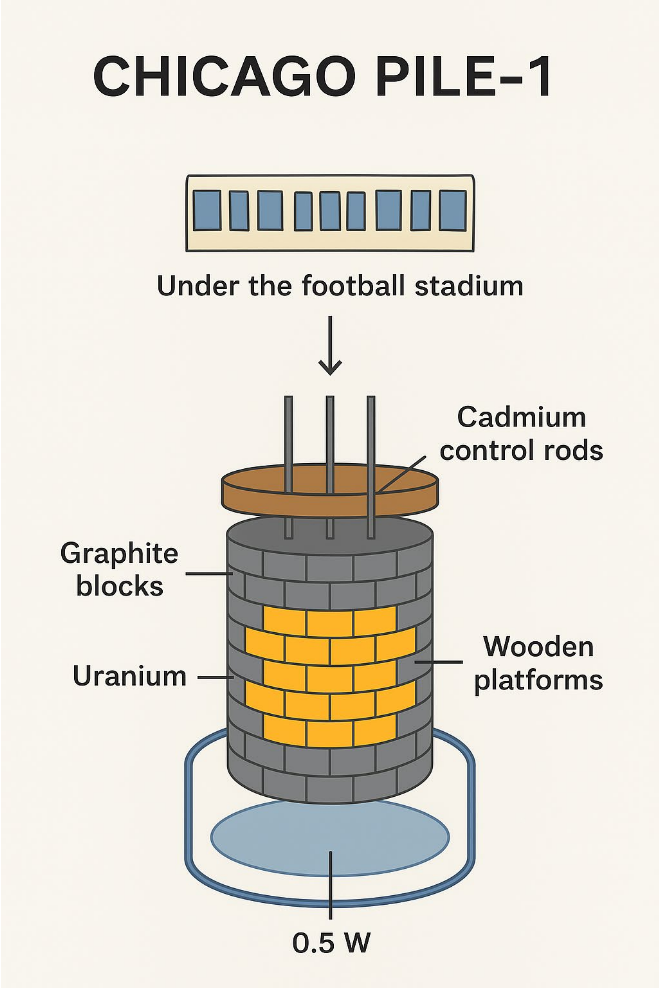
*Figure 1 - Diagram of ^{235}**U** fission reaction*

The first interest in fission reactions was their potential military use.

U-235 could produce a chain reaction that would release an enormous amount of energy in a very short time ($\ll$ 1 s), but that required enriching natural uranium -0.7% U-235- to over 90%.

An alternative route was to produce Pu-239 by bombarding U-238 with neutrons.

Chicago Pile-1 (CP-1) was the **world's first artificial nuclear reactor.** It marked a historic milestone in science and technology by proving that a **self-sustaining nuclear chain reaction** could be achieved and controlled.



- A Very Brief Introduction to Nuclear Reactor Physics
- Part of the material from: https://www.iaea.org/online-learning/courses/171/multimedia-on-nuclear-reactor-physics

The average energy of prompt neutrons can be calculated by the expression:

$$\overline{E} = \int_0^\infty E \cdot Y(E)dE = 1.98 MeV$$

The most probable energy is given by the peak of the function ***Y(E)***, being equal to ***0.73 MeV***.

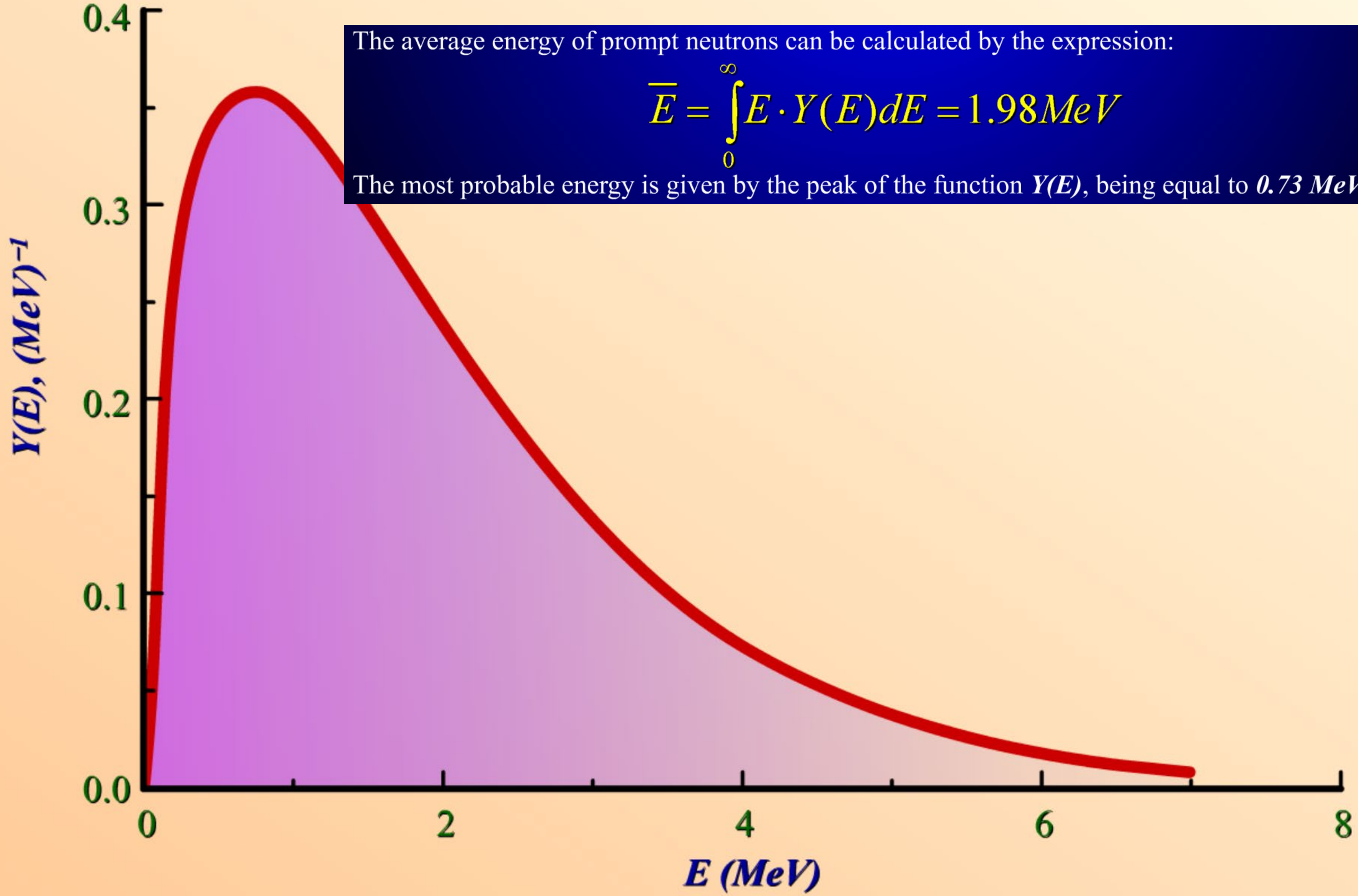
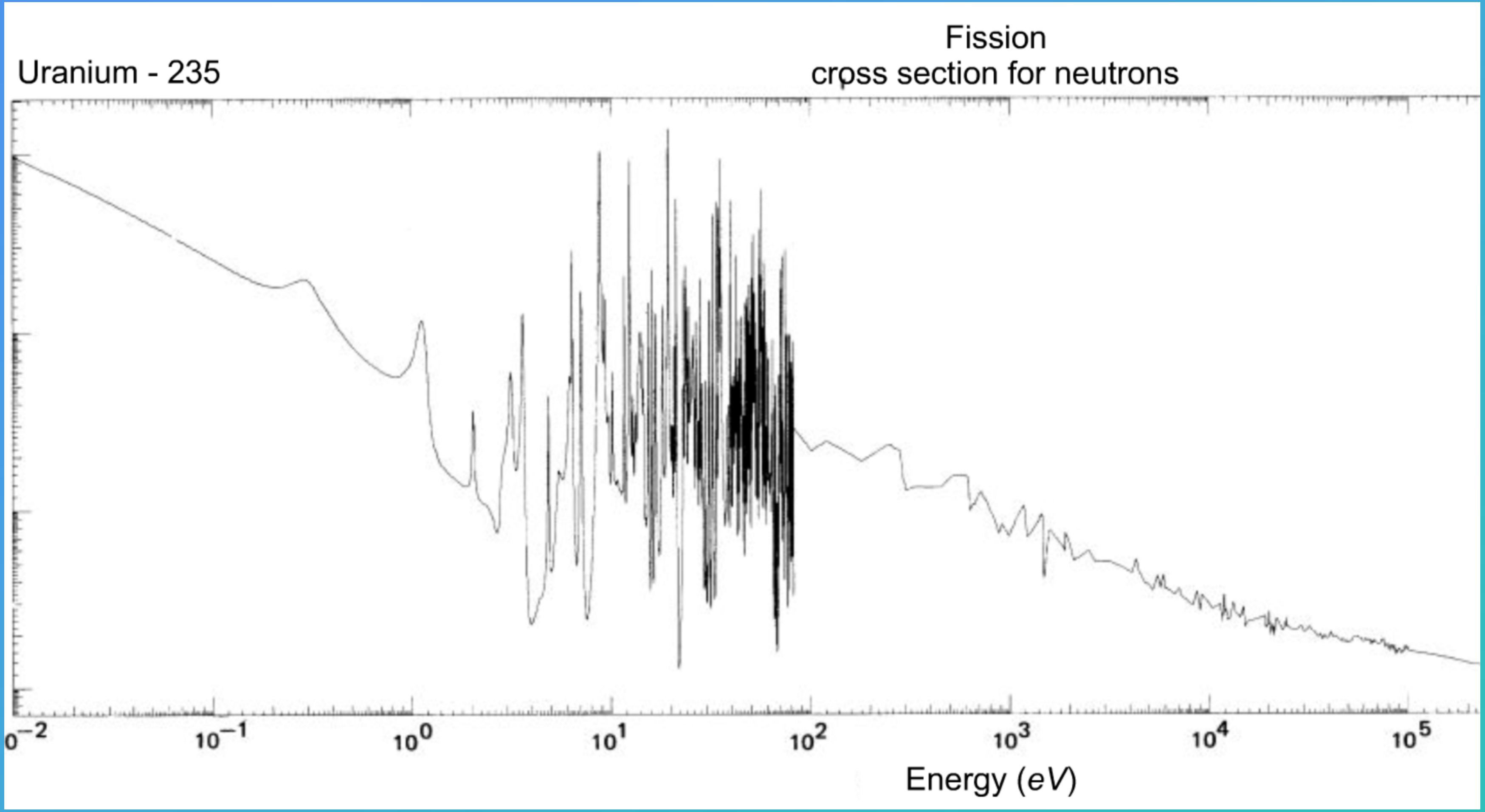


Figure 8 - Energy spectrum for ^{235}U prompt neutrons



Uranium - 235
Fission
cross section for neutrons
0⁻²
10⁻¹
10⁰
10¹
10²
10³
10⁴
10⁵
Energy (eV)

When a neutron is absorbed by a fissile nuclide as ^{235}U, it can induce fission. But it is also possible that the compound nucleus that is formed ($^{236}U^*$), can decay returning to its ground state via gamma emission. The relative balance between the probabilities of fission and radiative capture is an extremely important factor in nuclear applications. This capture-fission relationship is defined as:

$$\alpha \equiv \frac{\sigma_\gamma}{\sigma_f} \qquad (1)$$

where σ_γ is the radiative capture cross section and σ_f is the fission cross section.

For example, in the case of ^{235}U, for ***0.0253 eV*** neutrons (thermal), $\sigma_f = 582{,}2\ b$ and $\sigma_\gamma = 98{,}6\ b$. Therefore, when the ^{235}U absorbs a neutron with this energy, α is equal to ***0.169***. Taking the inverse value, $\sigma_f/\sigma_\gamma = 5.9$, it can be concluded that the fission occurrence probability is ***5.9*** times greater than the radiative capture one.

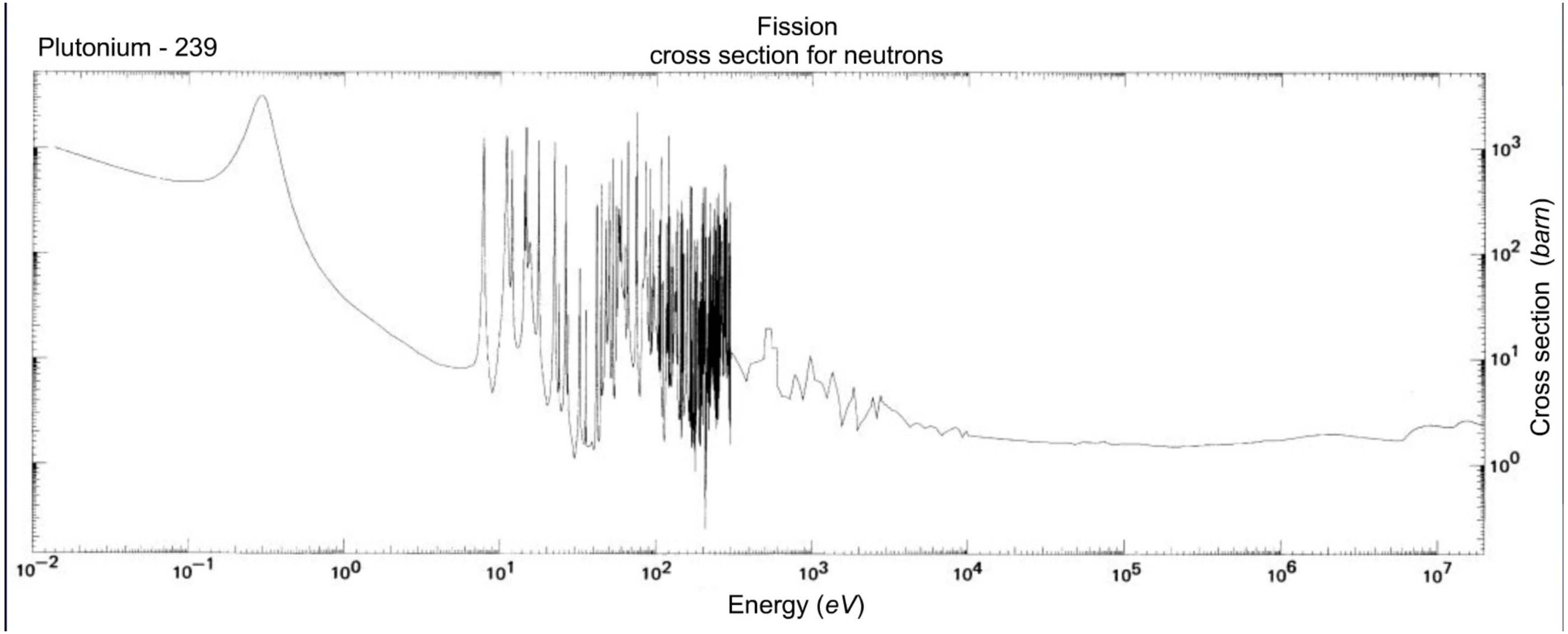
Another way of obtaining fissile isotopes is using fertile isotopes. Through the absorption of neutrons, and a certain sequence of radiative decay chain, it can result in the formation of fissile isotopes. The two most important examples are:

$$^{232}Th(n,\gamma)^{233}Th \xrightarrow[22\ \text{min}]{\beta^-} {}^{233}Pa \xrightarrow[27\ d]{\beta^-} {}^{233}U$$

$$^{238}U(n,\gamma)^{239}U \xrightarrow[23\ \text{min}]{\beta^-} {}^{239}Np \xrightarrow[2.3\ d]{\beta^-} {}^{239}Pu$$

Both isotopes exist in abundance in nature.

But, where the neutrons required for this transformation process come from? The answer is from a nuclear reactor. In fact, many of the existing reactors use uranium as fuel, containing about ***95%*** of ^{238}U, and the process of transmutation into plutonium occurs naturally when the fertile nuclides capture the surplus of neutrons coming from the fission chain reaction. The main parameter in this process is the number of neutrons produced in each fission reaction per neutron absorbed by the fuel.


Plutonium - 239
Fission
cross section for neutrons
Cross section (barn)
10^3
10^2
10^1
10^0
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
Energy (eV)

Another fact to consider is that nuclides such as ^{232}Th, ^{238}U and ^{240}Pu can also suffer what is called fertile capture, becoming fissile nuclides, ^{233}U, ^{239}Pu and ^{241}Pu. They are called *fertile nuclides*. ***Figure 2*** presents the production chains of the main fertile nuclides.

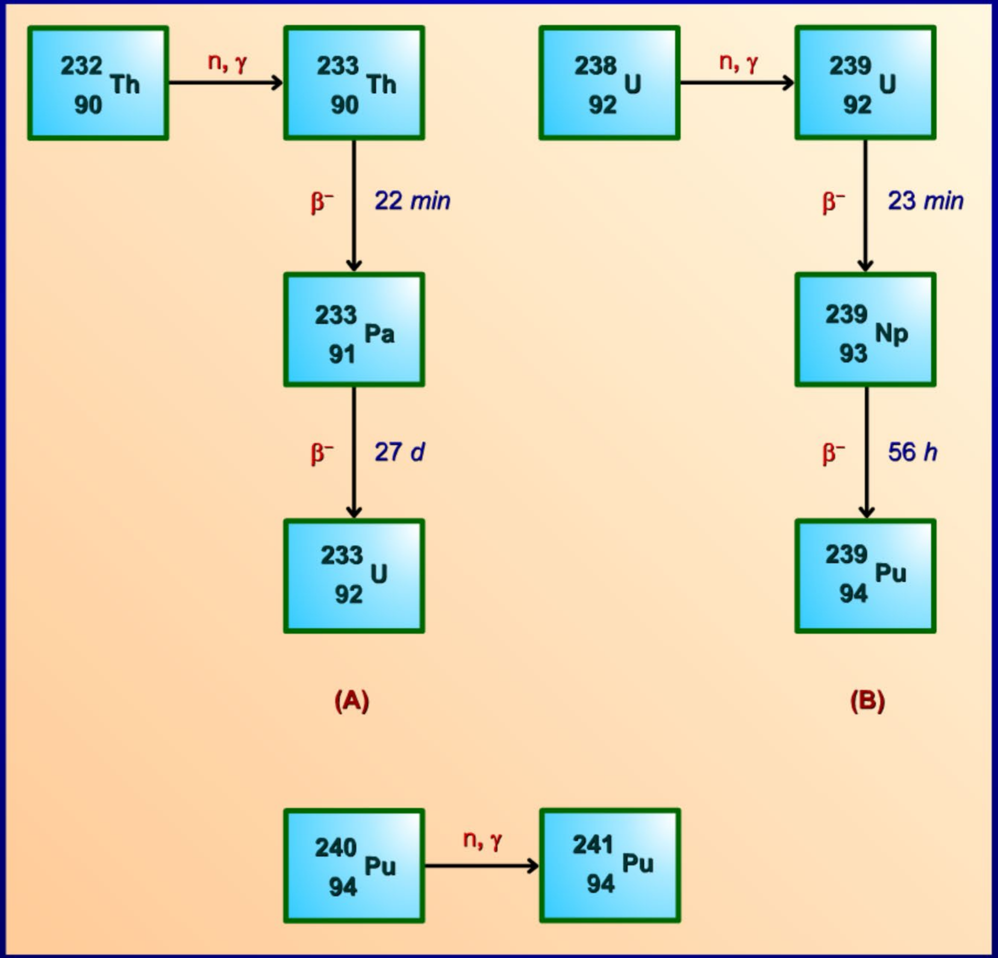


Figure 2 - Main production chains of fertile nuclides

Natural uranium

U-238	99.2745%
U-235	0.72% (or 0.711% by mass)
U-234	0.0055%

Nuclear fuels

On the basis of previous explanations, it may seem that there is a certain amount of potential isotopes that could serve as fuel for a fission chain reaction system. In particular, the main isotopes for nuclear reactor applications are:

Fissile isotopes: ^{233}U , ^{235}U , ^{239}Pu , ^{241}Pu

While those that may undergo fission through fast neutron capture are:

Fissionable isotopes: ^{232}Th , ^{238}U , ^{240}Pu , ^{242}Pu

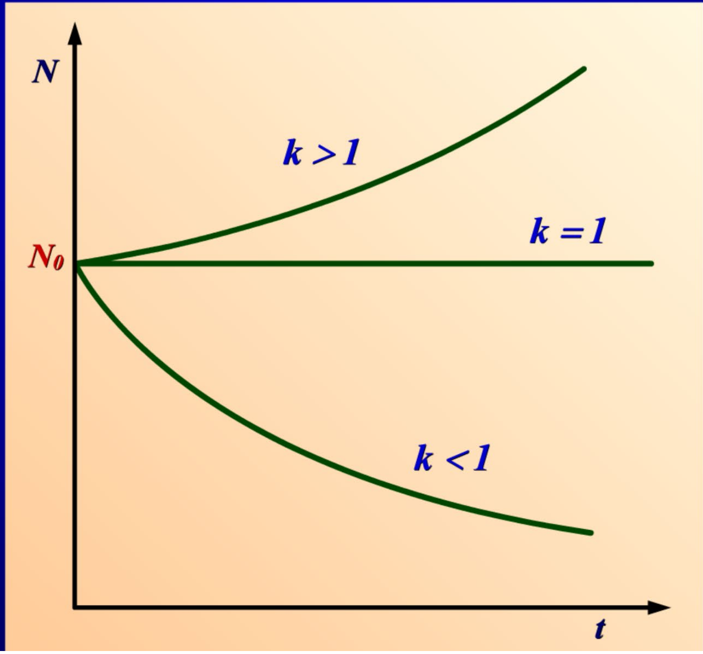
Incident neutrons should always have enough energy to induce fission, and because of the greater value of α (capture-fission ratio) that characterizes these isotopes, only the first class of nuclides is capable of maintaining a fission chain reaction. Of these, only the ^{235}U exists in nature, and constitutes a fraction of only ***0.711%*** of natural uranium, which consists mostly of ^{238}U. Even though reactors fuelled with natural uranium, with its low concentration of ^{235}U, do exist, most of currently operating reactors use uranium with a higher percentage of ^{235}U as fuel. or what is called enriched uranium. The enrichment process is a complex and costly procedure.

If k is defined as the ratio between the number of neutrons of two successive generations, then:

$$k = \frac{N_2}{N_1} = \nu \cdot P_f \cdot P_{AF} \cdot P_{NL} \quad (9)$$

$$k = \frac{\textit{number of fissions (or neutrons) of a given generation}}{\textit{number of fissions (or neutrons) of the last generation}} \quad (1)$$

Depending on the value of k, three different situations can show up, represented in ***Figure 3***:



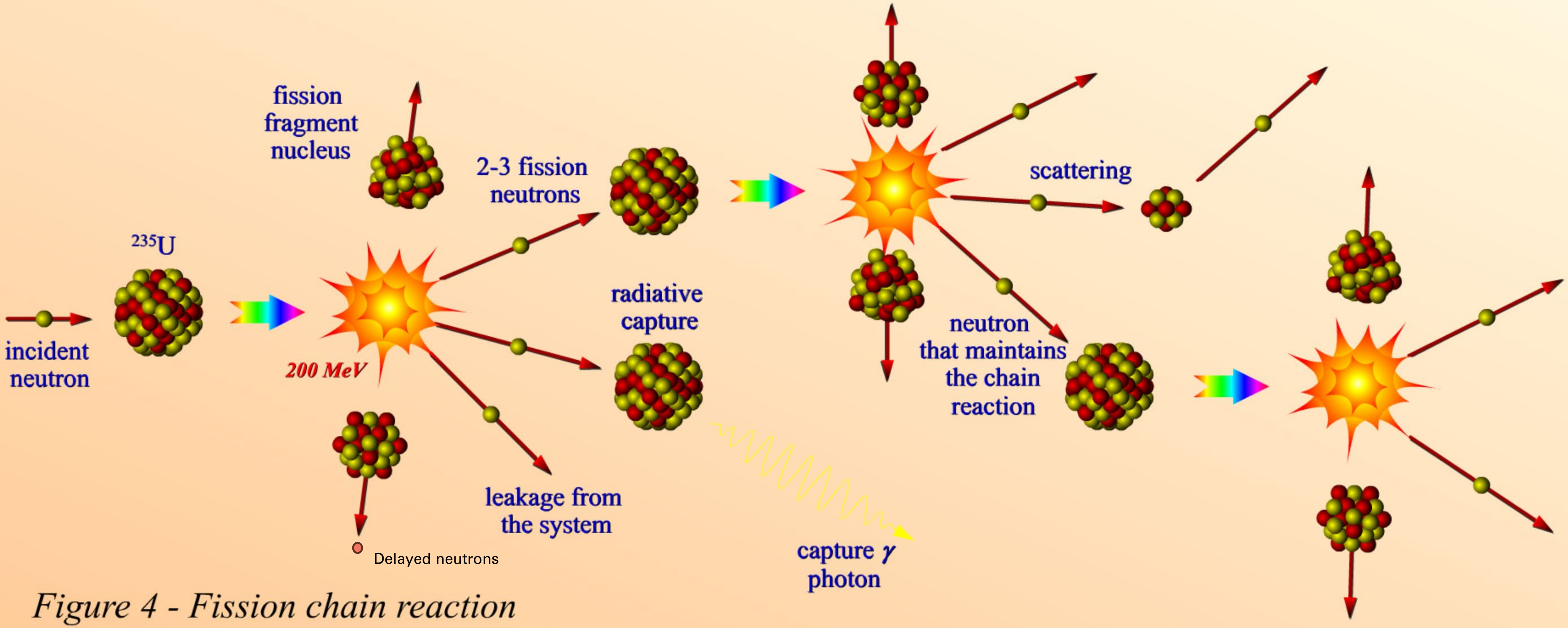


Figure 4 - Fission chain reaction

In order to adjust ***k*** to the desired value, the neutron production rate has to be adjusted with the rate of disappearance.

Neutrons from the reactor may disappear in two ways:

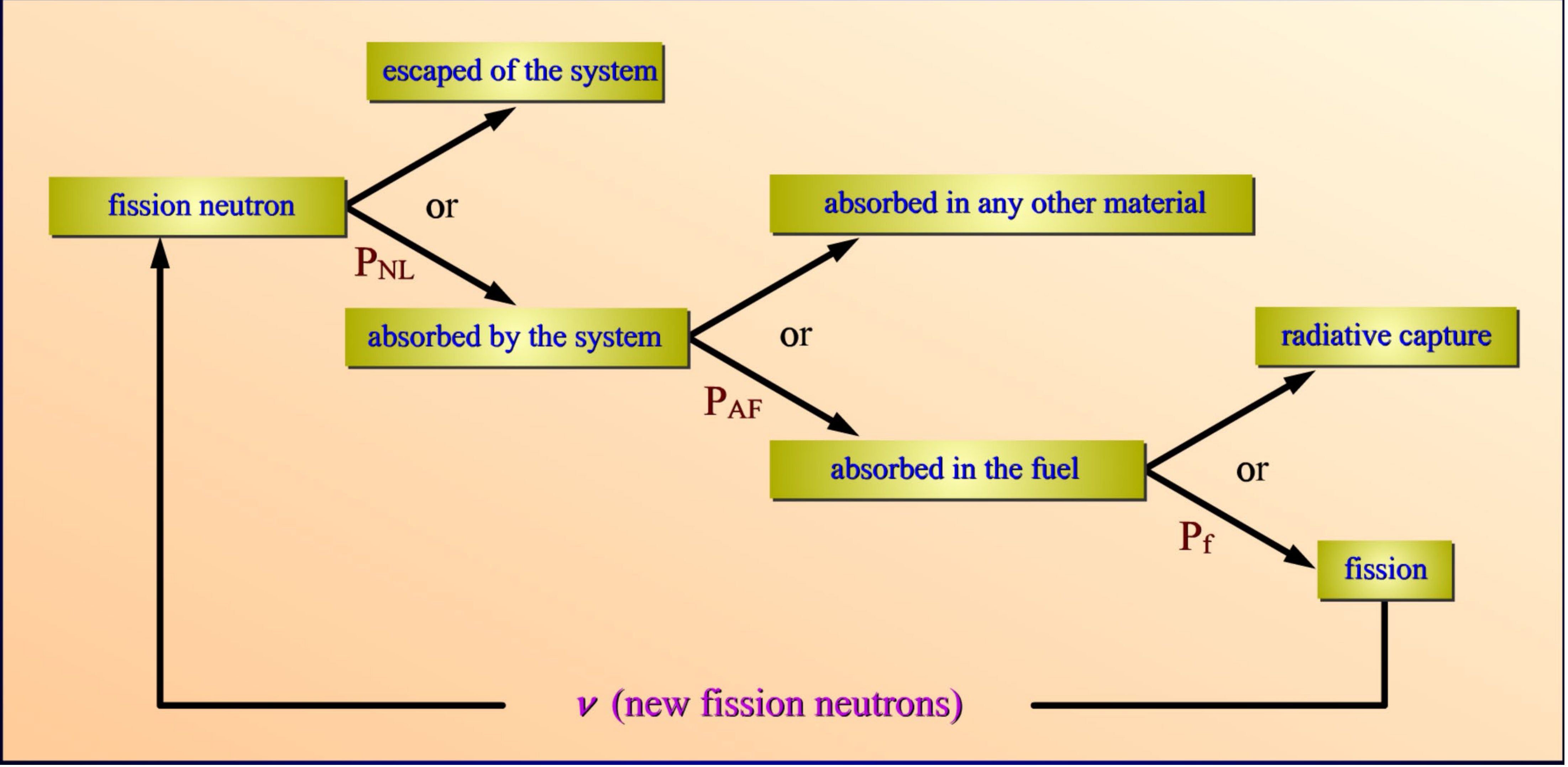
(a) escaping from the reactor through its surface and
(b) being absorbed by nuclear reactions and radiative capture reactions in the materials that constitute the reactor.

Formally defining the probabilities for each of these events:

P_{NL} ≡ probability that the neutron remains and is absorbed in the system.

P_{AF} ≡ probability that, being absorbed in the system, it is actually absorbed in the fuel.

P_f ≡ probability that, being absorbed in the fuel, it induces a fission reaction.



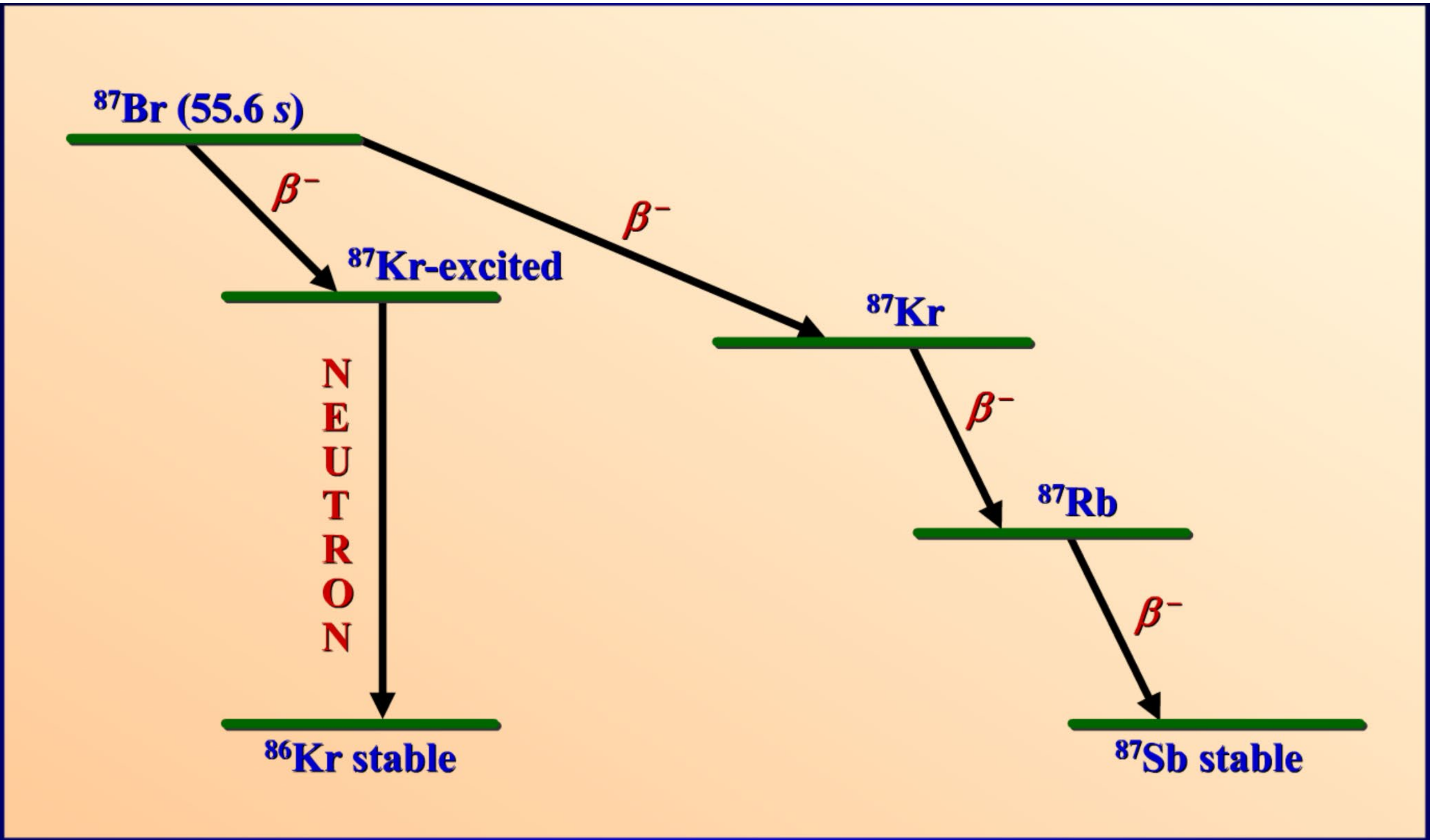


Figure 9 - Emission mechanism of a delayed neutron

In terms of *delayed neutrons*, it has to be said that even if they constitute a small fraction of fission neutrons (***0.65%*** for ^{235}U), they play a very important role in the control of nuclear reactors. As an example of the mechanism by which they are emitted, consider the case of ^{87}Br. It is one of the products formed in the fission of ^{235}U. The ^{87}Br changes into ^{87}Kr by β^- emission, reaching an energy level that is enough to emit a neutron.

Reactivity and Reactor control

Excess reactivity: $\Delta k = k-1$

Generation *i*: *n* neutrons => *i+1*: *n* Δk additional neutrons.

$\frac{dn}{dt} = \frac{n\,\Delta k}{l}$ being l(lifetime of a neutron) =>, then defining

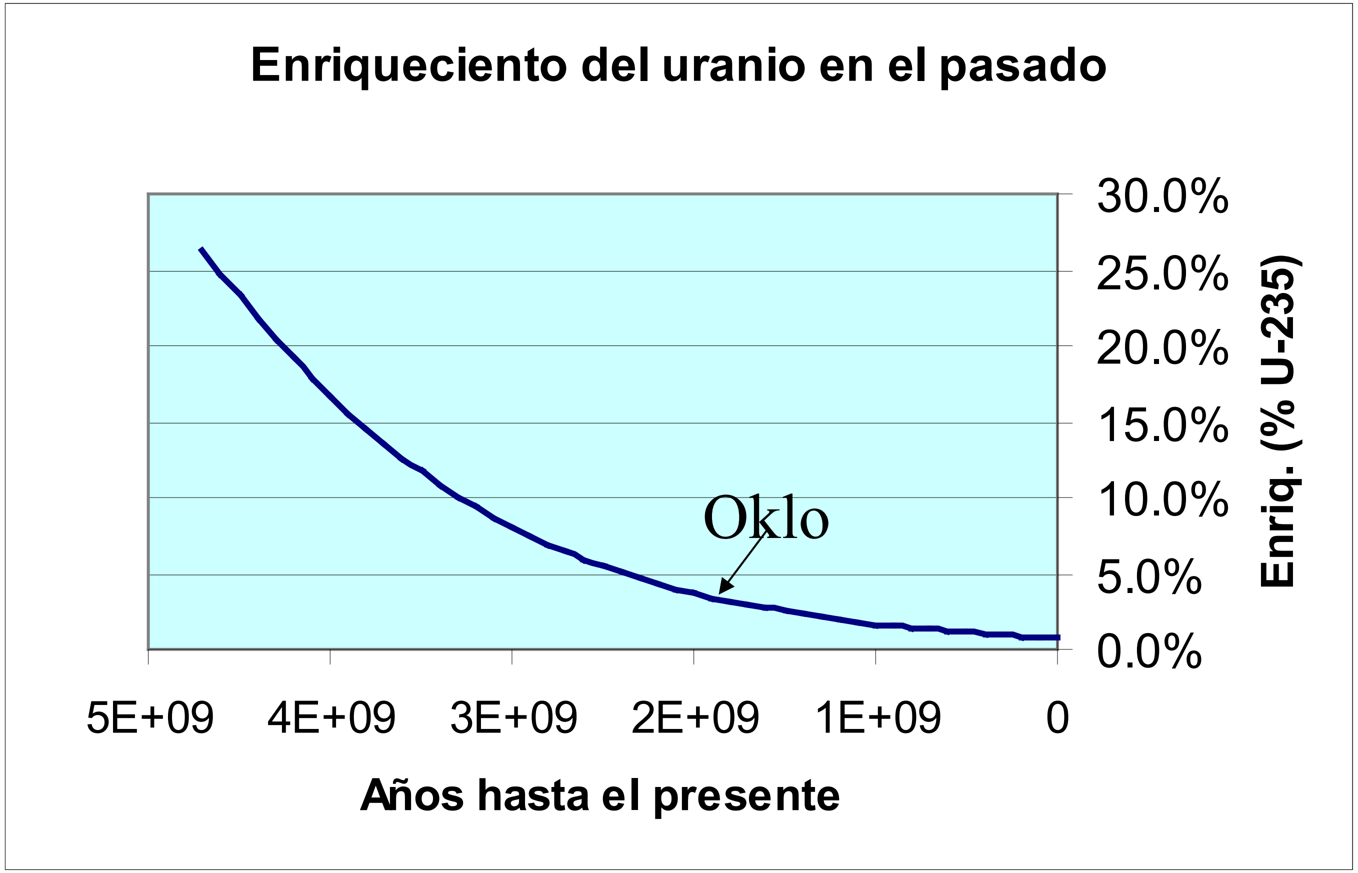
T (Reactor period) as the time during which the neutron (an the power level) would increase by a factor *e* => $\frac{\Delta k}{l} = \frac{1}{T}$ => $T = \frac{l}{\Delta k}$:

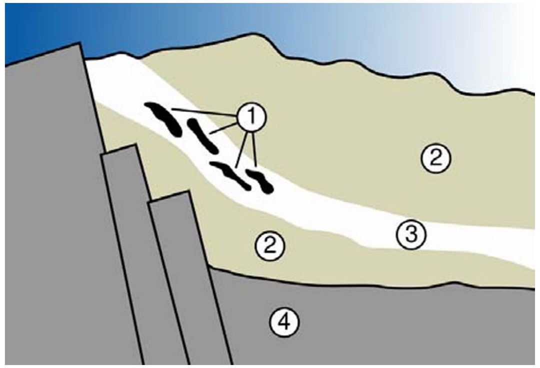
ej: $l = 0.001\ s,$ $\Delta k=0.005$ (or 0.5%) => T=0.2 s =>

$\frac{n}{n_0} = e^{\frac{t}{T}};\ \{t: 1\ s\}\ \ e^{\frac{1}{T}} = 150$

However, taking into account the delayed neutrons (0.64%) l = 0.084 s=>

$T = \frac{l}{\Delta k} = 0.0084/0.005 =$ *16.8 s* => $\frac{n}{n_0} = e^{\frac{t}{T}} = e^{1/16.8} =$ *1.06*





Los reactores nucleares naturales seguramente abundaron pocos después de la formación de la Tierra, cuando el uranio estaba enriquecido por encima del 5%

Sánchez G. El Reactores nucleares de hace 2000 millones de años y las constantes del universo. Nuclear España. Marzo 2009. ISSN/ISBN:1137-2885 (https://www.revistanuclear.es/wp-content/uploads/hemeroteca/294/NE294-06.pdf)

¿$\alpha = e^2/(\hbar c)$?

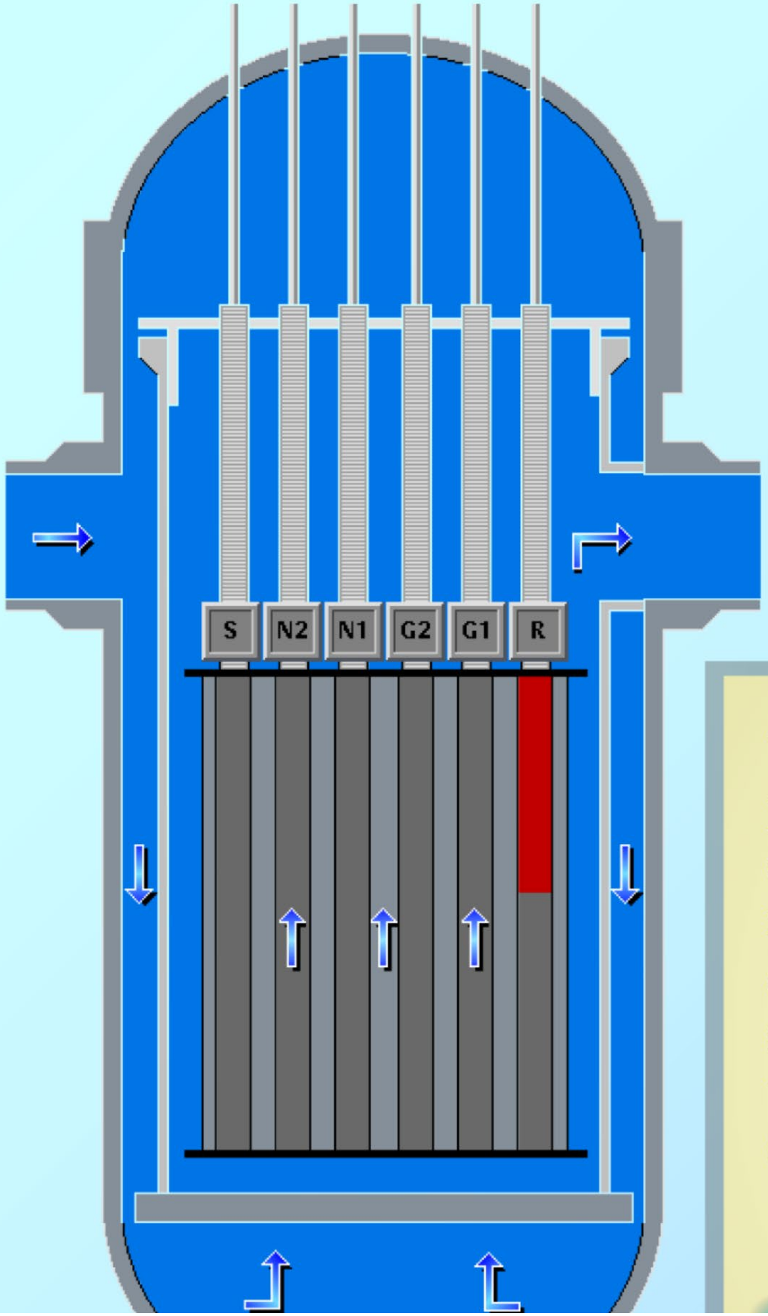
The **first military nuclear reactor** was the **X-10 Graphite Reactor** at **Oak Ridge, Tennessee (USA)** — built during the **Manhattan Project**.

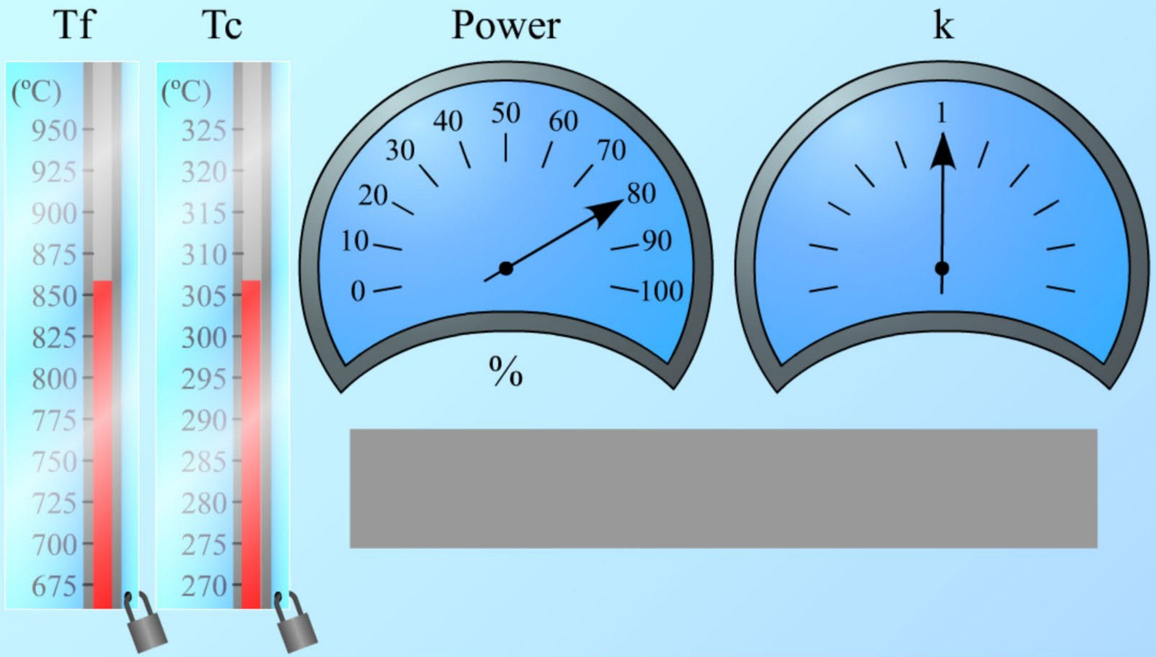
Summary Table

Reactor	Country	First Grid Connection	Power Output	Type	Commercial Purpose
Obninsk AM-1	USSR	1954-06-27	5 MWe	Graphite-moderated, water-cooled	**Pioneering**, but small scale
Calder Hall	UK	1956-10-17	50 MWe	Magnox gas-cooled	**First large-scale commercial**

⚓ S1W Prototype Reactor — Idaho, USA

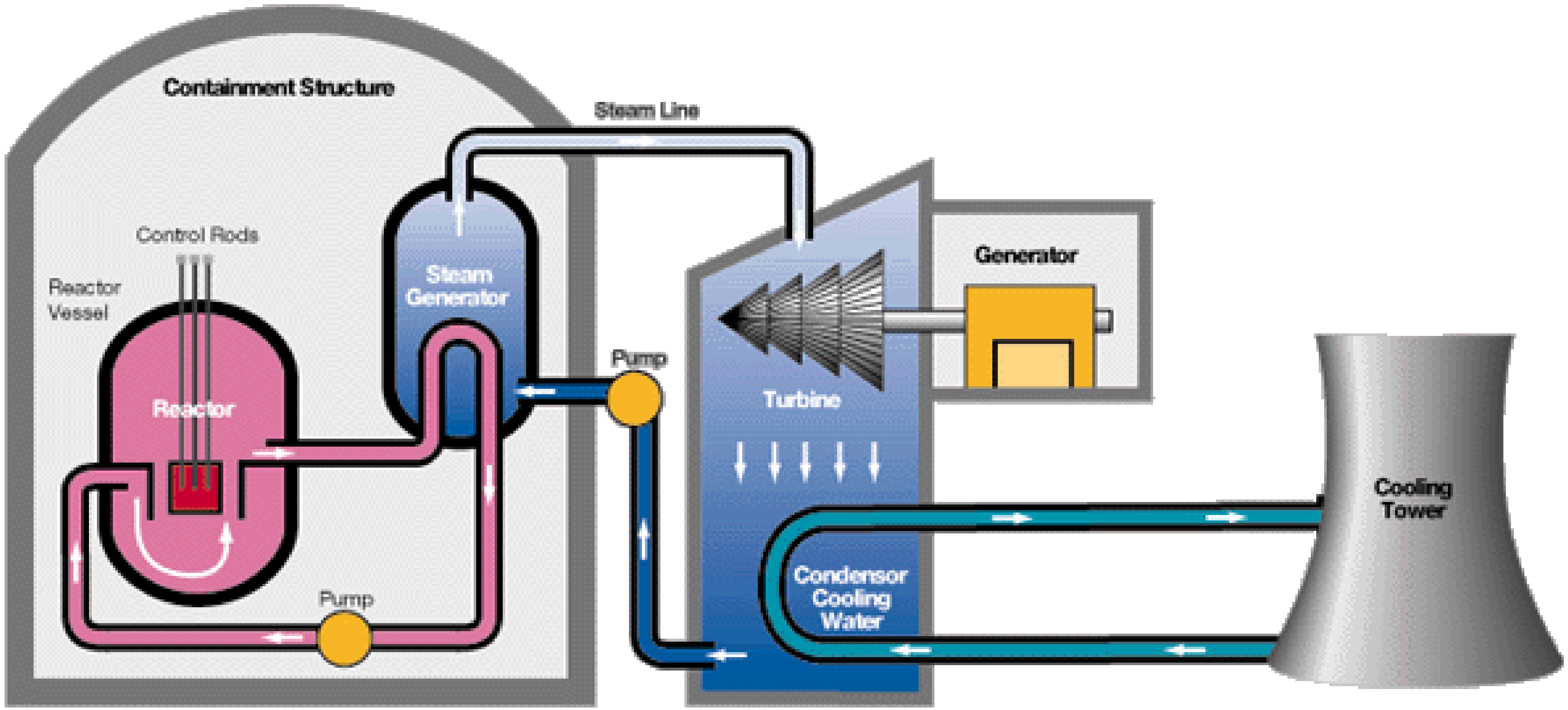
- 📍 **Location:** National Reactor Testing Station (now Idaho National Laboratory)
- 📅 **First criticality: March 30, 1953**
- 🧭 **Purpose:** Land-based prototype to develop and test a nuclear propulsion plant for submarines.
- 🧱 **Reactor type:**
  - **Pressurized Water Reactor (PWR)**
  - Highly enriched uranium fuel
  - Closed-loop water cooling system
- 🚢 **S1W designation:**
  - **S** = Submarine platform
  - **1** = First generation
  - **W** = Westinghouse (manufacturer)





To increase the number of fissions, and therefore, the reactor power, the reactor operator makes the appropriate adjustments so that the value of ***k*** becomes greater than ***1***, turning the reactor supercritical. When the reactor power reaches the desired level, the operator introduces additional changes in the system so that the value of ***k*** becomes equal to ***1*** and, therefore, the reactor power is stabilized at a constant level (maintaining the reactor critical).

PWR Reactor



https://3d.energyencyclopedia.com/npp-pwr

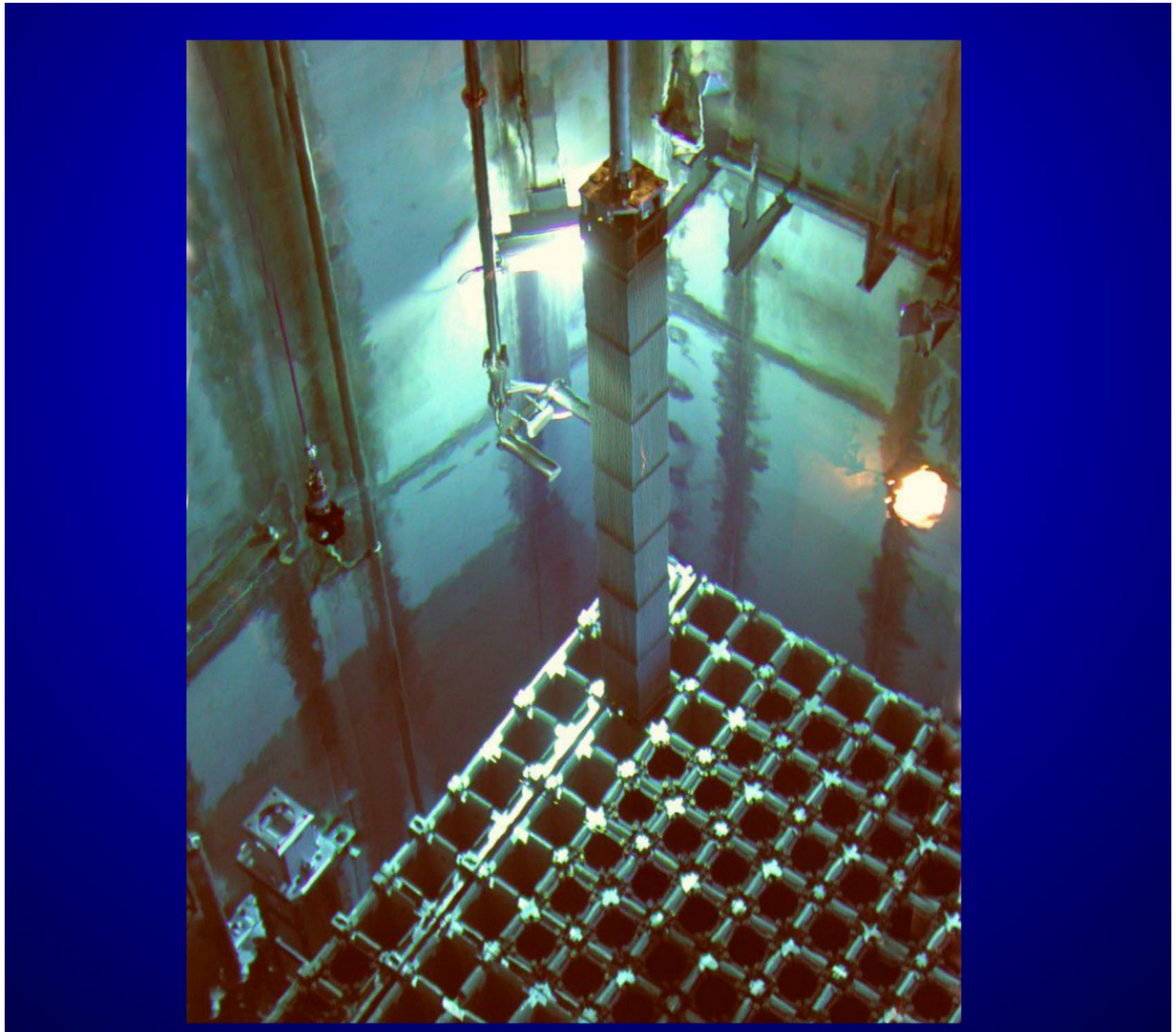
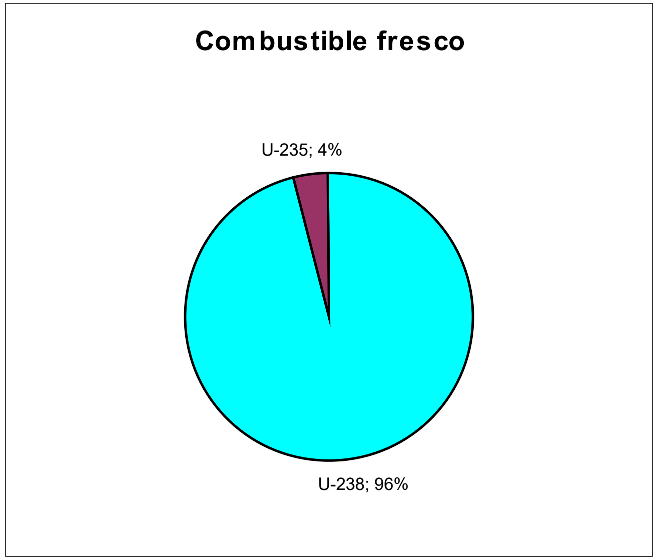


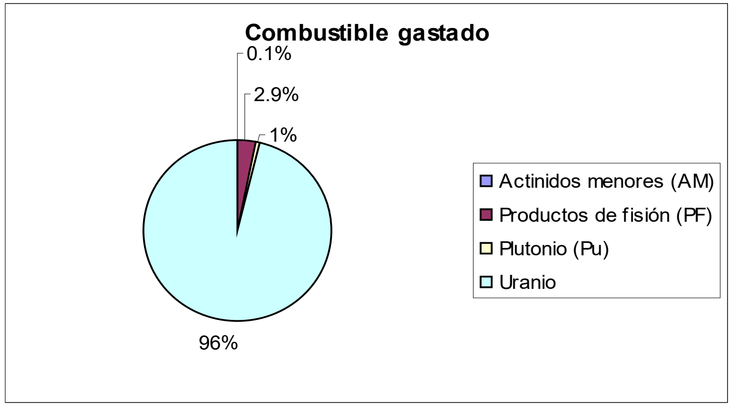
Figure 31 - Manipulation of a fuel assembly in the fuel pool

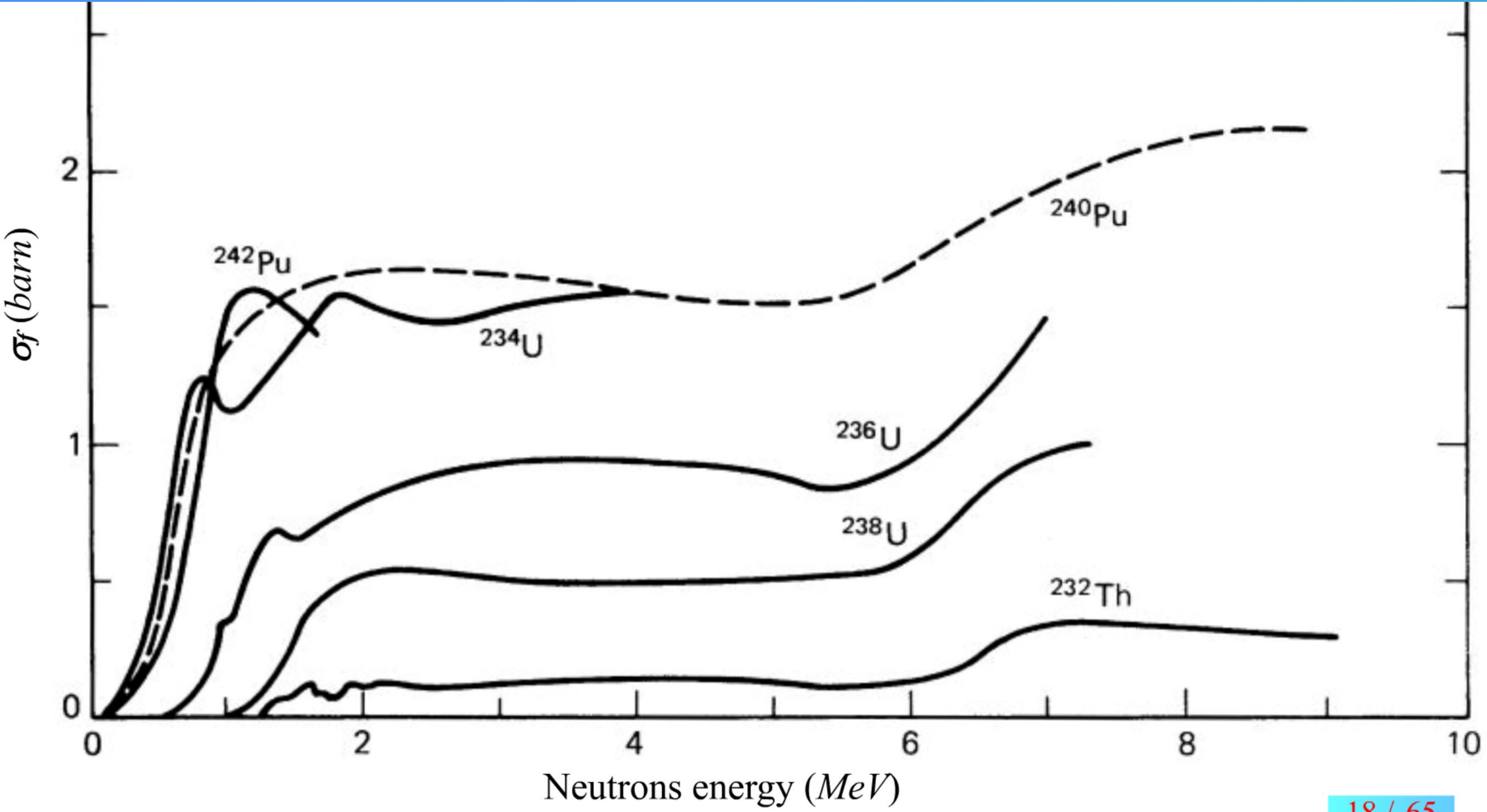
Uranio: Actualmente sólo utilizan el 1.5% de la energía del U . Gran parte del combustible quemado es susceptible de reprocesamiento. Ademas puede ser utilizado combustible en reactores rápidos de sales fúndicas.

Composición combustible gastado , por tU inicial, tras 5-6 años en el reactor (≈4% U-235-> ≈1% U-235)

Isótopo	kgU	Periodo semidesintegración(año)	Porcentaje
Uranio 238	942.8	4.47E+09	94.28
Plutonio 239	5.2	24000	0.52
Neptunio 237	0.48	2140000	0.05
Uranio 235	9	7.02E+08	0.90
Plutonio 240	2.1	6563	0.21
Americio 241	0.21	432.7	0.02
Uranio 236	4.3	2.35E+07	0.43
Plutonio 241	1	14	0.10
Cesio 137	1.1	30.17	0.11
Estroncio 90	0.51	28.8	0.05
Total U	956.1		**95.61**
Total Pu	8.3		**0.83**
Otros (Am+Np)	0.69		**0.07**







$\sigma_f\,(barn)$
0
1
2
0
2
4
6
8
10
Neutrons energy (MeV)
^{242}Pu
^{240}Pu
^{234}U
^{236}U
^{238}U
^{232}Th

Trends

In a **nuclear reactor** (or more generally, any power plant), the **load factor** (LF) or **capacity factor** is a measure of how effectively the plant is being used over a period of time.

$$\textbf{Load } \textit{\textbf{Factor}} \text{ or } \textbf{capacity factor} = \frac{\textit{Actual Energy Generated in a Period}}{\textit{Maximum Possible Energy Generation in the Same Period}}$$

- LF 65% (1985) ->90-95% (2024)
- How?=> Enrq: 3% -> 4.5%; Better nuclear design with burnable poisson=> Reload 12 months-> 18-24 months=>Core Burnup: 25 MWd/tU 45-50 MWd/tU

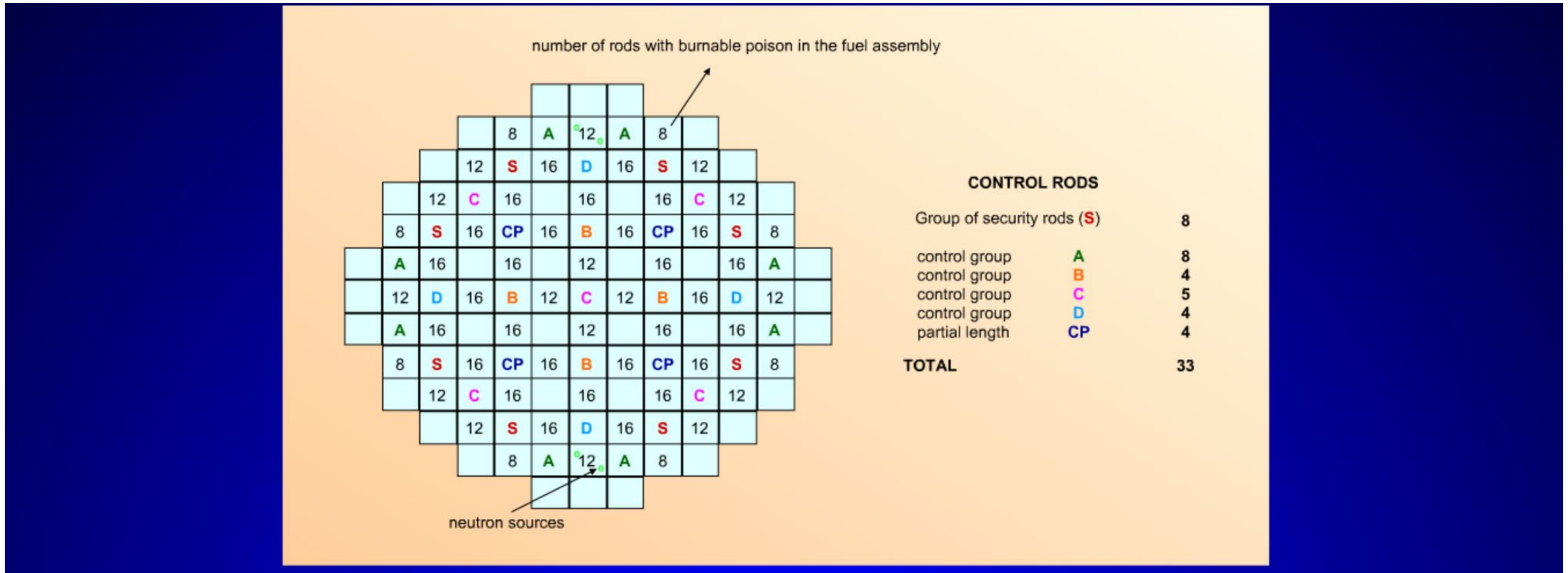
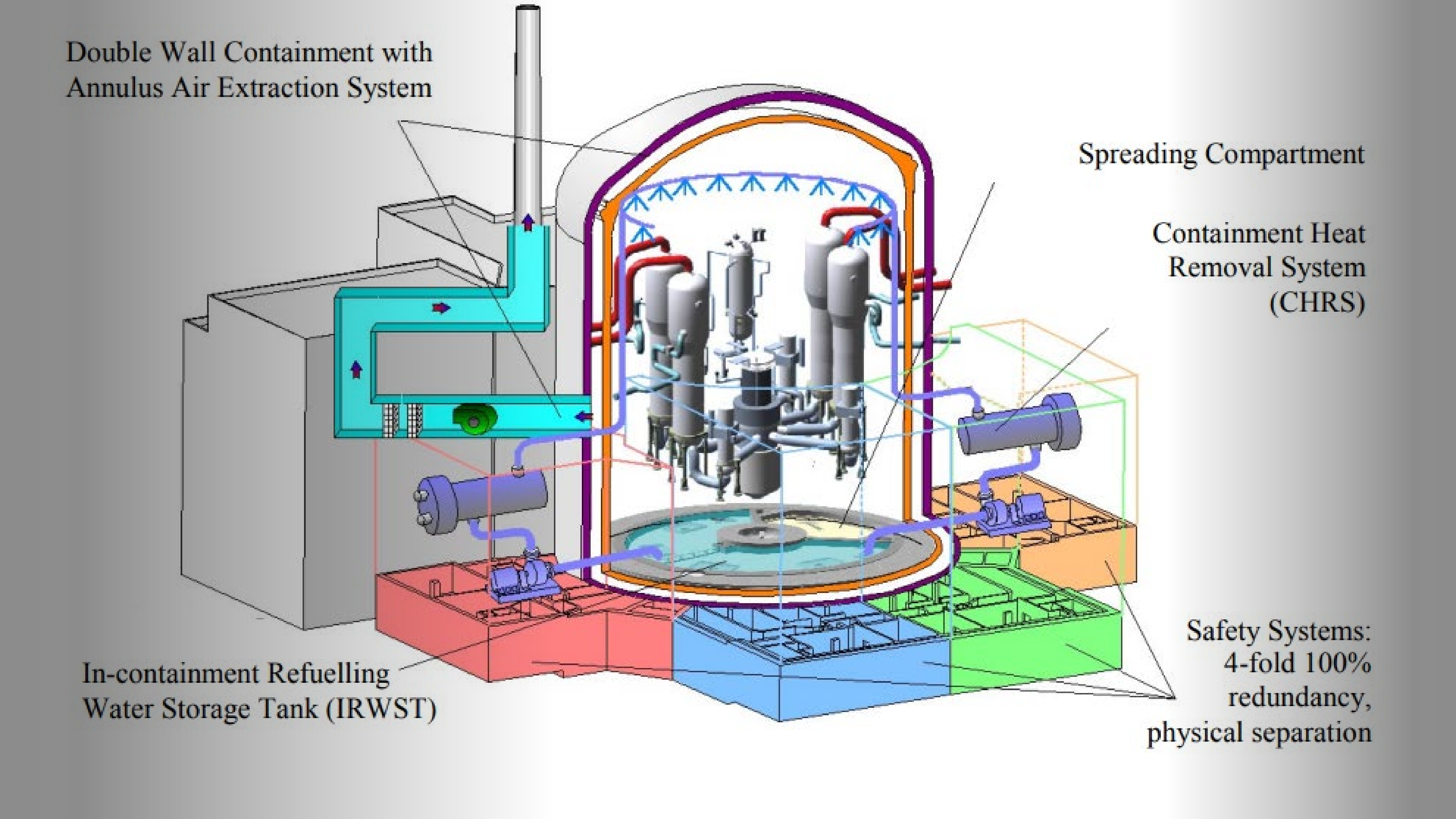
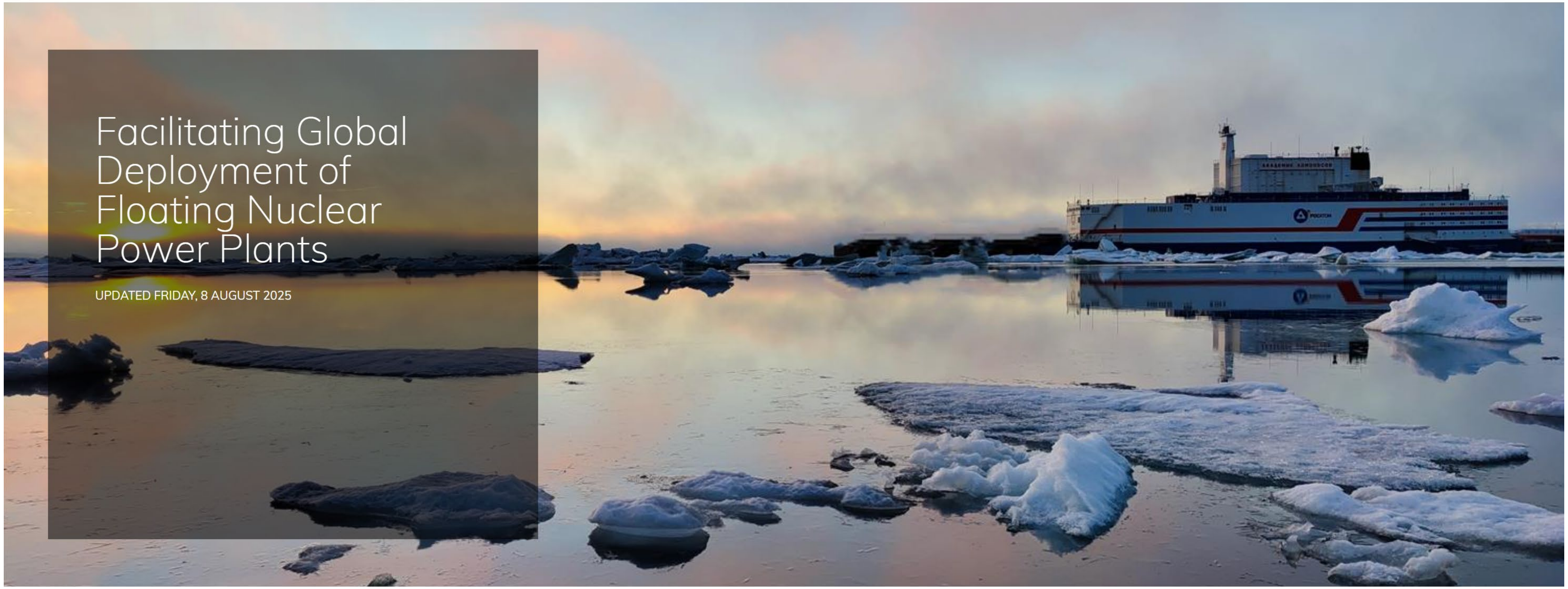


Figure 12 - Location of the groups of control rods, neutron sources and fuel

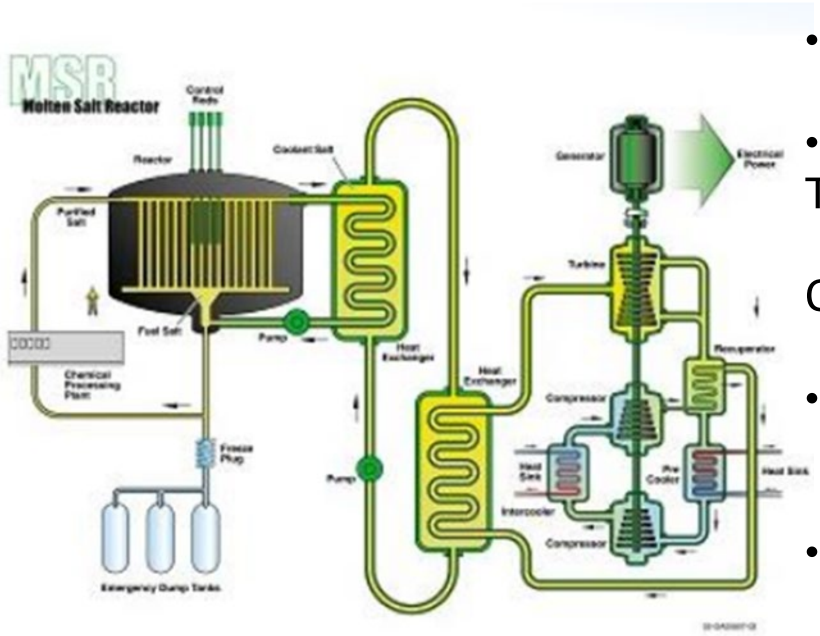


Double Wall Containment with
Annulus Air Extraction System
Spreading Compartment
Containment Heat
Removal System
(CHRS)
Safety Systems:
4-fold 100%
redundancy,
physical separation
In-containment Refuelling
Water Storage Tank (IRWST)

https://world-nuclear.org/information-library/nuclear-fuel-cycle/nuclear-power-reactors/generation-iv-nuclear-reactors#gif-reactor-technologies



Reactores de SALES FUNDIDAS



- Sal fundida como Combustible y refrigeración por sal fundida son las subclases principales

- Temperaturas más altas (400-800 °C) que los actuales reactores (alrededor de 300 °C)

- Presión atmosférica o muy baja

- Espectro térmico o rápido:

Típicamente, diseños moderados por grafito o de espectro rápido

Otras variaciones incluyen:

- Sal combustible dentro de barras de combustible refrigeradas por otra sal fundida;

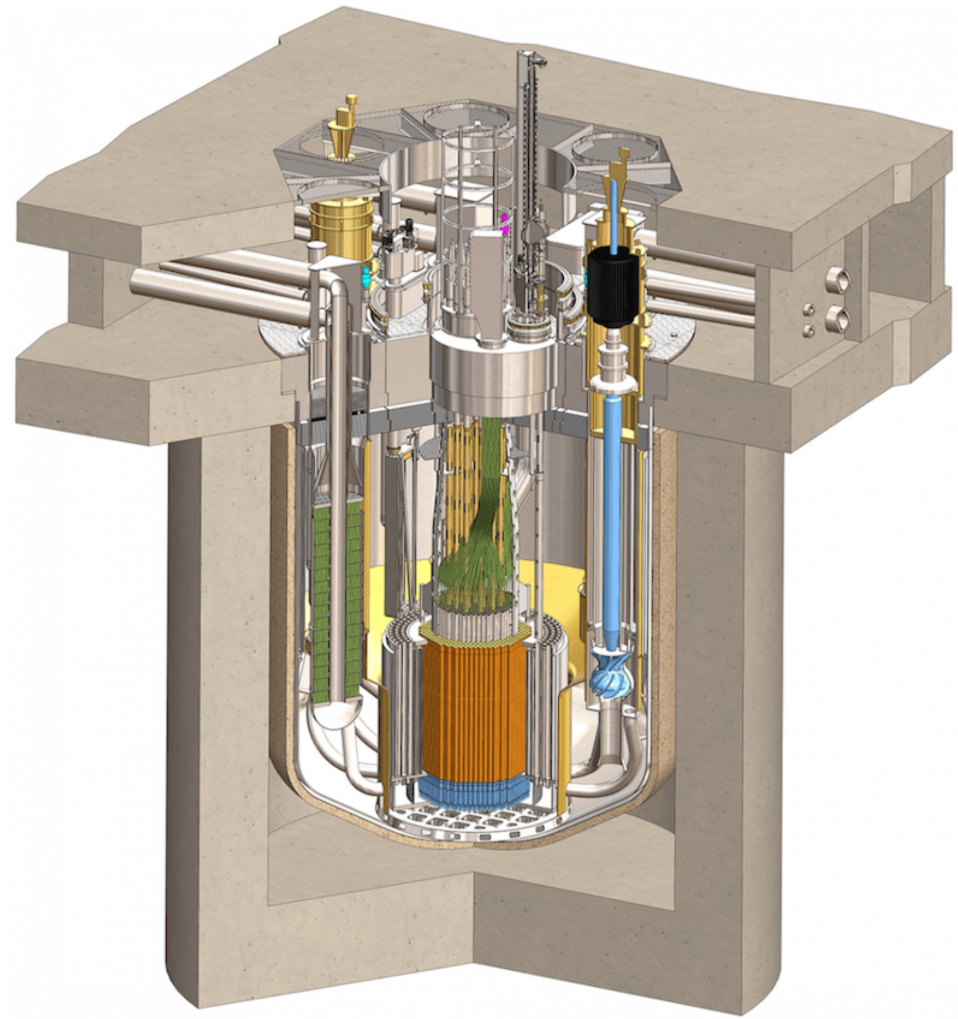
- o partículas de grafito recubiertas (similares a las utilizadas en los reactores de alta temperatura, llamadas TRISO)

- Sales de refrigerante y combustible de cloruros y fluoruros

Ref: Small Modular Reactors and Generation-IV. A Short Overview. Frederik Reitsma
Nuclear Power Technology Development Section. Department of Nuclear Energy.
Joint IAEA-ICTP Workshop on the Physics and Technology of Innovative High Temperature Nuclear Energy Systems

TERRAPOWER

https://www.terrapower.com/natrium/
https://entechonline.com/terrapower-reactor-take-a-

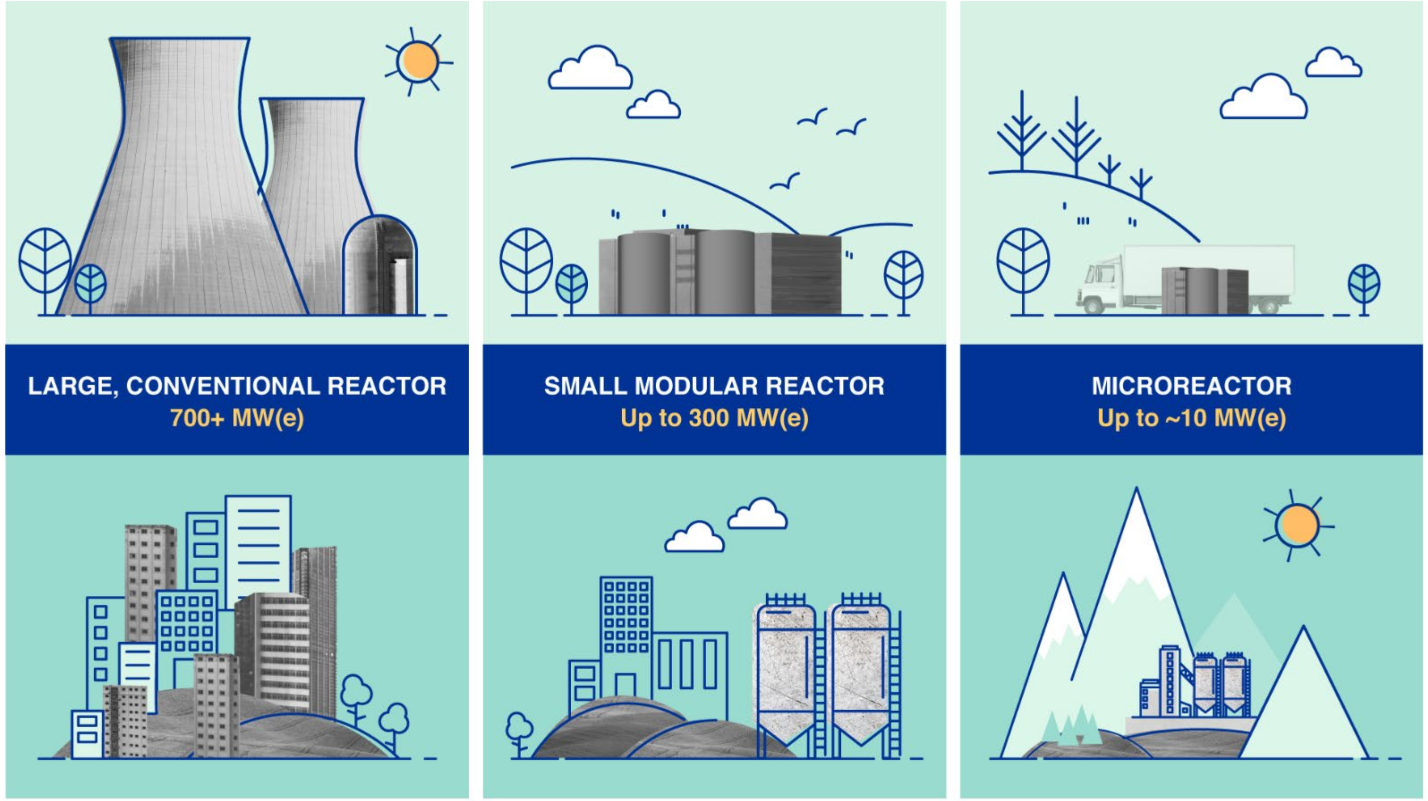


TerraPower es una empresa de tecnología nuclear fundada por Bill Gates, con inversores como NVIDIA y ArcelorMittal.

Reactor Natrium:
Es un reactor rápido refrigerado por sodio.
Se combina con un sistema de almacenamiento de energía en sales fundidas.
Está **en fase de construcción** un prototipo de demostración en Kemmerer, Wyoming.

MCFR (Molten Chloride Fast Reactor): en fase de desarrollo
Se trata de una clase de reactor rápidos que usa cloruros como sales fundidas.

REACTORES MODULARES (SMR)

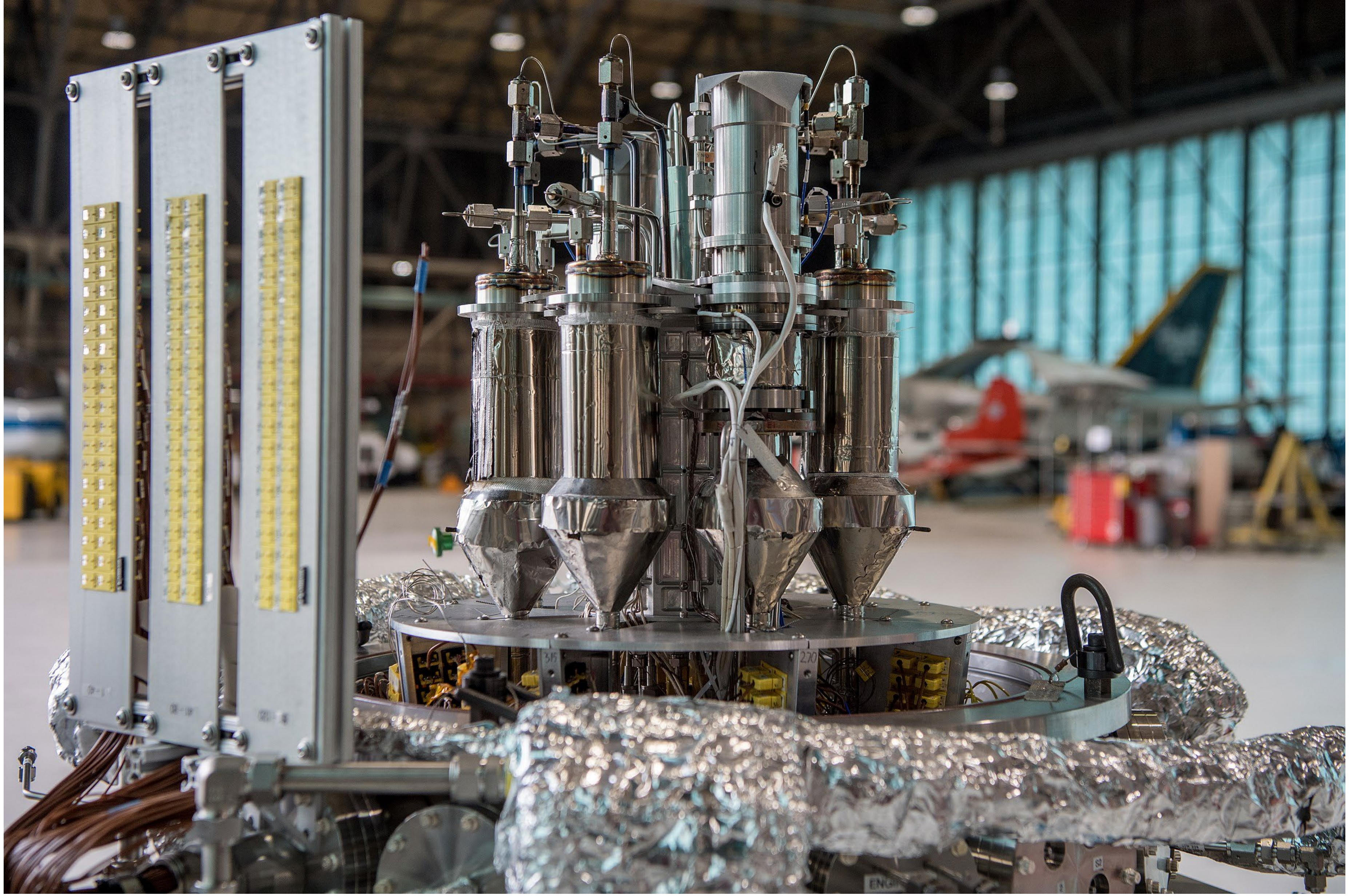


Small modular reactors (SMRs) have a power capacity of up to 300 MW(e) per unit. Many SMRs, which can be factory-assembled and transported to a location for installation, are envisioned for markets such as industrial applications or remote areas with limited grid capacity. (Image: A. Vargas/IAEA)

Oct 28, 2025

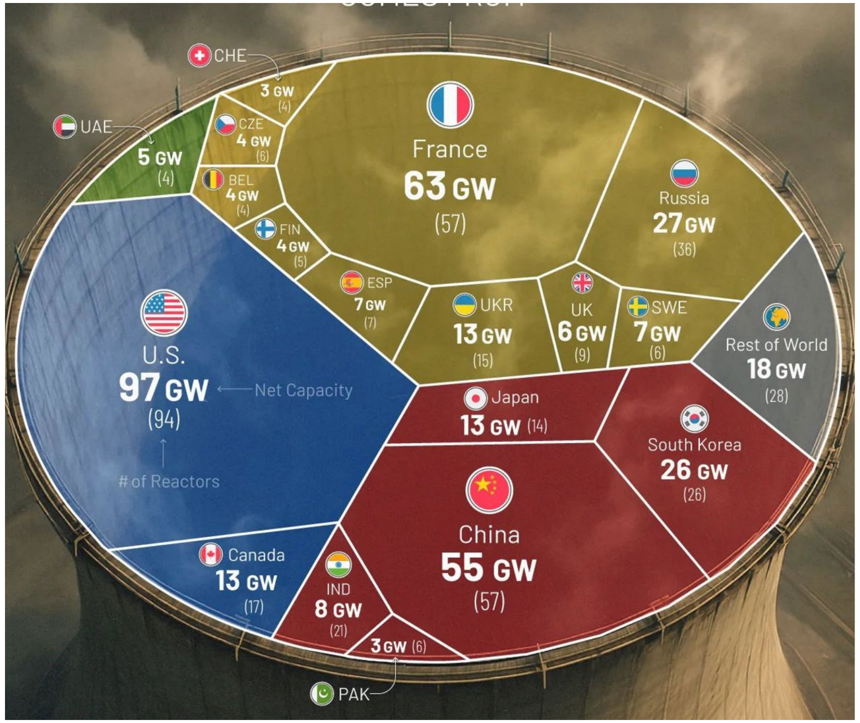
At least $80 billion to construct new Westinghouse nuclear power reactors Partnership will accelerate nuclear power and artificial intelligence deployment in America

https://westinghousenuclear.com/strategic-partnership/press-releases/brookfield/



https://www.nasa.gov/sites/default/files/thumbnails/image/kilopower_experiment.jpg

Reactor Database



438

OPERABLE REACTORS

396,599 MWe

9%

SHARE OF GLOBAL ELECTRICITY GENERATION

2,667,383 GWh (2024)

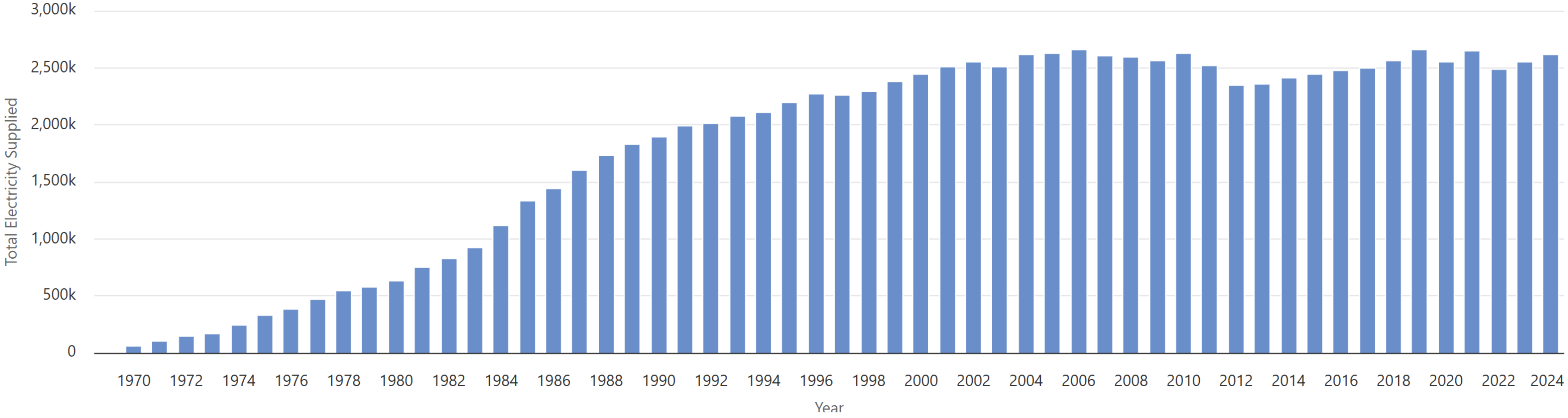
70

REACTORS UNDER CONSTRUCTION

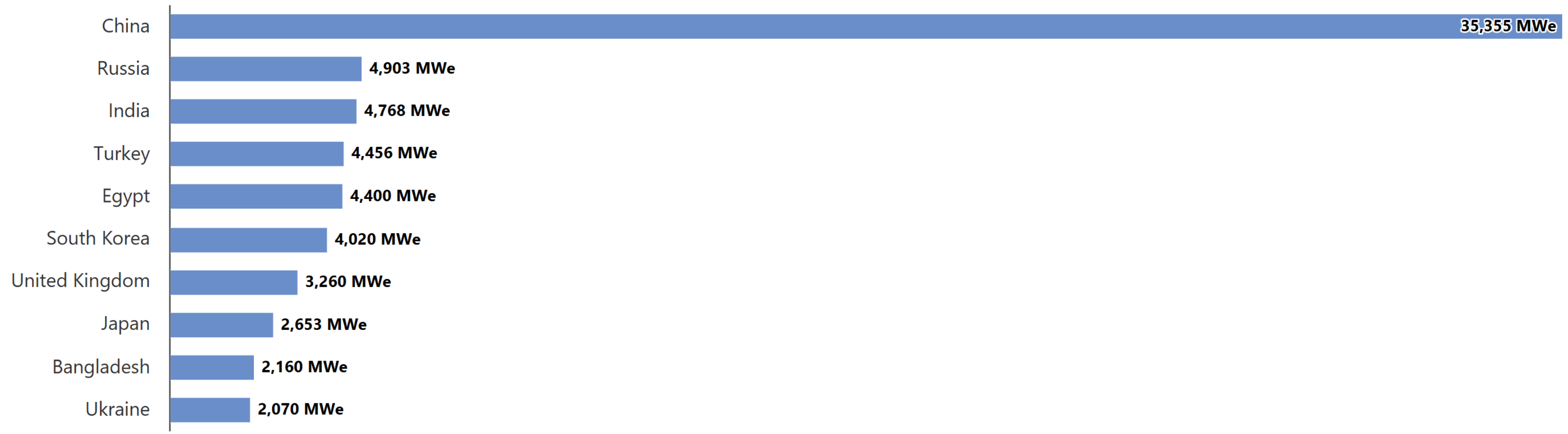
71,924 MWe

GLOBAL NUCLEAR GENERATION BY YEAR

https://world-nuclear.org/nuclear-reactor-database/summary



REACTORS UNDER CONSTRUCTION NET CAPACITY (TOP 10)



- 88 new nuclear power plants are planned. The nuclear reactor has been purchased, or the site for their construction has been selected.
- 344 new nuclear power plants have been proposed and the site is being selected and/or the nuclear reactor vendor is being chosen.

All of this data is updated monthly on the following website: ***https://world-nuclear.org/information-library/facts-and-figures/world-nuclear-power-reactors-and-uranium-requireme***.

Nuclear power plants have demonstrated extraordinary reliability. However, the three major accidents that have occurred have had a significant media and economic impact:

- a) **TMI-2 (1979)** greatly increased the costs of operating and constructing nuclear power plants, as safety measures were multiplied. The United States did not begin construction of new reactors for many years.
- b) **Chernobyl (1986)** in Ukraine (then USSR), with RMBK-type reactors and no containment building, was the only accident that had consequences for the population, although its effects were far smaller than initially predicted (*). Reactor IV was destroyed, but the other reactors continued operating until the year 2000.
- c) **The 2011 tsunami in Japan** rendered the six reactors at Fukushima inoperative. Its effects on the population were negligible compared to those of the tsunami itself. Germany decided to shut down its reactors in the following years, and other countries avoided building new ones. The countries where the accidents occurred decided to continue with their nuclear programs — the most recent example being Japan.

(*)

1986-2016: CHERNOBYL at 30 https://cdn.who.int/media/docs/default-source/documents/publications/1986-2016-chernobyl-at-30476d83ab-985d-416f-b936-576b0c0ca17f.pdf

BBC Chernobyl: Cómo viven quienes volvieron a la zona del peor accidente nuclear de la historia (https://www.youtube.com/watch?v=BWQNETpjPMM)

Visitamos la fauna de Chernóbil 33 años después del accidente nuclear (https://theconversation.com/visitamos-la-fauna-de-chernobil-33-anos-despues-del-accidente-nuclear-112893) por Germán Orizaola (profesor de la Universidad de OVIEDO Lleva más de 10 años haciendo trabajo de investigación "in situ" en Ucrania, Chernóbil). Entrevista: EUREKA, Radio USAL, https://radio.usal.es/wp-content/uploads/2015/02/Eureka-29-04-2021parte1.mp3

Energía nuclear en España:

7 reactores que cubren el 20% de la demanda de electricidad. 1 Fábrica de Combustible en Juzbado Salamanca que exporta 2/3 de lo fabricado.

Previsto cierre, empezando en 2027 (Almaraz I), y última en 2035. Quizás se retrase. Producir esta energía al año con gas equivale a emitir 30 millones de toneladas de CO_2.

En total se consumen 70-80 t combustible gastado, que se almacenan en cada central de forma indefinida. Estaba previsto un Almacén temporal centralizado (Villar de Cañas, Cuenca), en el que se había invertido mas 100 millones de euros

No equivocar potencia instalada con energía producida Una CC NN funciona a su potencia nominal entre 85-95% de las 8.760 horas que tiene el año-. Una central solar fotovoltaica o eólica raramente excede, en media, el 20% de la potencia instalada=>1 MW nuclear genera 5 veces la energía que 1 MW eólico o solar

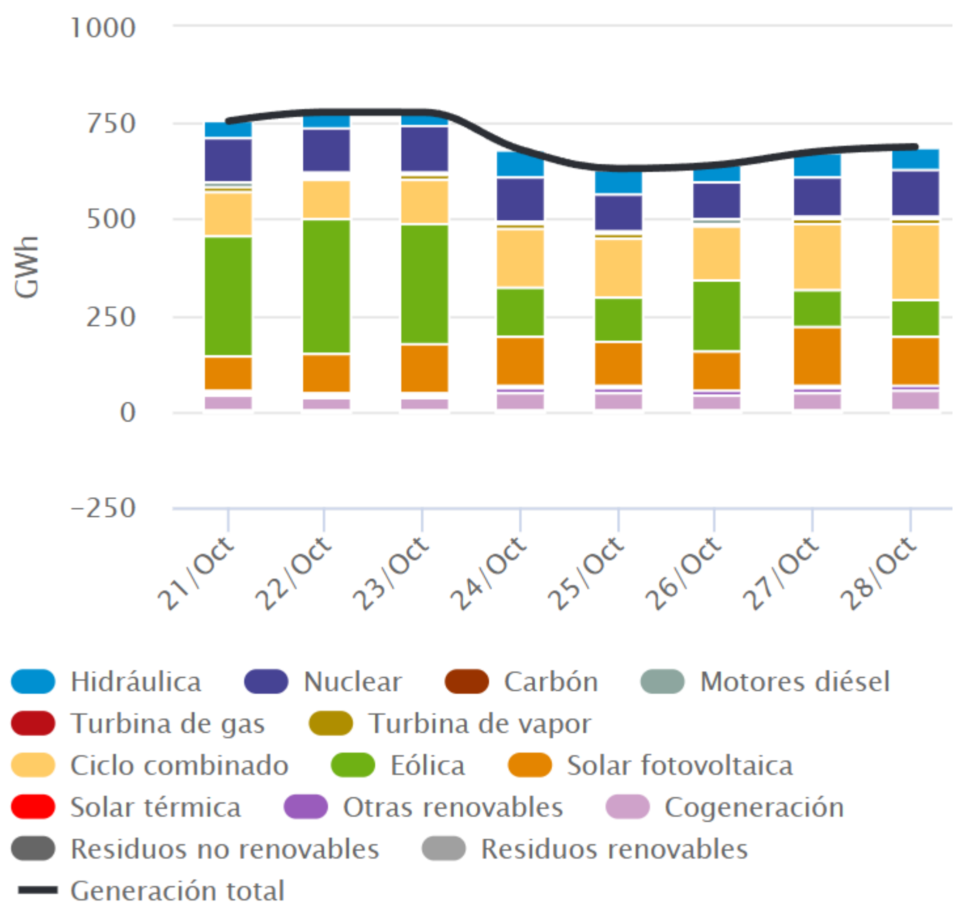
Historia y futuro del almacén de residuos radiactivos de El Cabril. TheConversation. 2024-06-21 (también: Lo que sabemos sobre el único almacén de residuos radiactivos en España. National Goegraphic. 2024-06-21)
El cierre de las centrales nucleares en España, ¿una decisión acertada? TheConversation. 2024-04-02
Residuos y Centrales Nucleares | Guillermo Sánchez León
Cementerios nucleares for dummies (Naukas 13-08- 2015).

Mercado eléctrico español una semana cualquiera.

El precio de la energía eléctrica se asigna por subasta: que suele oscilar entre 0 (en horas con hace sol) y 150 €/MWh, debido a la especialmente a la variabilidad de la solar fotovoltaica.

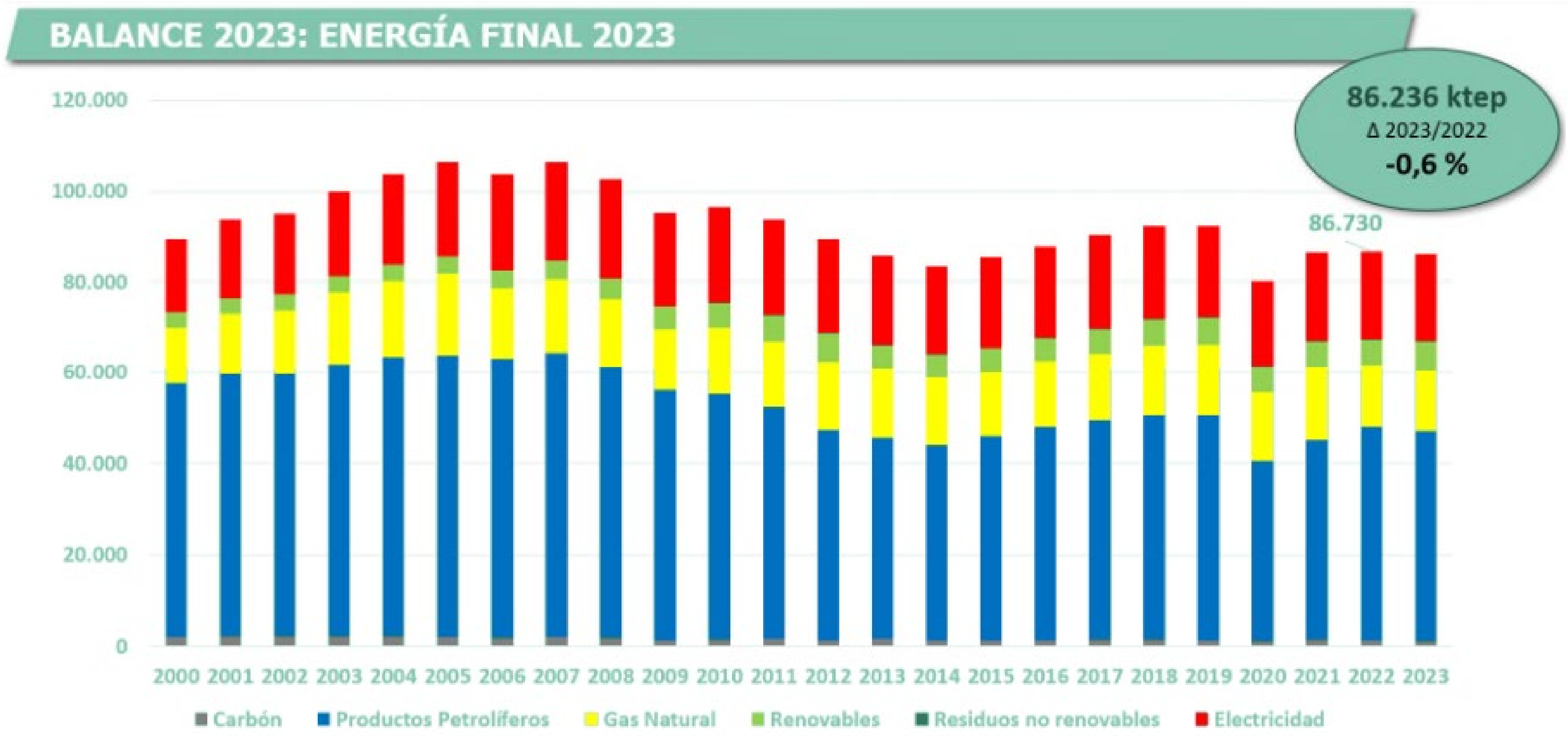
Como la demanda de electricidad en España no aumenta, está provocando una competencia entre las fuentes de energía: *Por qué el precio de la luz en España está por los suelos* (https://theconversation.com/por-que-el-precio-de-la-luz-en-espana-esta-por-los-suelos-228163)

Del 21/10/2025 al 28/10/2025



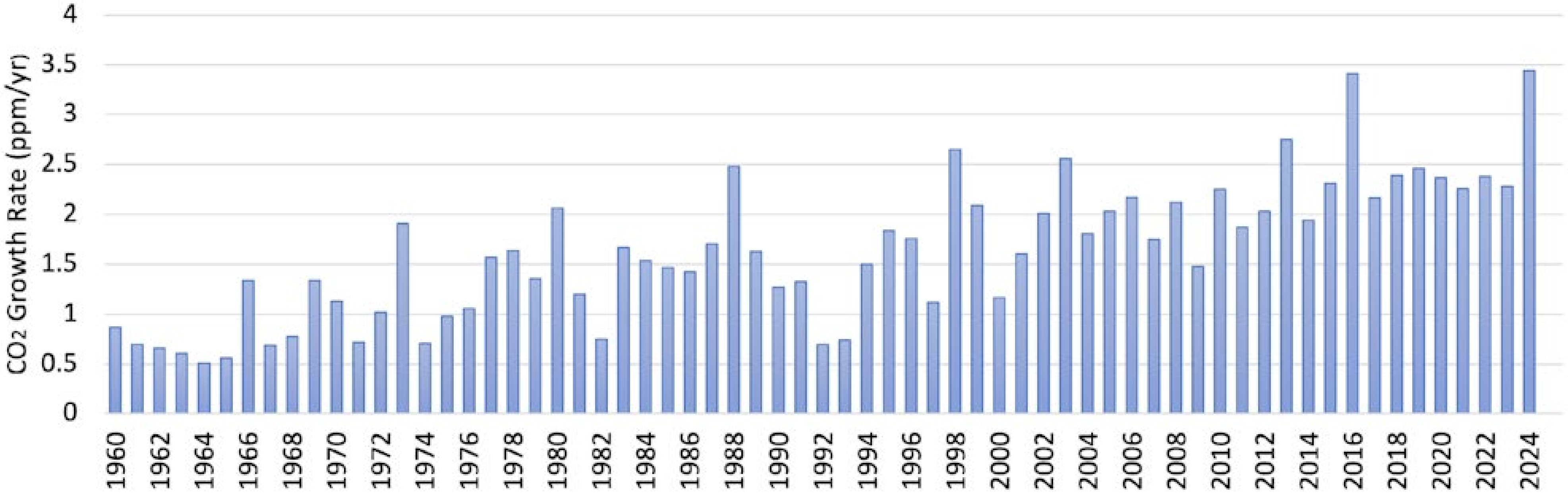
CONSUMO de ENERGIA PRIMARIA en ESPAÑA 2000- 2023. La tendencia ha sido ligeramente decreciente. La energía eléctrica, es menos de 1/3 de la energía primaria.

Figura 1.4. Consumo de energía final, incluyendo usos no energéticos, 2000-2023



https://www.miteco.gob.es/

La generación de energía eléctrica con fuentes no emisoras de CO2 está creciendo desde hace años pero el contenido de CO2 en la atmósfera continua aumentado.



Aumento de las medias anuales de dióxido de carbono atmósférico. WMO/NOAA/SIO,

SUMMARY

- The first nuclear reactor was built in 1942 in record time and in a location that today we would find unbelievable. However, nature itself had already "manufactured" nuclear reactors billions of years earlier.
- Only a few years later, the physics and mathematics required to develop nuclear technology were established—initially for military purposes, but soon transferred to civilian applications, particularly the generation of electricity.
- After a period of remarkable expansion, the construction of new reactors slowed down considerably. Nevertheless, significant improvements were made in the design of fuel reloads for operating reactors, allowing a substantial increase in electricity production with the same installed capacity.
- This slowdown had a negative effect on education and research in nuclear technology. In recent years, however, the urgent need for energy sources that do not emit greenhouse gases, combined with the demand for stable and reliable electricity generation, has led to a renewed interest in nuclear power. In the United States, this revival is being driven by major technology companies.
- Spain, on the other hand, plans to shut down its nuclear power plants over the coming years and to build, next to each facility, small storage units where the spent fuel will be kept indefinitely.

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Mathematica Beyond Mathematics: The Wolfram Language in the Real World. 2nd Edition.
https://www.mathematicabeyondmathematics.com/

https://diarium.usal.es/guillermo/publicaciones

BIOKMOD: https://diarium.usal.es/guillermo/biokmod/ : An application for solving system of differential equations, fitting coefficients, convolution, and more, with application for modeling Linear and Nonlinear Biokinetic Systems. Some ICRP biokinetic models are included . It can be applied in pharmacokinetic, internal dosimetry, bioassay evaluations, nuclear medicine and more.

EUREKA, un programa de divulgación científica de Radio Universidad de Salamanca
https://diarium.usal.es/guillermo/eureka-videos-en-youtube/