A nuclear reactor : how it works ?

WNU – SI – Oxford, July 2012

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Nuclear Consulting

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- ***A quick look at history***
- The atoms
- The fission process and the reaction chain
- Basic principles of nuclear reactors
- Genesis of nuclear reactor technology

Nuclear energy: a glance at history (1/2)

- **1896** **Discovery of natural radioactivity by Henry Becquerel* (Paris)**

- 1898 Discovery of Radium by Pierre et Marie Curie* (Paris) (they create the term "radioactivity"**)

Albert Einstein

- 1905 Theory of relativity by Albert Einstein (Germany): equivalence between mass and energy is established (the basic phenomena involved in energy release by fission)

Ernest Rutherford

- **1911** **Rutherford creates a model of the atoms (England)**

- 1919 First observation of artificial transmutation ($\propto$ particles on gold atom) by Ernest Rutherford (England), and discovery of the proton (same time)

James Chadwick

- **1932** **Discovery of the neutron by James Chadwick (England)**

- 1934 Discovery of artificial radioactivity ($\propto$ particles on Aluminum atoms) by Frederic Joliot and Irène Curie (Paris)***

** Both received the Nobel price of physics in 1903 for their discovery*
*** The official unit of « Curie » is adopted in 1910*
**** Nobel price in Chemistry (1935)*

Marie Curie

Nuclear energy: a glance at history (2/2)

- 1935 — "Liquid drop" model of atomic nucleus by Niels Bohr (Denmark)


Niels BOHR

- **1938 (Dec)** — Discovery of fission of uranium by Otto Hahn and Fritz Strassmann (Berlin) + Lise Meitner


Otto HAHN, Lise MEITNER, Fritz STRASSMAN

- 1939 (Jan) — Interpretation of fission by mass defect variation and liquid drop model of atomic nucleus: Lise Meitner and Otto Frisch (Germany)
- **1939 (May)** — **Publication of 3 fundamental patents on nuclear energy by Frederic Joliot (Paris) : reactor and weapon principles**

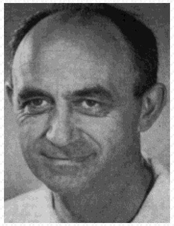

Frédéric JOLIOT

- 1941 — Plutonium is discovered by Gleen Seaborg (Berkeley)

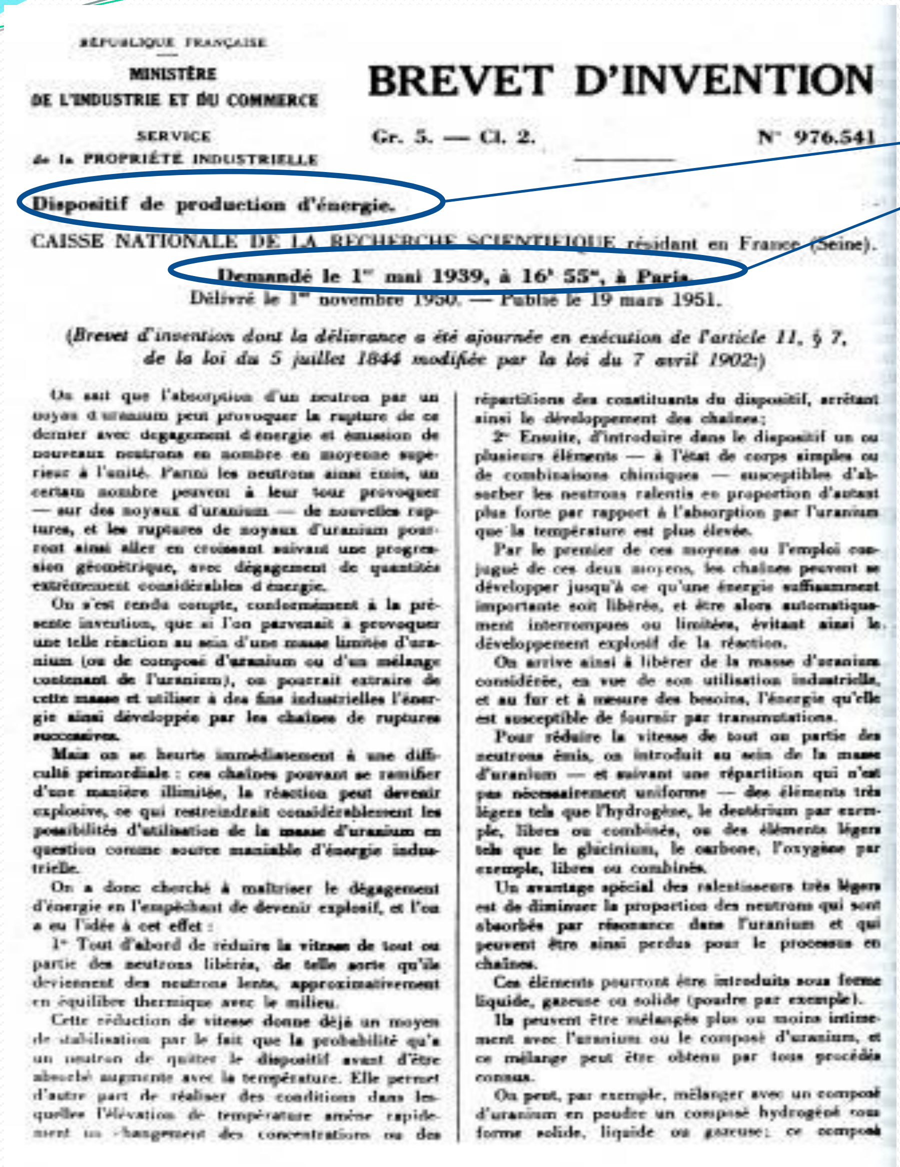

Gleen SEABORG

- **1942 (Dec. 2)** — **First divergence** (self-sustaining chain reaction) in a « pile » built at Chicago (USA) by Enrico Fermi (CP1)
- 1945 July 16 — First explosion of an atomic bomb "Trinity" (Alamogordo - USA)
- Aug.6 — Destruction of Hiroshima by an atomic weapon

Enrico FERMI



The French patents in May 1939



RÉPUBLIQUE FRANÇAISE

MINISTÈRE DE L'INDUSTRIE ET DU COMMERCE

SERVICE de la PROPRIÉTÉ INDUSTRIELLE

BREVET D'INVENTION

Gr. 5. — Cl. 2.

N° 976.541

Dispositif de production d'énergie.

CAISSE NATIONALE DE LA RECHERCHE SCIENTIFIQUE résidant en France (Seine).

Demandé le 1er mai 1939, à 16h 55m, à Paris.

Délivré le 1er novembre 1950. — Publié le 19 mars 1951.

(Brevet d'invention dont la délivrance a été ajournée en exécution de l'article 11, § 7, de la loi du 5 juillet 1844 modifiée par la loi du 7 avril 1902.)

On sait que l'absorption d'un neutron par un noyau d'uranium peut provoquer la rupture de ce dernier avec dégagement d'énergie et émission de nouveaux neutrons en nombre en moyenne supérieur à l'unité. Parmi les neutrons ainsi émis, un certain nombre peuvent à leur tour provoquer — sur des noyaux d'uranium — de nouvelles ruptures, et les ruptures de noyaux d'uranium pourront ainsi aller en croissant suivant une progression géométrique, avec dégagement de quantités extrêmement considérables d'énergie.

On s'est rendu compte, conformément à la présente invention, que si l'on parvenait à provoquer une telle réaction au sein d'une masse limitée d'uranium (ou de composé d'uranium ou d'un mélange contenant de l'uranium), on pourrait extraire de cette masse et utiliser à des fins industrielles l'énergie ainsi développée par les chaînes de ruptures successives.

Mais on se heurte immédiatement à une difficulté primordiale : ces chaînes pouvant se ramifier d'une manière illimitée, la réaction peut devenir explosive, ce qui restreindrait considérablement les possibilités d'utilisation de la masse d'uranium en question comme source maniable d'énergie industrielle.

On a donc cherché à maîtriser le dégagement d'énergie en l'empêchant de devenir explosif, et l'on a eu l'idée à cet effet :

1° Tout d'abord de réduire la vitesse de tout ou partie des neutrons libérés, de telle sorte qu'ils deviennent des neutrons lents, approximativement en équilibre thermique avec le milieu.

Cette réduction de vitesse donne déjà un moyen de stabilisation par le fait que la probabilité qu'a un neutron de quitter le dispositif avant d'être absorbé augmente avec la température. Elle permet d'autre part de réaliser des conditions dans lesquelles l'élévation de température amène rapidement un changement des concentrations ou des répartitions des constituants du dispositif, arrêtant ainsi le développement des chaînes;

2° Ensuite, d'introduire dans le dispositif un ou plusieurs éléments — à l'état de corps simples ou de combinaisons chimiques — susceptibles d'absorber les neutrons ralentis en proportion d'autant plus forte par rapport à l'absorption par l'uranium que la température est plus élevée.

Par le premier de ces moyens ou l'emploi conjugué de ces deux moyens, les chaînes peuvent se développer jusqu'à ce qu'une énergie suffisamment importante soit libérée, et être alors automatiquement interrompues ou limitées, évitant ainsi le développement explosif de la réaction.

On arrive ainsi à libérer de la masse d'uranium considérée, en vue de son utilisation industrielle, et au fur et à mesure des besoins, l'énergie qu'elle est susceptible de fournir par transmutations.

Pour réduire la vitesse de tout ou partie des neutrons émis, on introduit au sein de la masse d'uranium — et suivant une répartition qui n'est pas nécessairement uniforme — des éléments très légers tels que l'hydrogène, le deutérium par exemple, libres ou combinés, ou des éléments légers tels que le glucinium, le carbone, l'oxygène par exemple, libres ou combinés.

Un avantage spécial des ralentisseurs très légers est de diminuer la proportion des neutrons qui sont absorbés par résonance dans l'uranium et qui peuvent être ainsi perdus pour le processus en chaînes.

Ces éléments pourront être introduits sous forme liquide, gazeuse ou solide (poudre par exemple).

Ils peuvent être mélangés plus ou moins intimement avec l'uranium ou le composé d'uranium, et ce mélange peut être obtenu par tous procédés connus.

On peut, par exemple, mélanger avec un composé d'uranium en poudre un composé hydrogéné sous forme solide, liquide ou gazeuse; ce composé

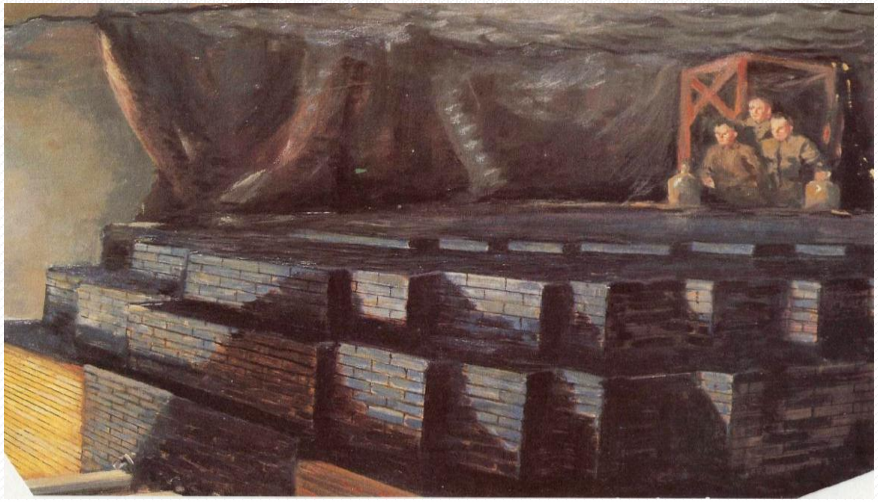
Patent I (May 1st 1939) :
"Device for energy production"

"We know that the absorption of a neutron by a nucleus of uranium can cause the rupture (the break) of this one with a release of energy and an emission of new neutrons in average number upper than one. Among these neutrons, some can cause new ruptures of other nucleus of uranium, thus making these ruptures increasing according to a geometric progression …. We have realized, in accordance with the present invention, that if one manage to cause such a reaction within a limited mass of uranium, one could extract from this mass the energy then developed by the chains of successive ruptures"

Two other patents were applied for in may 1939 : one for the control of the "reaction chain" and the other one relating to "explosive charges"

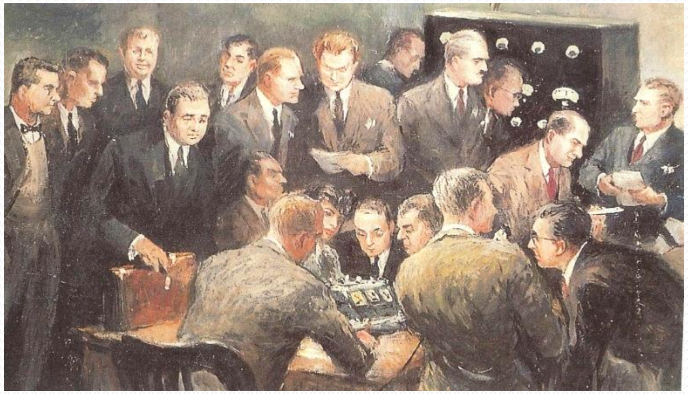
December 2, 1942, 3:25 p.m.

…..the Chicago Pile N°1, CP-1, was ready for a demonstration. Before a group of dignitaries, a young scientist named George Weil worked the final control rod while Fermi carefully monitored the neutron activity. The pile reached the critical mass for self-sustaining reaction at 3:25 p.m.



A secret language phone call (Compton – Conant) :
- « Jim, you'll be interested to know that the Italian navigator has just landed in the new world »
- « Were the native friendly ? ».
- « Every one landed safe and happy ».

The place : Stagg Field stadium



Reunion photo from 1962 of most of the scientists who participated with Fermi on CP1

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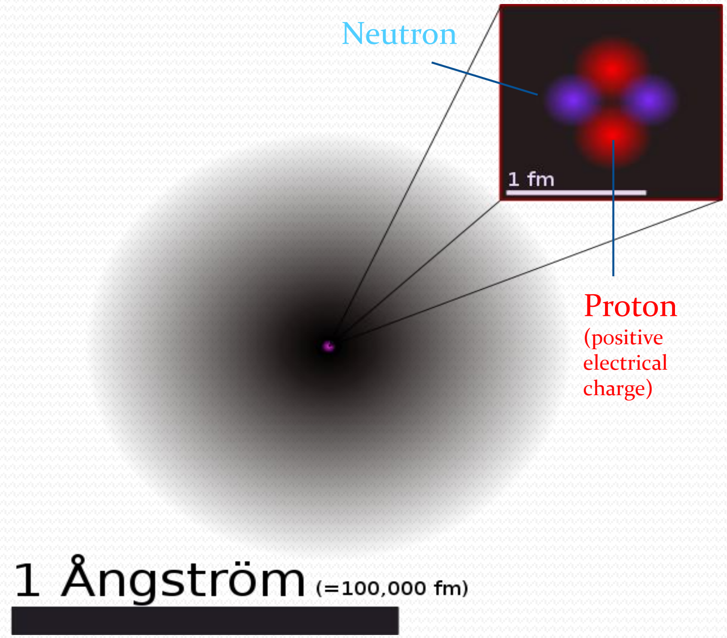
The atomic nucleus

Number of protons = Z : chemical element :
92 natural, from Z = 1 (H) to Z = 92 (U), except Z = 43 (Tc) and Z = 61 (Pm)

$$^{A}_{Z}X$$



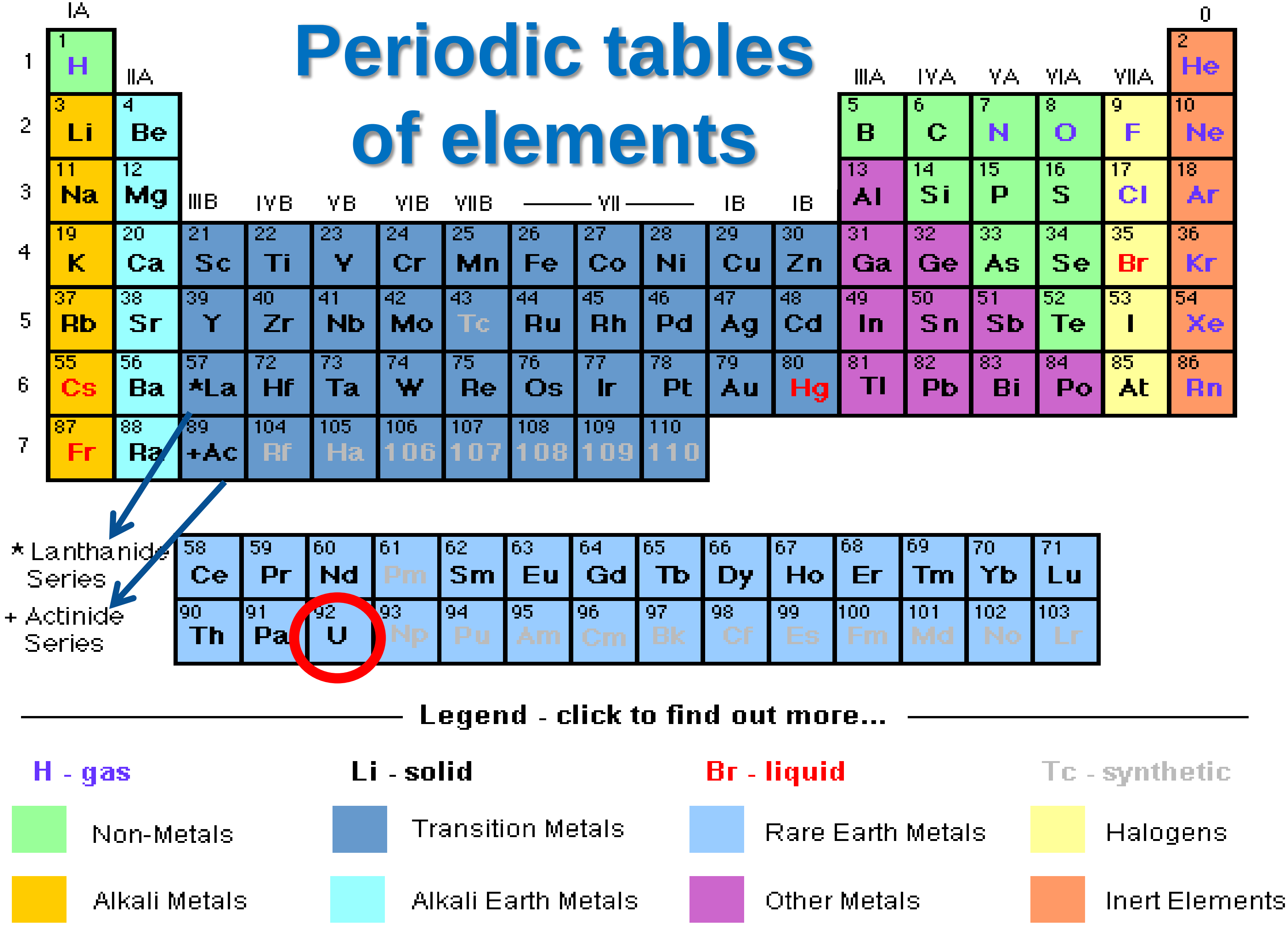
- **<u>Atomic number :</u>** A = Z + N = number of "nucleons"

- **<u>Isotopes :</u>**

  Same chemical element (= same Z) but <u>different</u> number of neutrons N
  (ex : H1 H2 and H3, U232 to U239, Pu238 to Pu 242)

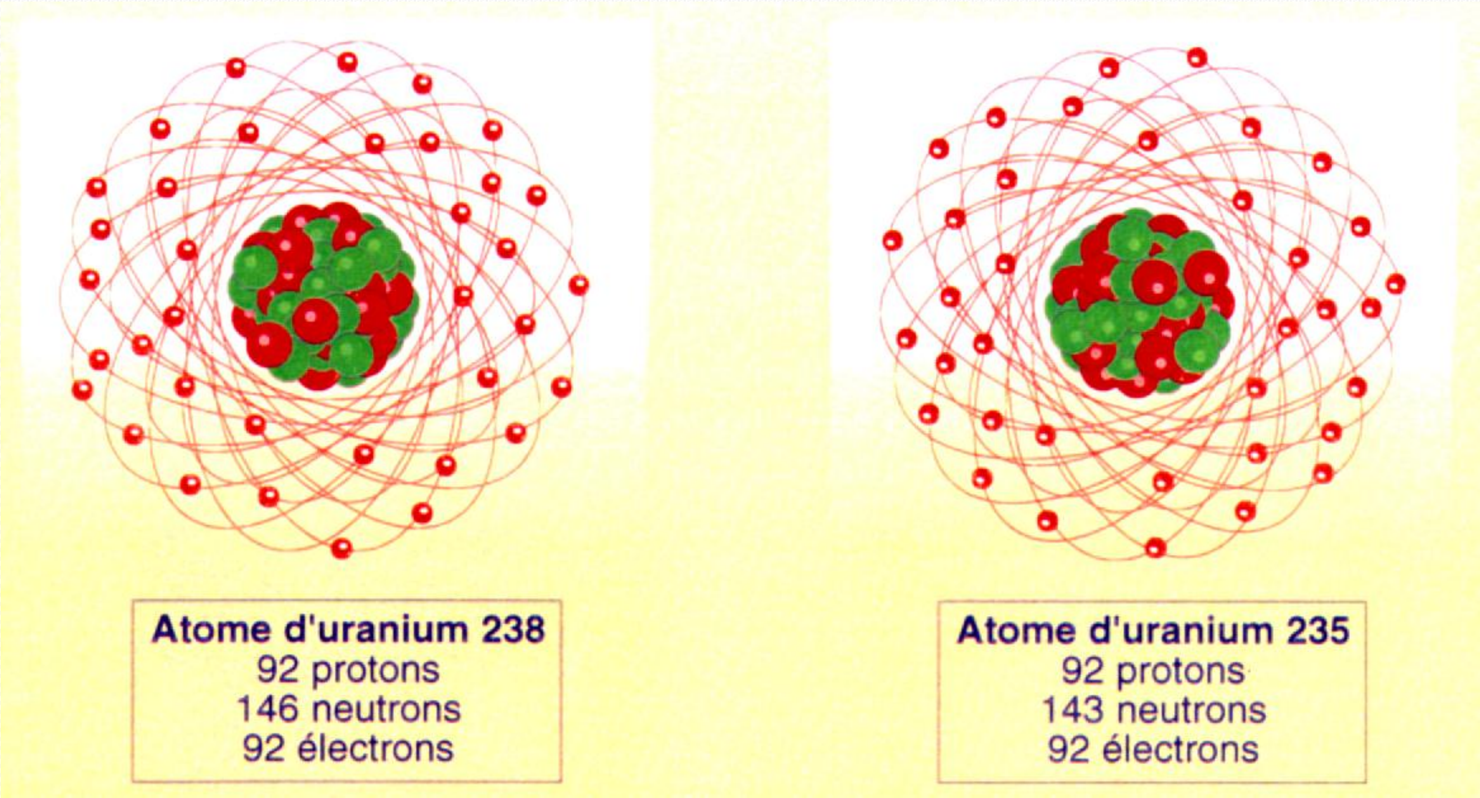
- **<u>Atomic Mass :</u>** the mass of **N = ** 6,022 10^{23} atoms , roughly equal to A because the mass of **N** nucleons is almost equal to **1 Gram**

Periodic tables of elements



The two main isotopes of natural uranium

U238 (99.3 %) – U235 (0.7 %)



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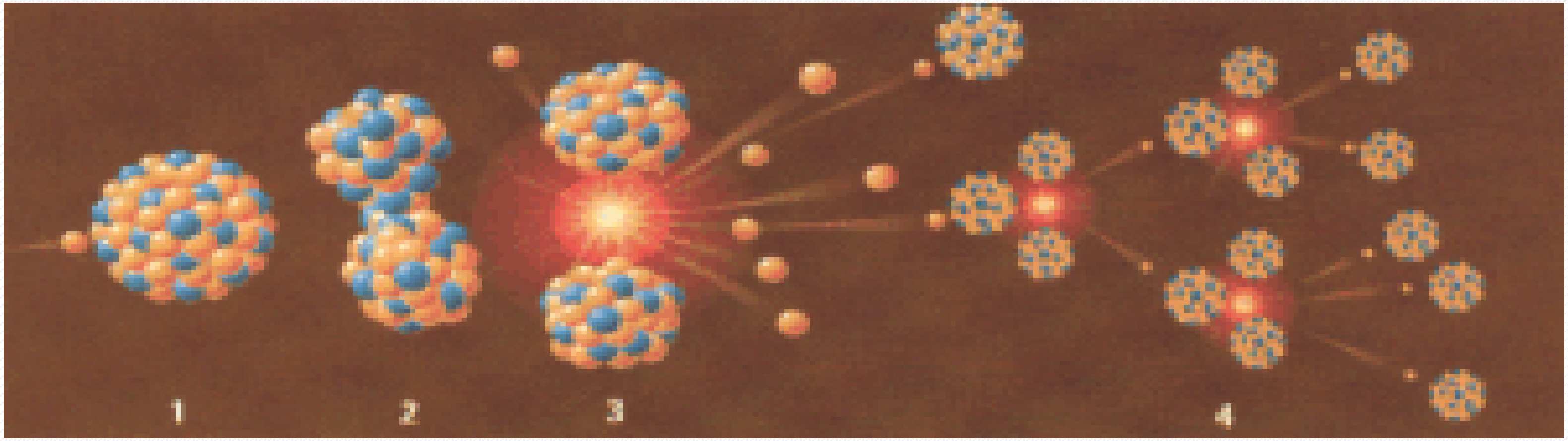
The FISSION process …



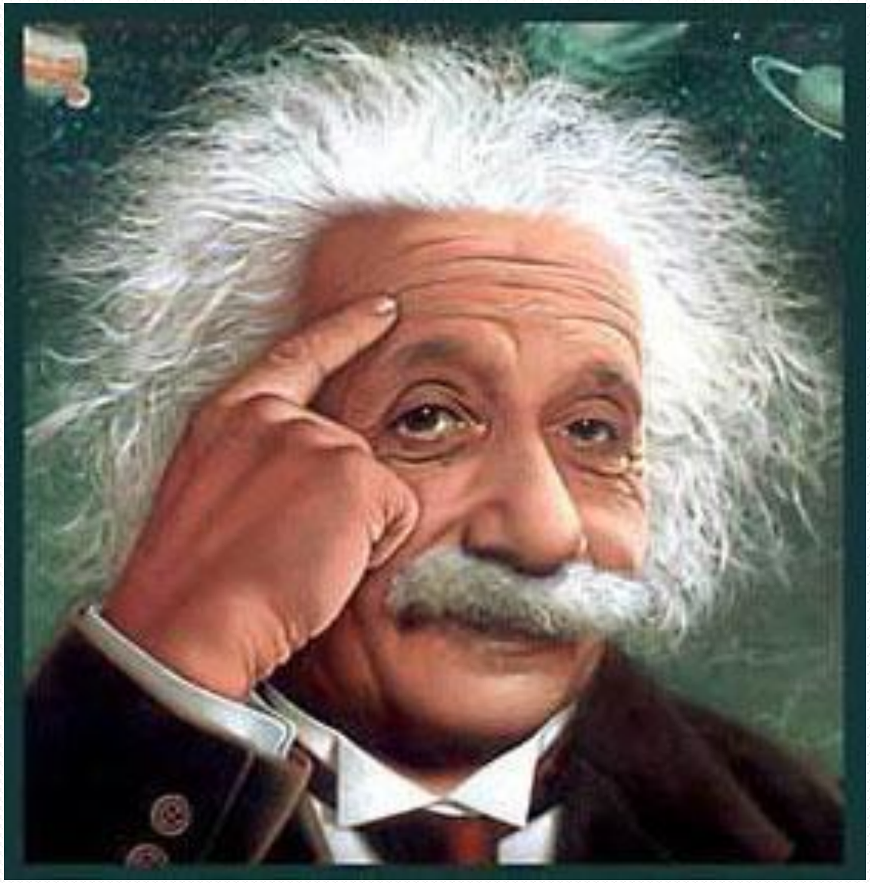
<u>The RESULT :</u>

<u>*1 – Energy : very high*</u>

2 – Several neutrons : very fast (average number for U235: $\overline{\nu}$ = 2,5)

3 – Two « pieces » (the fission products, fp) : very cumbersome !

An amazing amount of energy….



$$E = m \cdot C^2$$

Order of magnitude (to be reminded !)

- **1 fission** : 200 Mev (1 ev = 1,6 10^{-19} Joules) :
- To generate 1 joule, it needs 3,1 10^{10} fissions
- 1 gram of fissions releases an energy of **1 MWj**

This a million times more than a chemical reaction

ONE TON of fissions is enough to supply the heat needed for the production of the total electrical energy of 1 Gwe reactor operating at full power during 1 year (assuming an efficiency of 0,34).
This is equivalent to 2 Mtoe

Note : ***in France, nuclear electricity = 420 TWhe = 48 GWe-Year ➔ 48 tons of fission products (waste) - In the world = 350 GWe-Year ➔ 350 tons of f.p. (waste)***

Energy from fissions : how it appears ?

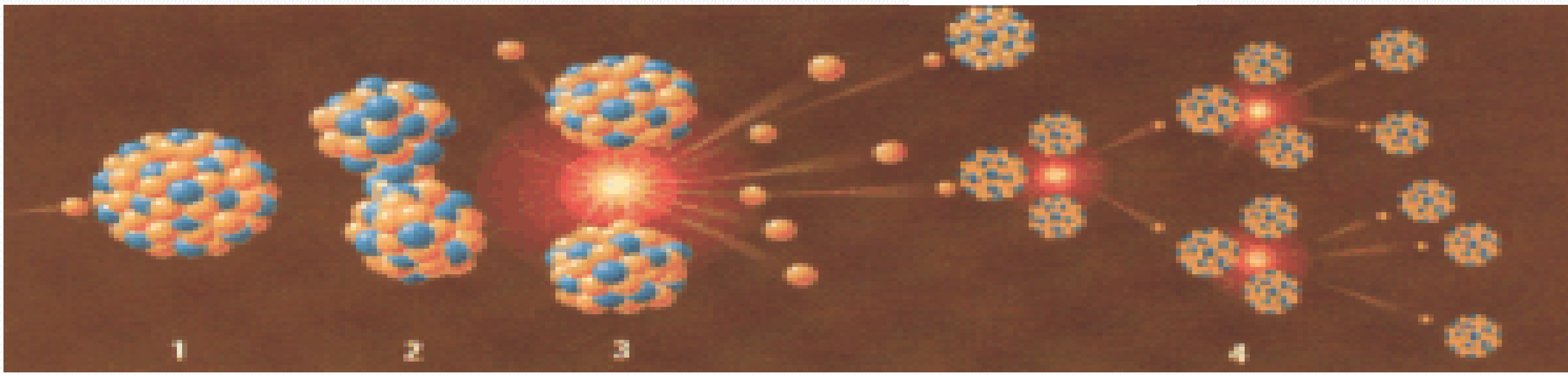
MODE OF APPEARANCE		Mev	%	Comments
Directly from fission	Kinetic energy of fission fragments	**166.2**	82.4	Mean path of fragments are of few tens of microns in the fuel matrix
	Prompt gamma rays	**8**	4.2	Strong gamma rays are emitted when the nucleus is fissioned
	Kinetic energy of neutrons from fission	**4.8**	2.4	The bulk of this energy is transferred to the moderator
From the radioactive decay of fission products (delayed)	GAMMA	**7.2**	3.6	This is the origin of the RESIDUAL POWER (when reaction chain has stopped)
	BETA	**7**	3.5	
	NEUTRINOS	**(9.6)**	0	**NOT RECOVERED IN THE REACTOR**
From gamma emissions of neutron captures	(n , γ) reactions	**8.4**	4.2	Average "binding energy" of neutrons in nucleus is 6 Mev and 1.4 neutrons are captured in nucleus (2.4-1)

TOTAL (without neutrinos) : 201.6 Mev / fission

Residual power released by of a reactor core after its shut down

	en %	*REP 900*	*REP 1300*
Avant l'arrêt	100 %	2 700 MW	3 900 MW
Après 1 seconde	7 %	190 MW	270 MW
Après 1 minute	5 %	135 MW	195 MW
Après 1 heure	1,5 %	40 MW	58 MW
Après 1 jour	0,6 %	16 MW	24 MW
Après 1 semaine	0,3 %	8 MW	12 MW
Après 1 mois	0,15 %	4 MW	6 MW

The FISSION process …



The RESULT :

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Distribution of the number and of the energy of neutrons from fissions

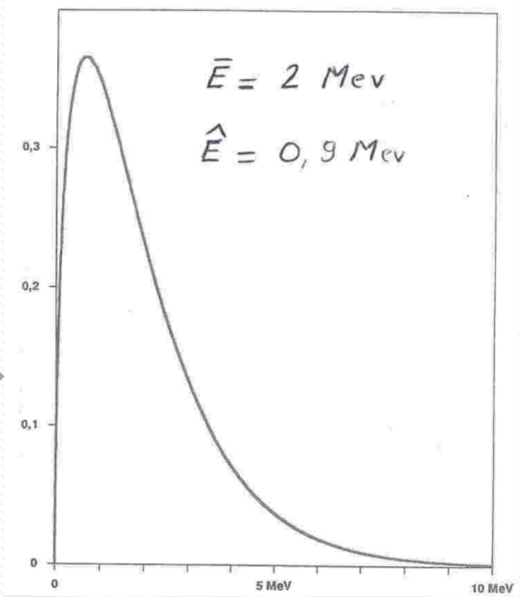
1. Number ν (U235)

ν	0	1	2	3	4	5
Probability to emit ν	2 %	17 %	36 %	31 %	12 %	3 %

$\overline{\nu}$ = 2,439

Note : the value of $\overline{\nu}$ for Pu239 is 2.862 (significantly higher than for U235) + it increases with the energy of the neutron inducing the fission of Pu239.
Ex. : = 3,0 at 1 Mev, = 4,24 at 10 Mev.

2. Energy spectrum

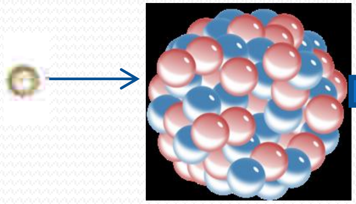


Note :
Average speed ≃ 20 000 km/s (2 Mev)
Maximum speed ≃ 45 000 km/s (10 Mev)

The "reproduction factor" η

The excess energy of the nucleus is released through gamma rays emissions (for U235 this leads to **the formation of U236**)

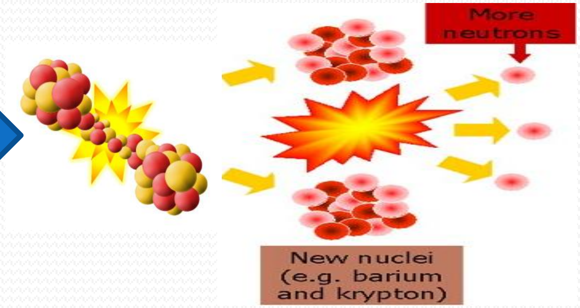
Absorption of a neutron by a fissile nucleus



14,5 % of the cases

The nucleus is an highly excited state

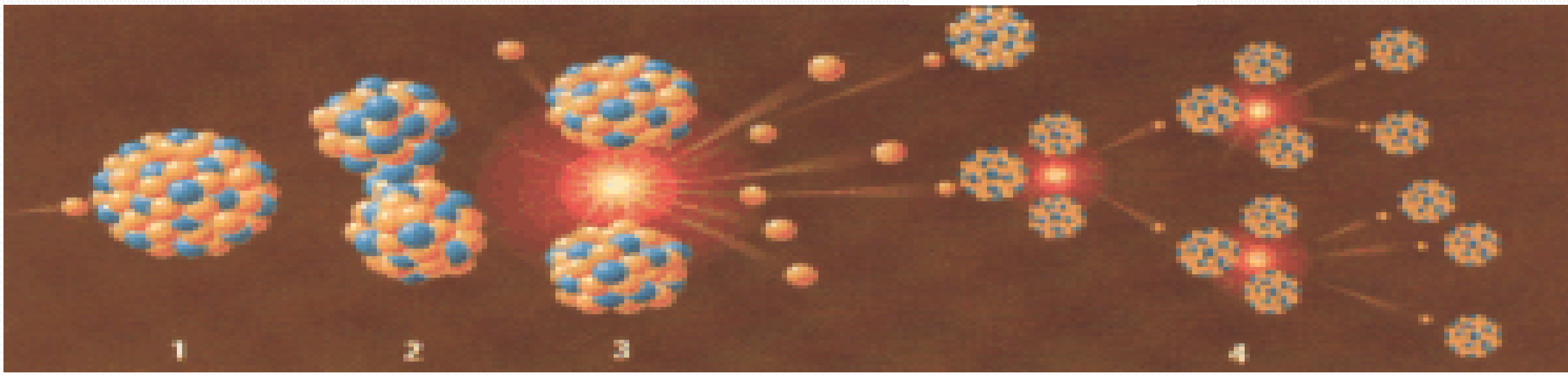
85,5 % of the cases



The excess energy of the nucleus makes the nucleus "broken" in 2 peaces (**fission)** and releases several neutrons (υ)

For **U235**, υ = 2,439 and thus the number of neutrons "recoverded" from ONE neutron absorbed the nuclmeus is **η = 2,439 * 0,855 = 2,085**

The FISSION process …



<u>The RESULT :</u>

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The Fission Products (FP) - 1/3

- **Noxious :**
  - Shielding is needed (water in pools, thick concrete walls of hot cells, …)
  - **Releases in accidents** (particularly volatile, **Iodine**, Cs, Rb, Te)
  - They constitute the bulk of « nuclear waste » (some of them with a very long life)

- **Neutron poisons**
  - Particularly Xenon and samarium (piloting the core is more difficult)
  - Fuel « wearing » (neutron capture + structural damages)

- **Residual power**
  - Reactors: **complex core cooling systems (safety) + pools of spent fuel**
  - Transport : complex casks to evacuate the heat
  - Cooling systems in some parts of « back-end » facilities (ex : liquid storage of FP)

And …..

The Fission Products (FP) - 2/3

- **Gaseous FP**
  - Internal pressure of fuel pins increases (➔ plenum)
  - Releases of reprocessing plants (Kr)

- **Damages to fuel matrix**
  - Swelling (bubble formation, …) and other modifications of thermal and mechanical properties of the fuel.

But … some of them keep few neutrons after the fission : the « delayed neutrons » which play a positive and fundamental role in reactor kinetic (make the reactor core controllable)

The Fission Products (FP) – 3/3

- More than 30 chemical elements from Z = 34 (selenium) to Z = 66 (Dysprosium)

- More than 500 isotopes (up to 20 isotopes or so per element)

- Fortunately, after few years, about 15 only remains radioactive (11 % in mass) and among them only : 7 FP are « Long Lived » FP, LLFP, (decay period 10^5 years)

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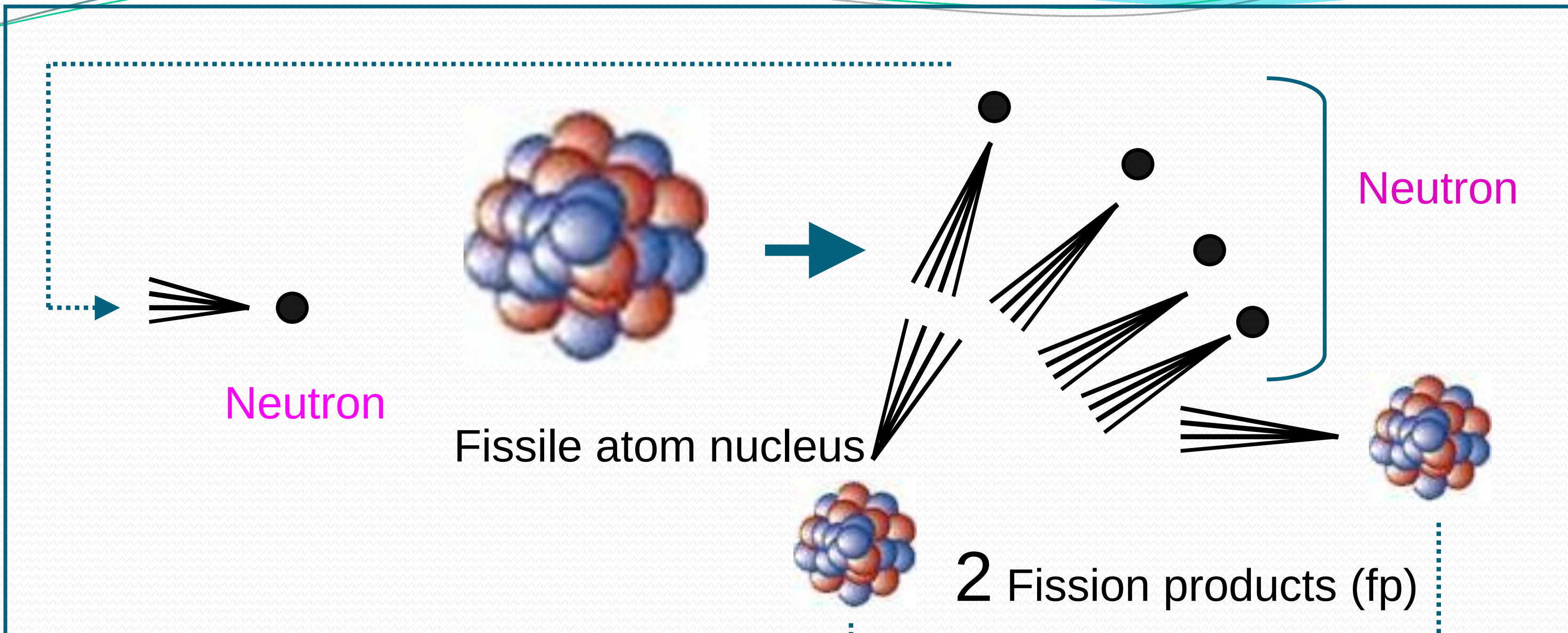
  - ***The b.a.-ba***
  - The "moderation" of neutrons
  - The multiplication factor and critical mass / Volume
  - The kinetic of the reaction chain
  - Temperature effects and void coefficient
  - Plutonium production and breeding
- Genesis of nuclear reactor technology

A nuclear reactor : how it works ?



Very high speed of the 2 fp
➔ Huge kinetic energy
(+ radiations)

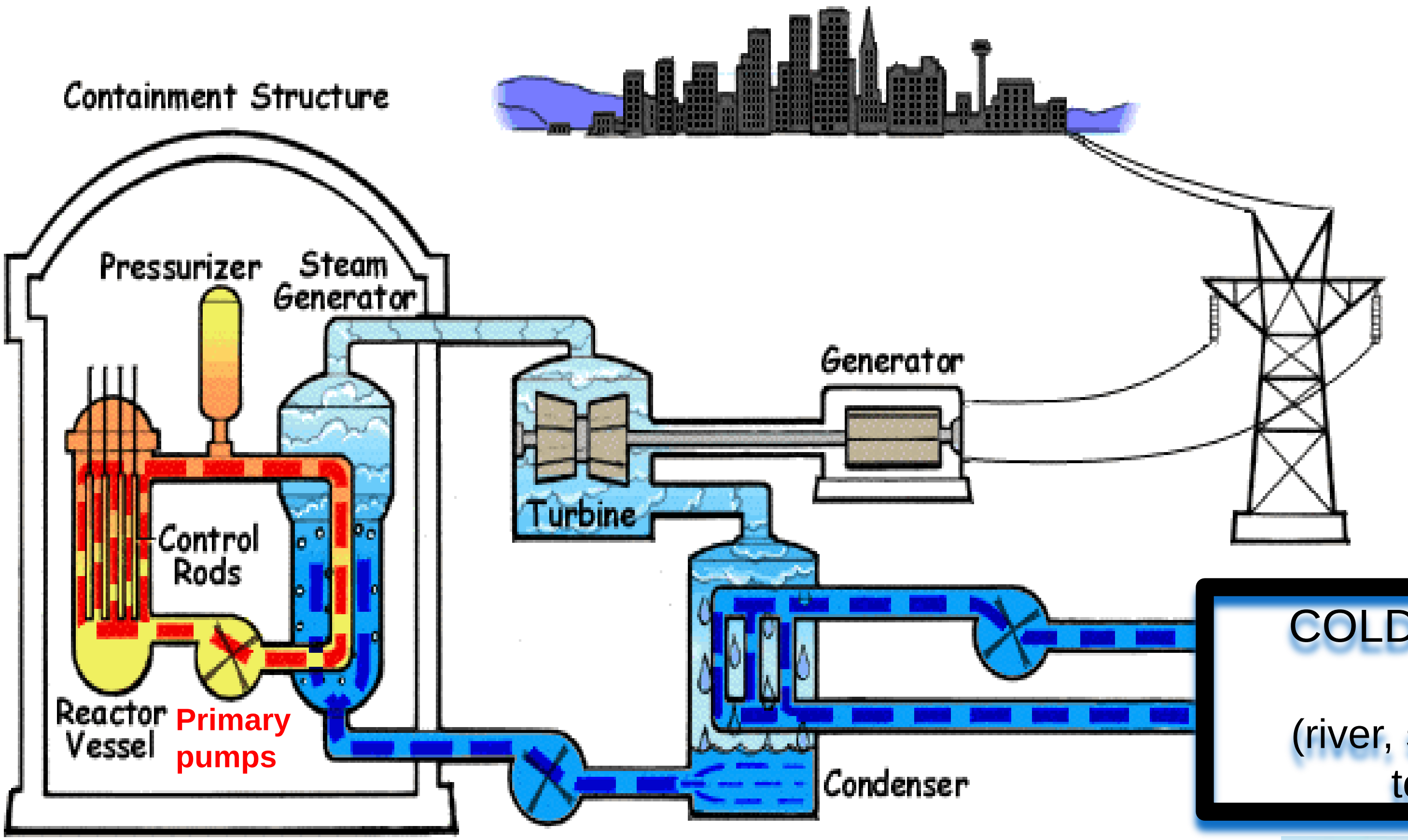
« breaking »in the matter
(until a complete stop)

HEAT RELEASE

Heat removal by a coolant
(a liquid or a gas)

Transformation into energy
(electrical or other, via vapor or other)

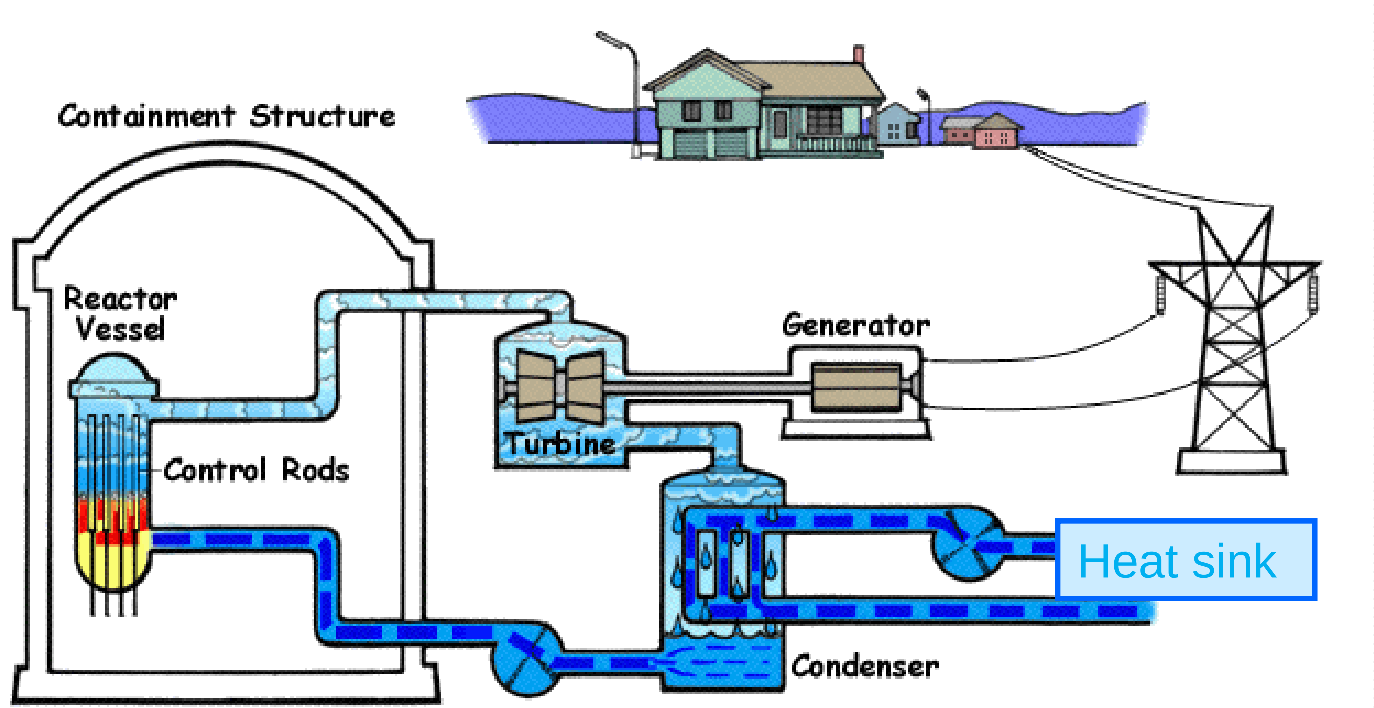
The basic operation principle of a PRESSURIZED water reactor (PWR)



COLD SOURCE

(river, sea, cooling towers)

BOILING water reactor (BWR)



- Only one circuit of water which is under a pressure corresponding to saturation
- Vapor is produced directly in the core and sent to the turbine (direct cycle)

Boiling Water Reactors (BWR) :a comparison with PWR

ADVANTAGES	DISADVANTAGES
The reactor vessel and associated components operate at a substantially lower pressure (155 b ➔ 75 b)	Lower power density (because of the two-phase coolant flow (the "void fraction") in the top part of the core➔ effect on overall cost
Pressure vessel is subject to significantly less irradiation compared to a PWR (➔ less embrittlement)	Much larger pressure vessel than for a PWR of similar power, with correspondingly higher cost (reasons are steam separators and dryer plates above the core , low power density,…).
Operates at a lower nuclear fuel temperature (320 ➔ 285 °c)	Contamination of the turbine by radioactive activation products (➔ shielding + access control around the steam turbine are required during normal operations)
NO steam generator (a source of troubles in PWRs) and NO pressurizer	More complicate core arrangement and fuel management : Complex calculations + more instrumentation in the reactor core
Fewer pipes, fewer large diameter pipes, fewer welds	Control rods are inserted from below, which do not allow their gravity drop (need of highly reliable and redundant rod insertion systems)
Can operate at lower core power density levels using natural circulation without forced flow.	More complex management of transients and adaptation of the power level to the electrical network requirements
BWRs do not use boric acid to control , leading to less possibility of corrosion within the reactor vessel and piping	Mitigation of core melt accidents seems more difficult (core volume, smaller containment ➔ hydrogen issue, …)

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The slowing down of neutrons: why ?

In nuclear reactors, fissions yield fast neutrons **BUT**

➔ the probability[(1)] for a fast neutron to cause a U235 nucleus to fission is small (compared to the probability of being captured or scattered)

and

➔ the natural proportion of U235 is small (7 U235 nuclei out of 1000)

Consequence: ***a self sustained chain reaction is not possible with fast neutrons and natural uranium***

(1) Related to the **cross section (CS)** of U235 : equivalent to an “attractive zone” surrounding the nucleus (the unit of CS is the one of a surface : “barns” = 10^{-24} cm^2)

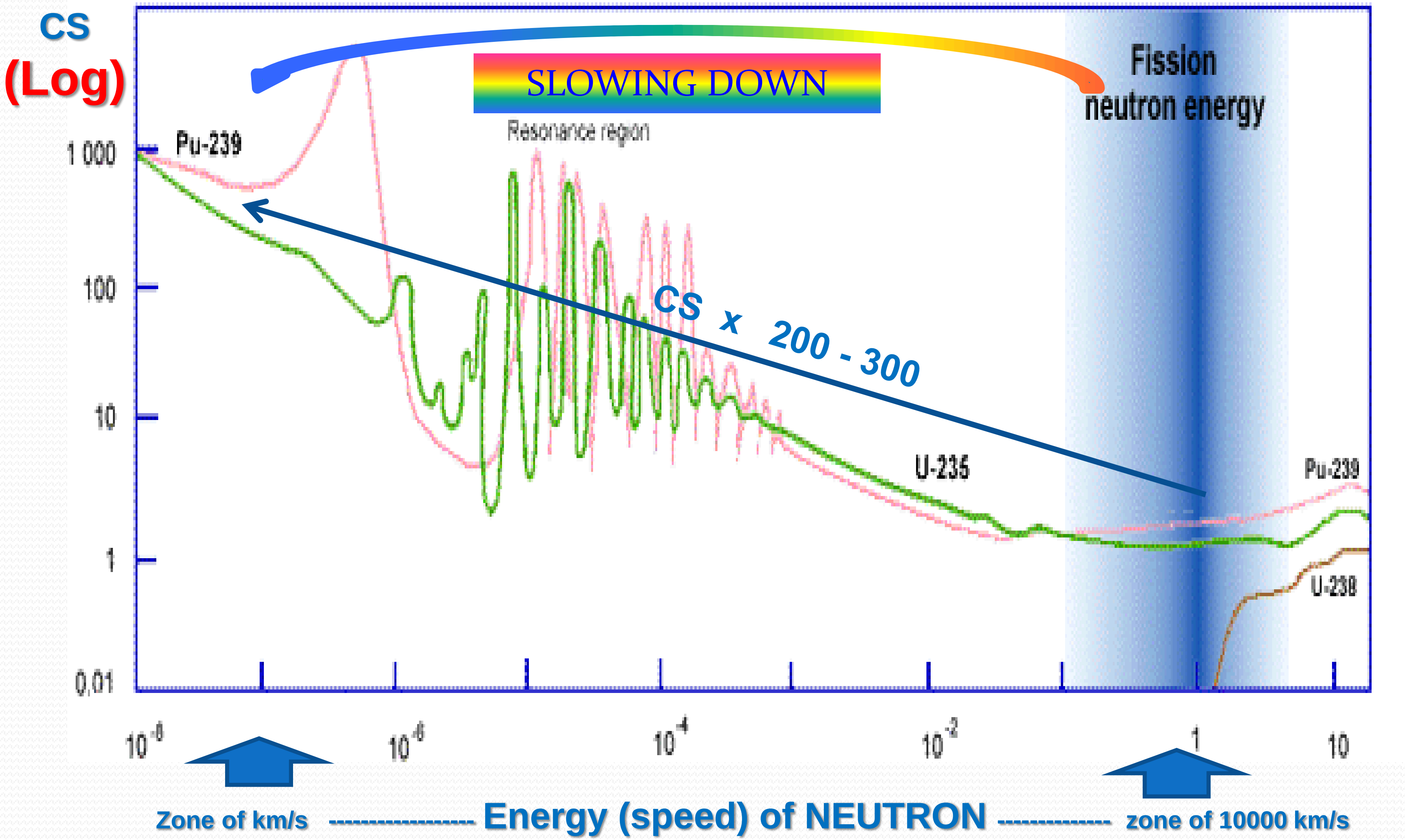
The two main types of reactors

Two solutions

Slow the neutrons down	Enrich uranium in U235 isotope
because	thus
the probability for slow [(1)] neutrons to cause a fissile nucleus to fission is much bigger (fission cross-section of U235 is 200 times bigger with slow versus fast neutrons)	**increasing the number of fissile targets** **U235 assay > 20 %** (or, better, use plutonium > 15 %)
« thermal » reactors	**Fast neutron reactors**

(1) few km/s

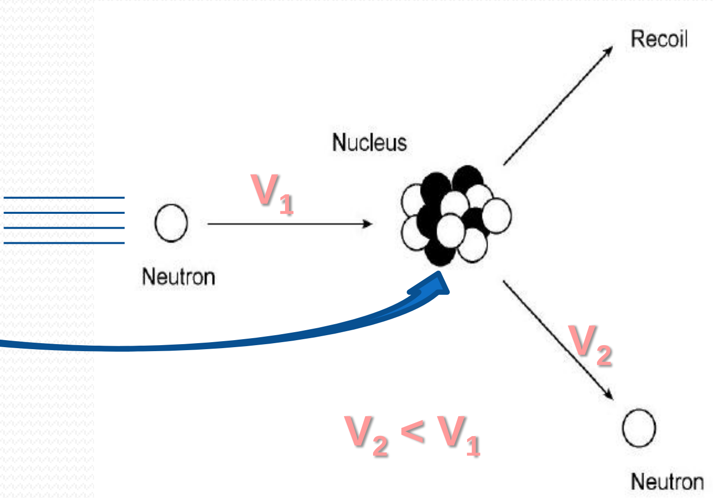
U235 (and Pu239) fission cross sections (CS) as function of energy (speed) of neutrons



How to slow down neutrons ?

Only ONE MEAN : To make them hit light nucleus on which they can rebound (like billiards balls) and thus loose part of their speed (elastic or inelastic scattering). We can use the image of neutrons which « race down a staircase ». Such light nucleus are called

MODERATORS



The 2 main qualities of a moderator are

➔ Be **as LIGHT as possible** : a moderator efficiency is **characterized by a « slowing down parameter »** □ , which ranges from 1 for the best moderator (hydrogen) to a value tending towards 0 for the less efficients (heavy nucleus) (□ is a decreasing function of the atomic mass of the nucleus)

➔ Be **as less "capturing" as possible** (□$_c$ as low as possible)

The choice of a moderator

The first light elements of the periodic table of natural elements												
Element		**Hydrogen (H)**		**Helium (H_e)**		**Lithium (Li)**		**Beryllium (B_e)**	**Boron (B)**		**Carbon (C)**	
Number of protons		1		2		3		4	5		6	
Number of neutrons		0	1	1	2	3	4	4	5	6	6	7
Number of nucleons A =		**1**	**2**	**3**	**4**	**6**	**7**	**8**	**10**	**11**	**12**	**13**
Natural abundance (%)		99,9885	0,0115	10^{-4}	> 99,99	7,6	92,4	100	20	80	99	1

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Number of protons	⊕	1		2		3		4	5		6	
Number of neutrons	●	0	1	1	2	3	4	4	5	6	6	7
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Natural abundance (%)		99,9885	0,0115	10^{-4}	> 99,99	7,6	92,4	100	20	80	99	1

GAS

… to eliminate (too low density)

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Number of neutrons		0	1	1	2	3	4	4	5	6	6	7
Number of nucleons A =		**1**	**2**	**3**	**4**	**6**	**7**	**8**	**10**	**11**	**12**	**13**
Natural abundance (%)		99,9885	0,0115	10^{-4}	> 99,99	7,6	92,4	100	20	80	99	1
Main natural form (on the earth)		light water (H_2O)	Heavy water (D_2O)	GAS		SOLID		SOLID	SOLID		SOLID	
Capture CS (Barns)		**0,644**	**0,0013**			70,56		**0,0076**	764,9		**0,00337**	

Helium: … to eliminate (too low density)

Lithium: … to eliminate (too high capture CS)

Boron: … to eliminate (too high capture CS)

The choice of a moderator

The first light elements of the periodic table of natural elements											
Element	**Hydrogen (H)**		**Helium (H_e)**		**Lithium (Li)**		**Beryllium (B_e)**	**Boron (B)**		**Carbon (C)**	
Number of protons	1		2		3		4	5		6	
Number of neutrons	0	1	1	2	3	4	4	5	6	6	7
Number of nucleons A =	**1**	**2**	**3**	**4**	**6**	**7**	**8**	**10**	**11**	**12**	**13**
Natural abundance (%)	99,9885	0,0115	10^{-4}	> 99,99	7,6	92,4	100	20	80	99	1
Main natural form (on the earth)	light water (H_2O)	Heavy water (D_2O)	GAS		SOLID		SOLID	SOLID		SOLID	
Capture CS (Barns)	**0,644**	**0,0013**			70,56		**0,0076**	764,9		**0,00337**	
	Can be used as a moderator		... to eliminate (too low density)		... to eliminate (too high capture CS)		**Can be used as a moderator** (but toxicity is an issue)	... to eliminate (too high capture CS)		**Can be used as a moderator**	

The choice of a moderator

The first light elements of the periodic table of natural elements											
Element	Hydrogen (H)		Helium (H_e)		Lithium (Li)		Beryllium (B_e)	Boron (B)		Carbon (C)	
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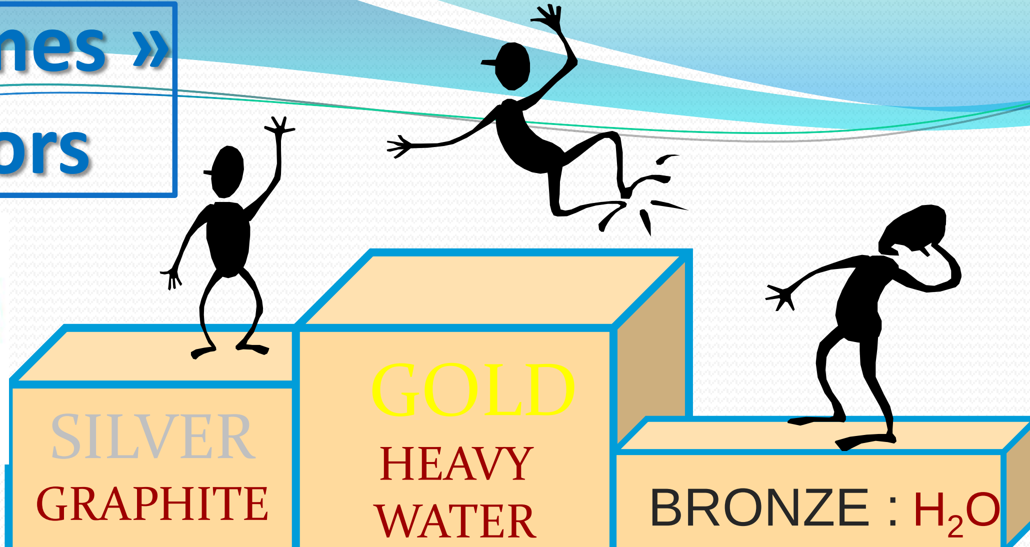
	Can be used as a moderator		... to eliminate (too low density)		... to eliminate (too high capture CS)		Can be used as a moderator (but toxicity is an issue)	... to eliminate (too high capture CS)		Can be used as a moderator	

« Olympic games » of moderators



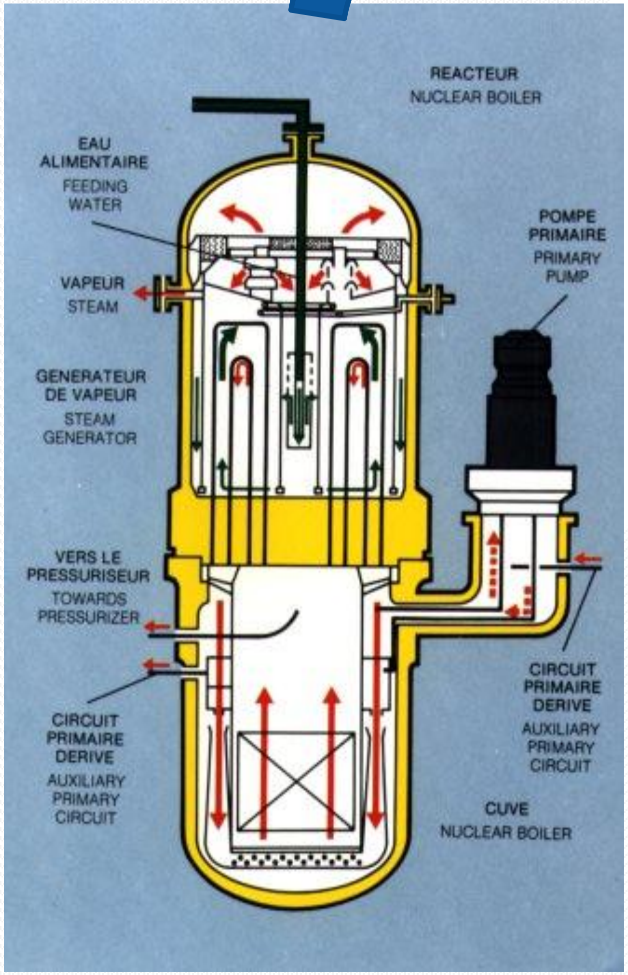
	SILVER GRAPHITE	GOLD HEAVY WATER	BRONZE : H_2O
Slowing down parameter □ 1 down to 0)	0,158	0,509 (D_2 : 0,7261)	0,926 (H : 1,000)
Average and minimum of chocks (*)	124 and 59	27 and 9	19 and 1
Capture CS ("macroscopic") $□_c$ ($10^{-4}cm^{-1}$)	2,73	0,44	215
Quality Index □ □s /□c (x 100)	223	4080	64
Optimum of the moderation ratio	50	30	4

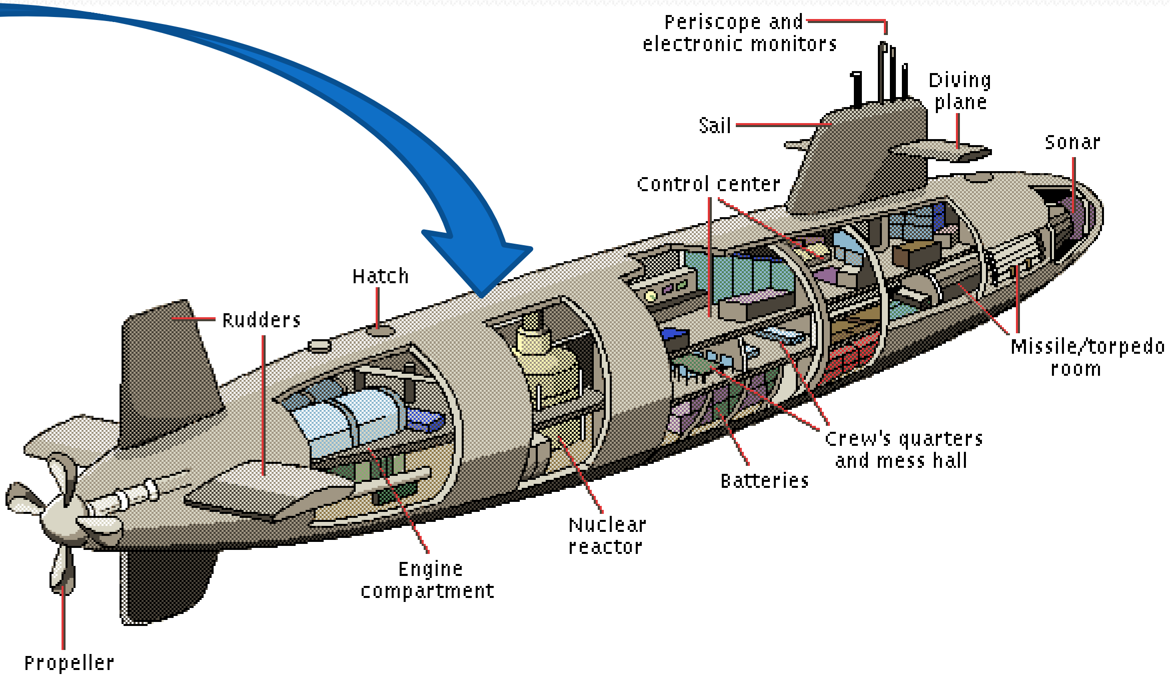
Enrichment needed

SMALL CORES (submarines)

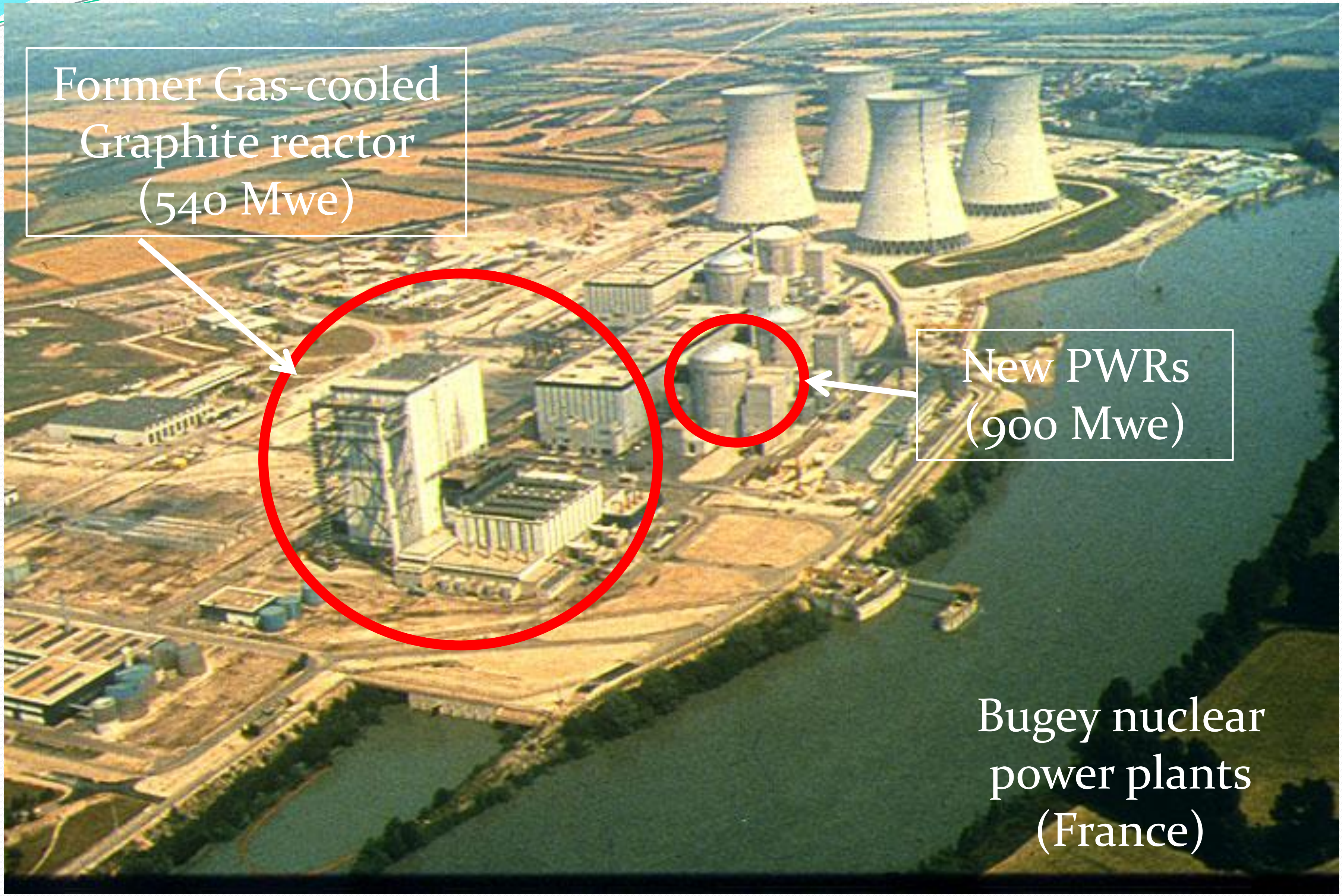
(*) : This the average number of collisions that a fast neutron (20000 km/s) needs to have with a nucleus of moderator to achieve a "thermal" speed (about 1 km/s). The other number is the MINIMUM number of collision (maximum loss of speed)

Water moderated reactors are SMALL …

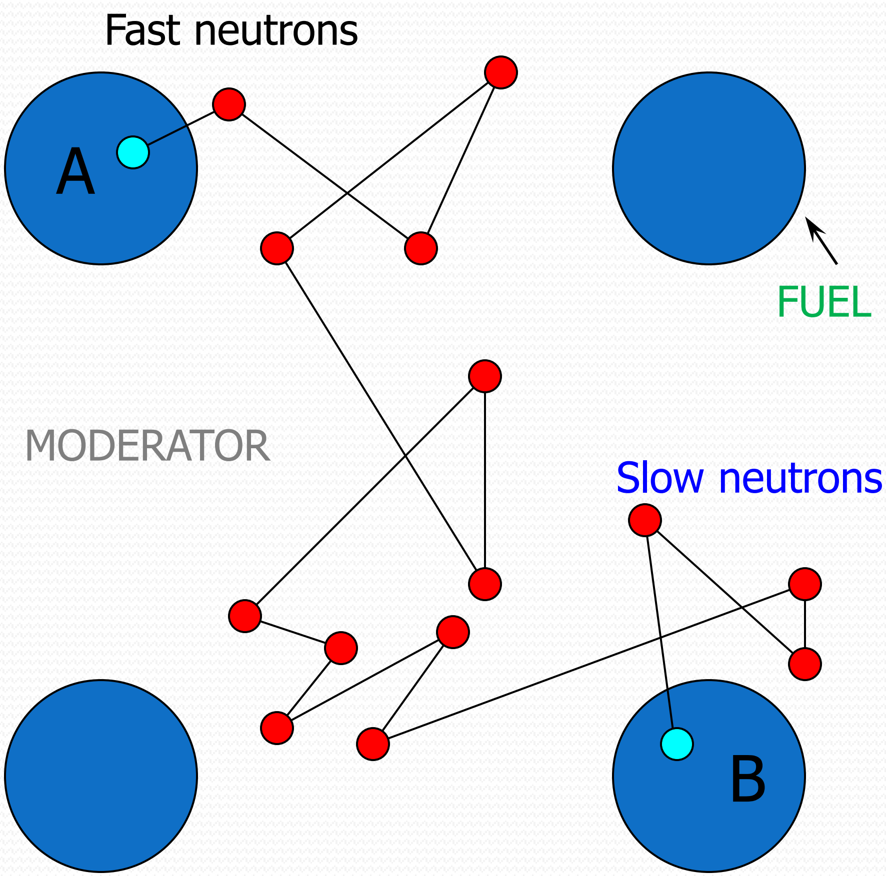




Graphite moderated reactors are BIG !



Neutron are slowed down in the moderator region to escape their capture by the « resonances » of heavy nucleus in the fuel



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Multiplication coefficient of neutrons K

$$K = \frac{\text{Neutrons born}}{\text{Neutrons disappeared}}$$

At a given time in a given volume

- IF :
  - K > 1,00000… : divergence (rapid growth of the neutrons « population »)
  - K = 1,00000… : Maintain a reaction chain (all reactors in normal operation)
  - K < 1,00000… : shutdown of the reaction chain (the reactor stops)

- Reactivity : $\rho = (K - 1) / K$ The unit is the « pcm »[(1)] (or dollar)

- Critical Mass : minimal mass needed to maintain a reaction chain (K = 1), taking into account neutron leakages ouside the volume containing this mass (which can be reduced by adding a neutron reflector surrounding this mass)

(1) : 1 pcm = 10^{-5} = 0.00001 = 0.001 % - 1 "dollar" = 650 pcm (in uranium fuels)

Criticality

$= k_{inf} > 1$ M U S T be greater than 1

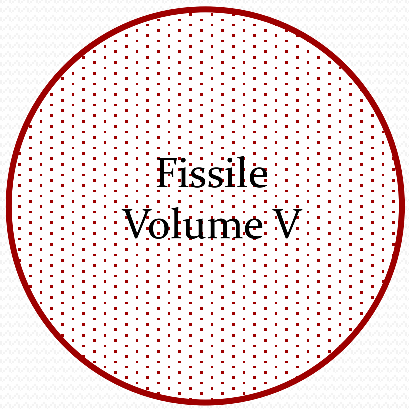
Uranium enrichment	0.71 %	3 %	8 %	100 %
For **FAST** neutrons	0,456	0,677	1,0	1,882
For **SLOW** neutrons (speed = 2 200 m/s)	1,364	1,879	2,027	2,12

Multiplication factor in an infinite media

$$K_{eff} = \frac{k_{inf}}{1 + F / A}$$

Multiplication coefficient in a limited volume V (surrounded by a surface S)

Surface S



Sphere radius R

F = leakages: increases with S, that is R^2

A = Total absorptions in the volume : increases with V (and density), that is with R^3

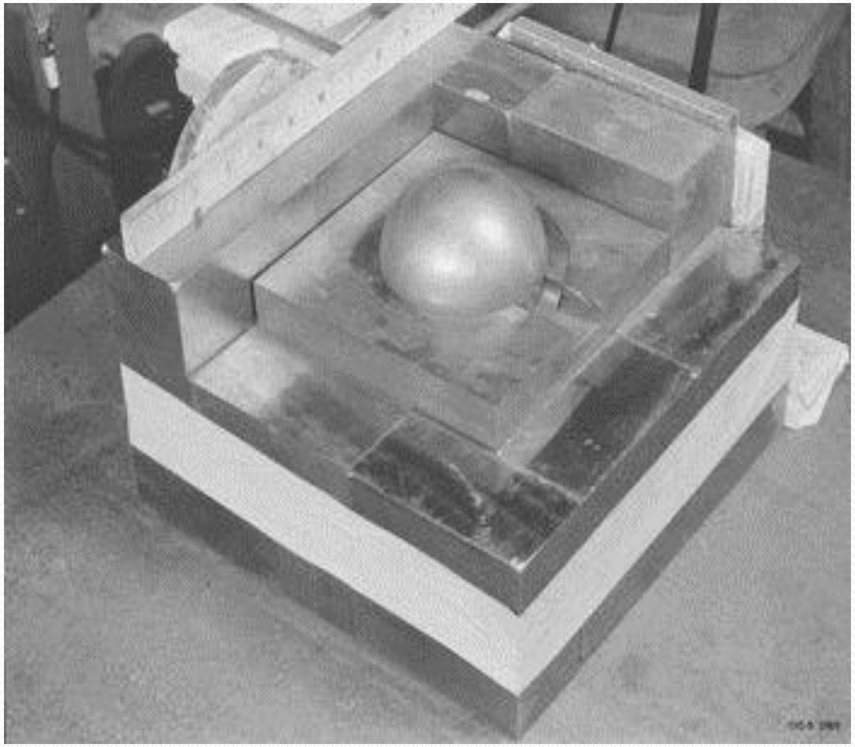
One can show that if :

- R increases (with the mass), F/A decreases, and thus there is a "critical" value of R **ABOVE** which k_{eff} become > 1
- R decreases (the density increases), there is also a critical value of R **BELOW** which keff become > 1 (atomic weapons)

For a nuclear reactors, and for a given fissionable material (with K_{inf} >1), there a minimum volume (thus a minimum mass) to reach a sustained reaction chain (k > 1). This is called :

CRITICAL SIZE or CRITICAL MASS

Critical mass of fissionable nucleus



Critical experiment (LANL, 1945): sphere of Plutonium surrounded by a “tamper”

It depends on :

➔The identity of the nucleus
➔Its physic-chemical form (density, phase, purity, …)
➔Its geometry (shape)
➔The presence or not of a REFLECTOR surrounding the mass
➔The presence or not of a MODERATOR

Example (pure “bare” sphere)

Pu239 : 11 kg (phase alpha)
U235 : 48 Kg
U233 : 16 Kg

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Neutron lifetime in a reactor (LWR)

- **Neutron lifetime in a reactor** (in a light water moderated reactor)

  - Duration of the slowing down : ≅ between 10^{-6} et 10^{-5} sec.
    - Number of collisions (H_2O): few tens
    - Average distance between 2 collisions: few centimeters
    - Speed of neutrons: from few 10^4 to 0,01 km/sec

  - Once they are slowed down, they scatter (mainly on the moderator nucleus) until they are absorbed in a fissile nucleus (for most of them). The duration of this part of their journey is ≅ between 10^{-5} and 10^{-4} sec.

In the overall

From its "birth" (from fission) and its "death" (by absorption in a fissile nucleus), a neutron the total lifetime of neutrons in a reactor is

$$\ell_o = 2,5\ 10^{-5}$$

Neutron multiplication speed

- **Neutrons multiplication :**

If we note **N(t)** the neutron density, and **k** the multiplication factor of the neutrons, we have :

t =	0	ℓ_o	$2\,\ell_o$	$3\,\ell_o$	$4\,\ell_o$
N(t) =	N0	k N0	k (k N0) = k^2 N0	k^3 N0	k^4 N0

We get immediately the **exponential law** :

$$N(t) = No \ \exp. \frac{(k-1)}{\ell_o} t$$

With k = 1,0001, N (t) would be ………

multiplied by 55 in one second !

UNCONTROLABLE SO .....

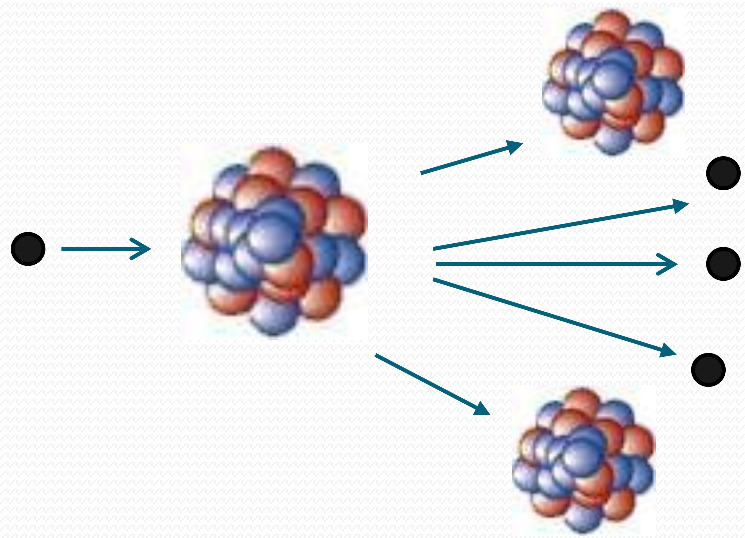
The delayed neutrons (1/3)

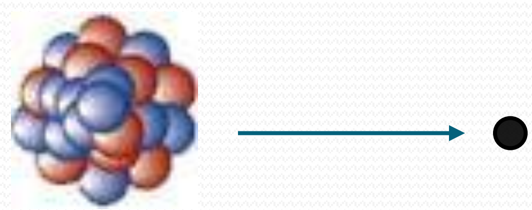
- Fission : more than 99% of all neutrons appear at the time of the fission. They are called « prompts neutrons»

(average number 2,477 pour U235 on the total of 2.493 neutrons)

- The remainder , called « delayed neutrons » are a very few but they are very significant contributor to the time dependence behavior on the neutron population. They are emitted by some fission products called « precursors » (after a beta radioactive decay ejecting a neutron kept « in jail »)

Ex : Br^{87} β- (55 sec.) → Kr^{87} → 1n ; → Kr^{86}





There are about one hundred « precursors » which decay period ranges from few fractions of seconds to several minutes
(about 20 have been explicitly identified)

The delayed neutrons (2/3)

- The average time life ℓ_d of this delayed source is τ = 13 sec.
- Noting β the total proportion of these « delayed neutrons », the overall average lifetime of ALL neutrons from fissions is NO MORE ℓ_o but $\boldsymbol{\ell = \ell_o(1 - \beta) + \tau.\beta}$ which is a far more longer average lifetime.
- In effect, for U235, β ***= 0.0065*** so that the prompt neutron lifetime which was 0,000025 becomes in reality 0.000025 + 0,085 $\cong$ 0.085 ($\cong \tau.\beta$)
- This COMPLETLY change the kinetic behavior of the reaction chain : in the previous example (k = 1.0001), after one second, N(t) is multiplied only by a factor 2 instead a factor 55 !

The delayed neutrons (3/3)

- A more detailed analysis (study of “kinetic equations”), shows however that there is a LIMIT of reactivity excess ρ that can be introduced in the reactor, in order to let the delayed neutrons contribute to the time dependence of the growth of the neutron population (and thus to have enough time to master it

- This limit is :

$$k < 1 + \beta = 1.0065 \quad (\text{ or reactivity } \rho < \beta)$$

BEYOND this limit, the reaction chain becomes practically UNCONTROLABLE
(the reactor becomes “prompt critical” : this happened at Tchernobyl !)

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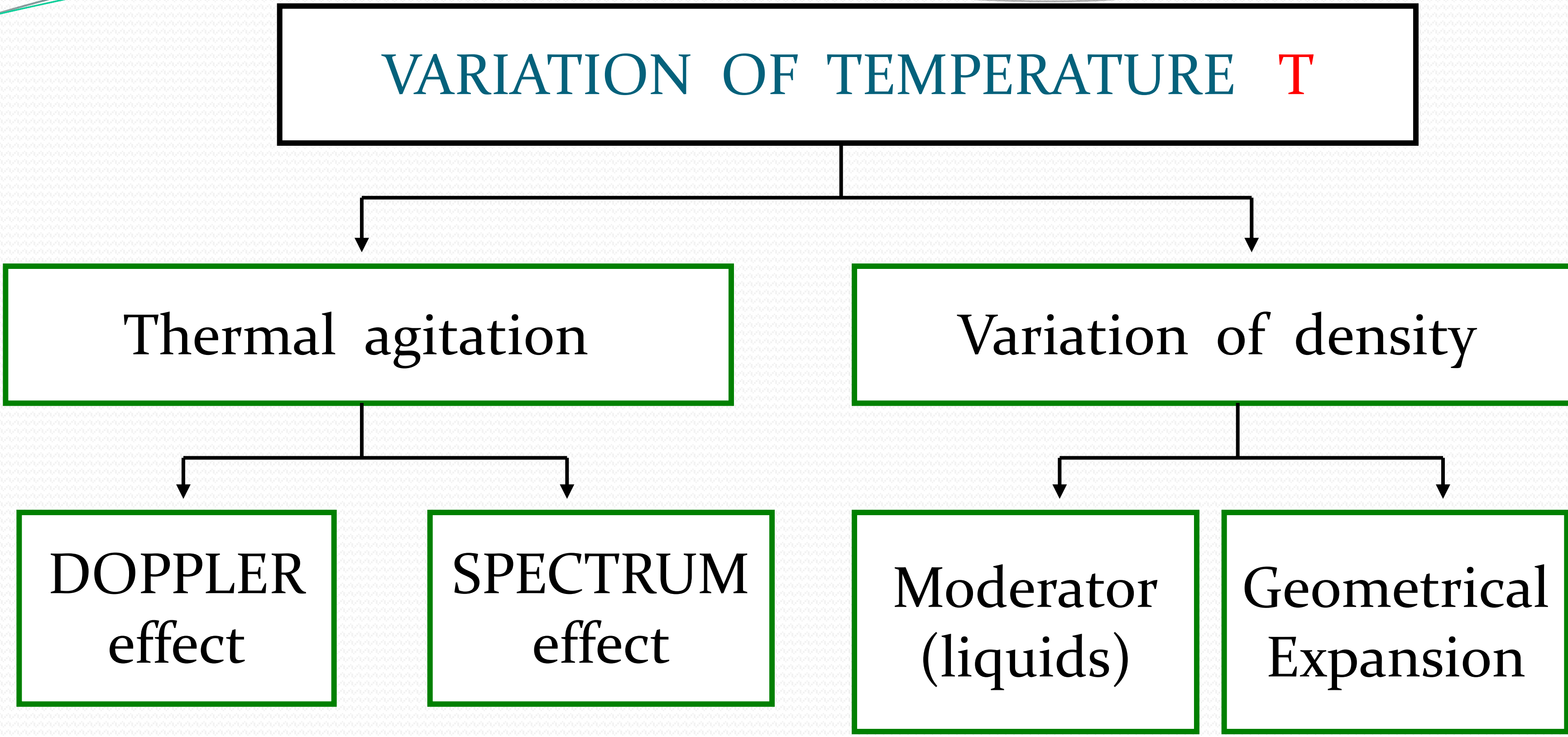
Temperature effects



Température coefficient :

θ = variation of k (ou ρ) / variation of T (pcm/°c)

Having θ < O in all situations is CAPITAL for the SAFETY

Void effect (for water reactors)

Some severe accidental situation can lead to a significant loss of water in the reactor…

➔…this leads to a strong "**hardening"** of the neutron spectrum which can go up a "fast" neutron spectrum (in the case of a total loss of water, which means a total loss of moderation of neutrons).

- For uranium fuels, the analysis shows that the overall reactivity of the reactor core decreases when there is less and less water : the void effect is thus **NEGATIVE** (this is OK !)

- For fuels containing a **significant amount** of plutonium (MOX fuels) the reactivity decreases also INITIALLY but from a certain void fraction , the reactivity increases and therefore the void coefficient **may becomes positive**.

  This phenomena starts when plutonium concentration is greater than 12 - 12,5 % (whatever the isotopic vector is): this is a limit of concentration of plutonium for MOX fuels

Fast neutron reactors (FNRs) : the coolant density effect (or "void coefficient") for sodium cooled reactors

This effect is the result of 3 phenomena

- **Spectral effect**
  - – Reduced moderation as sodium density decreases ➔ "harder" neuron spectrum ➔increase of "reproduction factor" (η) of Pu239 = number of neutrons emitted for one neutron absorbed by Pu239
  - – In fast regime, this is a positive reactivity effect

  Leakage effect
  - – Sodium density decrease allows more neutron leakage
  - – This is a negative reactivity effect in the peripheral regions
- **Capture effect**
  - – Sodium density decrease results in less sodium capture
  - – This is a relatively positive reactivity effect (but a minor one)

Void coefficient and overall temperature effect for FNRs (sodium cooled)

- Typical void coefficients (in dollars[(1)])

	Capture	Spectral	leakage	TOTAL
Large cores (1000 Mwe reactors)	0.5	9.1	-5.2	4.4
Small cores (250 Mwe)	0.4	6.4	-5.8	1.0

- Overall temperature coefficient
  - Depends on Doppler effects + Na-density effect + expansions coefficients (axial, radial, control rods drive lines) : it is always **NEGATIVE**

(1) : it is a unit of "reactivity", equal to the delayed neutron fraction, which in the range of 0.3 – 0.4 % (300 – 400 10^{-5} Δk)

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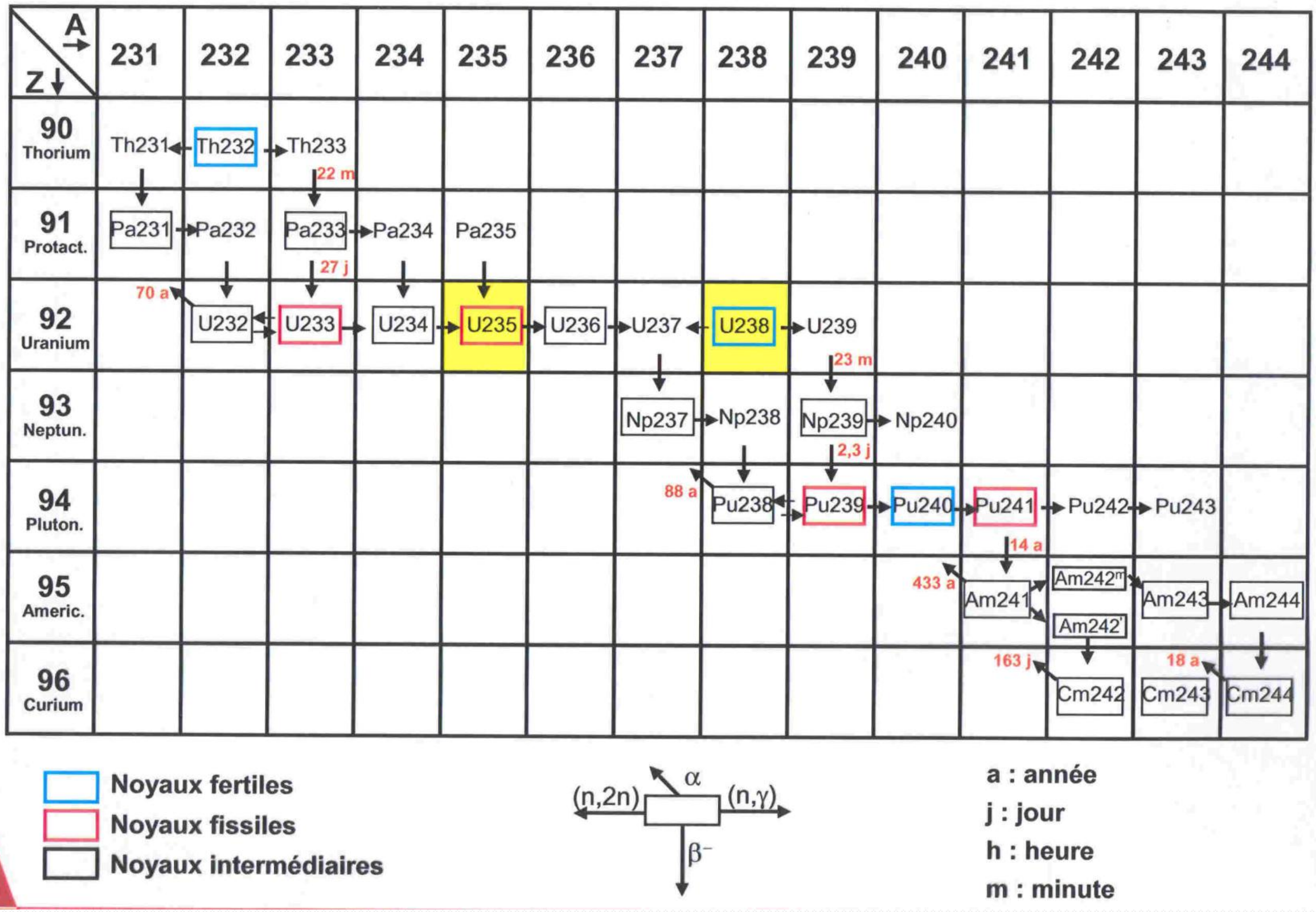
Fuel depletion



A fundamental phenomena :
the conversion of fertile nucleus into fissile nucleus

For one neutron absorbed in a fissile nucleus, **η neutrons** are emitted

1 Neutron

ONE must be devoted to the next absorption in the fissile nucleus (to sustain the chain reaction)

It remains **η - 1** neutrons

A fraction of them, **L** , are « lost » because of sterile captures and leakages

The other fraction , F , are captured in the **"fertile"** nucleus (U238) and thus **"fabricate"** a new **fissile** nucleus (Pu239)

Values of η-1	U235	Pu239
Neutrons "thermal"	**1,085**	**1,11**
Neutrons « fast» FNR	**0,88**	**1.33**

F (η-1) is the **CONVERSION RATIO**

If **L** is sufficiently low (case of Fast Neutrons Reactors) and **η** sufficiently high (case of Pu239), then **F (η-1)** can be **superior to ONE** : this the **BREEDING** process

The conversion ratio (CR)

CR : $\dfrac{\text{Number of fissionable nucleus created}}{\text{Number of fissionable nucleus destroyed}}$

(per unit of time or along a given period of time which can be the total irradiation time of the fuel)

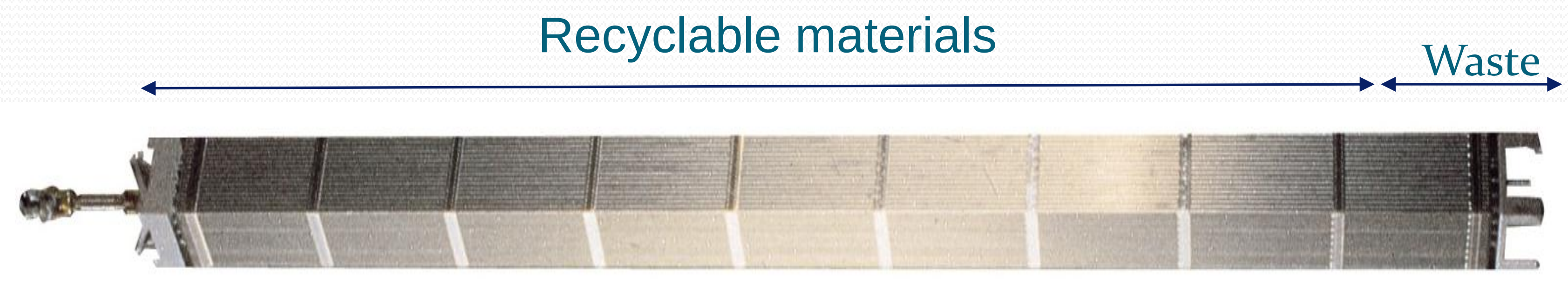
Typical value are :

- Heavy water reactors : 0, 8
- Light water reactors : 0,65
- High temperature reactors : 0,6 – 0,9 (depending on the type of fuel)
- FAST NEUTRON REACTORS : ≥ 1

In a water reactor, for 3 nucleus fissioned, 2 new nucleus of plutonium are created, of which about half is fissioned IN THE REACTOR during fuel irradiation (1 nucleus) : globally, 40 % of the nuclear energy produced in the reactor comes from the fissions of the plutonium created in the reactor ! (and then the plutonium recycling increases this amount by 12 % points)

Composition of a PWR spent fuel assembly

Note: BEFORE irradiation in the reactor, a new PWR fuel assembly is made of about 500 Kg of UO_2 (that is about 440 Kg of 4 – 5 % enriched uranium)



U 475 to 480 kg
(94 to 96 %)

Can be RECYCLED

Pu 5 kg
(1 %)

Can be RECYCLED

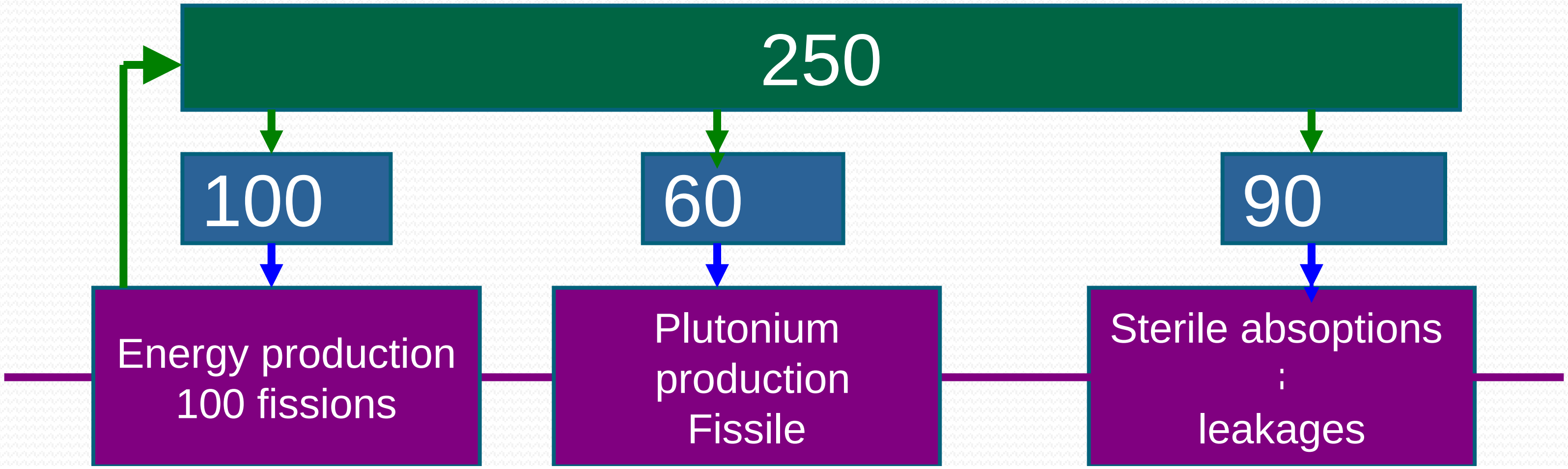
FP 15 to 20 kg
(3 to 5 %)

FINAL RESIDUES

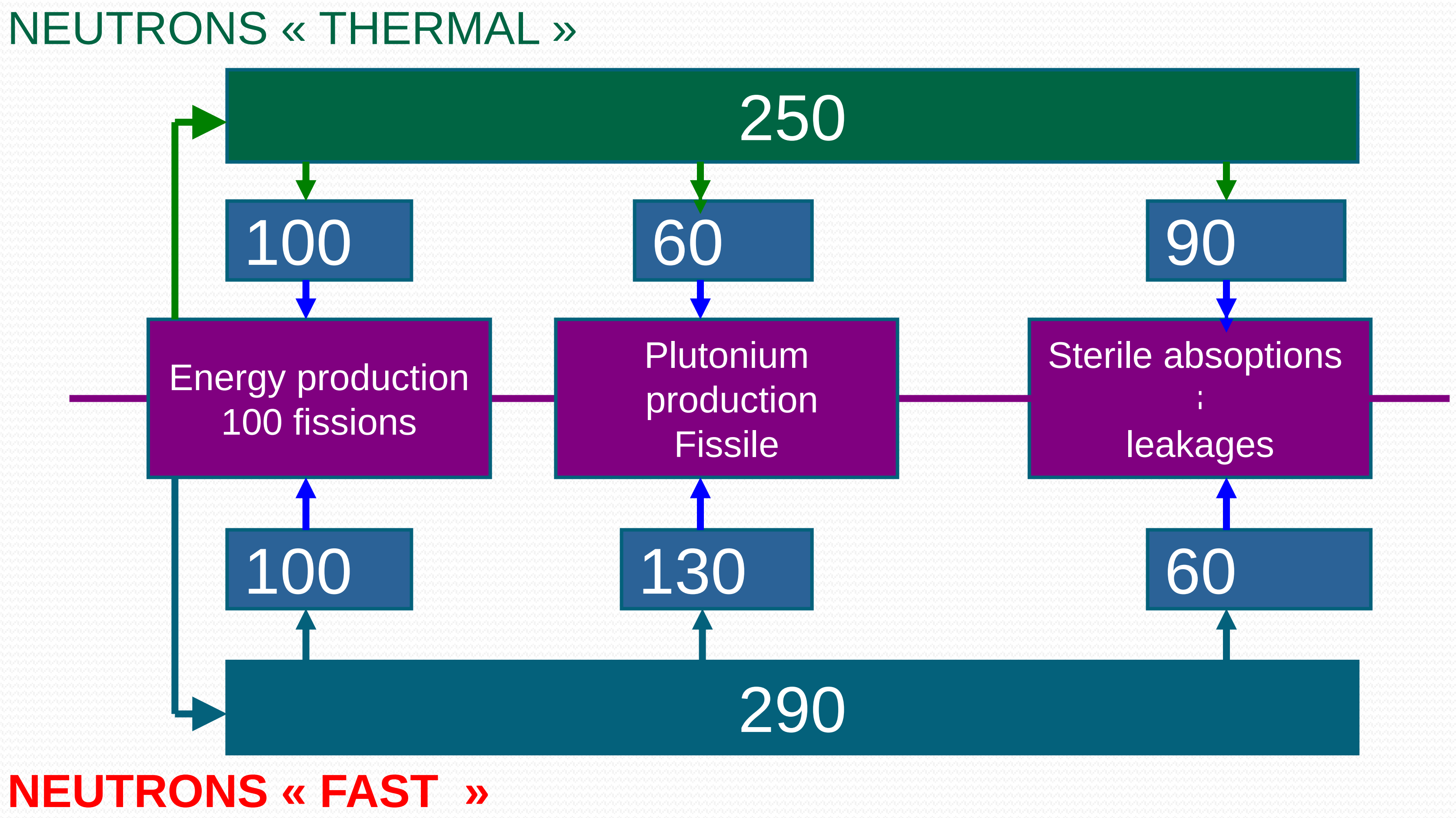
NOTE : **percentages can vary slightly with burnup**

An illustration of the breeding capabilities of fast neutron reactors

NEUTRONS « THERMAL »



An illustration of the breeding capabilities of fast neutron reactors



- Multiplication factor for neutrons is much better for plutonium than for uranium 235 for fast neutrons : + 30 % to + 50 %
- Almost all heavy nucleus are fissile for fast neutrons (including U238)
- Sterile captures of neutrons are much lower for fast neutrons than for slow neutrons (capture CS are much lower for almost all nucleus)

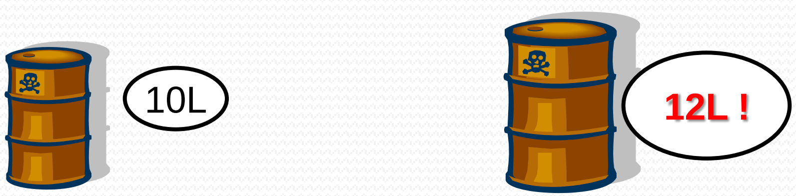
THUS ……

A fast breeder reactor can fabricate more fuel than it consumes to make electricity !

The comparison with a "breeding" car consuming 10 liters / 100 km

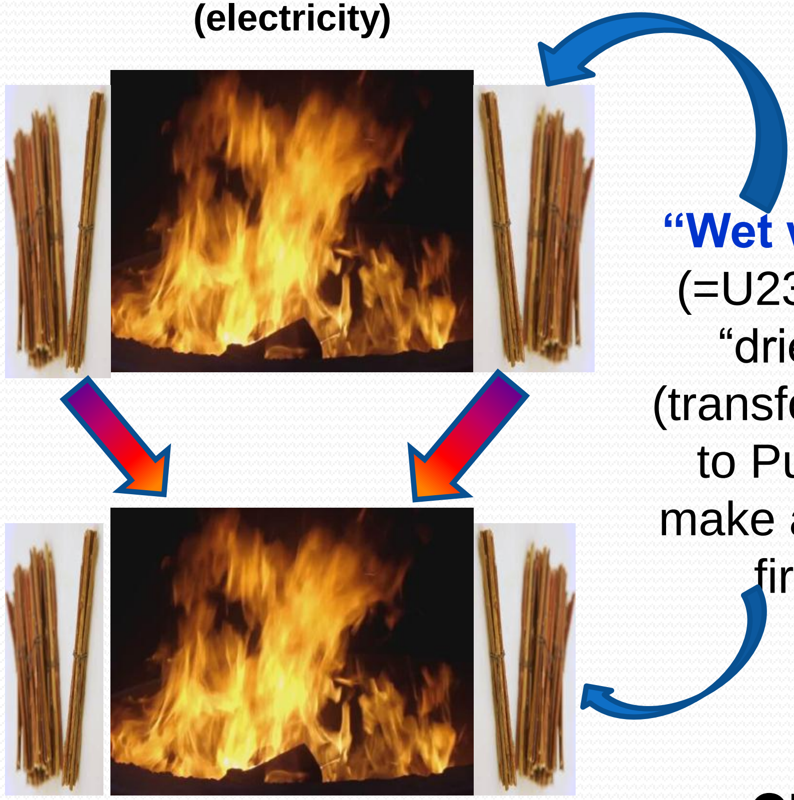
At the start … At the arrival

…100 km…



The image of dry and wet wood

"**Dry wood**" **= U235 or Pu to make fire (electricity)**



"**Wet wood** (=U238) is "dried" (transformed to Pu) to make a new fire

…etc

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A huge amount of combinations to make a nuclear reactor

Fissile element	Fertile element	Neutron energy	Fuel mix	Coolant	Moderator	Fuel form	Barriers
U-235	U-238	Thermal	U natural	H_2O pressurized or boiling	H_2O	Pellets in rods	Fuel in pebble/matrix
U-233	Th-232	Fast	3% U-235	D_2O	D_2O	Pellets in plates	Fuel element + cladding
Pu-239		+ Spallation	U + Pu MOX	CO_2 gas	Graphite	Pebbles in beds	F+C+ pressure vessel/tube
				He gas	none	Spheres in matrix	F+C+PV + concrete shell
				Na liquid metal			F+C+PV+CS + steel liner
				Pb or Pb/Bi liquid metal			F+C+PV+CS+SL + core catcher
				Molten salt	Molten salt	Molten salt	

3 x 2 x 3 x 3 x 7 x 5 x 4 x 6

= 45360 !

One tried every things ….

….not to forget one thing…

According to Claude Bienvenu (« l'aventure nucléaire » Explora, 1995 (page 61)

- **200 000** : number of all possible combinations of fuels, moderators and coolants with different forms
- **1000** : combinations on which studies have been carried out
- **100** : designs more or less completed among all these combinations
- **30** : projects which have been at least partially tested in laboratories or for which prototype facilities have been built
- **17** : of these systems have been carried out up to the construction and then operation of nuclear power plants (producing energy)

… for a great number of applications

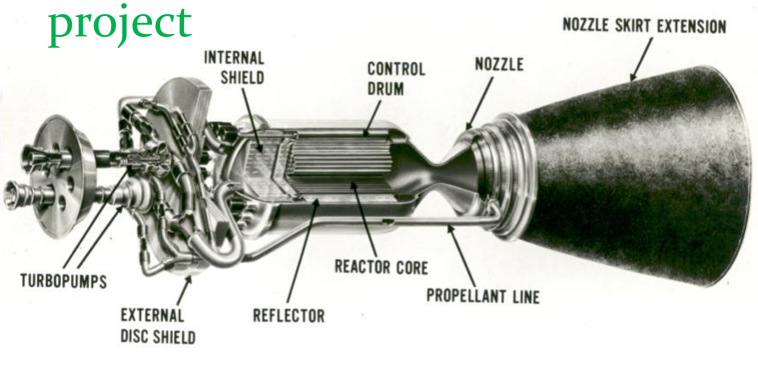
- Large reactors for electricity production ("Nuclear Power Plants")

- Smaller (or even zero) power reactors for:
  - Space applications :
    - Rockets : heating of liquid hydrogen with coated particle fuels in graphite matrix (US programs like NERVA and ROVER)
    - Space vehicle: many sorts of energy transfer systems (thermoelectric or thermionic conversion, heat pipes, even turbines with vapor of mercury !
  - Naval propulsion, either for surface ships or submarines, or even foaircraft propulsion ("the atomic airplane")
  - Heat production : industrial process, district heating, …
  - Desalination
  - Medicine: radioisotopes production, …
  - Reactor for experiments : material or fuel behavior under irradiation, computer codes qualification, safety studies, …
  - Teaching and training

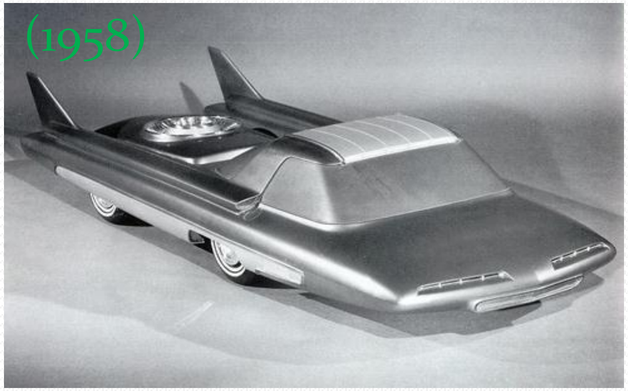
and even… aircrafts ("the atomic airplane"), trains and cars !

Nuclear reactors for …

Space : the NERVA / ROVER project

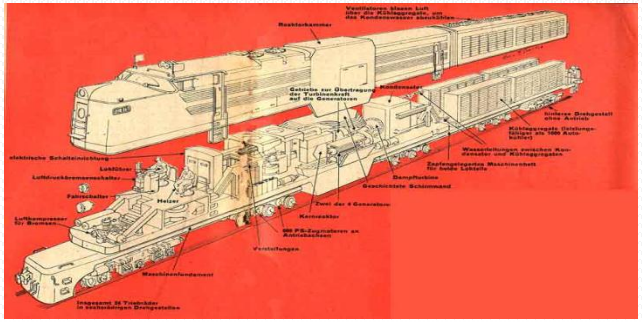


Cars : the “Ford Nucleon” (1958)

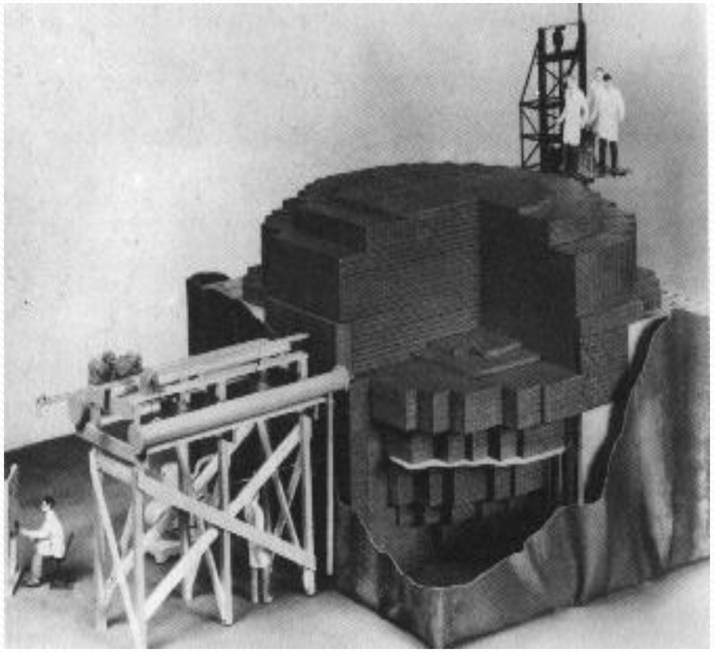


Nuclear powered aircraft

The atomic locomotive



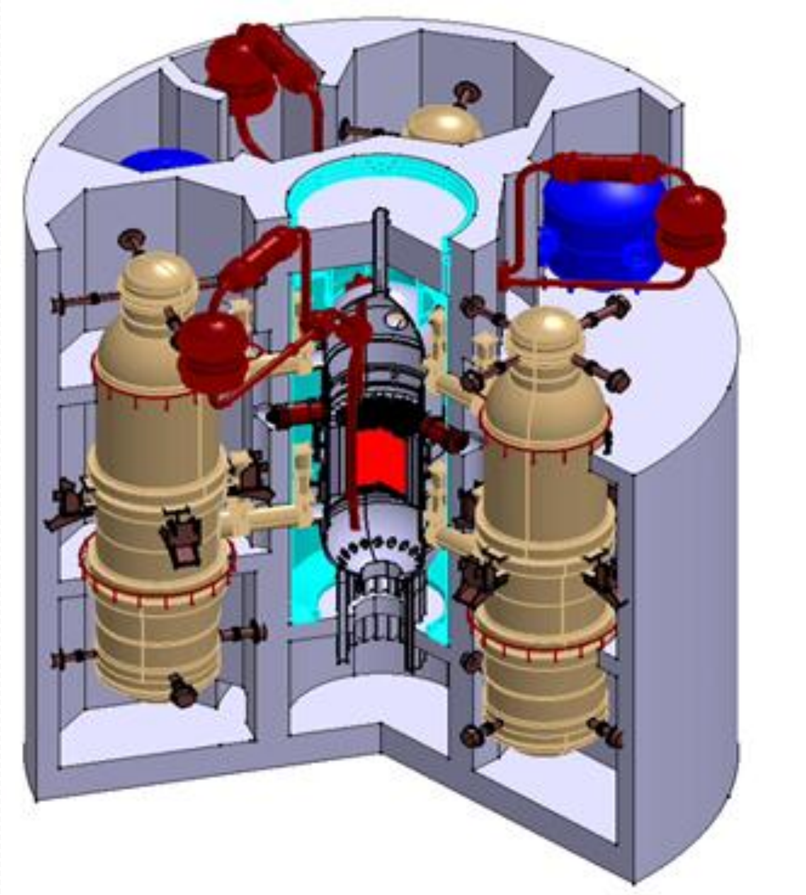
The development of nuclear systems :
From CP1 (2/12/1942) to next generation (Gen-IV)



Chicago Pile : Dec. 2, 1942

Première “pile atomique” Russe qui divergea le 25 décembre 1946 (Kourtchatov)

Gas cooled fast reactor (GFR)



Obstacles and stimulus of the past

- ***Vexations***
  - Excessive ambitions (aircraft propulsion)
  - Crippling technical problems (organic liquids, C-Na association)
  - Wrong « timing » (HTR)
  - Accidents (Windscale (air),TMI(Babcock), RBMK)
  - Inconvenience (Q244 : French project of a heavy water reactor for the propulsion of military submarines, 1954-1955)
- ***Driving forces (motors) of the development***
  - Better use of natural uranium (FNR)
  - Independence will (UNGG, MAGNOX, CANDU)
  - Commercial aggressiveness (Westinghouse, General Electric)
  - The weight of the history (CANDU)
  - Dualities and synergies between civil and military applications (propulsion, Plutonium use)
  - Technological breakdowns (HTR, Zr metallurgy,…)

The "purification" of the Seventies

- After the flowering of the Fifties and Sixties, one witnesses a **drastic selection** of the "reactor systems " which leads to a crushing supremacy of the ordinary water reactors (PWR or BWR) but many alternatives

- Only heavy-water reactors survive this invasion, but for how long time still? (the species of the MAGNOX and English AGR is in the process of disappearance

- **Two reactor systems** incipient die out prematurely for various reasons:
  - HTRs : they arrive badly (troubles of FSV) and too late and they finish in the storm of after TMI (1979)
  - FNRs : too early and too expensive ! (+ the target of anti-nuclear movements)

BUT …

They are reappearing today (on paper), with Gen-IV

Coolants / reactor association

			Acronym (english)	Other systems (variants)
LIQUID	LIGHT WATER	Pressurized	PWR (Pressurized water)	RBMK (graphite moderated
		Boiling	BWR (Boiling water)	ATR (moderator D_2O) – Japon HWLWR (same)- GB
		Super critical	SCWR (Super-critical water)	•"thermal » version •« fast » version
	HEAVY WATER		PHWR (1) (Pressurized heavy water)	ACR (U enriched)
	LIQUID METAL	Sodium	SFR (2) (Sodium fast)	• In vessel version • « loop » version
		Lead	LFR (2) (Lead cooled)	Eutectic lead-Bismuth
GAS	CO_2		GG –France (Gas-Graphite)	MAGNOX (Unat) – GB AGR (UO_2 enrichi) – GB
	HÉLIUM		HTR (High temperature)	2 kinds of fuel • Pebble bed • Prismatic

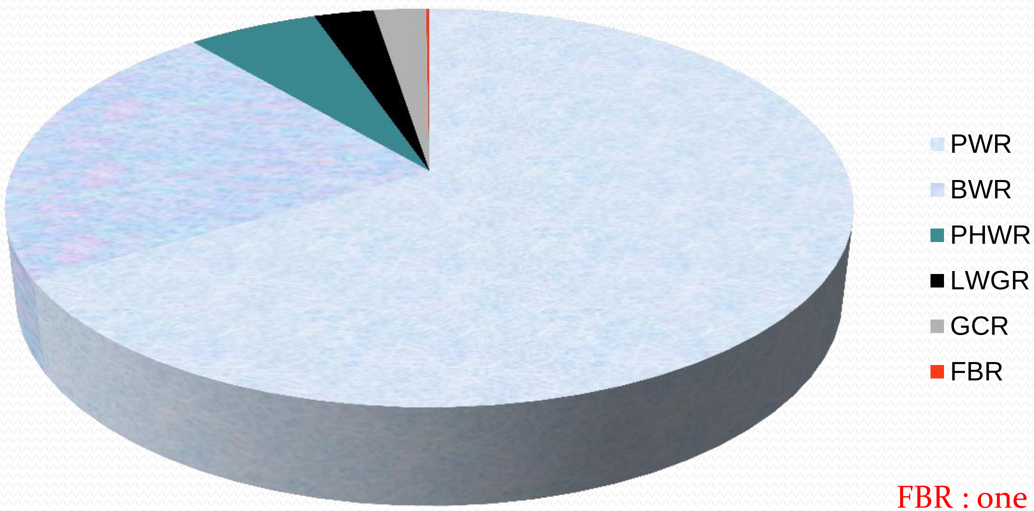
(1) or CANDU (2) GEN IV acronyms

First electric generation supplied by a NPP

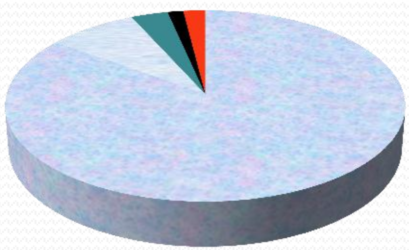
Country	Startup date	Unit name (and type)	Definitive shutdown year
USA	20/12 - 1951	EBR-1 (FBR) - Idaho	1963
Russia	27/06 - 1954	AES-1 (RBMK) - Obninsk	1988
UK	27/08 - 1956	Calder Hall (Nat.U – GCR)	2003
France	28/09 - 1956	Marcoule G1 (“UNGG”)	1968
Germany	17/06 - 1961	V.A. Kahl (BWR)	1985
Canada	04/06 - 1962	Rolphton NPD-2 (BHWR)	1987
Belgium	10/10 - 1962	Mol – BR3 (PWR)	1987
Italy	12/05 - 1963	Latina (Nat.U – GCR)	1987
Japan	26/10 - 1963	Tokai JPDR-1 (BWR)	1969
Sweden	20/03 - 1964	Agesta (PHWR)	1974
Switzerland	29/01 - 1968	Lucens (HWGCR)	1969
Spain	11/07 - 1968	Jose Cabrera (PWR)	2006
Netherland	25/10 - 1968	Dodewaard (BWR)	1997
India	01/04 - 1969	Tarapur-1 (PHWR)	-

World NPP in 2011 (1/1/2011)

Reactor type	Connected to the grid			Under construction (2010)		
	Number of units	MWe net	%	Number of units	MWe net	%
PWR	269	248637	**66,4**	56	54471	**85,0**
BWR	92	84062	**22,4**	4	5250	**8,2**
PHWR	45	22205	5,9	4	2154	3,4
LWGR	15	10219	2,7	1	915	1,4
GCR	18	8949	2,4	0	0	0,0
FBR	1	560	0,1	2	1274	2,0
TOTAL	440	374632	100,0	67	64064	100,0



Water cooled reactors = 89%



Water cooled reactors = 93%

FBR : one in India (470 MWe) + one in Russia (804 MWe)
LWGR : one in Russia (915 Mwe)
PHWR : one in Argentina (692 Mwe) and 3 in India (1462 Mwe)

Take away points (1/2)

- The energy release by the **fission** process of atomic nucleus is **millions times higher** than the one released by any **chemical reaction** (which involves electrons layers surrounding the nucleus of atoms)

- To sustain a reaction chain in **NATURAL** uranium (0,7% of U235), the fast **neutrons** emitted by a fission must be **slowed down** to increase their probability to induce a new fission (otherwise it's **IMPOSSIBLE**)

- The 3 main moderators used for this purpose are:
  - Graphite (HTRs)
  - Heavy water - D_20 (Candu)
  - Light water - **H_20** (PWR & BWR)

- The use of **H_20 require** to slightly **enriched** uranium (3% – 5%) because too many neutrons are lost by being captured in H_20

Take away points (2/2)

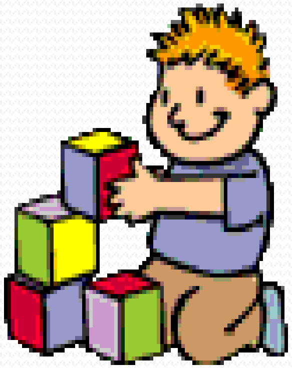
- Using only FAST NEUTRONS (**no** slowing down) is possible provided that **enough concentration of fissile** nucleus is achieved, which can be obtained through:
  - **Medium enriched uranium** (at least 20%)
  - The use of **PLUTUNIUM** (mixed with natural or depleted uranium) : > 15%
- In that case it is possible to design "**Fast Neutron Reactors**" (Gen-IV) that are able to **produce more new fissile nucleus** ("fuel") than they consume to make electricity. This is achieved by the transformation of enough U238 in plutonium while the reactor is operating.

This is the BREEDING process

With 7 millions tons of natural uranium, we can generate 7 MIILIONS GWe-Years (GY) of electricity. To day, world nuclear electricity is 350 GY ➔ that's …..

electricity for 20 000 years!

Thank you



Questions ?