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"**)

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

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

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

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

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

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* 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)

A nuclear reactor: how it works - Dominique GRENECHE
Nuclear energy: a glance at history (2/2)

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

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

- 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

- 1941  Plutonium is discovered by Gleen Seaborg (Berkeley)

- **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

A nuclear reactor: how it works - Dominique GRENECHE
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 No. 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

A nuclear reactor: how it works - Dominique GRENECHE
CONTENTS

- A quick look at history

- The atoms

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- Basic principles of nuclear reactors

- Genesis of nuclear reactor technology
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)

Atomic number: \( A = Z + N \) = number of “nucleons”

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

Atomic Mass: the mass of \( N = 6,022 \times 10^{23} \) atoms, roughly equal to A because the mass of N nucleons is almost equal to 1 Gram
Periodic tables of elements

<table>
<thead>
<tr>
<th>Periodic Table</th>
<th>Non-Metals</th>
<th>Transition Metals</th>
<th>Rare Earth Metals</th>
<th>Halogens</th>
</tr>
</thead>
<tbody>
<tr>
<td>H - gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Li - solid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Br - liquid</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tc - synthetic</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

A nuclear reactor: how it works - Dominique GRENECHE
The two main isotopes of natural uranium

U238 (99.3 %) – U235 (0.7 %)
CONTENTS

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

The RESULT:

1 - Energy: very high

2 - Several neutrons: very fast (average number for U235: $\bar{v} = 2.5$)

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

A nuclear reactor: how it works - Dominique GRENECHE
An amazing amount of energy....

A nuclear reactor: how it works - Dominique GRENECHE

\[ E = m \cdot C^2 \]
Order of magnitude (to be reminded !)

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

This is 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?

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

**TOTAL (without neutrinos): 201.6 Mev / fission**
Residual power released by a reactor core after its shut down

<table>
<thead>
<tr>
<th>Time Period</th>
<th>en %</th>
<th>REP 900</th>
<th>REP 1300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avant l’arrêt</td>
<td>100 %</td>
<td>2 700 MW</td>
<td>3 900 MW</td>
</tr>
<tr>
<td>Après 1 seconde</td>
<td>7 %</td>
<td>190 MW</td>
<td>270 MW</td>
</tr>
<tr>
<td>Après 1 minute</td>
<td>5 %</td>
<td>135 MW</td>
<td>195 MW</td>
</tr>
<tr>
<td>Après 1 heure</td>
<td>1,5 %</td>
<td>40 MW</td>
<td>58 MW</td>
</tr>
<tr>
<td>Après 1 jour</td>
<td>0,6 %</td>
<td>16 MW</td>
<td>24 MW</td>
</tr>
<tr>
<td>Après 1 semaine</td>
<td>0,3 %</td>
<td>8 MW</td>
<td>12 MW</td>
</tr>
<tr>
<td>Après 1 mois</td>
<td>0,15 %</td>
<td>4 MW</td>
<td>6 MW</td>
</tr>
</tbody>
</table>
The FISSION process ...

1 – Energy: very high

2 – Several neutrons: very fast (average number for U235: $\bar{\nu} = 2.5$)

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

The RESULT:

A nuclear reactor: how it works - Dominique GRENECHE
Distribution of the number and of the energy of neutrons from fissions

1. **Number \( \nu \) (U235)**

<table>
<thead>
<tr>
<th>( \nu )</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probability to emit ( \nu )</td>
<td>2 %</td>
<td>17 %</td>
<td>36 %</td>
<td>31 %</td>
<td>12 %</td>
<td>3 %</td>
</tr>
</tbody>
</table>

\[ \bar{\nu} = 2.439 \]

*Note:* the value of \( \bar{\nu} \) for Pu239 is 2.862 (significantly higher than for U235) and it increases with the energy of the neutron inducing the fission of Pu239.

Ex. : \( \bar{\nu} = 3.0 \) at 1 Mev, \( \bar{\nu} = 4.24 \) at 10 Mev.

2. **Energy spectrum**

*Note:*
- Average speed \( \approx 20,000 \) km/s (2 Mev)
- Maximum speed \( \approx 45,000 \) km/s (10 Mev)
The “reproduction factor” $\eta$

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

For **U235**, $\nu = 2.439$ and thus the number of neutrons “recovered” from ONE neutron absorbed the nucleus is  

$$\eta = 2.439 \times 0.855 = 2.085$$
The FISSION process ...

1 – Energy: *very high*

2 – Several neutrons: *very fast* (average number for U235: \( \bar{V} = 2.5 \))

**3 – Two « pieces » (the fission products, fp): very cumbersome!**
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)
• 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 \( \geq 10^5 \) years)
CONTENTS

• A quick look at history

• The atoms

• The fission process and the reaction chain

• **Basic principles of nuclear reactors**
  • *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?

- Neutrons hit the fissile atom nucleus.
- The fissile atom nucleus splits into two fission products (fp).
- The fission products release huge kinetic energy (+ radiations).
- The kinetic energy is transformed into heat.
- Heat is removed by a coolant (liquid or gas).
- The heat is then transformed into energy (electrical or other, via vapor or other).

HEAT RELEASE

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

« breaking »in the matter (until a complete stop)
The basic operation principle of a PRESSURIZED water reactor (PWR)

COLD SOURCE
(river, sea, cooling towers)

A nuclear reactor: how it works - Dominique GRENECHE
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

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

The atoms

The fission process and the reaction chain

**Basic principles of nuclear reactors**
- 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
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

**Slow the neutrons down**

because
the probability for slow \(^{(1)}\) neutrons to cause a fissile nucleus to fission is much bigger (fission cross-section of U\(_{235}\) is 200 times bigger with slow versus fast neutrons)

**Enrich uranium in U\(_{235}\) isotope**

thus
increasing the number of fissile targets
U\(_{235}\) assay > 20 %
(or, better, use plutonium > 15 %)

**« thermal » reactors**

(1) few km/s

**Fast neutron reactors**

A nuclear reactor: how it works - Dominique GRENECHE
U235 (and Pu239) fission cross sections (CS) as function of energy (speed) of neutrons

A nuclear reactor: how it works - Dominique GRENECHE
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 » $\Delta$, which ranges from 1 for the best moderator (hydrogen) to a value tending towards 0 for the less efficient (heavy nucleus) ($\Delta$ is a decreasing function of the atomic mass of the nucleus)

- Be **as less "capturing" as possible** ($\Delta_c$ as low as possible)
# The choice of a moderator

## The first light elements of the periodic table of natural elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Hydrogen (H)</th>
<th>Helium (He)</th>
<th>Lithium (Li)</th>
<th>Beryllium (Be)</th>
<th>Boron (B)</th>
<th>Carbon (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of protons</td>
<td>+</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of neutrons</td>
<td></td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Number of nucleons $A =$</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Natural abundance (%)</td>
<td>99,9885</td>
<td>0,0115</td>
<td>$10^{-4}$</td>
<td>&gt; 99,99</td>
<td>7,6</td>
<td>92,4</td>
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A nuclear reactor: how it works - Dominique GRENECHE
The choice of a moderator

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<td>0</td>
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<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Number of nucleons A</td>
<td></td>
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<td>92,4</td>
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<tr>
<td>Main natural form (on the earth)</td>
<td>light water (H$_2$O)</td>
<td>Heavy water (D$_2$O)</td>
<td>GAS</td>
<td>SOLID</td>
<td>SOLID</td>
<td>SOLID</td>
</tr>
<tr>
<td>Capture CS (Barns)</td>
<td>0,644</td>
<td>0,0013</td>
<td>70,56</td>
<td>0,0076</td>
<td>764,9</td>
<td>0,00337</td>
</tr>
</tbody>
</table>

A nuclear reactor: how it works - Dominique GRENECHE
The choice of a moderator

The first light elements of the periodic table of natural elements

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</tr>
</tbody>
</table>

- 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

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<th>Hydrogen (H)</th>
<th>Helium (He)</th>
<th>Lithium (Li)</th>
<th>Beryllium (Be)</th>
<th>Boron (B)</th>
<th>Carbon (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of protons</td>
<td>+</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
<td>Number of neutrons</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Number of nucleons ( A = )</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Natural abundance (%)</td>
<td>99,9885</td>
<td>0,0115</td>
<td>( 10^{-4} )</td>
<td>&gt; 99,99</td>
<td>7,6</td>
<td>92,4</td>
</tr>
<tr>
<td>Main natural form (on the earth)</td>
<td>light water (H(_2)O)</td>
<td>Heavy water (D(_2)O)</td>
<td>GAS</td>
<td>SOLID</td>
<td>SOLID</td>
<td>SOLID</td>
</tr>
<tr>
<td>Capture CS (Barns)</td>
<td>0,644</td>
<td>0,0013</td>
<td>70,56</td>
<td>0,0076</td>
<td>764,9</td>
<td>0,00337</td>
</tr>
</tbody>
</table>

Can be used as a moderator

... to eliminate (too low density)

... to eliminate (too high density)

Can be used as a moderator (but toxicity is an issue)

... to eliminate (too high capture CS)

Can be used as a moderator

A nuclear reactor: how it works - Dominique GRENECHE
A nuclear reactor: how it works - Dominique GRENECHE

### Slowing down parameter

<table>
<thead>
<tr>
<th></th>
<th>SILVER GRAPHITE</th>
<th>GOLD HEAVY WATER</th>
<th>BRONZE : H₂O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0,158</td>
<td>0,509 (D₂ : 0,7261)</td>
<td>0,926 (H : 1,000)</td>
</tr>
</tbody>
</table>

### Average and minimum of chocks (*)

|                  | 124 and 59      | 27 and 9         | 19 and 1     |

### Capture CS

|                  | 2,73            | 0,44             | 215          |

### Quality Index

|                  | 223             | 4080             | 64           |

### Optimum of the moderation ratio

|                  | 50              | 30               | 4            |

(*) : 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 ...

A nuclear reactor: how it works - Dominique GRENECHE
Graphite moderated reactors are BIG!

Former Gas-cooled Graphite reactor (540 Mwe)

New PWRs (900 Mwe)

Bugey nuclear power plants (France)

A nuclear reactor: how it works - Dominique GRENECHE
Neutron are slowed down in the moderator region to escape their capture by the « resonances » of heavy nucleus in the fuel.
- A quick look at history
- The atoms
- The fission process and the reaction chain

**Basic principles of nuclear reactors**
- 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
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**: $\rho = \frac{(K - 1)}{K}$
  - 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 outside 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**

\[ \kappa_{\text{inf}} \geq 1 \]

**Uranium enrichment**

<table>
<thead>
<tr>
<th></th>
<th>0.71 %</th>
<th>3 %</th>
<th>8 %</th>
<th>100 %</th>
</tr>
</thead>
<tbody>
<tr>
<td>For <strong>FAST</strong> neutrons</td>
<td>0.456</td>
<td>0.677</td>
<td>1.0</td>
<td>1.882</td>
</tr>
<tr>
<td>For <strong>SLOW</strong> neutrons (speed = 2200 m/s)</td>
<td>1.364</td>
<td>1.879</td>
<td>2.027</td>
<td>2.12</td>
</tr>
</tbody>
</table>

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

**CRITICAL SIZE** or **CRITICAL MASS**

---

A nuclear reactor: how it works - Dominique GRENECHE
Critical mass of fissionable nucleus

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
CONTENTS

- A quick look at history
- The atoms
- The fission process and the reaction chain

**Basic principles of nuclear reactors**
- 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
Neutron lifetime in a reactor (LWR)

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

- Duration of the slowing down: \(\cong\) 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 \(\cong\) 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

\[ \ell_o = 2.5 \times 10^{-5} \]
Neutron multiplication speed

- **Neutrons multiplication:**

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

  \[
  N(t) = N_0 \exp\left((k - 1)\frac{t}{\ell_o}\right)
  \]

  We get immediately the **exponential law**:

  \[
  N(t) = N_0 \exp\left((k - 1)\frac{t}{\ell_o}\right)
  \]

<table>
<thead>
<tr>
<th>( t = \ell_o )</th>
<th>( 2\ell_o )</th>
<th>( 3\ell_o )</th>
<th>( 4\ell_o )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(t) ) =</td>
<td>( N_0 )</td>
<td>( kN_0 )</td>
<td>( k(kN_0) = k^2N_0 )</td>
</tr>
</tbody>
</table>

  With \( k = 1,0001 \), \( N(t) \) would be ........

  **multiplied by 55 in one second!**
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- (sec.)

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 $\ell_d$ of this delayed source is $\tau = 13$ sec.

- Noting $\beta$ the total proportion of these « delayed neutrons », the overall average lifetime of ALL neutrons from fissions is NO MORE $\ell_o$ but $\ell = \ell_o(1 - \beta) + \tau.\beta$ which is a far more longer average lifetime.

- In effect, for U235, $\beta = 0.0065$ so that the prompt neutron lifetime which was 0,000025 becomes in reality 0.000025 + 0,085 $\approx 0.085 (\approx \tau.\beta)$

- This COMPLETELY 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 $\rho$ 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!)
A quick look at history

The atoms

The fission process and the reaction chain

**Basic principles of nuclear reactors**
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- The kinetic of the reaction chain
- **Temperature effects and void coefficient**
- Plutonium production and breeding

Genesis of nuclear reactor technology
**Temperature effects**

VARIATION OF TEMPERATURE $T$

- Thermal agitation
  - DOPPLER effect
  - SPECTRUM effect

- Variation of density
  - Moderator (liquids)
  - Geometrical Expansion

Température coefficient:

$$\theta = \frac{\text{variation of } k \text{ (ou } \rho \text{)}}{\text{variation of } T (\text{pcm}/\text{o}^{\circ}c)}$$

Having $\theta < 0$ in all situations is CAPITAL for the SAFETY
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” neutron spectrum → increase of “reproduction factor” ($\eta$) 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\(^{(1)}\))

<table>
<thead>
<tr>
<th></th>
<th>Capture</th>
<th>Spectral</th>
<th>leakage</th>
<th>TOTAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large cores (1000 Mwe reactors)</td>
<td>0.5</td>
<td>9.1</td>
<td>-5.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Small cores (250 Mwe)</td>
<td>0.4</td>
<td>6.4</td>
<td>-5.8</td>
<td>1.0</td>
</tr>
</tbody>
</table>

- 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 \(10^{-5}\) \(\Delta k\))

A nuclear reactor: how it works - Dominique GRENECHE
CONTENTS

• A quick look at history

• The atoms

• The fission process and the reaction chain

• **Basic principles of nuclear reactors**
  • 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
### Fuel depletion

#### A nuclear reactor: how it works - Dominique GRENECHE

<table>
<thead>
<tr>
<th>231</th>
<th>232</th>
<th>233</th>
<th>234</th>
<th>235</th>
<th>236</th>
<th>237</th>
<th>238</th>
<th>239</th>
<th>240</th>
<th>241</th>
<th>242</th>
<th>243</th>
<th>244</th>
</tr>
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<tbody>
<tr>
<td>Z</td>
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<td>Th231</td>
<td>Th232</td>
<td>Th233</td>
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<td></td>
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</tr>
<tr>
<td>Pa231</td>
<td>Pa232</td>
<td>Pa233</td>
<td>Pa234</td>
<td>Pa235</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>U232</td>
<td>U233</td>
<td>U234</td>
<td>U235</td>
<td>U236</td>
<td>U237</td>
<td>U238</td>
<td>U239</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Np237</td>
<td>Np238</td>
<td>Np239</td>
<td>Np240</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pu238</td>
<td>Pu239</td>
<td>Pu240</td>
<td>Pu241</td>
<td>Pu242</td>
<td>Pu243</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Am241</td>
<td>Am242</td>
<td>Am243</td>
<td>Am244</td>
<td></td>
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<td></td>
<td></td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Cm242</td>
<td>Cm243</td>
<td>Cm244</td>
<td></td>
<td></td>
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<td></td>
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<td></td>
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</tr>
</tbody>
</table>

- **Noyaux fertiles**: Fertile nuclei
- **Noyaux fissiles**: Fissile nuclei
- **Noyaux intermédiaires**: Intermediate nuclei

**Symbols**:
- $\alpha$: anné
- $\beta^{-}$: day
- $h$: hour
- $m$: minute

---

**Notes**:
- **Th231** to **Th233**: Transuranium elements
- **Pa231** to **Pa235**: Protactinium isotopes
- **U232** to **U239**: Uranium isotopes
- **Np237** to **Np240**: Neptunium isotopes
- **Pu238** to **Pu243**: Plutonium isotopes
- **Am241** to **Am244**: Actinium isotopes
- **Cm242** to **Cm244**: Curium isotopes
A fundamental phenomena: the conversion of fertile nucleus into fissile nucleus

For one neutron absorbed in a fissile nucleus, \( \eta \) neutrons are emitted

1 Neutron \[ \rightarrow \] ONE must be devoted to the next absorption in the fissile nucleus (to sustain the chain reaction)

It remains \( \eta - 1 \) 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 \( \eta - 1 \)

<table>
<thead>
<tr>
<th>U235</th>
<th>Pu239</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutrons &quot;thermal&quot;</td>
<td>1,085</td>
</tr>
<tr>
<td>Neutrons « fast » FNR</td>
<td>0,88</td>
</tr>
</tbody>
</table>

F (\( \eta - 1 \)) is the CONVERSION RATIO

If \( L \) is sufficiently low (case of Fast Neutrons Reactors) and \( \eta \) sufficiently high (case of Pu239), then \( F (\eta - 1) \) can be superior to ONE : this the BREEDING process
The conversion ratio (CR)

\[
\text{CR} : \frac{\text{Number of fissionable nucleus created}}{\text{Number of fissionable nucleus destroyed}}
\]

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

Typical values 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: \( \geq 1 \)

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 \textit{plutonium} created in the reactor! (and then the plutonium recycling increases this amount by 12% points)
**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)

**Composition of a PWR spent fuel assembly**

- **Recyclable materials**
  - 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

A nuclear reactor: how it works - Dominique GRENECHE
An illustration of the breeding capabilities of fast neutron reactors

NEUTRONS « THERMAL »

Energy production
100 fissions

250

Plutonium production
Fissile

60

90

Sterile absorptions + leakages

Multiplication factor for neutrons is much better for plutonium than for uranium 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)
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)
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...

“Dry wood” = U235
or Pu to make fire (electricity)

“Wet wood” (=U238) is “dried” (transformed to Pu) to make a new fire

...etc
A nuclear reactor: how it works - Dominique GRENECHE

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

**Genesis of nuclear reactor technology**
A huge amount of combinations to make a nuclear reactor

<table>
<thead>
<tr>
<th>Fissile element</th>
<th>Fertile element</th>
<th>Neutron energy</th>
<th>Fuel mix</th>
<th>Coolant</th>
<th>Moderator</th>
<th>Fuel form</th>
<th>Barriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>U-235</td>
<td>U-238</td>
<td>Thermal</td>
<td>U natural</td>
<td>H$_2$O pressurized or boiling</td>
<td>H$_2$O</td>
<td>Pellets in rods</td>
<td>Fuel in pebble/matrix</td>
</tr>
<tr>
<td>U-233</td>
<td>Th-232</td>
<td>Fast</td>
<td>3% U-235</td>
<td>D$_2$O</td>
<td>D$_2$O</td>
<td>Pellets in plates</td>
<td>Fuel element + cladding</td>
</tr>
<tr>
<td>Pu-239</td>
<td>+ Spallation</td>
<td>U + Pu MOX</td>
<td>CO$_2$ gas</td>
<td>Graphite</td>
<td></td>
<td>Pebbles in beds</td>
<td>F+C+PV pressure vessel/tube</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>He gas</td>
<td>Graphite</td>
<td></td>
<td>Spheres in matrix</td>
<td>F+C+PV + concrete shell</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Na liquid metal</td>
<td>Graphite</td>
<td></td>
<td></td>
<td>F+C+PV+CS + steel liner</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pb or Pb/Bi liquid metal</td>
<td>Graphite</td>
<td></td>
<td></td>
<td>F+C+PV+CS+SL + core catcher</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Molten salt</td>
<td>Molten salt</td>
<td>Molten salt</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$$= 45360 !$$

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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

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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)

A nuclear reactor: how it works - Dominique GRENECHE
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

<table>
<thead>
<tr>
<th>Light Water</th>
<th>Acronym (english)</th>
<th>Other systems (variants)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressurized</td>
<td>PWR (Pressurized water)</td>
<td>RBMK (graphite moderated)</td>
</tr>
<tr>
<td>Boiling</td>
<td>BWR (Boiling water)</td>
<td>ATR (moderator D₂O) – Japon HWLWR (same) – GB</td>
</tr>
<tr>
<td>Super critical</td>
<td>SCWR (Super-critical water)</td>
<td>&quot;thermal » version  « fast » version</td>
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</table>

<table>
<thead>
<tr>
<th>Heavy Water</th>
<th>Acronym (english)</th>
<th>Other systems (variants)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PHWR (1) (Pressurized heavy water)</td>
<td>ACR (U enriched)</td>
<td></td>
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</table>

<table>
<thead>
<tr>
<th>Liquid Metal</th>
<th>Acronym (english)</th>
<th>Other systems (variants)</th>
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<tbody>
<tr>
<td>Sodium</td>
<td>SFR (2) (Sodium fast)</td>
<td>In vessel version « loop » version</td>
</tr>
<tr>
<td>Lead</td>
<td>LFR (2) (Lead cooled)</td>
<td>Eutectic lead-Bismuth</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Gas</th>
<th>Acronym (english)</th>
<th>Other systems (variants)</th>
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</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>GG –France (Gas-Graphite)</td>
<td>MAGNOX (Unat) – GB AGR (UO₂ enrichi) – GB</td>
</tr>
<tr>
<td>HÉLIUM</td>
<td>HTR (High temperature)</td>
<td>2 kinds of fuel Pebble bed Prismatic</td>
</tr>
</tbody>
</table>

(1) or CANDU  (2) GEN IV acronyms

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### First electric generation supplied by a NPP

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

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### World NPP in 2011 (1/1/2011)

#### 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)

<table>
<thead>
<tr>
<th>Reactor type</th>
<th>Connected to the grid</th>
<th>Under construction (2010)</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Number of units</td>
<td>MWe net</td>
</tr>
<tr>
<td>PWR</td>
<td>269</td>
<td>248637</td>
</tr>
<tr>
<td>BWR</td>
<td>92</td>
<td>84062</td>
</tr>
<tr>
<td>PHWR</td>
<td>45</td>
<td>22205</td>
</tr>
<tr>
<td>LWGR</td>
<td>15</td>
<td>10219</td>
</tr>
<tr>
<td>GCR</td>
<td>18</td>
<td>8949</td>
</tr>
<tr>
<td>FBR</td>
<td>1</td>
<td>560</td>
</tr>
<tr>
<td>TOTAL</td>
<td>440</td>
<td>374632</td>
</tr>
</tbody>
</table>

**Water cooled reactors = 93%**

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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$_2$O (Candu)
- Light water - H$_2$O (PWR & BWR)

The use of H$_2$O require to slightly **enriched** uranium (3% – 5%) because too many neutrons are lost by being captured in H$_2$O.
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 MILLIONS GWe-Years (GY) of electricity. To day, world nuclear electricity is 350 GY ➔ that’s …..

electricity for 20 000 years!
Thank you

Questions?