A nuclear power plant?

* A quite simple process:
  - like most of electrical power plant

→ Pressurized Water Reactor & Boiling Water Reactor represent more than 81% of the existing reactors

→ There are 435 reactors operated in the world
  ~ 10% of electricity (2 500 TWh/y)
  ~ 5% of primary energy

→ Thermal efficiency ~33%
Nuclear energy in France

19 power plants
58 reactors
65 millions of inhabitants
78% of french electricity

One reactor for 1,1 millions of inhabitants

Nuclear energy is very (very) concentrated
30 tons of enriched uranium ~ 1,8 Mtons of coal

- A single technology: Pressurized water reactors (PWR)
- Newest : Civaux 2 (1999)
- Oldest : Fessenheim (1&2) (1977)
- 1 under construction (EPR de Flamanville) –
  Planned for 2012 ; full operation 201?

- Which geographical framework for the debate ?
  - Germany : quit nuclear energy ASAP
  - Poland : want to build two reactors ASAP
  - Italy : no return to nuclear energy
  - France : Energy transition law (willing of reduction)
    ... But
    Construction of 2 EPR in UK
For the future and in the world

- **WWF scenario**: 0 TWh in 2050
- **Oil industry scenario (Exon & Total)**: Stable in 2050; translation from Europe to Asia
- **IAE scenario**: between x2 (NPS) and x3 (450) in 2035
- **IIASA Scenario (type 450)**: x 16 in 2100

**Hypothesis**: 3 constraints
- Climate (*2°C limitation*)
- Energy production (*20 Gtep*)
- Consommation share (4/2/1)

**Adjustment**:
- Nuclear share in 2050

Issues and technologies are strongly dependent of the global nuclear evolution
1/ Reactor physics 101
   Neutron interaction with matter
   Why pressurized water reactors?

2/ Nuclear waste
   What’s that?
   The CIGEO project
   The plutonium issue

3/ Natural uranium resources
   The limits of current technology
   Transition towards sodium fast reactors

4/ What about today?
   Nuclear costs
   Challenges for PWR
   ASTRID project
Fission of heavy nuclei release between **2 and 3 neutrons** with a huge quantity of energy (200MeV) and produces **two fission fragments**.

Fission is provoked by a neutron absorption (neutron balance = +1.5).

Neutrons interact with nucleus... not atoms!!

Natural uranium: $^{235}\text{U} (0.7\%)$ and $^{238}\text{U} (99.3\%)$.

Fissionable with any kind of neutrons

Fissionable with energetic neutrons

Kinetic energy of fission neutron from $^{235}\text{U}$ is not sufficient

No chain reaction are possible with $^{238}\text{U}$.
Neutron interaction with matter and criticality
Neutrons’ range are huge in comparison to their typical size
If a neutron interacts with a nucleus, several options are possible:

1/ Elastique scattering: the neutron gives a part of its energy to the target.
If a neutron interacts with a nucleus, several options are possible:

1/ Elastic scattering: the neutron gives a part of its energy to the target
2/ Neutron absorption: the neutron is captured by the nucleus leading to a new one (radioactive)

If the nucleus is fissile ($^{235}\text{U}$, $^{239}\text{Pu}$, ...), this absorption can lead to fission

→ Neutron balance = +1.5 neutrons

If there is no fission, the absorption is then a sterile capture

→ Neutron balance = -1 neutron
Microscopic cross section quantifies the probability of neutron interaction with a given nucleus.
Everything happens like if the nucleus radius is a function of the neutron kinetic energy

- The slower the neutrons are, the higher is the relative radius of $^{235}$U

To maximise the fission probability by neutron interaction, one should use slow neutrons

Unfortunately, neutrons emitted by fission are fast
The water inside reactors is needed to:
- Cool down the fuel (and produce steam)
- Slow down the neutrons

If the reactor is critical, one and only one neutron emitted by fission induces another fission.
Pressurized water reactors

- Compromise between enrichment and reactor technology
  - Enriched Uranium (between 3 et 5%)
  - Each assembly is composed by 264 fuel pins (17 x 17)

![Image of fuel pins](image-url)
The fission

Number of protons

Number of neutrons

Fissioning nuclei (U-235; Pu-239)

→ Fission products are then (very) radioactive
  - Even if the reactor is shut down, there is a huge heat production
  ➢ Safety issue: to maintain the reactor cooling whatever happens - No reactor without wastes

Even if the reactor is shut down, there is a huge heat production

Safety issue: to maintain the reactor cooling whatever happens - No reactor without wastes

Fissioning nuclei (U-235; Pu-239)

Fissioning nuclei (U-235; Pu-239)
Fuel irradiation produces heavy nuclei
- Plutonium is produced by 238U neutron capture
- Elements heavier than plutonium are called minor actinides
“96 % of the nuclear spent fuel is reusable”

Wastes: « Radioactive wastes are radioactive matter which NO further utilization is planed » French law (2006)

Open cycle: ex USA

U nat → U enr

« Closed » cycle: ex France

U nat → U enr

Pu monorecycling

U & Pu

Fission Product

-100% U et Pu
-100% Np, Am, Cm

Fission Product

-0,1% U et Pu
-100% Np, Am, Cm
How to qualify nuclear waste?

Radiotoxicity (Sievert) : a way to quantify the impact of nuclear wastes

The Sievert is a unit built to quantify the damages of radiation on the human body

→ Hypothesis of calculation : all radioisotopes have scattered into drinkable water
→ Source term : not a real meaning but is a good way to compare different contributions

Regarding your strategy the radioactivity you have to deal with in the storage is greatly diminished

The goal of storage is to limit the diffusion of long living wastes (T ~300 years)

→ However, the heat is due to FP (T~30 years)
CIGEO concerns only the waste already produced and the one to be produced of the current reactors.

→ “There is solution for our nuclear waste”

<table>
<thead>
<tr>
<th>Capacity</th>
<th>Already produced</th>
<th>After 40 years with reprocessing</th>
<th>After 40 years without reprocessing</th>
<th>CIGEO Capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>HA-LV</td>
<td>5 700 m³</td>
<td>8 000 m³</td>
<td>93 500 m³</td>
<td>10 000 m³</td>
</tr>
<tr>
<td>MA-VL</td>
<td>57 500 m³</td>
<td>67 500 m³</td>
<td>59 000 m³</td>
<td>70 000 m³</td>
</tr>
</tbody>
</table>

In the end, the total surface at the surface would be 15 km².

The nuclear debate paradox →
The use of Pu in current reactor to decrease radiotoxicity

Plutonium can replace uranium

→ Construction of Mox fuel in order to save natural uranium
→ To burn plutonium in order to decrease the radiotoxicity of Pu

7 Uox spent fuel assembly produce enough Pu for 1 Mox assembly

→ Comparison of 8 Uox spent fuel and 1 Mox spent fuel + 7 glasses

Spent MOX fuel contains Pu → It is not a waste... temporally stored for further use... (if there are uranium tension)
Plutonium valorization

Based on the use of $^{235}\text{U}$ (0.7% of the natural uranium)

- 1 ton of matter that have actually fissioned
- 27 tons of enriched uranium
- 200 tons natural uranium
- improving the enrichment process
- recycling uranium
- recycling plutonium

It is possible to improve this consumption by a factor 130!

$^{238}\text{U} + n \rightarrow ^{239}\text{U} \rightarrow ^{239}\text{Np} \rightarrow ^{239}\text{Pu}$

$^{239}\text{Pu}$

$\rightarrow$ The mass of plutonium inside the reactor is constant
$\rightarrow$ 1 ton of depleted uranium for 1 Gwe.an

For the chain reaction, 2 neutrons are needed
- For the fission
- For the plutonium production

New technology: SFR

For the french park 1000 tons are needed (we've got 300 tons)

300 000 tons of depleted uranium in France
$\rightarrow$ 5000 years of electricity
Sodium cooled fast reactors

Superphénix example

- Cooling: liquid sodium
  - Cheep
  - Industrial know how
  - Atm. pressure

- However, sodium is not stable with air neither with water
  - Internal

- Improved safety

SPX shut down (and dismantling) in 1996 by French government decision

Increase of construction costs
Economic viability

Natural uranium price ($) vs. Electricity price ($)

- **Breeder**
- **PWR-type**

"Maximum" natural price that defines the ultimate resources

Investment for the reactor construction

Natural uranium price ($) vs. Electricity price ($)
Economic viability, with error bars!

Electricity price ($)

Natural uranium price ($)  

Breeder

“Maximum” natural:  
From 130 $/kg until > 1000$/kg

PWR-type

Huge uncertainty regarding the natural uranium available that will justify the change of a new technology

Today: 285 Gwe (Full power equivalent)  
60 000 tons of natural uranium/years

Estimated resources: 10 – 23 millions of tons
The nuclear energy in the economy

- **Unknown resources**
  - Phosphates (~ 7.3 Mt)
  - Sea water (~4.5 Gt)

- **Today**
  - 45 000 tons of natural uranium / year
  - Cigar lake: planned for 2007; open in 2014
    - Nominal production: 10 900 t/years

- **Beware of simple arguments!**

**Graphs**

- **Uranium cost as a function of mined uranium**
  - Identified
  - Speculative
  - Unknown

- **Nuclear demand**

- **Cumulative uranium consumption**
  - Identified: 5.9 Mt, 7.6 Mt
  - Speculative: 6.5 Mt, 6.9 Mt

- Nominal production: 10 900 t/years

- Cost of identified resources: < 130$/kg, < 260 $/kg

- Cost of speculative resources: 400 $/kg
Plutonium issue:

Due to the fast neutron spectrum, the global amount of plutonium in SFR is very important → Phase out considerations

It takes 1000 years to produce the waste that are as “nasty” as the fuel
A small sum-up

**Take home messages:**

- Nuclear current technology is based on the fission of 235U
  - The only natural fissionable nuclei

- Natural uranium resources allow around a century of nuclear operation at current level
  - 1 GWe = 1 ton of fission = 30 tons of enriched uranium = 130 tons of natural uranium (at best)

- Regarding the strategy, Plutonium is a valuable matter or a painful waste

- It is possible to operate a nuclear fleet without any needs of natural resources
  - Transition to SFR

**A global increase of the nuclear energy?**

- **YES** More than factor 8
  - Current technology (PWR, BWR) is consuming too much natural uranium
  - Need to change towards Fast reactors (huge plutonium is needed to start up)
  - Plutonium is a valuable and expensive matter

- **NO** Less than a factor 2
  - We don’t need uranium savings
  - Current reactors are satisfying if operated in safe conditions
  - Plutonium is the principal waste
Different cost evaluations

- Theory

Production ~ 440 TWh (for 60 years)

- Construction
- Operation

Total costs

Dismantling + waste repository

« coût comptable »

- Construction time: 5 years
- Discount rate: 5%
- Reactor costs: 3 G€

Beware: one euro today is different from one euro in 2050

- Construction time: 10 years
- Discount rate: 8%
- Reactor cost: 9 G€

44 €/MWh

110 €/MWh
Different cost evaluations

- Discount rate: a way to reduce future expenses uncertainties

\[ \text{Taux d'actualisation} = 0\% \quad \text{Taux d'actualisation} = 5\% \]

Different figures from literature

<table>
<thead>
<tr>
<th>Coût comptable</th>
<th>Coût courant économique</th>
<th>Cout ARENH</th>
<th>Coût courant économique (2014)</th>
</tr>
</thead>
</table>

Levelised cost of electricity (LCOE)

Take into account future reactors (capital valorization)

EDF selling price to other producers

Big volume market price 2015 ~ 35 €/MWh

French government = share holders or consumers?
French reference scenario

- Making efforts today to keep the possible choice tomorrow
  - (Very) long term strategy
  - The plutonium is a valuable matter

- What if?
  - There is a delay in fast reactor deployment?
An ambitious project for French fast reactors

**ASTRID (CEA) – 600 MWe**

Goals: Insure « a passive » safety of the core

→ If the temperature increases, the chain reaction has to stop
→ A very ambitious fuel loading plan

From the French law in 2006 : a road map
- 2020 : Building a GENIV prototype
- 2012 : CEA report on the 2006 law
- Tome 3 : dedicated to ASTRID conception
A very innovative project that redefine nuclear systems concept: Molten Salt Reactors

- Liquid fuel
- Thorium molten salt
  - High temperature
- Fast neutron spectrum
  - Uranium breeding
  - Minor actinides burning
- In-line reprocessing

The concept has been proven experimentaly, (as many reactor concepts) but remains too innovative for a near future.
General conclusions

Nuclear is an energy source for the XXI century!
  ➔ Where? Asia, Eastern Europe, Latin America? Africa? Middle East?

Regarding the different objectives scenarios predict basically every possibility for nuclear future
  ➔ But only politics take actions

Nuclear power deployment will be driven by Asia
  ➔ A crisis on the uranium market would justify the deployment of new type of reactors
  ➔ In that case, the plutonium is a valuable matter that should be stored
  ➔ At the opposite, it could become the major issue of nuclear waste

The are lots of uncertainties and the choices have to be anticipated
  ➔ The Pu needed for one SFR the total production of 40 years of PWR operation

The French strategy is to make efforts now to have a choice tomorrow
  ➔ Is it compatible with the energy transition?

Thank you for your attention