Spent fuel management

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Future Nuclear Energy Systems
CEA/Nuclear Energy Division/Division of Nuclear Development and Innovation
Outline of presentation

1 – Present situation in France
   1.1 – General context
   1.2 – Present situation

2 – Fuel
   2.1 – MOX in LWR
   2.2 – Thorium
   2.3 – Gen IV systems

3 – Reprocessing/refabrication

4 – Waste
French Energy Policy

- Nuclear energy confirmed as an essential part of the French energy Mix and recognition of EPR in the Energy bill

- **EPR**
  - Decision by TVO to order an EPR in Finland
  - EDF in the process to launch a first EPR unit in Flamanville

- **EDF**
  - Opening of the capital of EDF
  - Progressive opening of the electricity market since 1999: 70% in 2004 towards 100% in 2007


- R&D on 4th generation nuclear systems
1 – Development of Fast Reactors with a closed fuel cycle along 2 tracks:
- Sodium Fast Reactor (SFR)
- Gas Fast Reactor (GFR)
- New processes for spent fuel treatment and recycling

→ Decision around 2015/2020 on prototypes
→ Industrial deployment around 2040

2 – Nuclear hydrogen production and very high temperature process heat supply to the industry
- Very High Temperature Reactor (VHTR)
- Water splitting processes

3 – Innovations for LWRs (Fuel, Systems...)
Law of 1991: history

- No end point yet available for HL-LL waste
- URL siting studies met with strong public opposition in 1989
- Moratorium on siting studies
- The Parliament office for science and technology investigated the situation and issued a report which led to the adoption of the legislative framework on December 30, 1991: the 1991 law.
3 areas of R&D set out by law of December 30, 1991:

- minimization of the quantity and toxicity of waste, by **partitioning and transmutation**, 

- feasibility of **deep geological disposal**, whether reversible or irreversible. 

- packaging and **conditioning**, for safe long lasting containment, and also studying **long term surface storage**, 

15 years of R&D → 2006; evaluation by National Evaluation Commission

CEA: in charge of P&T and conditioning & long term storage

R&D in cooperation between CEA, EDF, AREVA, ANDRA, CNRS, universities, and international cooperations
French Fleet of Nuclear Power Plants

**Installed capacity in 2002**
- Nuclear: 63.3 GWe (55%)
- Thermic: 27.1 GWe (23%)
- Hydro: 25.4 GWe (22%)
- Total: 90.4 GWe

**Electricity Generation in 2002**
- Production: 533 TWh
- Exports: 80.6 TWh

**Nuclear Electricity Generation**
- 58 NPP in operation (EDF)
- Production: 415 TWh
- % electricity: 78%

*(source: RTE - 2003)*
Fuel Management in France

- Front-End Sector
- Reactors & Services Sector
- Back-End Sector

- Natural Uranium
- Enrichment
- Reactors & Services
- Recycling: MOX Fuel fabrication
- Spent Fuel Reprocessing
- Uranium recyclable
- Plutonium
- Enriched Uranium
- Ultimate Waste Disposal
- Vitrified Waste

- Mines
- Chemistry
- MELOX Plant
- Dampierre
- Mines Enrichment
- Fuel fabrication
- La Hague Plant
- Uranium recyclable
- Plutonium
- Enriched Uranium
- Ultimate Waste Disposal
- Vitrified Waste
Reprocessing & Recycling: Key to Future Energy Resources

Recover all energy available in the fuel

Valuable materials (96%)

Uranium (94 to 96 %)

Plutonium (1 %)

Reprocessing & Recycling

Waste (4%)

Fission Products (3 to 5 %)

Minor Actinides (0.1 %)

Drastically minimise waste radiotoxicity

Plutonium

Minor actinides

Fission products

Radiotoxicity after 1,000 years

Pu inventory stabilisation: Pu produced can be used in LWR
Nuclear waste management: reduce the long term noxiousness

- Urgent matter for public acceptance of nuclear energy
- Minimize the volume and the long term radiotoxicity
- **1st contributor: Pu**; **2nd contributor: Minor Actinides (MA)**

```
Nuclear Ore (mine)  P&T of MA  Spent Fuel  No reprocessing

Pu + MA + FP

10000

1000

100

10

1

0,1

0,01

0,001

FP

Plutonium recycling

Time (years)
```

Relative radio toxicity

```
uranium Ore (mine)  P&T of MA  Spent Fuel  No reprocessing

Pu + MA + FP

10000

1000

100

10

1

0,1

0,01

0,001

FP

Plutonium recycling

Time (years)
```

Relative radio toxicity

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1

0,1

0,01

0,001

FP

Plutonium recycling

Time (years)
```

Relative radio toxicity

```
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10000

1000

100

10

1

0,1

0,01

0,001

FP

Plutonium recycling

Time (years)
```

Relative radio toxicity
Waste management strategy

Ultimate disposal (USA, Suède,…)?

Interim storage ?

French strategy : Reprocessing in La Hague And then disposal
# Radwaste types: classification and management paths

<table>
<thead>
<tr>
<th></th>
<th><strong>Short lived</strong></th>
<th><strong>Long lived</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Half-life</strong></td>
<td>Half-life &lt; 30 years</td>
<td>Half-life &gt; 30 years</td>
</tr>
<tr>
<td><strong>for most key elements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Very Low Level (VLL)</strong></td>
<td>Dedicated repository (in operation since 2003)</td>
<td>Capacity: 650,000 m³</td>
</tr>
<tr>
<td></td>
<td>108,219 m³ (as of end of 2002)</td>
<td>11,1% of total volume</td>
</tr>
<tr>
<td><strong>Low Level (LL)</strong></td>
<td>Final disposal Centre de l’Aube (in operation since 1992)</td>
<td>Capacity: 1 M m³</td>
</tr>
<tr>
<td></td>
<td>778,322 m³ (as of end of 2002)</td>
<td>0,07% radioactivity</td>
</tr>
<tr>
<td></td>
<td>79,5% of total volume</td>
<td></td>
</tr>
<tr>
<td><strong>Medium Level (ML)</strong></td>
<td>Dedicated repository being studied for radium bearing waste (35,717 m³) and graphite waste (8,842 m³)</td>
<td>0,01% radioactivity, 4,5% of total volume</td>
</tr>
<tr>
<td></td>
<td>45,359 m³ end of 2002</td>
<td>3,87% radioactivity</td>
</tr>
<tr>
<td></td>
<td>3,87% radioactivity</td>
<td>4,6% of total volume</td>
</tr>
<tr>
<td></td>
<td>Under study</td>
<td></td>
</tr>
<tr>
<td><strong>High Level (HL)</strong></td>
<td>December 30, 1991 Law</td>
<td>Capacity: 1,639 m³</td>
</tr>
<tr>
<td></td>
<td>96,05% radioactivity</td>
<td>0,2% of total volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

90% of the overall radwaste volume is currently handled in operating disposal facilities.

In green, the two waste categories targeted in the law.

\( \Rightarrow \) figures are quoted from the *Inventaire national* document (October 2004);
R&D for waste management

- 1976: start of SF reprocessing in UP2 at La Hague
- PUREX process
- significant and successful track record: > 19 000 tHM reprocessed as of end of 2003
- 850 tHM reprocessed each year (out of 1150 tHM unloaded from reactor)
- 8 t/a of Pu recycled
- in 20 NPP using MOX fuel
- HL-LL W vitrification

La Hague SF reprocessing facilities
Specific waste volume for the UP3 plant

- **Bitumen**
- **Grout concrete**
  - Technological waste
- **Glass**
- **Concrete**
  - Hulls & end fittings
- **Compaction**
  - Hulls, end fittings & technological waste
- **Conditioned spent fuel**

**Volume of waste in m³/tHM**

Pu losses: 1% 0.1% 0.1% 100%

1989 (Design) 1995 2000
Decreasing of the environmental impact

Release to the sea relative to the throughput for La Hague plants

<table>
<thead>
<tr>
<th>Year</th>
<th>$\beta_\alpha$ Release (TBq)</th>
<th>$\beta_\gamma$ Release (TBq)</th>
<th>Tritium (GBq)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1980</td>
<td>0.74</td>
<td>0.37</td>
<td>0</td>
</tr>
<tr>
<td>1985</td>
<td>0.74</td>
<td>0.37</td>
<td>8</td>
</tr>
<tr>
<td>1990</td>
<td>1.10</td>
<td>1.48</td>
<td>16</td>
</tr>
<tr>
<td>1995</td>
<td>1.10</td>
<td>1.48</td>
<td>0</td>
</tr>
</tbody>
</table>

Throughput

Tritium Release
The reprocessing-recycling option...

- Recovers reusable materials with very high energy potential and even today ensures major savings of natural uranium and oil through the use of MOX fuel:
  - producing more than 10% of the nuclear electricity generated in France.
  - reducing natural uranium consumption by more than 10% in France.
  - avoiding the high cost of enriching natural uranium.
- Reduces the quantities of spent fuel: 7 UOX → 1 MOX
- Diminishes the quantity and toxicity of high-level nuclear waste:
  - waste volume reduction by a factor of about 5.
  - waste radiotoxicity reduction by a factor of 10.
- Contributes to plutonium nonproliferation.
- Contributes to reducing the excess weapons-grade plutonium inventory.
Fuel and reactor perspectives

MOX and Thorium fuel

Gen IV Systems
The AREVA group industrial facilities

- An industrial complex comprising:
  - 2 plants in France
  - 2 plants at Dessel (Belgium), BELGONUCLEAIRE and FBFC-I (assemblies), are part of the COGEMA MOX platform.

- MELOX (145 tHM/year) - The world leader of the MOX production
- COGEMA Cadarache (42 tHM/year) - End of commercial MOX production on July 31, 2003
- BELGONUCLEAIRE
- DESSEL (40 tHM/year)
Mature and competitive industry

- ~20,000 t of spent fuel have been treated at La Hague, with continuous optimization of industrial spent fuel treatment
- Significant cumulative production of MOX: 1840 tHM of MOX fuel pellets produced by the end of 2004

Cumulative production of MOX fuel pellets (tHM)
MOX annual production in MELOX

* 2005 target (140 t)
100 tHM/year of MOX fuel manufactured at MELOX Plant (full capacity since 1998)

Since 1987, 1800 MOX fuel assemblies delivered by Fragema

• 20 French, 2 belgian, 3 german reactors loaded with MOX
• 2 Reactors (Cruas 3 & 4) loaded with reprocessed uranium
Key advantages of MIMAS process

- Powder mixing is the key point of MIMAS process.
- MIMAS process allows an on-line recycling of almost all the scraps.
- MIMAS process performances and reliability are world-wide recognized.
- More than 30 years operational experience in reactors (PWR & BWR) have demonstrated the high quality of MOX fuel fabricated by the COGEMA group.
- MOX fuel behavior in reactor is similar to UO₂ fuel, in normal and incidental conditions.
The fuel fabrication process

1. Powder blend
2. Pressing or pelletizing
3. Sintering
4. Grinding
5. Rod cladding
6. Assemblies fabrication
37 commercial LWR loaded with MOX significant cumulative production of MOX

**In Japan**
- Delivery of 60 MOX fuel assemblies to TEPCO in 1999 and 2001
- 10 utilities committed to load MOX

**En Europe**
36 «moxified» reactors

- ELECTRABEL
- E-ON, GKN, RWE, EnKK
- EDF
- NOK, KGD
- KEPCO, KYUSHU, JAPCO, SHIKOKU, HOKKAIDO
- TEPCO, CHUBU, CHUGOKU, JAPCO, TOHOKU, HOKURIKU
• 4,122 MOX fuel assemblies delivered to customers by end of 2004.
  – 83% of whom for PWR
  – 17% of whom for BWR
## MOX review in Europe

<table>
<thead>
<tr>
<th></th>
<th>Reactors in operation</th>
<th>MOX authorized reactors</th>
<th>&quot;Moxified&quot; reactors</th>
<th>First MOX loading date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germany</td>
<td>21</td>
<td>11</td>
<td>11</td>
<td>1972</td>
</tr>
<tr>
<td>Switzerland</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>1984</td>
</tr>
<tr>
<td>France</td>
<td>58</td>
<td>20</td>
<td>20</td>
<td>1987</td>
</tr>
<tr>
<td>Belgium</td>
<td>7</td>
<td>2</td>
<td>2</td>
<td>1995</td>
</tr>
</tbody>
</table>

MOX, a recycling solution used for more than 30 years
• In France: 58 reactors in operation, 20 "moxified" reactors with 1/3 MOX in the core*

**MOX loaded reactors**

**Technically capable reactors**
- Gravelines C5 et C6
- Blayais 3 et 4
- Cruas 1 à 4

* EPR: 100% moxification possible
3rd generation: improving the backend of the fuel cycle: Higher flexibility for MOX

Increased capacity for consuming Plutonium

Possibility of cores with 100% MOX

Net balance of Plutonium in Kg Pu/year

- PWR 900 UO₂: +200
- PWR 900 MOX: 0
- EPR 100% MOX: -670
The studies about the Thorium cycle have stopped in 1970/1980 but some new interest arises in 90’:

- Possibility of a higher Pu consumption with Th matrix
- Minimizing the wastes radiotoxicity and the MA production

with today questions about natural resources and the capability for Thorium to replace Uranium.
Thorium : natural resources

<table>
<thead>
<tr>
<th></th>
<th>Réserves (Mt)</th>
<th>Ressources (Mt)</th>
<th>Average natural abundance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranium</td>
<td>4</td>
<td>12 (conventionnal)</td>
<td>2 à 4 ppm (earth's crust)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 (unconventionnal, sea water excepted)</td>
<td>3.3 ppb (sea water)</td>
</tr>
<tr>
<td>Thorium</td>
<td>1.5</td>
<td>4.1 (conventionnal)</td>
<td>5 à 10 ppm (earth's crust)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.5 ppb (sea water)</td>
</tr>
</tbody>
</table>

- **Estimation : two times more Thorium than Uranium**
- Radioactive period is three times larger
- But the accessibility is lower

- **Thorium is localized mainly in Asia (India) and South America (Brasil)**
Thorium : main isotopes

<table>
<thead>
<tr>
<th>Thorium</th>
<th>Uranium</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$^{235}\text{U}$</td>
</tr>
<tr>
<td>100 %</td>
<td>0.70 %</td>
</tr>
<tr>
<td>fertile</td>
<td>fissile</td>
</tr>
</tbody>
</table>

$^{232}\text{Th} + 1 \text{ neutron} \rightarrow ^{233}\text{Pa} (27.4 \text{ j, } \beta^{-}) \rightarrow ^{233}\text{U} + 1 \text{ neutron}$

$^{238}\text{U} + 1 \text{ neutron} \rightarrow ^{239}\text{Np} (2.3 \text{ j, } \beta^{-}) \rightarrow ^{239}\text{Pu} + 1 \text{ neutron}$
Thorium : neutronical properties

<table>
<thead>
<tr>
<th>Fissile Isotopes</th>
<th>$^{235}\text{U}$</th>
<th>$^{239}\text{Pu}$</th>
<th>$^{233}\text{U}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal</td>
<td>Fast</td>
<td>Thermal</td>
</tr>
<tr>
<td>$\sigma_f$ (barn)</td>
<td>582</td>
<td>1,81</td>
<td>743</td>
</tr>
<tr>
<td>$\sigma_c$ (barn)</td>
<td>101</td>
<td>0,52</td>
<td>270</td>
</tr>
<tr>
<td>$\alpha = \sigma_c / \sigma_f$</td>
<td>0,17</td>
<td>0,29</td>
<td>0,36</td>
</tr>
<tr>
<td>$\nu$</td>
<td>2,42</td>
<td>2,43</td>
<td>2,87</td>
</tr>
<tr>
<td>$\eta^{-1}$</td>
<td>1,07</td>
<td>0,88</td>
<td>1,11</td>
</tr>
<tr>
<td>$\beta_{\text{eff}}$</td>
<td>650 pcm</td>
<td></td>
<td>210 pcm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Isotopes fertiles</th>
<th>$^{238}\text{U}$</th>
<th>$^{232}\text{Th}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Thermal</td>
<td>Fast</td>
</tr>
<tr>
<td>$\sigma_c$ (barn)</td>
<td>2,73</td>
<td>0,32</td>
</tr>
<tr>
<td>$\beta_{\text{eff}}$</td>
<td>1480</td>
<td></td>
</tr>
</tbody>
</table>

Thorium cycle ($^{232}\text{Th}$, $^{233}\text{U}$) will perform the best in thermal or epithermal spectra.
Recyclage de l'ensemble des actinides

- MOX 1
- U naturel pour cycle ouvert
- Th/Pu 2
- FISSION 5
- U / Th / Pu 2
- Th/U 1

Dose (n+γ) | Fuel Fabrication | Spent fuel management
--- | --- | ---
MOX | 1 | 1
Th/Pu | 2 | 5
U / Th / Pu | 2 | 30400 (γ >> n)
Th/U | 1 | 13100 (γ >> n)

➢ **hot cells, and automatic remote-controlled facility, are needed for Thorium cycle**

➢ **No clear advantage for radiotoxicity**
## Thorium cycle: Historic

<table>
<thead>
<tr>
<th>Location</th>
<th>Reactor Type</th>
<th>Power (MWe)</th>
<th>Temp (°C)</th>
<th>Fuel Composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indian Point</td>
<td>PWR</td>
<td>162</td>
<td>62-80</td>
<td>Th + U 93%</td>
</tr>
<tr>
<td>Elk River</td>
<td>BWR</td>
<td>22</td>
<td>63-68</td>
<td>Th + U 93%</td>
</tr>
<tr>
<td>Shippingport</td>
<td>REP</td>
<td>60</td>
<td>77-82</td>
<td>Th + U233, FIR 1.01</td>
</tr>
<tr>
<td>Peach Bottom</td>
<td>HTR</td>
<td>40</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dragon</td>
<td>HTR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AVR</td>
<td>HTR</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MSRE</td>
<td>MSR</td>
<td>7.5</td>
<td>65-69</td>
<td></td>
</tr>
</tbody>
</table>
Le Retour d'Expérience des HTR. Des prototypes de réacteurs HTR ont été réalisés dans les années 60 à 90.

<table>
<thead>
<tr>
<th>EXPERIMENTAL REACTORS</th>
<th>DEMONSTRATION OF BASIC HTGR TECHNOLOGY</th>
</tr>
</thead>
<tbody>
<tr>
<td>DRAGON (U.K.)</td>
<td>THTR (FRG)</td>
</tr>
<tr>
<td>AVR (FRG)</td>
<td></td>
</tr>
<tr>
<td>PEACH BOTTOM 1 (U.S.A.)</td>
<td></td>
</tr>
<tr>
<td>FORT ST. VRAIN (U.S.A.)</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DRAGON</th>
<th>Peach Bottom</th>
<th>AVR</th>
<th>Fort Saint Vrain</th>
<th>THTR300</th>
<th>HTTR</th>
<th>HTR10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lieu</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winfrith (GB)</td>
<td>Pennsylvanie (EU)</td>
<td>Jülich (Allemagne)</td>
<td>Colorado (EU)</td>
<td>Schmehausen (Allemagne)</td>
<td>Oarai (Japon)</td>
<td>(Chine)</td>
</tr>
<tr>
<td>MWth</td>
<td>20</td>
<td>115.5</td>
<td>46</td>
<td>842</td>
<td>750</td>
<td>30</td>
</tr>
<tr>
<td>MWe</td>
<td>40</td>
<td>15</td>
<td>330</td>
<td>300</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pression He (bar)</td>
<td>20</td>
<td>24.6</td>
<td>10</td>
<td>48</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>T entrée</td>
<td>335</td>
<td>343</td>
<td>175</td>
<td>406</td>
<td>262</td>
<td>395</td>
</tr>
<tr>
<td>T sortie</td>
<td>835</td>
<td>715</td>
<td>850</td>
<td>785</td>
<td>750</td>
<td>850-950</td>
</tr>
<tr>
<td>Puissance volumique (MW/m³)</td>
<td>14</td>
<td>8.3</td>
<td>2.3</td>
<td>6.3</td>
<td>6</td>
<td>2.5</td>
</tr>
<tr>
<td>Eléments combustible</td>
<td>primes</td>
<td>prisms</td>
<td>boulets</td>
<td>prisms</td>
<td>boulets</td>
<td>prisms</td>
</tr>
<tr>
<td>Cycle</td>
<td>varié</td>
<td>U/Th</td>
<td>U5/Th</td>
<td>U5/th</td>
<td>U5/Th</td>
<td>U enrichi</td>
</tr>
</tbody>
</table>
Thorium: Summary

- Natural resource larger than uranium
- Physical properties favourable in thermal and epithermal spectra
- Past experience in PWR, HTR and MSR
- Small advantage for waste radiotoxicity before 10,000 years

but

- U5 or Pu needed for starting
- Fuel cycle closing has not be demonstrated
- Penalties compared to Uranium in fuel cycle facilities and necessity to create specific facilities
Development of future nuclear energy systems

- Technical maturity by 2030
- With significant advances in:
  - Sustainability
  - Safety and reliability
  - Proliferation and physical protection
  - Economics
- Competitive in various markets
- Designed for different applications
  - Electricity, Hydrogen Desalinated water, Heat
Generation IV: systems selected

6 Innovative concepts with technological breakthroughs

- Sodium Fast Reactor
  - Closed Fuel Cycle
- Lead Fast Reactor
  - Once Through
  - Closed Fuel Cycle
- Gas Fast Reactor
  - Once/Closed
  - Closed Fuel Cycle
- Very High Temperature Reactor
  - Once Through
- Supercritical Water Reactor
  - Once/Closed
- Molten Salt Reactor
  - Closed Fuel Cycle
Generation IV fuel cycle options

- Recycling of all Actinides
- Group separation of all Actinides
- Integration of treatment and re-fabrication processes and technologies
- Minimizing waste

Drastic reduction of ultimate waste long-term radio-toxicity

Process of “external gelation”
Sodium Fast Reactor SFR

- A new generation of sodium cooled Fast Reactors
- Reduced investment cost
- Simplified design, system innovations
  (Pool/Loop design, ISIR – SC CO₂ PCS)
- Towards a passive safety approach
- Integral recycling of actinides
- Remote fabrication of TRU fuel


SFR Steering Committee

France

U.S.A.

Euratom countries

United Kingdom

Japan

South Korea
CEA contribution for Advanced fuels SFR

• Advanced Fuel Fabrication
  – SUPERFACT Irradiation (Synthesis documents are available at JNC)
  – FUTURIX fuel fabrication
  – METAPHIX (Joint study with EU under collaboration of CEA)
  – Technological developments for Remote Fabrication: innovative equipments; simulation
  – Remote fabrication (FR) e.g. at MELOX (MOX) and ATALANTE (for experimental fuels)
  – Current PHENIX irradiations including SOL GEL fuels

• Irradiation behaviour of advanced fuels
  – CAPRIX high Pu content fuels in Phenix
  – SUPERFACT MA bearing oxide fuel in Phenix
  – FUTURIX irradiation
  – PIE of experiments on nitride fuel from Phenix [FUTURIX irradiation] and current irradiation in BOR-60: BORA BORA
  – CONFIRM irradiation in R2 of Studsvik
  – NIMPHE 1 & 2
  – METAPHIX (Joint study with EU under collaboration of CEA)

• Advanced core material
  – 12YWT material irradiation in OSIRIS
  – Current PHENIX irradiations including advanced austenitic materials

• Tools for core design
  – Set of available CEA computer codes
A new concept of Gas cooled Fast Reactor
→ Natural uranium resource saving, minimum production of waste

- Robust fuel (*ceramics*)
- 1200 MWe – t He ~ 850 °C – Co-generation (*electricity + H2*)
- Active + passive safety approach
- Integral recycling of actinides
- Remote fabrication of TRU fuel

→ 2012: Feasibility - 2017: ETDR
2020: Performance → 2025+: GFR Demo
GFR Candidate Fuel Concepts

- I-NERI on-going with the US

Composite Fuel (ceramics)

Advanced fuel Particles

Fuel Pins

0 25 50

40 % Gas
10 % Structures

% vol Actinides Compound

Nuclear Energy Division

Workshop on Modelling and Quality Control for Advanced and Innovative Technologies”– Trieste, November 14-25, 2005
Concept plaque à pastilles (ex-dispersé)

UPuC, 85%dth, 100MW/m$^3$

1MW/m$^2$

Ceramique composite

Joint gazeux

Composé d’actinides

Barrière de diffusion
Métal réfractaire (Mo, W, ...)

Nuclear Energy Division
Plaque à pastilles : schéma conceptuel actuel

Céramique « avancée »
Composé d’actinides
Plan de fermeture
Espace gaz
Liner (métal, x…)

H = 5 mm
D = 11.2 mm

Pas hexagonal: 14mm
Epaissseur des plaques d’échange: 1mm
Epaissseur des voiles hexagonaux: 1mm
Epaissseur de liner: 50 –100µm
320W max par pastille

~1 MW/m² max de surface d’échange
Dimensions plaque: 12x25 cm
Nombre de pastilles par plaques: 168
Nombre de plaques dans un cœur de 2400 MW: ~63000
Compatible avec une densité de puissance de 100MW/m³

Céramiques avancées:
Composite SiC-SiCf, f= Hi NICALON Stoechiométrique
Interfaces et interphases à définir (SiC, 11BN, PyC?…)
Travail sur fibres nanostructurées, évaluation du ZrC, du Ti₃SiC₂
Densification par imprégnation, ...
Matériaux d’étanchéité:
W-Re, Mo, Mo-Re, Ti, Nb, V, Cr
Traitements de surface éventuels à définir
ANTARES Design

A specific fuel concept

- TRISO particles
- Graphite
- Hélium

Double hétérogénéity:
- Particule
- Compact
Objectives for the MSR

- Regeneration with U-Th cycle
- Epithermal neutrons
- 1700 MWth - 800 °C
- Coupling to process heat applications
- Effective capacity of regeneration?
- Corrosion of structural materials
- Treatment of used salt
- Deployable around 2035

Main CEA activity on safety issues & pyrochemistry
Perspective for reprocessing
Gen IV Systems: an integrated cycle with full actinide recycling

A drastic minimization of ultimate waste:
- Very small volumes,
- Decrease the heat loading
- hundreds of years versus hundreds of thousands

An optimal use of energetic materials
Requirements

- High actinide recycling is of most importance (close or even better than 99%) as it impacts directly the potential of radioactivity of the final waste.

- Actinide grouped separation: managing the actinides altogether is good for simplifying the cycle (number of fluxes) and enhancing the resistance to proliferation risk.

- If possible, it is better to avoid blankets for proliferation risk, but also because it increases the amount of fuel to be reprocessed.
### « Unit operations » in the fuel cycle

<table>
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<tr>
<th>Head end processes</th>
<th>Dismantling</th>
<th>Reactor dependent</th>
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<tr>
<td></td>
<td>Waste management</td>
<td>Cross-cutting</td>
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</table>
Grouped Actinides Extraction: the GANEX Process

Diagram:
- **Used fuel**
  - Dissolution
    - **U** Preliminary Separation
      - An + Ln Co-Extraction
        - F.P.
        - Actinides Recycling
          - U (70 % min)
            - U, Pu
            - M.A.
      - An Back-Extraction
      - Ln Back-Extraction
    - Glasses

- **Solvent Recycling**
- **Actinides Recycling**
- **GANEX**
Example of technological blocks implementation

External impregnation

Pulsed currents destruction

Dissolution HNO₃

Clarification

Gas treatment

$^{85}$Kr, $^3$H

I₂, $^{14}$C

Si

Glass

FP

Solgel

AnC

An

U nat

GANEX

Dissolution HNO₃
Global Actinide management: technology demonstrations

- Term of 1991 Act
- Deployment of EPR
- Deployment of Gen IV FNS

Pu Mono-recycling & Spent MOX Int. storage
Spent MOX fuel treatment

Optimized Actinides Management

Optimization Workshop

PWR Fuel

Démo.

Partitioning Pilot plant
Transmut. Demo
GANEX Demo
MONJU

Qualification of waste packaging and interim storage (CECER)
SFR R&D : Fuel Cycle

• The GEN IV goal is to develop an integrated approach based on recycling of all the actinides in such a way that the actual waste to be definitely disposed will only be the fission products.

  This matter is a cross-cutting project with other GEN IV systems.

• Aqueous processes:
  – specifically suited for the treatment of ceramics fuels (oxydes, nitrides, carbides), the objective is to benefit from the very large industrial experience gained with current PWR and BWR fuels reprocessing while coping with the new SFR criteria.

• Pyroprocessing:
  – It is the natural choice for the treatment of metallic fuels which are still considered for the SFR. The program, run in collaboration with the EC (6th Framework Program), Japan and the US, focuses on the actinides separation feasibility (this has never been fully demonstrated yet).
R&D Axes (1) : dismantling

Strong incentive to improve dismantling (including fuel chopping and crushing technologies, sodium distillation and reduction technologies) for:

- Minimizing the volume of ultimate high activity waste
- Optimizing the interface with the dissolution step and the ancillary activities (gas trapping, waste production and management)
- Increasing the dissolution rate
- Reducing the inclusion of cladding/spurious materials inside the fuel solution
R&D Axes (2)

- **Dissolution**: R&D to focus on the assessment of the dissolution procedures for pyrometallurgy (with oxide or metal). No need for hydrometallurgy in the viability phase.

- **Separation**: Complementary R&D program for hydrometallurgy in order to validate the concepts and select one or two concepts for process development. For pyrometallurgy fundamental research is needed on process chemistry and engineering. Chloride or fluoride media, separation performance of molten salt, electrodeposition or precipitation have to be examined.

- **FP confinement**: In hydrometallurgy glass and vitrification to optimize. For pyrometallurgy nothing is proved today and the containment material has to be defined.
R&D Axes (3) : waste management

- **Hydrometallurgy**:
  - Treatment of organic solvent
  - Management of specific chemicals used for oxidation and reduction reactions procedures for pyrometallurgy (with oxide or metal). No need for hydrometallurgy in the viability phase.

- **Pyrometallurgy**:
  - To estimate the waste composition
  - To find the suitable treatment
  - To find stable condition process