TOWARDS GENERATION IV NUCLEAR SYSTEMS:
THE ASTRID PROGRAM

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1 - The current French nuclear fuel cycle
2 – Generation IV Systems: incentives and options
3 – The ASTRID program

Sino-French Seminar on the Back-End of the Nuclear Fuel Cycle
Beijing, 4-5 November, 2015
1 – THE CURRENT FRENCH NUCLEAR FUEL CYCLE
THE FRENCH NUCLEAR FLEET

Nuclear net capacity (Gwe)

La Hague

MELOX

58 LWR
24 licenced for MOX
4 licenced for REU

1st MOX fuel in LWR


900
1300
1500 MW
Total

900 MW
1.300 MW
1.500 MW

THE FRENCH NUCLEAR FLEET

MELOX

N4

La Hague

58 LWR
24 licenced for MOX
4 licenced for REU

1st MOX fuel in LWR


900
1300
1500 MW
Total

Nuclear net capacity (Gwe)
The principle of the French fuel cycle (rough amounts, per year):

- **Mining and milling**:
  - Natural U #8000 t

- **Uranium conversion**:
  - DEpleted RU #860 t

- **Uranium enrichment**:
  - Depleted uranium #7000 t
  - (REU 80 t)

- **Fuel fabrication**:
  - UOX 1000 t
  - (MOX 120 t)

- **LWRs**:

- **Recycling**:
  - Used MOX #120 t
  - Used REU #80 t
  - Used UOX 1000 t
  - Plutonium #10 t
  - Waste FPs & MAs #50 t
  - Uranium (RU) #940 t

- **THE PRINCIPLE OF THE FRENCH FUEL CYCLE (rough amounts, per year)**
RECYCLING TECHNOLOGIES:
DECADES R&D!

-high yields...

...technological waste
low amount
FINAL WASTE VITRIFICATION

#15% FPs

180 liters

# 17,000 glass canisters produced

# 10-15 glass canisters /reactor /per year
USED FUEL RECYCLING IN FRANCE

La Hague plant (UNF tons)

> 30 000 tons processed

MOX/REU Fuel re-loading (sub-assemblies)

# 2000 tons MOX fuel manufactured
CURRENT RECYCLING STRATEGY: THE RATIONALE

- saving uranium resources
  (#10% of French nuclear electricity from MOX fuels)

- safe & secure ultimate waste without plutonium;
  (volume, heat load, radiotoxicity decreased)

- mastering the growth of plutonium inventory
  (Pu flux adequacy: Pu from processing = Pu refueled)

- plutonium safely concentrated in used MOX fuels
  (available for future use)
GLASS CANISTERS DISPOSAL

~ 1μm /1000 years
(steady state, 25 °C)

MAXIMUM DOSE (Sv/year) →

TIME AFTER DISPOSAL →

1mSv/y

1μSv/y

100 000 y

1 M y

NP AFTER 200 000 Y (MOL/M3)

(from Andra)

(ANDRA, « CLAY REPORT », 2005)
2 – GENERATION IV: INCENTIVES & OPTIONS
2005 : FRENCH ACT ABOUT ENERGY
(Nuclear Energy : research on advanced systems )

2006 : FRENCH ACT about SUSTAINABLE MANAGEMENT OF NUCLEAR MATERIALS & WASTE
- *recycle* (decrease waste amounts);
- retrievable geological repository for final waste

2015 : “ENERGY TRANSITION and GREEN GROWTH” ACT
- *decrease GHG emissions*, fossil fuels and energy consumption
- *diversify power generation sources*:
  - Nuclear power capped at 63.2 Gwe *(current value)*
  - Target: 50% nuclear share around 2025
Declaration from Manuel VALLS, Prime Minister:

« Nuclear is an energy of the future. It is essential for our sovereignty and to fight global warming »

« …Gen IV reactors will allow to multirecycle the fuel and strengthen our supply security. These reactors of tomorrow must be a priority for R&D works, especially in CEA. »

[WNE, Paris, 2014]

Statement from Ségolène ROYAL, Minister for ecology, sustainable development and energy:

« the goal is to use the operational feedback of Gen III reactors (EPR, ATMEA1) and to prepare the Gen IV reactors, which will use less fuel, and will have integrated recycling capabilities, producing a lesser amount of less active radioactive wastes »

[ January 2015]
Pu burning in FRs favors Pu fission, allowing Pu multi-recycle

(1) **Systematic U & Pu recycle**, (2) in **fast neutron reactors**
- for a sustainable management of nuclear materials & waste,
- avoiding increasing of Pu-bearing stockpiles,
- opening the way to a drastic extension of the use of U resource
Pu stored in MOX SNF to launch FR deployment

FROM CURRENT FUEL CYCLE... TO FAST REACTORS FUEL CYCLES

CURRENT FRENCH FUEL CYCLE (LIGHT WATER REACTORS)

CURRENT FRENCH FUEL CYCLE (LIGHT WATER REACTORS)

WHICH TRANSITION SCENARIOS

URANIUM-PLUTONIUM MULTIRECYCLE (FAST NEUTRON REACTORS)
Uraniun among other resources...

- Coal: 50 Gtoe
- Oil: 420 Gtoe
- Gas: 160 Gtoe

Uranium use in thermal neutrons (current) reactors

Identified conventional resource

(BP statistical review, 2013 and OECD/NEA, 2012)
(Oil 235 Gt, Coal 860 Gt, Gas 187 Tm³, Uranium 4 Mt)
COAL: 420 Gtoe
OIL: 230 Gtoe
GAS: 160 Gtoe

Identified conventional resource
(BP statistical review, 2013 and OECD/NEA, 2012)
(OIL 235 Gt, COAL 860 Gt, GAS 187 Tm³, URANIUM 4 Mt)

Uranium use in thermal neutrons (current) reactors

Uranium & Plutonium multirecycled (in fast neutron reactors)
Minor actinide removal could provide an optimization of final waste management:
- by decreasing waste long-term radiotoxicity
- by decreasing the repository footprint (Am recycle mainly)

Fast neutron reactors incentives:
- MA production: 3-5 times lower in FR (vs. LWR)
- MA transmutation: possibly quantitative in FR (MA multi-recycle)
MINOR ACTINIDES TRANSMUTATION: DRIVERS...

1500 ha total, among which 1175 ha HLW, 7 Mm3 excavated

430 ha total, among which 120 ha HLW, 3 Mm3 excavated

[Andra-CEA 2012, cooling phase 120 years]

REPOSITORY FOOTPRINT

Glass canisters residual heat (diverse fuel cycle options)

- No transmutation
- Current glasses
- Am transmutation

Glass canister heat (W)

Relative radiotoxicity

Time (years)

Time (years)

U-ore
INCREASING SUSTAINABILITY BY RECYCLING …

no recycle (« once through »)

U Pu recycling in LWRs

U Pu multi-recycling in FRs

All TRU recycling…

HLW VOLUME

Once through

Pu recycle

all-TRU recycle

HLW « FOOTPRINT »
3 THE ASTRID PROGRAM
- Sodium Fast Reactor, the reference option: [ASTRID, the technology demonstrator]
  - maturity, possible further improvements (safety, operability, economics)

- Gas-cooled Fast Reactor, a long-term option:
  - attractive potentialities but heavy challenges...
THE ASTRID PROGRAM

- 600 Mwe, sodium-cooled, « pool-type »
- oxyde fuel
- transmutation capabilities
- Innovative design:
  - self-sustainable safer core
  - core catcher, residual heat removal
  - power conversion system

LARGE COOPERATIVE FRAME:
- RESEARCH and INDUSTRIAL BODIES
- FRENCH and INTERNATIONAL BODIES (AREVA, EDF, ALSTOM)

[staff involved : about 600]
ASTRID FUEL CYCLE

Reprocessing

Pu from MOX-LWR

1st STEP

2nd STEP

Astrid

Appropriate Fuel Cycle facilities
**FR-MOX FUEL FABRICATION**

Oxyde SFR fuels fabrications in ATPu between 1963 and 1999

<table>
<thead>
<tr>
<th>Réactors</th>
<th>Nb of pins</th>
<th>Nb of pellets (millions)</th>
<th>Pellets ($t_{HM}$)</th>
<th>Pu ($t_{HM}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapsodie</td>
<td>28 536</td>
<td>1</td>
<td>1,2</td>
<td>0,35</td>
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<tr>
<td>Phénix</td>
<td>180 941</td>
<td>12,6</td>
<td>32,4</td>
<td>8,2</td>
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<tr>
<td>Super-Phénix</td>
<td>208 396</td>
<td>16,9</td>
<td>71,2</td>
<td>12,7</td>
</tr>
<tr>
<td>PFR (GB)</td>
<td>9 555</td>
<td>0,7</td>
<td>1,6</td>
<td>0,54</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>427 428</strong></td>
<td><strong>31,2</strong></td>
<td><strong>106,4</strong></td>
<td><strong>21,8</strong></td>
</tr>
</tbody>
</table>

**FR-MOX FUEL REPROCESSING**

25 tons PHENIX fuel reprocessed at La Hague and Marcoule
DOZENS PINS and THOUSANDS UPuO2 PELLETS

June 2015: FIRST CAMPAIGN in MELOX plant (300 pellets)
*MINOR ACTINIDE P&T: ON GOING R&D*

**The «integral experiment» for Am P&T**

- **Used fuel (#4kg)**
- **Dissolution**
- **U et Pu separation**
- **Concentration**
- **Am separation**
- **EXAm**
- **Co-precipitation (U,Am)**
- **Pellets (U,Am)O₂**

**Timeline:**
- 2010: Dissolution
- 2011: U et Pu separation
- 2013: Concentration
- 2014: Am separation EXAm
- 2014: Concentration Am
- 2014: Co-precipitation (U,Am)
- 2015: Pellets (U,Am)O₂

**Notes:**
- The «integral experiment» for Am P&T used fuel (#4kg) in-pile Transmutation.
THANK YOU FOR YOUR ATTENTION!

INPRO Dialogue Forum on Cooperative Approaches to the Back End of the Nuclear Fuel Cycle
Vienna, May 2015