FUTURE NUCLEAR FUEL CYCLES: GUIDELINES...

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Program Director, Nuclear Fuel Cycle Back-end

1. The current french nuclear fuel cycle
2. Towards sustainable nuclear systems
3. Drivers for R&D
Nuclear fuel cycle in France – Status & prospects

**THE PRINCIPLE OF THE FRENCH CLOSED FUEL CYCLE**
(approximative amounts/year)

- **Uranium (RU)** #950 t
- **Plutonium** #10 t
- **Depleted uranium** #7000 t
- **Natural U** #8000 t
- **Uranium conversion**
- **Uranium enrichment**
- **Mining and milling**
- **Fuel fabrication**
- **LWRs**
- **Recycling**
- **Used MOX** #100 t
- **Used REU** #150 t
- **Used UOX** 1000 t
- **Waste FPs and MAs** 40 t

**FINAL WASTE VITRIFICATION**

- #15% FPs
- 180 liters

# 10-15 glass canisters /reactor /per year
GLASS CANISTERS DISPOSAL

(ANDRA, « CLAY REPORT », 2005)

DOSE AT FINAL OUTLET

#1 μm/50d, early stages
#1 μm/1000 years, steady state

CURRENT RECYCLING STRATEGY:

THE RATIONALE

- saving uranium resources
  (#10% of French nuclear electricity from MOX fuels);
- mastering the growth of plutonium inventory
  (Pu flux adequacy: Pu from processing= Pu refueled)
- safe & secure ultimate waste without plutonium;
- the plutonium available for future use is concentrated in MOX spent fuels (7 UOX → 1 MOX);
- an already large industrial experience, operated under international safeguards
  (#25 000 tons reprocessed, # 2000 tons MOX)
- suitable option for Generation III reactors
LONG TERM SUSTAINABLE NUCLEAR SYSTEMS

- **RECYCLE**, (2) **IN FAST REACTORS**…
- efficient burning of plutonium,
- full use of uranium,
- potentialities for improving waste management,
- no enrichment needs

**FOSSILE FUELS POTENTIAL RESERVES**

Identified conventional resources, Gtoe

1 (mémento sur l’énergie, CEA, 2010)

(Pétrole 165 Gt, charbon 826 Gt, gaz 180 Tm³, uranium 3,3Mt)

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Main contributors to intrinsic toxicity

Pu>MAs>>>FPs

Estimated dose, Saulx, spent fuel
(Andra, rapport argile, 2005)

SPENT FUEL TOXICITY

Main contributors to intrinsic toxicity

Total combustible
Plutonium
Uranium
Actinides minor
Produits de fission

Inventaire radiotoxique (Sv/TWh e)

Temps (années)

Main contributors to intrinsic toxicity

Pu>MAs>>>FPs

FUEL FABRICATION

MOX-FR
450t

FRs

used MOX-FR
450t

RECYCLING

WASTE FFpS
(MAs)
(40t)

ACTINIDE MULTI-RECYCLE IN A FR FLEET
(principle values, self-balanced fleet, 400 TWh/y)

depleted uranium (40I)

plutonium (#20%)

uranium (#80%)

(minor actinides (# 5t))
LONG TERM SUSTAINABLE NUCLEAR SYSTEMS

- efficient burning of plutonium,
- full use of uranium,
- potentialities for improving waste management,
- no enrichment needs

A progressive deployment?

- initially fueled with plutonium coming from spent MOX
- FR/LWR deployment could be adjusted in the future (according to energy needs)
- able to recycle more - in a later step - (transmutation of “minor actinides”…)

FROM LWRs TO FRs… A SCHEMATIC PATHWAY
TOWARDS SUSTAINABLE NUCLEAR SYSTEMS

- reactors?

- fuel cycle technologies?

- deployment dynamics (strategy)?

FAST REACTORS DEVELOPMENT: FRENCH STRATEGY

- Sodium Fast Reactor, the reference option: ASTRID, the prototype
  - maturity, possible further improvements (safety, operability, economics)
  - commercial level 2040
  - developed with industrial and international partners

- Gas-cooled Fast Reactor, a long-term option: (ALLEGRO, experimental-scale project)
  - attractive potentialities but heavy challenges (materials, fuel, safety)
  - in Europe?
THE ASTRID FAST REACTOR PROTOTYPE

sodium-cooled pool type oxide fuel #600 Mwe

« Advanced Sodium-cooled Technological Reactor for Industrial Demonstration »

TOWARDS SUSTAINABLE NUCLEAR SYSTEMS

- reactors?
- fuel cycle technologies?
- deployment dynamics (strategy)?
RECYCLING TECHNOLOGIES

• FUEL: (MIXED) OXIDE (far future: carbide, metal…?)

• PROCESSING SNF: HYDRO-PROCESSES [reliability, high yields, low waste amount]

• FUEL MANUFACTURING: POWDERS BLENDING

RECYCLING TECHNOLOGIES : DECADES R&D!

U, Pu, FPs, MAs solution

high yields…

…technological waste low amounts
RECYCLING: GUIDELINES FOR R&D…

1-ADAPTATION
(HBU, MOX fuels,…
…FR fuels!…)
FAST REACTOR OXIDE FUELS

many differences FR fuels / LWR fuels

Fuel sub-assembly, structure elements

Higher Pu content
Higher In-core temperature
Higher burn-up
Fission products resp. yields

FAST REACTORS OXIDE FUELS FABRICATION

Fabrications de combustibles oxydés pour RNR de 1963 à 1999

<table>
<thead>
<tr>
<th>Reactor</th>
<th>Nb. of fuel elements</th>
<th>Nb. of pellets (tons)</th>
<th>Pellets (Pct.)</th>
<th>Mass Pu (t)</th>
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<tbody>
<tr>
<td>Phenix</td>
<td>28 528</td>
<td>1</td>
<td>12.6</td>
<td>32.4</td>
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<tr>
<td>Super-Phenix</td>
<td>208 366</td>
<td>16.8</td>
<td>71.2</td>
<td>12.7</td>
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<tr>
<td>PPF (GB)</td>
<td>9 555</td>
<td>0.7</td>
<td>1.6</td>
<td>0.54</td>
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<tr>
<td>Total</td>
<td>427 429</td>
<td>31.2</td>
<td>(106.4)</td>
<td>(21.0)</td>
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</table>
PROCESSING FR FUELS

Process adaptation needed…

- Fuel dissolution (dismantling, dissolving)
- U-Pu (AM) /PF separations (performance required?)
- Liquid to solid conversion (high Pu flux)
- Structure elements management (nature, amount, radioactivity)
- FPs vitrification (platinoids)
- Criticality risk management (specific design)

Pu RECYCLE IN PHÉNIX

1973 : start of operation
1980 : 1er sub-assembly loaded with recycled Pu

520 sub-assemblies processed
4.4 t Pu recycled
RECYCLING: GUIDELINES FOR R&D...

1-ADAPTATION
(innovative fuels)

2-IMPROVEMENTS
(a « sustainable goal »…)

THE COEX CONCEPT

• no pure plutonium
• a solid solution (U,Pu)O2

VITRIFICATION: *THE COLD CRUCIBLE TECHNOLOGY*

- Cooled wall, direct induction heating
- Corrosion issues drastically decreased
- Higher temperature, higher reactivity

**in operation at La Hague, 2010**

**RECYCLING: GUIDELINES FOR R&D…**

1-ADAPTATION  
(innovative fuels)

2-IMPROVEMENTS  
(a « sustainable goal »…)

3-EXPLORATION P&T  
(minor actinide recycle)
**MINOR ACTINIDE IN SPENT FUEL**

![Table](image)

**MINOR ACTINIDE RECYCLING**

**WHAT ARE THE DRIVERS?**

Minor actinide transmutation may provide:

- A drastic decrease of long term radiotoxicity of final waste
- A significant decrease of the repository footprint

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**FINAL WASTE RADIOTOXICITY**

**REPOSITORY « FOOTPRINT »**
THE 2006 FRENCH ACT
(RW & nuclear materials management)

PRINCIPLES:

- **RECYCLE** (reprocess)
  to decrease waste amount & toxicity

- **RETRIEVABLE GEOLOGICAL REPOSITORY**, for ultimate waste

⇒ A « ROADMAP »:

- **2012**: assess the industrial potentialities of advanced recycling options (prototype 2020)

- **2015**: repository defined (operation by 2025)

MA PARTITIONING

innovative partitioning processes developed by CEA based on the design of new extractants

MA recovery processes have been successfully experimented, (kgs -sale, genuine spent fuel)
MA RECYCLING OPTIONS

HOMOGENEOUS (diluted in the fuel) (#1% MA)
The GACID experiment in MONJU!

HETEROGENEOUS:
« once through targets » (inert matrix)
multi-recycled «MA-bearing blankets» (# 10-20% MA on UO2)

« DEDICATED STRATA » (ADS)

Am TRANSMUTATION

ECRIX H in PHENIX

90% transmuted
30% fissionned

Initial AmO3
Metals FPs

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AN OPTION FOR MA TRANSMUTATION:
“Am-bearing blankets”

CORE : UPuO₂

“BLANKETS” : UAmO₂

U-Pu

Pu

FP

U-AM

(Diagram showing the nuclear fuel cycle with core and blankets)

1-ADAPTATION (innovative fuels)

2-IMPROVEMENTS (a « sustainable goal »…)

3-EXPLORATION P&T (minor actinide recycle)

4- ALTERNATIVE PROCESSES ?? (« dry » processes…)

(Diagram showing fuel cycle technologies guidelines for R&D…)

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THE ATALANTE FACILITY

TOWARDS SUSTAINABLE NUCLEAR SYSTEMS

- reactors?
- fuel cycle technologies?
- deployment dynamics (strategy)?
**ASTRID PROTOTYPE Schedule**

- Preliminary choice of options
- Decision to continue
- Decision to build
- Fuel loading

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>2009</td>
<td>Conceptual design -1</td>
</tr>
<tr>
<td>2010</td>
<td>Conceptual design -2</td>
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<tr>
<td>2011</td>
<td>Basic design</td>
</tr>
<tr>
<td>2012</td>
<td>Detailed design &amp; Construction</td>
</tr>
<tr>
<td>2013</td>
<td>Facilities</td>
</tr>
<tr>
<td>2014</td>
<td>ASTRID</td>
</tr>
</tbody>
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- Feasibility Report on minor actinides partitioning
- Position Report on minor actinides partitioning and transmutation
- Core manufacturing workshop (AFC)
- MA bearing fuels fabrication facility (ALFA)

**ASTRID FUEL CYCLE**

- Initial Feed
- Fuel Fabrication
- ASTRID
- Spent fuel processing

1st goal: Pu & U multirecycle
ASTRID FUEL CYCLE

1st goal: Pu & U multirecycle
2nd: Minor Actinide (Am) recycle

FR DEPLOYMENT:
MANY DIVERSE OPTIONS...

Progressive substitution FRs/LWRs from 2040...???
FR DEPLOYMENT:

MANY DIVERSE OPTIONS...

FLEET AND FUELS WILL EVOLVE...

LWRs  FRs

TODAY  (HBU, MOX)

THEN? (feeding FRs)

THEN? (multi-recycle FRs)

THEN? (minor actinide recycle?)

processes & technologies: flexible, efficient, cost-effective, clean, proliferation-resistant...