1 - The current French nuclear fuel cycle
2 - Trends and possible options for the future
USED NUCLEAR FUELS

- **Uranium**: 94%
  - **Fission products**: 5%
  - **Plutonium**: 1%
  - **Minor actinides**: ~ 0.1%

**Used fuel stockpiles**:

- *a concern*:
  - fissile elements
  - radiotoxic
  - heat emitter

- *an asset*

(1g Pu ≈ 1 toe)
1 – THE CURRENT FRENCH NUCLEAR FUEL CYCLE
THE FRENCH NUCLEAR FLEET

Nuclear net capacity (Gwe)

- 900
- 1300
- 1500 MW
- Total

La Hague

MELOX

58 LWR
24 licenced for MOX
4 licenced for REU

THE FRENCH NUCLEAR FLEET

1st MOX fuel in LWR

1987:
THE PRINCIPLE OF THE FRENCH FUEL CYCLE (rough amounts, per year)

- **Mining and milling**: 8000 t natural U
- **Uranium Conversion**: 860 t depleted RU, 7000 t depleted uranium
- **Uranium enrichment**: 1000 t (UOX), 80 t (REU), 120 t (MOX)
- **Fuel fabrication**: 1000 t (UOX), 120 t (MOX)
- **LWRs**: 940 t Uranium (RU), 10 t Plutonium
- **Recycling**: 80 t REU, 50 t used FPs & MAs, 120 t used MOX, 1000 t used UOX

**Used materials**:
- UOX: 1000 t (UOX 1000 t)
- MOX: 120 t (MOX 120 t)
- Used UOX: 1000 t
- Used REU: 80 t
- Used MOX: 120 t
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

Used MOX fuel
(#70 tons processed)

MELOX plant

FBFC plant

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 CANISTER 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 - TRENDS & OPTIONS FOR THE FUTURE
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
FROM CURRENT FUEL CYCLE... TO FAST REACTORS FUEL CYCLES

WHICH TRANSITION SCENARIOS

CURRENT FRENCH FUEL CYCLE (LIGHT WATER REACTORS)

LWRs

Fuel fabrication
Uranium enrichment
Uranium Conversion
Mining and milling

USED MOX #120t
used UOX 1000 t
used REU #150t

depleted uranium 7000t

depleted RU 800t

natural U 8000t

Pu stored in MOX SNF to launch FR deployment

FRs

FUEL FABRICATION

MOX-FR 450t

used MOX-FR 450t

URANIUM-PLUTONIUM MULTIRECYCLE (FAST NEUTRON REACTORS)

FUll RECYCLING

depleted uranium 50t

Uranium (#80%)
Plutonium (#20%)
(minor actinides (# 5t))

WASTE FPs (MAs) 50t

uranium (RU) t...

used UOX 1000t
FR REACTORS DEPLOYMENT:
THE FORMER VIEWS

Current fleet

Life-time extension

# 60 GWe

 FR

# 2040

LWR

(?)
FR REACTORS DEPLOYMENT: CURRENT SCENARIO STUDIES

Stage 1: recycle used LWR-MOX
a few FR needed (3 – 5 GWe?)

Used MOX-LWR amount stabilized

Natural U

LWR-UOX Pu → LWR-MOX Pu → FR-MOX

Used FR-MOX
Stage 2: recycle FR-MOX

More FR needed ( #20 GWe)

Pu multi-recycled

Pu amount stabilized
FR REACTORS DEPLOYMENT: CURRENT SCENARIO STUDIES

Stage 3: only MOX fuels
No natural uranium needs
More FR needed (# >40 GWe)

Current fleet
# 60 GWe

2020 2050
FR REACTORS DEPLOYMENT: CURRENT SCENARIO STUDIES

EDF-AREVA-CEA joint studies

Stage 1: recycle used LWR-MOX
- a few FR needed (3 – 5 GWe?)
- Used MOX-LWR amount stabilized

Stage 2: multi-recycle FR-MOX
- More FR needed (#20 GWe)
- Pu amount stabilized

Stage 3: only MOX fuels
- No natural uranium needs
- More FR needed (# >40 GWe)

Current fleet

# 60 GWe

2025 ASTRID demonstrator

# 2050
# Fuel Cycle Options Performance Assessment

## (1) Nuclear Materials

**PRELIMINARY RESULTS**

<table>
<thead>
<tr>
<th></th>
<th>Open Cycle</th>
<th>Mono-Recycle LWR</th>
<th>Bi-Recycle LWR – (FR)</th>
<th>Multi-Recycle LWR - FR</th>
<th>Multi-Recycle no U needs FR</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNR share (GWe %)</td>
<td>0</td>
<td>0 %</td>
<td>5%</td>
<td>40%</td>
<td>100%</td>
</tr>
<tr>
<td>Natural U consumption (t/y)</td>
<td>8000</td>
<td>6500</td>
<td>6000</td>
<td>2500</td>
<td>0</td>
</tr>
<tr>
<td>Pu net Production (t/y)</td>
<td>+10,5</td>
<td>+7,5</td>
<td>+7</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Used fuels amount (t/y)</td>
<td>+1000 UOX</td>
<td>+160 MOX+REU</td>
<td>+100 RNR+REU</td>
<td>stabilized</td>
<td>stabilized</td>
</tr>
</tbody>
</table>

*CEA, report to be issued, July 2015*
*(scenario studies, AREVA-EDF-CEA, 420 TWh/year)*
*(HAVL footprint estimates from ANDRA-CEA studies)*

*(tons / year)*
### Preliminary Results

#### Fuel Cycle Options Performance Assessment

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<thead>
<tr>
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<th>MONO-RECYCLE</th>
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<tbody>
<tr>
<td></td>
<td>LWR</td>
<td>LWR</td>
<td>LWR-FR</td>
<td>FR</td>
</tr>
<tr>
<td>BACK-END ILW</td>
<td>0.07</td>
<td>0.6</td>
<td>0.6</td>
<td>1.4</td>
</tr>
<tr>
<td>((m^3/TWh))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BACK-END HLW</td>
<td>8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>((m^3/TWh))</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>USED FUELS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>((\text{tons/TWh}))</td>
<td>0.2 (REU)</td>
<td>0.2 (REU)</td>
<td>0.2 (REU)</td>
<td>0.06 (MOX-RNR)</td>
</tr>
<tr>
<td></td>
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</tr>
</tbody>
</table>

**CEA, report to be issued, July 2015**

*(scenario studies, AREVA-EDF-CEA, 420 TWh/year)*

*m^3/TWh: estimate for final waste packages*
**FUEL CYCLE OPTIONS PERFORMANCE ASSESSMENT (3) REPOSITORY FOOTPRINT**

**PRELIMINARY RESULTS**

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<tbody>
<tr>
<td></td>
<td>LWR</td>
<td>LWR</td>
<td>LWR-FR</td>
<td>FR</td>
<td>AII TRU-FR</td>
</tr>
<tr>
<td>HLW WASTE FOOTPRINT (m²/TWh)</td>
<td>490</td>
<td>150</td>
<td>170</td>
<td>170</td>
<td>20</td>
</tr>
<tr>
<td>USED FUELS POTENTIAL ADDITIONAL FOOTPRINT (m²/TWh)</td>
<td>0</td>
<td>180</td>
<td>120</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>GLOBAL POTENTIAL FOOTPRINT (m²/TWh)</td>
<td>490</td>
<td>330</td>
<td>290</td>
<td>170</td>
<td>20</td>
</tr>
</tbody>
</table>

*CEA, report to be issued, July 2015*  
*(scenario studies, AREVA-EDF-CEA, 420 TWh/year)*  
*(HAVL footprint estimates from ANDRA-CEA former studies)*
MINOR ACTINIDES TRANSMUTATION:

**DRIVERS**

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

No transmutation

MA transmutation

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

[Andra-CEA 2012, cooling phase/120 years]

No transmutation

Current glasses

Am transmutation

Time (years)

Glass canisters residual heat (diverse fuel cycle options)

REPOSITORY FOOTPRINT

Glassform canister heat (W)

Relative radiotoxicity

Temperature (années)

Radiotoxicité relative

U-ore
THE ASTRID PROGRAM

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


Preliminary selection options
Conceptual design -1
Conceptual design -2
Basic design
Detailed design & Construction
Decision to build
commissioning
Reprocessing and recycling today:
- well-proven technologies, at commercial scale
- thanks to important R&D (research & industrial bodies)
- provides significant benefits:
  - natural resource savings
  - optimization of final waste management
  - mastering plutonium inventory

A first step towards more and more sustainable systems
- a “step by step approach,
- with the progressive deployment of generation IV reactors
  (for Pu full burning, natural uranium utilization drastic increase, long-lived elements transmutation...)
no recycle (« once through »)

U Pu recycling in LWRs

U Pu multi-recycling in FRs

All TRU recycling...

INCREASING SUSTAINABILITY BY RECYCLING ...

100

150000 m³

Once through

Pu recycle

all-TRU recycle

10

10

100

30

<5

HLW VOLUME

HLW « FOOTPRINT »
THANK YOU FOR YOUR ATTENTION!
> 66 000 TWh (cumulative)

> 250 000 tons used fuels

[Pu content > 2000 tons]
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)
Uranium use in thermal neutrons (current) reactors

Identified conventional resource

(BP statistical review, 2013 and OECD/NEA, 2012)

(OIL 235 Gt, COAL 860Gt, GAS 187 Tm³, URANIUM 4Mt)
URANIUM among OTHER RESOURCE...

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

Uranium use in thermal neutrons (current) reactors

Uranium & Plutonium multireycled (in fast neutron reactors)