Nuclear Fuel Cycle from operator point of view

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SFEN : Atoms for the Future
Synopsis

1. The Nuclear Fuel Cycle in France
2. The Front-End of the Nuclear Fuel Cycle
3. The Fuel management in the reactors
4. The Back-End of the Nuclear Fuel Cycle
5. Some economical elements
6. Conclusions
EDF is operating 58 Nuclear Power Plants in France....

Nuclear = 65% of installed generation capacity

Nuclear = 85% of electricity generation

+ One EPR under construction

....and some other projects overseas
French Nuclear Fuel Cycle

Uranium extraction and concentration

Conversion

Enrichment

Fabrication

Yellow cake 8 000 t

8 600 t

UF6

UF6 e

Depleted Uranium 110 t

1 080 t

Nuclear Power Plants

430 TWh

Reprocessing (1050 t/an)

Reprocessed Uranium (RU) 1 000 t

Plutonium 10 t

Spent fuel

Geological Disposal ≥ 2025 (28 juin 2006 Law)

Near Surface Disposal

Fuel Assemblies MOX URE UNE

Oxidation RU Storage

Depleted Uranium 110 t

1 200 t

120 t

80 t

1 000 t

French Nuclear Fuel Cycle

Yellow cake 8 000 t

8 600 t

UF6

UF6 e

Depleted Uranium 110 t

1 080 t

Nuclear Power Plants

430 TWh

Reprocessing (1050 t/an)

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The three industrial challenges linked with nuclear fuel cycle

- Security of supply
- Safety and fuel performance in reactors
- U & Pu Recycling and management of radioactive waste
  - U & Pu recycling after spent fuel reprocessing reduces natural uranium requirements
Distinct supplies covered by EDF Security of Supply approach in the area of nuclear fuel

- Natural uranium
- Uranium conversion services
- Uranium enrichment services
- Final fuel assemblies
- Control rods

EDF relies on a security of supply approach for each step of the front-end of the nuclear fuel cycle.
Nuclear Fuel Cycle (Front End)

Ore

Yellow cake $\text{U}_3\text{O}_8$

Refining, Conversion

UF$_4$

UF$_6$

Enrichment

Enriched UF$_6$

Fuel Fabrication Plants

Concentration Plant: Crushing, milling and chemical treatment, …

Mines: Canada, Niger, Gabon, USA, (France), Australia, Kazakhstan, CEI, …

"Yellow cake" containing around 75% of Uranium

Green Powder (Gaseous from 65°C)
THE FUEL CYCLE CLOCK

Front end

Core loading

Fuel manufacturing

Enrichment

Conversion

Uranium purchase + milling

Back end

Core unloading

Cooling period in the core pool

Spent fuel transport and storage

Treatment – separation of materials and waste

Geological disposal

4.5 years in the reactor

Core unloading

T0 – 24 months

T1 + 12 years

T1 + 3 years

T1 + 16 months

T0 – 16 months

T0 – 12 months

> T1 + 20 / 60 years

T0

T1

T0 – 21 months

Reprocessed Uranium

Plutonium

> T0 – 24 months

> T0 – 21 months

Centrales nucléaires
The 5 levers used by EDF to achieve security of supply

- **Diversifying and securing sources of supply**
  - At each stage of the supply chain – uranium extraction, conversion, enrichment and fabrication – long-term contracts of 5 to 20 years, depending on the specific industrial contexts

- **Strategic stocks (inventories)**
  - Natural uranium (UF6 and UF6e) and Reprocessed uranium

- **Recycling**
  - Saves 17% of annual natural uranium requirements

- **Trade-offs**
  - More or less natural uranium / more or less enrichment
  - More or less natural uranium / more or less recycling

- **Control logistics**
  - Transportation, containers, storage …
Some risks and uncertainties which can jeopardize fuel supply

- Geopolitical risk: political uncertainties in some countries
- Environmental risks
- Technical risks: operating incident in a uranium mine, or in a fuel cycle plant, non-conformance on fuel assemblies,…
- Financial risk: disappearance of a supplier or a sub-supplier
- Logistics risk: insufficient number of containers, non-renewal of a transportation agreement for a given container, transportation route closure, nuclear opponents actions
The Fuel Assembly

- 264 Fuel Rods in one Fuel Assembly

- Spider
- Control Rod
- Holdown spring system
- Top Nozzle
- Upper Grid
- Guide Tubes
- Fuel Rod
- Grid
- Bottom Grid
- Bottom Nozzle
- Fuel Rod
- Upper plug
- Al₂O₃ pellet
- Cladding
- Bottom Plug

Fuel Pellet (UO₂ or MOX)
The Fuel Assembly: a strong safety key issue

- Complex product filled with nuclear materials
- Consumable so improvable to reach a better operation performance
- Where the nuclear reaction take place and so source of radioactive risk in case of accident:
  - Cladding: first safety barrier
  - Basic element for the safety studies of the reactor
Fuel assembly description

Stand-up view:
- Axial maintain spring
- Top nozzle
- Rod bundle
- Intermediate mixing grid
- Mixing grid
- Lower grid
- Bottom nozzle

View from above:
- Width: 21.5 cm
- 264 fuel rods
- 24 guide-tubes
- 1 instrumentation tube

Height: 12 or 14 feet (3.66 or 4.27 m)
Width: 21.5 cm

264 fuel rods
PWR Fuel Core

- Control rods
- Fuel Assemblies (FA)

900/1000 MWe → 157 Fuel Assemblies
1300 MWe → 193 Fuel Assemblies
1450 MWe → 205 Fuel Assemblies
EPR → 241 Fuel Assemblies
For EDF, 58 NPPs mean 10 200 Fuel Assemblies under irradiation at a time...

... in an aggressive environnement:

- Coolant Temperature ~300°C
- Coolant Flow speed >4m/s
- Coolant chemistry
- Up to 5 years in the reactor

- Corrosion
- Grid-to-rod fretting
- FA distortion
- Leakages, ...
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Fuel in the core, answer to the operator and the optimizer requirements

- Safety/reliability in the reactor for the operator
  - Robust and proven products

- High-performance fuel management for the Optimizer
  - Products adapted to more demanding fuel managements
Grid requirements

Maintain the generation/consumption balance:

- Outages schedule seasons:
  adapting the power generation supply to the annual energy demand curve: maximum in winter and minimum in summer in France

- Load follow:
  adaptation of the generation to the daily consumption curve, maximum in the day and minimum at night: power variations between 30 and 100 %NP

- Primary frequency control:
  regulation of the European interconnected grid at 50 Hz ± some tens mHz: power fluctuations between 95 and 100 %NP

- Primary + Secondary frequency control:
  regulation of frequency and energy exchanges with neighboring countries: power variations between 84 et 100 %NP
As a Utility generating 85% of its electricity from nuclear, EDF has to face …. 

....multiple constraints :

- **Economical**: produce the cheapest kW/h
- **Industrial**: plan the outages with enough flexibility such that “cheap” nuclear electricity is available when the demand is high
- **Environmental**: minimize the waste by using reprocessed fuel

The response :

- Balance the fuel cycle,
- Power up-rates

- More and more aggressive conditions for the fuel
- Leakers less and less accepted
The choice of a fuel management is the "best" compromise at a certain time between economic aims and technical constraints:

- **Economic target**: reduce the cost of the generation
  - Cycle cost: fuel manufacturing and reprocessing
  - Grid cost: substitute energy
  - Target: cycle length
  - Main means: fractioning (proportion of fresh assemblies per reload) and enrichment (fissile isotopes concentration)

- **Adaptation to the generation / consumption balance**: 
  - If $P > C$, increased importance of cycle cost ("short" cycles)
  - If $P < C$, increased importance of grid cost ("long" cycles)

- **Adaptation to outages schedule**: 
  - Outages season dependence: spring/summer/fall
  - Availability of special tools
  - Availability of rare resources
  - Local constraints: minimum intervals between two outages on the same site
  - Necessity of cycle length modulation: anticipation/stretch-out
Optimum depending on electricity market and fuel market prices
Enrichment and fractioning optimization

Relation between fractioning and enrichment to obtain a cycle length

- Discharge burn-up (GWj/t)
  - 10
  - 20
  - 30
  - 40
  - 50
  - 60

- Cycle length (EFPD)
  - 200
  - 250
  - 300
  - 350
Fuel management constraints

The economic performances are limited by technical and regulatory constraints:

- **Technical Constraints**:
  - **Type of fuel**: ENU, MOX, ERU:
    - Safety analysis imposes a limit of one third of MOX fuel assemblies in the core
  - **U235 Enrichment or Plutonium weight fraction**
    - Criticality analysis in the fuel storage pit imposes a limit of 5% to the enrichment
    - Safety analysis limits Plutonium weight fraction to 11%
  - **Maximal fuel burn-up**
    - The fuel rod behavior analysis leads to a limit of 52 GWj/t (62 GWj/t)
  - **Maximal hot spot peaking factor**: for the most powerful rod $F_{xy} \leq 1.44$
  - **Fractioning**: between $1/5$ and $1/2$
  - **Core intrinsic stability**: boron concentration limitation by use of burnable integrated absorbers

- **Regulatory Constraints**:
  - **Pressurized devices periodic control**
    - These devices have to be checked every 2 years
## Fuel management schemes main characteristics

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of fresh F/A</th>
<th>Equilibrium Natural cycle length</th>
<th>Average discharge burn-up</th>
<th>Maximum discharge burn-up</th>
</tr>
</thead>
<tbody>
<tr>
<td>UO2 1/4 3.7 %</td>
<td>40 assemblies (900 MW CPY units)</td>
<td>278 235</td>
<td>46 GWd/t</td>
<td>52 GWd/t</td>
</tr>
<tr>
<td>UO2/MOX 1/4 3.7 %</td>
<td>40 assemblies 28 UO2 + 12 MOX (900 MW CPY units)</td>
<td>286 242</td>
<td>46 GWd/t (UO2) 46 GWd/t (MOX)</td>
<td>52 GWd/t (UO2) 49 GWd/t (MOX)</td>
</tr>
<tr>
<td>UO2 1/3 4.2 %</td>
<td>52 assemblies (900 MW CP0 units)</td>
<td>385 353</td>
<td>47 GWd/t</td>
<td>52 GWd/t</td>
</tr>
<tr>
<td>UO2 1/3 4.0 %</td>
<td>64 assemblies (1300 MW units)</td>
<td>395 360</td>
<td>47 GWd/t</td>
<td>52 GWd/t</td>
</tr>
<tr>
<td>UO2 1/3 4.0 %</td>
<td>68 assemblies (1450 MW units)</td>
<td>375 345</td>
<td>47 GWd/t</td>
<td>51 GWd/t</td>
</tr>
</tbody>
</table>
EDF Fleet : Fuel management schemes

Number of units

- PWR 900 CPY ENU 1/4 3.7 % or ERU 1/4 3.7 %: 6
- PWR 900 CPY ENU 1/3 4.2 % or ENU 1/4 3.7 %: 7
- PWR 900 CPY ENU 1/4 3.7 % MOX 1/3 7 %: 4
- PWR 900 CPY ENU 1/4 3.7 % MOX 1/4 8.65 %: 17
- PWR 1300 ENU 1/3 4 %: 28
- PWR 1450 ENU 1/3 4 %: 4
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THE FUEL CYCLE CLOCK

Front end

Core loading

Fuel manufacturing

Enrichment

Conversion

Back end

Core unloading

Cooling period in the core pool

Spent fuel transport and storage

Treatment—separation of materials and waste

Geological disposal

T0 – 24 months

T0 – 21 months

T0 – 16 months

T0 – 12 months

T0 – 4.5 years

Reprocessed Uranium

Uranium purchase + milling

4.5 years in the reactor

> T1 + 20 / 60 years

T1 + 12 years

T1 + 3 years

T1
Two strategies of Nuclear Fuel Cycle Back End Management in the world

- The open cycle
  - Spent fuels are considered as waste and are stored
  - Sweden, Finland, Spain, Canada

- The closed cycle
  - Spent fuels are not considered as waste because they contain ~ 95 % of reusable materials (U, Pu): strategy “Treatment – Packaging – Recycling"
  - France, Japan, Russia

- Strategies which can evolve over time for other countries
Reprocessing Interest

- A management solution for conditioning and storage on an industrial scale for long-lived waste...
  - Recovery of recyclable Materials (U, Pu)
    - U and Pu recycling produces 17% of total nuclear electricity of EDF
  - Waste management
    - Intermediate Level Long Live Waste (ILLL) ➔ Compacted
    - High Level Long Live Waste (HLLL) ➔ Vitrified
    - Compacted and Vitrified Residues: Long Term Storage

... to be supplemented by a solution of long-term management (2006 Law, Article L.542 of the Environment Code)
Reprocessing Interest

Reprocessing divides by 10 the volume of HLLL waste at storage and allows to recover reusable materials (U and Pu)

Without treatment:
1.5 m$^3$ of HLLL waste conditioned

With treatment:
0.07 m$^3$ of HLLL waste conditioned and
0.1 m$^3$ of ILLL waste conditioned
Uranium recovered: 470 kg (94%)
Plutonium recovered: 5 kg (1%)

1 Fuel Assembly:
~500 kgU
Equilibrium flow
(referred from 2010)

- 1200 tons/year of Spent fuel (UOX and MOX)
  - La Hague
- Plutonium Recycling: 120 tons/year of MOX
- MELOX
- Reprocessing: 1050 tons/year
- 10.5 tons/year of plutonium
- ~ 1000 tons/year of uranium
- Oxidation and storage in reserve (AREVA warehouses)
- Packaged waste stored
- ~ 300 m³/year
- ~ 1080 tons of UOX Fresh FA (ENU + ERU Contracts)
- 430 TWh/year
- EDF NPP’s including 22 Reactors loaded with MOX Fuel
- Transportation + Receiving and storage in La Hague
  - 1200 tons/an

Uranium Recycling: 70t/year of ERU
- AREVA/TENEX
- 60%
Spent fuel is stored on NPP for 12 to 18 months in the spent fuel pool storage located in the fuel building (BK)
Spent fuel Transportation

The spent fuel is then transported to AREVA La Hague plant in containers (or "casks"), chosen for their mechanical, thermal and radioprotection characteristics.
Reprocessing allows to sort out, on one hand, the waste contained in spent fuel (5% of the nuclear material and the metal structure of the FA) and, on the other hand, recyclable materials (uranium: 94% and plutonium: 1%), contained in spent fuel:

- Waste is packaged and stored at AREVA La Hague plant,
- Plutonium recovered from reprocessing must be recycled in the short term (its quality is degrading due to the decay of plutonium 241 into americium 241),
- Uranium is managed as a reserve of uranium (currently about 1/3 is recycled, more than 50% in a near future)

1 EDF FA: approximately 500 kg

- 5 kg of plutonium and 470 kg of uranium
- 0.07 m³ of High Level Long Lived waste and 0.1 m³ of Intermediate Level Long Lived waste
Reprocessing: a separation process

Reprocessing operations
(shearing - dissolution - separation - purification)

Fuel Elements
Receiving Storage
Processing facilities

Waste from plant operations
Hulls and End-fittings
Vitrified waste (UC/V)
Compacted waste (UC/C)

Recyclable materials
Uranium
Plutonium
Process waste
Waste Storage (CSD-C and CSD-V)

The final waste, packaged in the form of CSD-V (vitrified waste) and CSD-C (compacted waste) are stored awaiting final disposal.
To close the fuel cycle: a geological disposal expected to be opened in 2025
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The Supply Chain

Operational Stock (related to the Processes):

- **C**: Conversion Process
- **E**: Enrichment Process
- **F**: Manufacturing process

- Intermediate Security Stock
- Security stock

- NU Purchases
- NU
- NU UF6
- ENU UF6
- Fuel Assemblies
- Deliveries
- Outage

16 to 20 months
Front End Economic approach

Front End Steps

- Natural uranium purchases
- Conversion
- Enrichment
- Manufacturing
- and delays associated with each step

- Depending on FA type (ENU, MOX, ERU) and U5 Enrichment assay or Pu content, the proportions vary ...
Back End Economic Approach

Back End Steps

- FA transportation from EDF NPP and FA reception
- FA storage and processing (reusable materials and waste separation)
- Reusable materials packaging (U and Pu)
- Waste packaging (CSD-C and CSD-V)
- Waste Storage
- Waste transport and disposal in dedicated site
Economic Approach

The objective is to link the FA costs to the energy produced by the same FA

- The fuel = 1 FA, characterized by its U5 Assay or Pu contents and its type (ENU, MOX, ERU, …)
- Associated costs: Front End and Back End
- Energy associated = the FA discharge burnup in MW day per ton of Heavy Metal (MWd/tHM) (thermal energy)
THE FUEL CYCLE CLOCK

Front end

1. Core loading
   - T0
2. Fuel manufacturing
3. Enrichment
4. Conversion

Back end

1. Core unloading
   - Cooling period in the core pool
   - T1
2. Spent fuel transport and storage
3. Treatment–separation of materials and waste
4. Geological disposal

Uranium purchase + milling

4.5 years in the reactor

T0 – 24 months
T0 – 21 months
T0 – 16 months
T0 – 12 months
T1 + 3 years
T1 + 12 years
> T1 + 20 / 60 years
Financial Translation of Nuclear fuel cycle

- Procurement in Separated Components:
  - NU Supply
  - Conversion
  - Enrichment
  - Manufacturing
  - FA Storage in EDF pools
- Future Expenditure:
  - Transport
  - Reprocessing
  - Waste disposal

Stocks for each component valued at weighted average cost

Consumption

Provisions updated for each type of expenditure

Nuclear Fuel Accounting cost by kWh
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Conclusions

- The different steps of the nuclear fuel cycle are strongly connected.

- Every stage is involved in the economical performance of the nuclear generation.

- A closed fuel cycle allows to save nuclear material and to reduce the environmental impacts of waste (volume reduction).