Environmental impacts of different fuel cycles options

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THE DIFFERENT NUCLEAR FUEL CYCLE OPTIONS

One Through Cycle
Thermal Reactors

Twice-Through Cycle
Thermal Reactors

Pu multi-recycling
Fast Reactors
Natural uranium is a finite resource
Global efficiency is currently very low: ~0.7%
- ~70t from the initial ~9500t U ore
Uranium conventional resource
- Limited for the far-future at a reasonable price (130$/kg U)
- Lifespan ~1-2 centuries (current consumption 75kt/y)

Need for preserving U resource

Rough estimates derived from French Fuel cycle assuming no recycling
SAVING THE NATURAL RESOURCE ⇔ RECYCLING THE ACTINIDES

Uranium ore

Depleted uranium

Up to -20%

9500 t

8000 t

1200t

1200t

Spent fuel

URE U re-enriched fuels

MOX fuels

1%

95%

Recycling plants

10 - 15/a Per reactor

FP 4.55%

0.76% oddPu
0.41% evenPu

0.75% 235U
0.54% 236U

238U
239U

93.0%

9300 tHM reprocessed

MELOX

MELOX

>2 000tHM of MOX fuel produced

>33 000 tHM reprocessed

Already allows saving ~20% U_ore ⇒ efficiency increased to ~1%

La Hague

AREVA

S. Bourg, TM IAEA – GCNEP, India, Nov 2019
IMPROVING FURTHER RESOURCE PRESERVATION ➔ PU-MULTIRECYCLING FOR TRANSFORMING 238U

Multirecycling limited by $^{2n}$Pu buildup ➔ GEN4 systems with fast neutrons

With current reactors

- 1GWe ~ 150t $U_{nat}$/y
- U=6% world energy potential

With fast neutrons reactors

- 7500 Gtoe
- U=90% world energy potential
- 1GWe ~ 1t $U_{nat}$/y

Very significant improvement of natural uranium efficiency
A BENEFICIAL LONG-TERM IMPACT OF RECYCLING ON THE WASTE ISSUE

With recycling

- Tailored for confining

Without recycling

- Tailored for producing KWh

1. No Pu, Long-term toxicity

2. Confinement performances

Radiotoxicity relative

\[ \text{Relative radiotoxicity} = \frac{\text{Radiotoxicity of recycling}}{\text{Radiotoxicity of non-recycling}} \]

Dose (Sv/y)

\[ \text{Dose} = \int_0^T \text{Dose rate} \, dt \]

Time (years)

Tailored for confining

Tailored for producing KWh

Without recycling
ENVIROMENTAL FOOTPRINT OF NUCLEAR ENERGY

Graph showing relative radiotoxicity over time for different disposal methods:
- U-ore
- Glass canisters, no Pu, no minor actinides
- Glass canisters (Pu and minor actinides)
- Direct disposal

The graph illustrates the decrease in relative radiotoxicity over time for each disposal method.
PRESENTATION OF THE REFERENCE CASE: FRENCH NUCLEAR POWERPLANTS FLEET

- 58 reactors located on 19 sites, capped at 63.2 GWe
- **Standardised fleet**: 1 single reactor types, with 3 different powers 900, 1300 et 1450 MWe
- Produce 70-80% of French electricity (~400-450 TWh), i.e. 40% of total French primary energy
- Reactors connected between 1977 and 1999
- 12 GEN1 generation reactors halted
- 1 GEN3 generation reactor under construction (Flamanville3, EPR)
**FRENCH REFERENCE FUEL CYCLE**
("TWICE-THROUGH CYCLE" – TTC)

Reference = 2010

**UOX manufacturing**
- U enriched 1053 t/y
- Romans

**MOX manufacturing**
- MOX 120 t/y

**Enrichment**
- Pierrelatte
- U natural 8247 t/y
- U depleted 7085 t/y

**Conversion**
- U depleted 109,5 t/y
- Malvési

**Storage**
- U ore

**Purification**
- U natural 7647 t/y

**Mines**

**Reactivity**

**Reactors**
- MELOX
- 58 reactors on 19 sites
- Spent fuel 1173 t/y
- UOX fuel 1053 t/y
- Pu 10,5 t/y
- La Hague

**Decay storage**
- Spent fuel 1050 t/y
- Spent fuel 1050 t/y
- Spent fuel 123 t/a
- glass: 149 m³/y
- Compacted waste: 189 m³/y
- Techno waste: 275 m³/y

**Reprocessing**
- U reprocessed 600 t/y
- U reprocessed 390 t/y
- La Hague

**Storage**

**Disposal**
- Bure
CHAP.II – RESULTS OF THE CURRENT FRENCH CYCLE
THE GENERAL ENVIRONMENTAL INDICATORS OF THE TTC

<table>
<thead>
<tr>
<th>(gCO₂ eq/kWhₑ)</th>
<th>(gSO₂eq/MWhe)</th>
<th>(gC₂H₄eq/MWhe)</th>
<th>(gPO₄eq/MWhe)</th>
<th>(g1,4-DCBeq/MWhe)</th>
<th>(g1,4-DCBeq/MWhe)</th>
<th>(m²/GWhₑ)</th>
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<tbody>
<tr>
<td>5,29</td>
<td>34,1</td>
<td>5,2</td>
<td>2,84</td>
<td>638</td>
<td>1233</td>
<td>211</td>
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</table>
THE POTENTIAL IMPACT INDICATORS OF THE TTC

<table>
<thead>
<tr>
<th></th>
<th>(mg/kWh_e)</th>
<th>(mg/kWh_e)</th>
<th>(mg/kWh_e)</th>
<th>(L/MWh_e)</th>
<th>(L/MWh_e)</th>
<th>(g/MWh_e)</th>
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</thead>
<tbody>
<tr>
<td>SOx</td>
<td>16,276</td>
<td>25,30</td>
<td>287.53</td>
<td>1507</td>
<td>72364</td>
<td>93.9</td>
</tr>
</tbody>
</table>
CONTRIBUTION OF THE DIFFERENT FUEL CYCLE STEPS TO THE OVERALL FOOTPRINT

Improve overall footprint ➔ improve or reduce front-end activities
Radioactive releases (KBq!):

- **53%** Rn release around mines … however strong overestimation since all the Rn is assumed to be instantaneously released (no kinetics)
- **45%** Rare gases release during reprocessing:
  - The overall radiological impact is estimated to be ~1% of natural radioactivity
- **2%** liquid release
  - Dominated by $^3$H release around reactors.
- **Necessity for considering dose impact … but scenarii are highly subjective and site-dependent**

**THE RADIOACTIVE RELEASES OF THE TTC**

Radioactive Releases

- **Gas - Radon (Mine)** 53%
- **Gas - Rare gases (Reprocessing)** 45%
- **Liq - Tritium (Reactors)** 2%
- **Gas - Tritium (Reprocessing)**
- **3,1 KBq/KWhe**
- **1245,6 KBq/KWhe**

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THE RADIOACTIVE WASTE OF THE TTC

- A very sensitive indicators for public acceptance
- Main outcomes
  - **VLLW**: surface repository in operation since 2003 in Morvilliers.
    - Overestimation since mine tailings are included
  - **ILW-SL**: shallow repository in operation since 1994 in Soulaines-Dhuys
    - Dominated by reactors operation
  - **ILW-LL and HLW** are planned to be disposed of in a deep underground repository around Bure (2025 according to the French Law)
    - Dominated by reprocessing activities (replace spent fuel)
WHAT ABOUT THE ENVIRONMENTAL-FRIENDLINESS OF NUCLEAR ENERGY?

Despite the usual feeling, nuclear energy is highly competitive in terms of environmental-friendliness.
Once-through cycle derived from the current French fuel cycle by suppressing the recycling loop and adjusting the materials annual streams.
Anticipated evolution of environmental indicators when implementing the recycling

- GHG emissions
- Sox emissions
- Nox emissions
- Particles emissions
- Land use
- Natural resource efficiency
- Water consumption
- Water withdrawal
- Acidification
- POCP
- Ecotoxicity
- Human toxicity
- Eutrophication
- Chemical liquid effluents
- Technological waste

Directly related to the decrease by 15-20% of the front-end activities
Radioactive release (Bq !!)

- Only $\Delta = \text{Rn}$, (time-dependent decay not accounted for).

Linked to recycling activities:
- Atmospheric release: $^{85}\text{Kr}$, $^{14}\text{C}$,
- Liquid release: mainly $^3\text{H}$, $^{129}\text{I}$

However, their impact is demonstrated to be negligible:
- 17-24 μSv/yr for the most exposed population
- ~1% natural radioactivity

Total 24.7 μSv (agriculteur)
Conservative case assuming 1700t/y. of 60GWd/t fuels reprocessed
EVOLUTION OF RADIOACTIVE WASTE FROM OTC TO TTC

- Strong modification of the waste typology
- Recycling reduces the repository surface area and excavated volume
### CHAP VI – WHAT ABOUT FUTURE NUCLEAR SYSTEMS?
### IMPACT OF GEN3 REACTORS: CASE OF EPR

#### Impact indicators

<table>
<thead>
<tr>
<th>Indicator</th>
<th>Unit</th>
<th>EPR</th>
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</thead>
<tbody>
<tr>
<td>GHG emissions</td>
<td>gCO₂ eq/kWhe</td>
<td>3.97</td>
</tr>
<tr>
<td>Atmospheric pollution SOx</td>
<td>g/MWhe</td>
<td>12.7</td>
</tr>
<tr>
<td>Atmospheric pollution NOx</td>
<td>g/MWhe</td>
<td>21.35</td>
</tr>
<tr>
<td>Land-use</td>
<td>m²/GWhe</td>
<td>161.6</td>
</tr>
<tr>
<td>Natural resource efficiency</td>
<td>kU/TWhe</td>
<td>15.2</td>
</tr>
<tr>
<td>Water consumption</td>
<td>L/MWhe</td>
<td>1437</td>
</tr>
<tr>
<td>Water withdrawal</td>
<td>L/MWhe</td>
<td>70132</td>
</tr>
<tr>
<td>Acidification potential</td>
<td>gSO₂ eq/MWhe</td>
<td>27.7</td>
</tr>
<tr>
<td>POCP</td>
<td>gC₂H₄ eq/MWhe</td>
<td>2.27</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>g₁,₄-DCB eq/MWhe</td>
<td>499.6</td>
</tr>
<tr>
<td>Human toxicity</td>
<td>g₁,₄-DCB eq/MWhe</td>
<td>967.1</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>gPO₄ eq/MWhe</td>
<td>4.18</td>
</tr>
<tr>
<td>Liquid chemical effluents</td>
<td>kg/GWhe</td>
<td>225.40</td>
</tr>
<tr>
<td>Technological wastes</td>
<td>kg/GWhe</td>
<td>20.42</td>
</tr>
<tr>
<td>Gaseous radioactive releases</td>
<td>Bq/KWhe</td>
<td>1.14E+06</td>
</tr>
<tr>
<td>Liquid radioactive releases</td>
<td>Bq/KWhe</td>
<td>3.35E+04</td>
</tr>
<tr>
<td>Total radioactive releases</td>
<td>Bq/KWhe</td>
<td>1.17E+06</td>
</tr>
<tr>
<td>VLLW</td>
<td>m³/TWhe</td>
<td>2.61E+03</td>
</tr>
<tr>
<td>ILW-SL</td>
<td>m³/TWhe</td>
<td>1.94E+01</td>
</tr>
<tr>
<td>ILW-LL</td>
<td>m³/TWhe</td>
<td>7.67E-01</td>
</tr>
<tr>
<td>HLW</td>
<td>m³/TWhe</td>
<td>2.98E-01</td>
</tr>
</tbody>
</table>

#### Impact indicators comparison

- **GHG emissions**: 3.97 gCO₂ eq/kWhe
- **Atmospheric pollution SOx**: 12.7 g/MWhe
- **Atmospheric pollution NOx**: 21.35 g/MWhe
- **Land-use**: 161.6 m²/GWhe
- **Natural resource efficiency**: 15.2 kU/TWhe
- **Water consumption**: 1437 L/MWhe
- **Water withdrawal**: 70132 L/MWhe
- **Acidification potential**: 27.7 gSO₂ eq/MWhe
- **POCP**: 2.27 gC₂H₄ eq/MWhe
- **Ecotoxicity**: 499.6 g₁,₄-DCB eq/MWhe
- **Human toxicity**: 967.1 g₁,₄-DCB eq/MWhe
- **Eutrophication**: 4.18 gPO₄ eq/MWhe
- **Liquid chemical effluents**: 225.40 kg/GWhe
- **Technological wastes**: 20.42 kg/GWhe
- **Gaseous radioactive releases**: 1.14E+06 Bq/KWhe
- **Liquid radioactive releases**: 3.35E+04 Bq/KWhe
- **Total radioactive releases**: 1.17E+06 Bq/KWhe
- **VLLW**: 2.61E+03 m³/TWhe
- **ILW-SL**: 1.94E+01 m³/TWhe
- **ILW-LL**: 7.67E-01 m³/TWhe
- **HLW**: 2.98E-01 m³/TWhe
COMPARISON OF EPR AND CURRENT PWR TTC

Anticipated impact on environmental indicators of the replacement of current GEN2 reactors by GEN3 EPR

- Improvement related to better efficiency of EPR reactor: higher turbine efficiency (37%), higher availability ratio (85%), higher design lifetime (60y) ➔ Lower fuel consumption (-19%)
- Increase of liquid release linked to a conservative estimate of $^3$H reactor discharge (75TBq)
TOWARDS GEN4: POTENTIAL IMPACT OF MULTIRECYCLING

- Future 4th generation reactors ⇔ fast neutrons reactors
  - Higher efficiency in natural resource consumption
  - What about their anticipated environmental footprint?

- LCA calculations have been performed for representative 4th generation fuel cycles:
  - SFR taken as a reference for the 4th generation reactors
  - Based on the data available for the former French SFR Phenix & Superphenix
  - 2 hypothetical cases have been calculated:
    - Transition stage: 66% EPR + 33% SFR
    - Theoretical stage: 100% SFR

![Diagram of fuel cycles and waste streams including depleted uranium, FNR MOx, spent FNR MOx, plutonium, and ultimate waste FP/MA (50 t)].
EXTRAPOLATED SODIUM FAST REACTOR CLOSED FUEL CYCLE

Electricity production 453 TWhe

Reactors

Spent fuel 448 t/y

Cooling

Spent fuel 448 t/y

Reprocessing

Glass: 135 m³/y
Metals: 475 m³/y
Tech. Waste: 170 m³

Milling

Storage

U ore

Mining

Storage

U depleted -49,1 t/y

Pu 69,4 t/y

U_reprocessed 355,8 t/y

MOX Fuel fabrication

Enrichment

MOX Fuel fabrication

Uox Fuel fabrication
**IMPACT OF GEN4 FUEL CYCLE: CASE OF SFR**

<table>
<thead>
<tr>
<th>Impact indicators</th>
<th>Unit</th>
<th>SFR scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>GHG emissions</td>
<td>gCO(_2) eq/kWhe</td>
<td>2.33</td>
</tr>
<tr>
<td>SOx emissions</td>
<td>g/MWhe</td>
<td>0.59</td>
</tr>
<tr>
<td>NOx emissions</td>
<td>g/MWhe</td>
<td>3.83</td>
</tr>
<tr>
<td>Land-use</td>
<td>m(^2)/GWhe</td>
<td>50.2</td>
</tr>
<tr>
<td>Water consumption</td>
<td>L/MWhe</td>
<td>1237</td>
</tr>
<tr>
<td>Water withdrawal</td>
<td>L/MWhe</td>
<td>60336</td>
</tr>
<tr>
<td>Acidification</td>
<td>gSO(_2) eq/MWhe</td>
<td>3.3</td>
</tr>
<tr>
<td>POCP</td>
<td>gC(_2)H(_4) eq/MWhe</td>
<td>0.18</td>
</tr>
<tr>
<td>Ecotoxicity</td>
<td>g1,4-DCB eq/MWhe</td>
<td>0.07</td>
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<tr>
<td>Human toxicity</td>
<td>g1,4-DCB eq/MWhe</td>
<td>4.8</td>
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<tr>
<td>Eutrophication</td>
<td>gPO(_4) eq/MWhe</td>
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<td>Liquid chemical effluents</td>
<td>kg/GWhe</td>
<td>12.6</td>
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<tr>
<td>Technological waste</td>
<td>kg/GWhe</td>
<td>18.70</td>
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<tr>
<td>Gaseous radioactive release</td>
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<td>5.28E+05</td>
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<tr>
<td>Liquid radioactive release</td>
<td>Bq/KWhe</td>
<td>3557</td>
</tr>
<tr>
<td>VLLW</td>
<td>m(^3)/TWhe</td>
<td>72.4</td>
</tr>
<tr>
<td>LILW-SL</td>
<td>m(^3)/TWhe</td>
<td>18.2</td>
</tr>
<tr>
<td>LILW-LL</td>
<td>m(^3)/TWhe</td>
<td>1.4</td>
</tr>
<tr>
<td>HLW</td>
<td>m(^3)/TWhe</td>
<td>0.30</td>
</tr>
</tbody>
</table>
• Improvement related to (i) the suppression of front-end activities and (ii) the higher thermal efficiency (~40% ≠ 33%)
No noticeable changes vs. the previous 100% SFR case-study difference <10%. Only significant differences = the radioactive waste, VLLW: -27% LILW-SL: -8% LILW-LL: +7%
ANTICIPATED BENEFICIAL IMPACT OF RECYCLING ACTIVITIES

Actinides recycling significantly improve the nuclear energy environmental footprint
ANTICIPATED BENEFICIAL IMPACT OF RECYCLING ACTIVITIES

Actinides recycling significantly improve the nuclear energy environmental footprint
A SIGNIFICANT IMPROVEMENT OF THE NUCLEAR WASTE ISSUES

- Relative decrease of HLW vs. ILW while total volume of waste ~ constant +/- 20%
- Decrease of thermal power due to Pu-recycling ➞ significant gain for the repository surface and volume
- Decrease of radiotoxicity & lifetime
RECYCLING THE MINOR ACTINIDES, A POTENTIAL CONTRIBUTION FOR DECREASING THE WASTE BURDEN

- Waste toxicity dominated by MA
  - Recycling MA ⇒ decrease waste lifetime and toxicity

- Preserve the valuable repository resource
  - ⇨ of the heat load ⇨
  - ⇨ density of the repository
  - With Am recycling, reduction of the repository volume by a factor up to 8
  - Very significant increase of the repository "lifespan"
THE RATIONALE OF FUTURE NUCLEAR FUEL CYCLES FOR AN IMPROVED SUSTAINABILITY

TOWARDS INCREASING SUSTAINABILITY

Once-through cycle
- Pu-mono-recycling
  - Twice-Through Cycle
  - LWR reactors
  - Pu-recycling in MOX fuel

Breakthrough=reactors
Evolution=cycle

Main incentives
- 1st step towards U resource saving
- Efficient waste conditioning

Main incentives
- Major resource saving
- Energetic independence
- Economic stability

Main incentives
- Decrease of waste burden,
- Optimisation of the repository
- Public acceptance

Pu multi-recycling
- Multi-Through Cycle
- Fast-Reactors (FR)
- Pu multi-recycling

Pu+MA multi-recycling
- Fast Reactors (FR)
- Pu multi-recycling
- MA burning

Pu-mono-recycling
- Gen. II & III

Pu-multi-recycling
- Gen. IV

...+ MA recycling
- Gen. IV

Dates are purely indicative

1980 2000 2200 2040 2060 2080 2100

Breakthrough=reactors
Evolution=cycle

Gen. IV

S. Bourg, TM IAEA – GCNEP, India, Nov 2019
CONCLUSIONS...
CONCLUSION

- Environmental footprint of nuclear energy (NE)
  - Competitive with respects to any other energy sources (within top-3)
  - Confirm the interest of NE for mitigating the global climate change
  - Dominated by the front-end activities, in particular ore mining ⇔ any improvement or reduction of front-end activities is anticipated to be beneficial for the overall footprint

- U/Pu recycling has an overall beneficial effect
  - Improve the generic environmental indicators
  - Although radioactive releases are increased, global effect remains beneficial:
    - **Short-term**: releases << natural radioactivity ⇒ no health impact
    - **Long-term**: beneficial impact for the repository: lifespan ↗, safety ↗, cost ⇐
  - Pu multi-recycling in FNR will enhance this beneficial effect

- Actinides recycling is a key option for reducing the environmental footprint
- Quantitative LCA evidences the significant bias between public perception and actual nuclear energy environmental footprint
TO GO FURTHER ...

**Energy, 2014**

Assessment of the environmental footprint of nuclear energy systems. Comparison between closed and open fuel cycles

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³AERadio 21 Consulting Sàrl, Pâques-Gare de France, 49-51, 1er étage, 42000 Lyon, France

**Energies, 2017**

Assessment of the Anticipated Environmental Footprint of Future Nuclear Energy Systems. Evidence of the Beneficial Effect of Extensive Recycling

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Received: 28 July 2017; Accepted: 16 September 2017; Published: 19 September 2017