Back-End of the Nuclear Fuel Cycle

Existing Recycling Solution at Orano

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National Academy of Sciences, Engineering and Medicine:
Merits and Viability of Different Nuclear Fuel Cycles and Technology Options and the Waste Aspects of Advanced Nuclear Reactors
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orano

Agenda

1. Orano industrial experience

a. Spent fuel recycling
b. Waste optimization
c. Impacts

2. Lessons learned

a. Economics
b. Final disposal

3. Ability to manage new fuels and development perspectives

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Orano Recycling Platform

A strategic asset with 50 years of experience, shared worldwide

Operational experience and excellence

Safe transport by train, truck & ship

Used fuel transport:

7,500 French used fuel shipments to La Hague

2,500 coming from abroad

La Hague reprocessing plants

LWR fuel reprocessing:

~27 000 tHM reprocessed for France

10 500 tHM reprocessed for 6 other countries

Melox fabrication plant

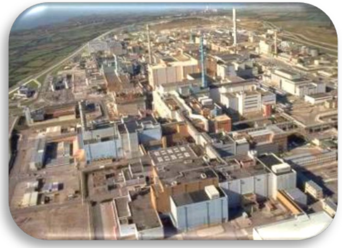
LWR MOX fabrication:

~ 2 900 tHM MOX fuel produced, loaded in 43 reactors worldwide

Recycling is a key asset addressing Back-End challenges

Orano Research Reactors’ UNF Reprocessing Experience

Several types of RRSF have been reprocessed in France
With enrichment up to 93% ^{235}U
Starting at Marcoule plant
18 tons of RRSF
from 21 reactors, 11 countries



Since 2005, at La Hague plant
150+ cask received, 5250+ fuel assemblies
10 tons+ of UAl fuel have been already reprocessed
including French and foreign (Belgian, Australian) fuels

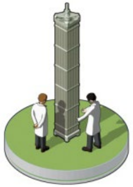
Orano has acquired broad experience in RRSF reprocessing

Plutonium

Incomparable energy potential

Worldwide, 43 reactors have been loaded with MOX fuel since 1972
In France: 56 reactors in operation, 22 “moxified” reactors with 1/3 MOX in the core

Plutonium recovered from Used fuel



MOX (Mixed Oxide) is fabricated at MELOX

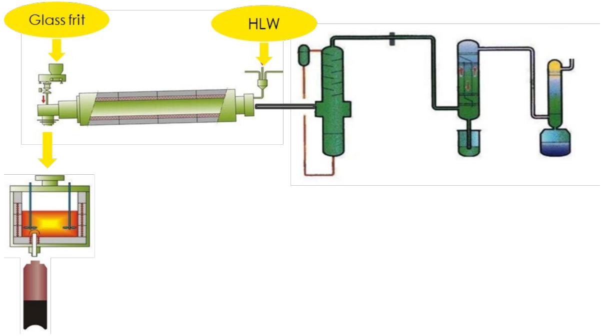
MOX = average of **8.5% Pu** and **91.5% depleted U**

In France, each year 10 tons of Plutonium supply more than 10% of the country’s electricity from nuclear origin

Fuel supply from reusable materials, from both Pu and RePu recycling, represent up to 25% of nuclear electricity

A safe and responsible management of final waste (1/2)

Conditioning process: vitrification of HLW



Universal Canister Vitrified characteristics

Glass volume
150 liters

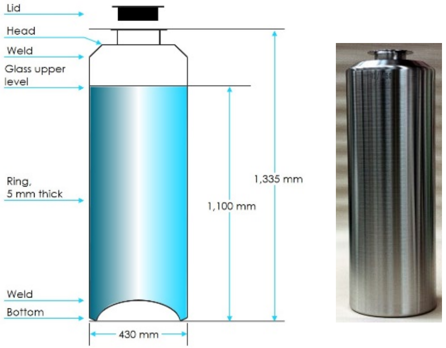
Glass weight
400 kg

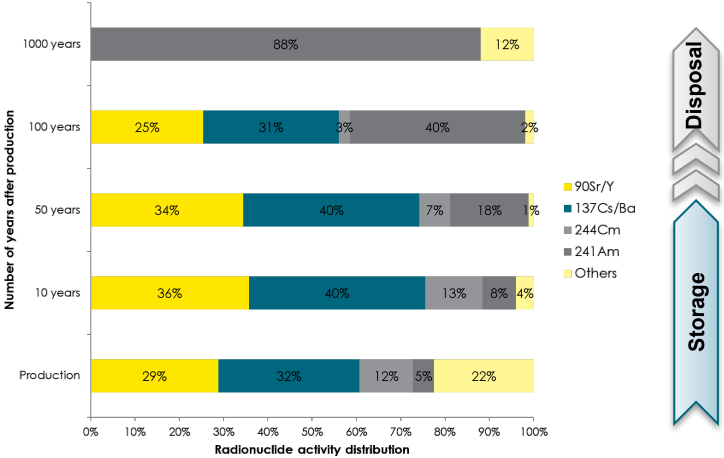
Thermal Power
~2,5 kW

Activity α
~140 TBq

Activity βγ
~28 000 TBq

Dose Rate βγ
1,4 .10^{4} Gy/h





A safe and responsible management of final waste (2/2)

Thanks to recycling operations,

→ The volume is reduced by 5

→ The toxicity is reduced by 10

Glass matrix: a standardized safe and stable conditioning over the very long term

> *French vitrified waste amounts to* ***5 grams per inhabitant per year***

Foreign waste is transported back to its country of origin

French waste is stored on-site awaiting the commissioning of CIGEO deep geological disposal facility

Interim storage hall for vitrified waste

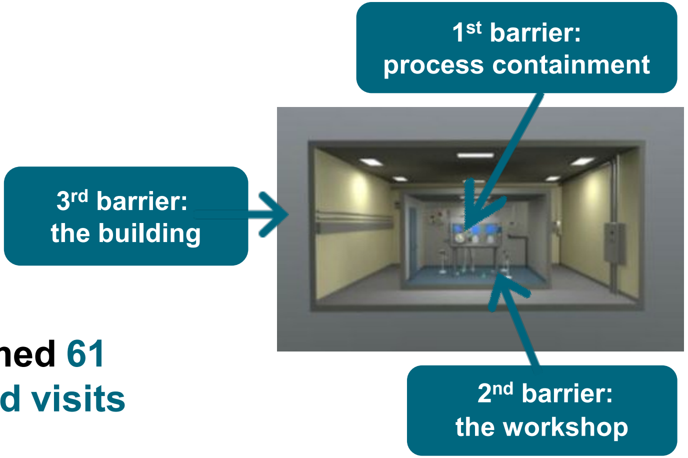
Safety of the Facilities

An absolute priority

Safety management ensured 24/7 along with numerous crisis drills

→ A confinement system composed of 3 barriers with higher contamination zones at lower pressures

→ A culture based on providing of feed-back, of continuous improvement and knowledge transfer



» **Independent Nuclear Safety Authority performed 61 inspections in 2020, including 5 unannounced visits**

Continuous & Effective System of Nuclear Material Safeguards

compliant with IAEA requirements to ensure non-proliferation

The control of nuclear material in La Hague and Melox is made by national bodies and by the international agencies EURATOM and IAEA

The control system was established by EURATOM in collaboration with French Authorities and operator from the design phase of Melox, with an objective of "Check of continuous Inventory"

This system is specific to the plant characteristics:

- Control of inputs/outputs
- Independent and automatic counting equipment
- Control of the nuclear material by annual inventory
- Sample analysis

"Considering the relative attractiveness of materials handled in each fuel cycle option and the effectiveness of the safeguards approached applied accordingly, the differences in terms of proliferation risk are not very significant among fuel cycle options."

– *Strategies and Considerations for the Back End of the Fuel Cycle, © OECD 2021, NEA No. 7469*

Worker's Health is Protected and Monitored

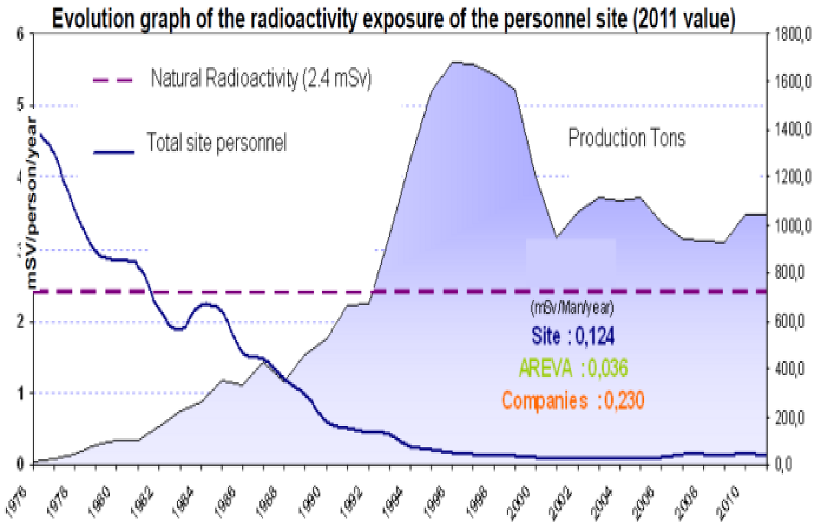
Regulated limit for nuclear workforce — **20 mSv / year**

Limit for public — **1 mSv / year**

Average natural exposition in France — **2.9 mSv / year**

La Hague workers — **0.175 mSv** in 2019

A transatlantic flight — **0.02 mSv**



No Health Impact

From a radiological point of view, the site's impact is 100 times lower than natural radioactivity levels

⟶ More than 20,000 samples in 2020

⟶ 52,000 analyses carried out

Impact calculated since 2004 using a model produced by the independent GRNC (Groupe Radio-écologie Nord-Cotentin). It is based on a reference group: population likely to be the most highly exposed due to its position and lifestyle.

Natural exposure 2.9 mSv per year

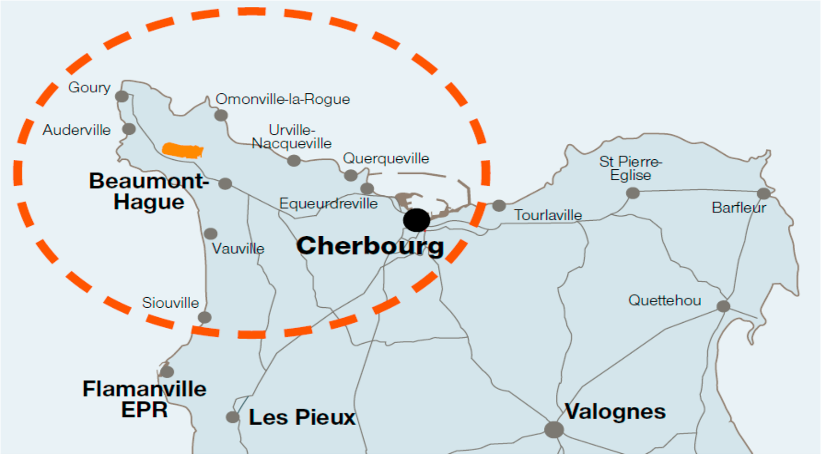
Orano la Hague: < 0.02 mSv per year

Stakeholders

regulatory frame and proactive programs

Key facts

- **3 Local Information Comity** per year
- **700 visitors** in 2020
- **16 press visits** in 2019
- **Frequent meetings** with local elected representatives



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The French Fuel Cycle: Key Benefits

22,000 t of Natural U saved

Energy independence reinforced:
2 years of strategic stockpile (RepU)

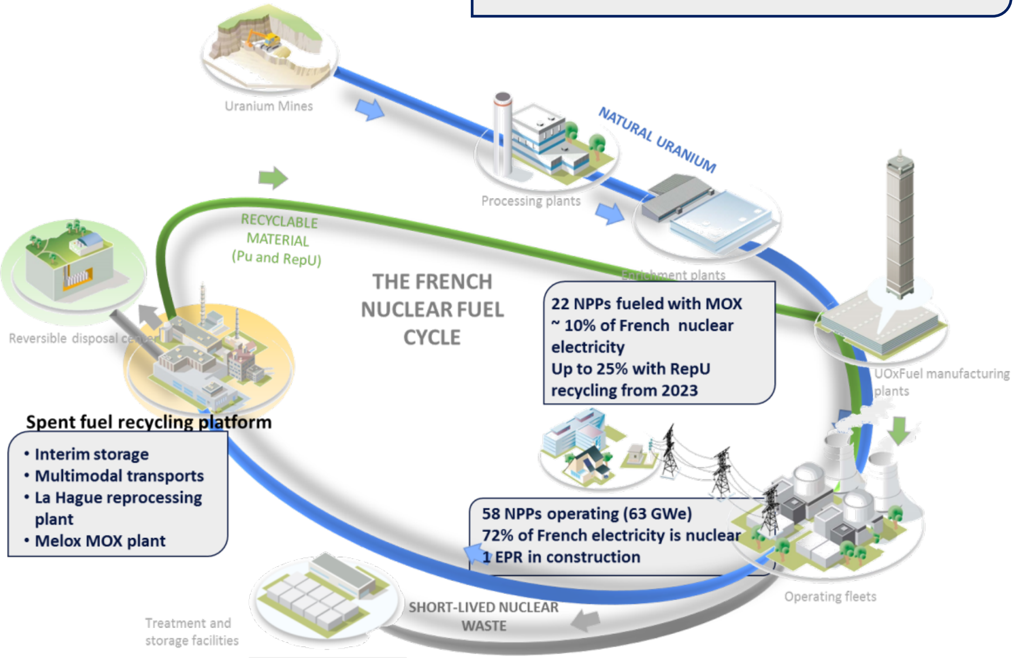
Savings of 23,000 tHM of Spent Fuel storage

IL/HL waste:
Volume reduced by 5
Toxicity reduced by 10

Standard waste packages licensed by 9 safety authorities for storage &disposal

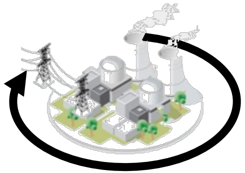
IL-HLW in-storage infrastructure licensed for 100 years minimum
HLW vitrified canister confinement durability in disposal (1000 years +)

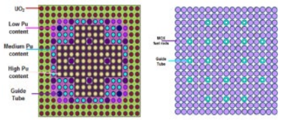
Geological disposal footprint and cost optimization



Assessment at the end of 2018

Strategic Industrial and R&D Roadmap for Closure of the Fuel Cycle



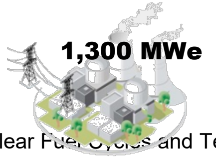


Mid-term R&D ambitions:
Multi-recycling in PWR: MOX-2 fuels
Industrial commissioning deemed feasible by around 2040

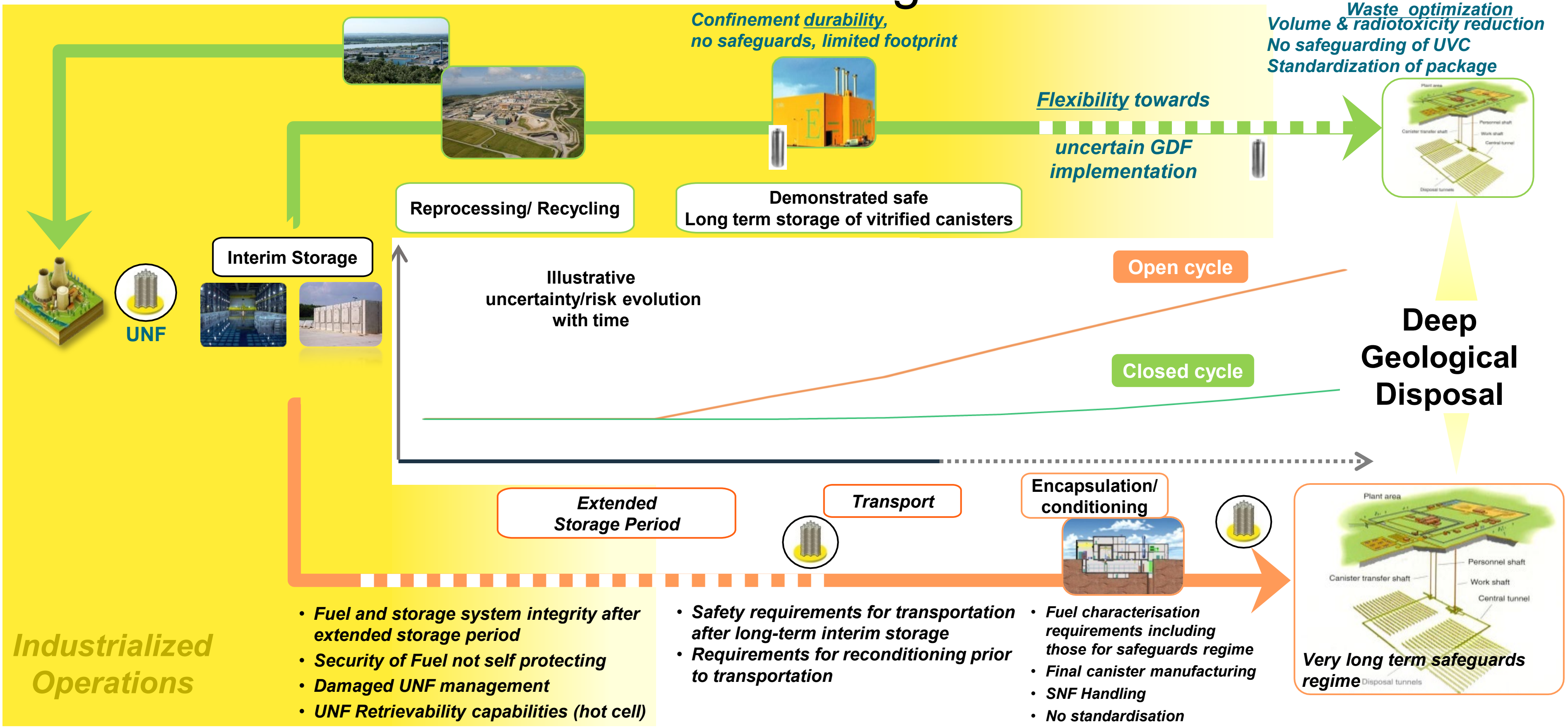
Long term stakes : Prepare the complete closure of the fuel cycle using GENIV reactors by the end of the century:

- increase **natural uranium savings**, up to 100%
- **decrease waste volume and toxicity**
  Preliminary studies of transmutation options using molten salt reactors

Short-term industrial performances:
MOX fuel Excellence program **for use in 1,300MWe** reactors: deployment to start in the late 2020s



UNF Management: A Very Long-term Strategic Matter with Risks and Uncertainties to Mitigate



HLW Vitrified Conditioning Eases Predisposal and Disposal Steps and Reduces Related Costs

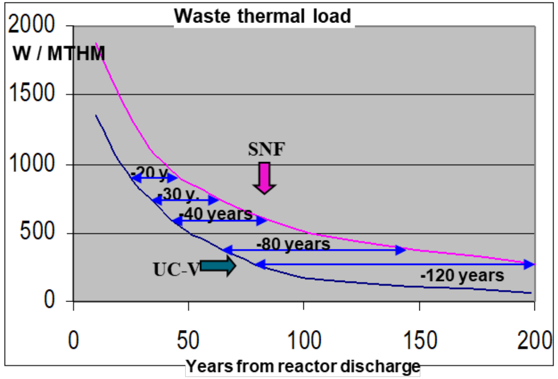
UC-V is a unique and standardized waste form: safe, stable, compact form, ready for highly reliable long term storage before disposal in final repository.

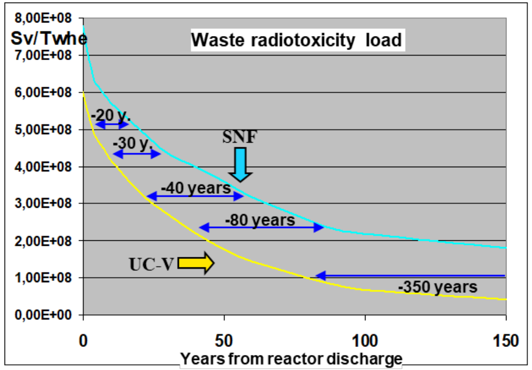
UC-V guaranteed for extended periods of time (>300 years) when stored in a VAULT dry storage facility, well mastered fully passive cooling system technology implemented at La Hague facility for decades and at Covra site in the Netherland with a 100 years license : limited capex, modular unit

Habog Facility, Netherland

As the heat load and radiotoxicity of UC-V decreases faster than for spent fuels, a longer interim storage prior to final disposal would allow to further:

- **optimize transport and ease handling of UC-Vs**
- **reduce the footprint of the deep geological repository**
- **bridge the gap with delayed implementation of the final repository, thus enabling to technically, socially and financially prepare the deep geological repository**



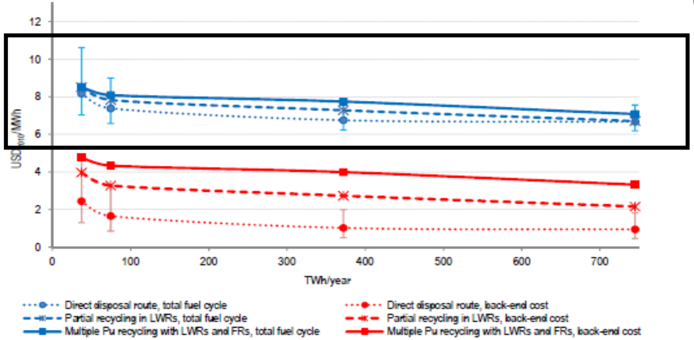


The Economics of the Back End of the Nuclear Fuel Cycle

High level analysis for idealized systems (an OECD/NEA No. 7061, © OECD 2013)

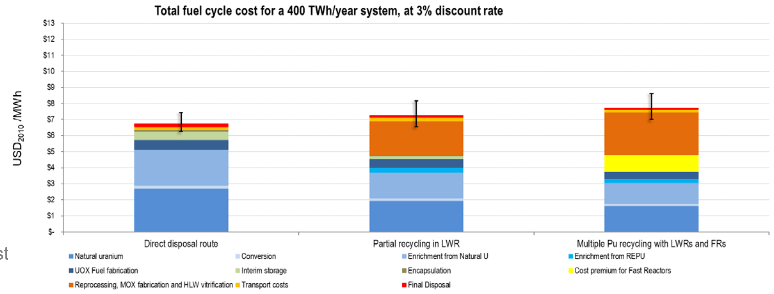
LCOE$_{Fuel\ cycle}$ for different reactor fleets and back-end strategies

(3% discount rate)



Notes:

- The central values represent the results from the REFERENCE cost scenario, and the error bars correspond to the LOW and HIGH cost scenarios.
- For small nuclear fleet, Reprocessing/recycling cost are based on service cost from shared infrastructure



- Comparisons should be drawn on the basis of the comprehensive fuel cycle costs beyond the sole BE costs
- Differences among the three options in the total fuel cycle component of the LCOE (Levelized Costs Of Electricity) are within the uncertainty margin, given the uncertainties around some input data.
- Such assessment cannot be implemented into a specific national context, it requires a detailed and adapted analysis to each specific country context

In the long run, Spent Fuel Management system involves multidimensional criteria that may lead to multiple decisions

- **Uncertain factors conditioning the decisional options in future times**
- **No fixed scenario**

Fuel Cost on the Projected Cost of Electricity

- **Harmonized Fuel cost for all countries including USA and France (but Japan and Russia) represents a third to 40% of the projected operating cost for nuclear, Front end levelized cost 7 $/MWh and back end levelized cost of 2.33 $/MWh (***source Projected Costs of Generating Electricity, NEA OECD, edition 2020***)**
- **In this simplified cost methodology , utilities consider that fuel costs depend mainly on two factors, the price of front end components (uranium resource, conversion, enrichment, fuel design and manufacture) and the efficiency of fuel management (evolution to longer operation fuel cycle and higher BU).**
- **In the levelized cost methodology, long term spent fuel and waste management costs become small when discounted over 60 or 80 years, the lifetime of a nuclear plant.**
- **Such generic assumptions inevitably abstract from unanticipated cost inflation or other uncertainties related to expenditures that will take place several decades later, some after the closure of the reactor**
- **Back end costs become much more important when approaching actual implementation of waste predisposal and disposal steps in particular for open cycle**

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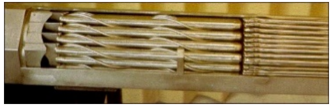
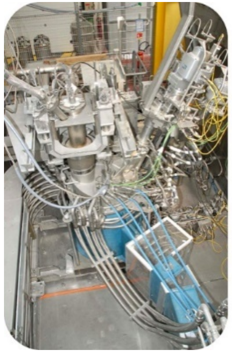
A Broad Range of Fuel Already Reprocessed at Various La Hague Production Units

• UNGG (Natural Uranium Graphite Gas reactor)	4 900 tHM	(1966 - 1990)
• PWR (UO2)	33 650 tHM	(1977 - now)
• BWR (UO2)	3 800 tHM	(1976 – 2010)
• LWR MOX	73 tHM	(1992 – 2008)
• LWR RepU	24 tHM	(2006 – 2020)
• FNR	10 tHM	(1979 – 1984)
• RTR (UAl, U_3SI_2)	3 100 SF	(2005 – now)



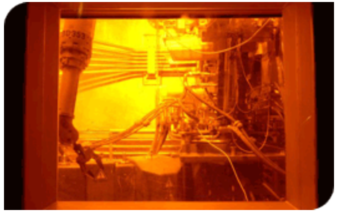
Going Forward…
Expanding Capabilities of Existing Plants

Vitrification of a wider range of product
(UMo…)
Cold Crucible Melter vitrification technology

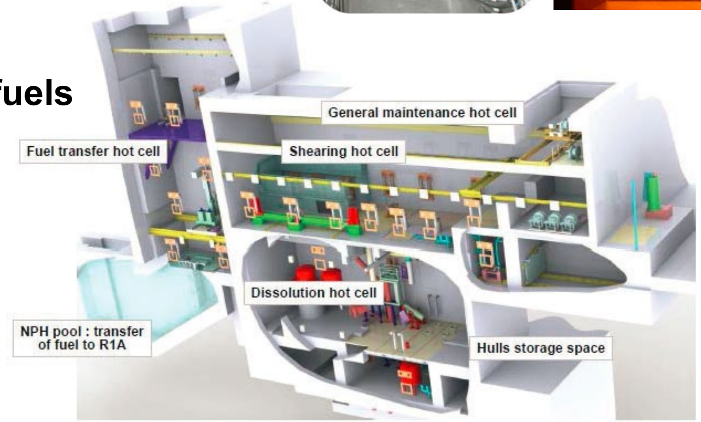


Vitrification cell constructed at the Beaumont-Hague Research Hall (HRB)

Vitrification cell, La Hague



Recycling additional types of fuels
TCP project
Research reactor fuels
MOX fuels from LWR and FR
Special material



TCP project, in R1 facility, La Hague

Preparing the Future: R&D Programs on Advanced Recycling

Multi-recycling of Pu in LWR

- **Evolution of the treatment process**
  - Voloxidation
  - Solvent extraction
  - Enhanced Waste management

- **Evolution of the MOX manufacturing process**
  (higher throughput, increase Pu level, lower fissile plutonium quality)

Fast spectrum Chloride MSR, to burn plutonium and minor actinides

- Partitioning process
- Preparation and recycling of chloride salt

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