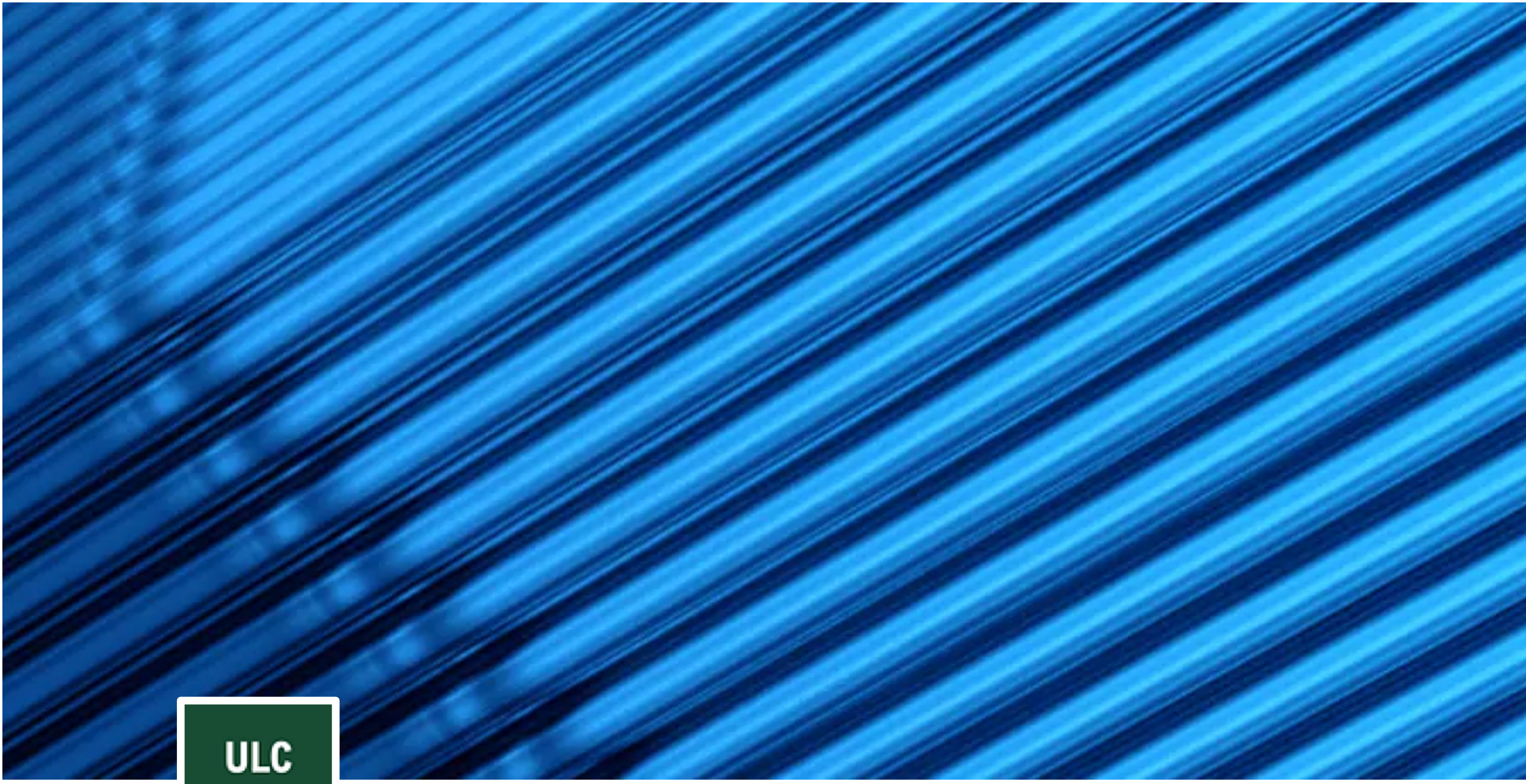

Spent Fuel Strategy

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ULC Energy B.V. Weesperstraat 107 1018 VN Amsterdam The Netherlands

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2. Introduction

This document describes the high level spent fuel strategy of ULC Energy for the deployment of the Rolls-Royce Small Modular Reactor (SMR) in the Netherlands. Spent fuel, which is often referred to nuclear waste, is an important considering when developing a nuclear power plant. Although the volumes of spent fuel are relatively small (see chapter 2), the radioactivity of spent fuel means it must be treated with care and must comply with strict regulations.

This document would not have been possible without the contribution of a group of companies and organisations who all bring significant expertise to this topic. The organisations who helped us are:

- Rolls-Royce SMR
- International Atomic Energy Agency (IAEA), especially the Common Research Project (CRP) project: CRP Challenges, Gaps and Opportunities for Managing Spend Fuel from Small Modular Reactors
- Dutch Ministry of Infrastructure and Water Management
- Dutch Central Nuclear Waste Facility (COVRA)
- World Nuclear Association (WNA), especially the working group Used Fuel Management

Because the scope of this document is about the spent fuel of the Rols-Royce SMR, it’s primary focus is the high level radioactive spent fuel from this nuclear power plant (NPP). We included also an overview of the intermediate level and low-level waste from NPPs. These forms will follow the same processes as today for these types of nuclear waste.

This document starts with a policy overview on nuclear waste in the Netherlands. This sets the guidelines and policy to which we need to comply. This is followed by a section in which we explain the spent fuel from the Rolls-Royce SMR and then go into the current practise in the Netherlands.

After this explanation of current practises, we outline three pathways we could take. The objective is not to choose one of these pathways, but to ensure that the Rolls-Royce SMR in the Netherlands could be ready for any of these three cases. All these cases comply with the policy set out in the next chapter.

3. The Netherlands nuclear waste policy overview

The Dutch National radioactive waste program falls under the direct responsibility of the Ministry of Infrastructure and Water Management. All European Union Member States are obliged to draw up a national program for the management of radioactive waste and spent fuel every 10 years. This national radioactive waste program states how a Member State deals with this now and in the future.

Dutch national radioactive waste program (NPRA)

The Ministry of Infrastructure and Water Management published the Dutch national radioactive waste program (NPRA) in 2016 [1] . The Netherlands must publish a new national program before 2026, and the ministry is currently working on an update of its policy. Nuclear waste is created during the production of nuclear energy, while conducting nuclear research, producing medical isotopes and administering nuclear medicine. It can also sometimes be released from natural materials, such as from some ores. Radioactive waste can remain hazardous for hundreds, or even thousands, of years, requiring careful and appropriate storage to ensure safety.

Radioactive waste policy

The Dutch policy for radioactive waste is based on four principles:

1. Minimizing the production of radioactive waste.
2. Ensuring the safe management of radioactive waste.
3. No undue burdens placed on future generations
4. The producer of radioactive waste is responsible for covering the costs of its management and storage.

Storage of radioactive waste

In the Netherlands, radioactive waste is stored above ground for a period of at least 100 years. This takes place at the Central Storage for Radioactive Waste (COVRA). COVRA is the sole company in the Netherlands tasked with collecting, processing and storing all radioactive waste.

All businesses in the Netherlands which have a permit pursuant to the Dutch Nuclear Energy Act [Kernenergiewet] to work with radioactive substances must send their radioactive waste to COVRA.

The Authority of Nuclear Safety and Radiation Protection (ANVS) is the government authority which issues permits under the Dutch Nuclear Energy Act. The ANVS is charged with ensuring that nuclear safety and radiation protection in the Netherlands adheres to the highest standards. The ANVS draws up rules, issues permit, monitors compliance with its regulations and can take enforcement action.

To fulfil its responsibility for managing radioactive waste, COVRA has established a storage and processing facility in Zeeland, located at the East Vlissingen harbour grounds in the municipality of Borssele. COVRA handles all low, medium, and high-level radioactive waste.

Type	Annually Produced (m3)	Total stored at COVRA (m3)
High-Level Radioactive Waste	4.5	111.5
Low and Medium-Level Radioactive Waste	1,100	38,355

Figure 1 – COVRA Waste volumes [2]

There are three main types of storage for high radiative waste in the world today:

- Wet system: smallest footprint and material stored in water, used in Sweden
- Vault System: safety in building, used by COVRA
- Dry storage casks type: safety in container, used in Switzerland (Zwilag) and Germany (Arhaus)

Currently the COVRA uses a Vault system because this system is most suited to store nuclear waste which has been reprocessed. For future, dry cask system could be considered, but is currently not in use by the COVRA. When a cask system is used it will be likely that the COVRA would require a hot cell facility because material does need to be repackaged and re-certified over time.

After 100 years of storage or more, some waste remains radioactive. At one point, the waste will be transferred to deep underground storage, known as final disposal. The radiative waste will have to stay at the COVRA facility till at least 2130 after which it will be transferred to an underground facility.

Since 2011, research into geological disposal of radioactive waste in the Netherlands has been conducted through the Research Program for Final Disposal of Radioactive Waste (OPERA) [3]. The COVRA coordinates this program. Elektriciteits Produktiemaatschappij Zuid-Nederland (EPZ), the operator of the Borssele nuclear power plant, and the government act as financiers of this program. In addition, a lot of research into disposal is being done in a European context.

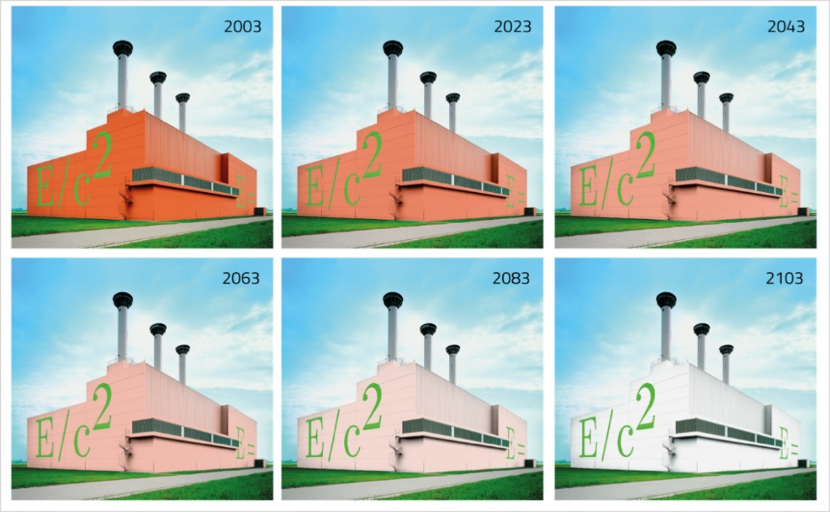

Figure 2 – COVRA (Central Organization for Radioactive Waste) in the Netherlands. Building is repainted every 10 years to reflect decrease in radioactivity of stored waste.

4. Spent fuel from Rolls-Royce SMR

The Rolls-Royce SMR is a 470 MW Pressurized Water Reactor (PWR). PWR technology is known technology and is currently used at nearly all nuclear power stations currently operating in the world. PWR require fuel that is enriched in the fissile isotope, U-235. This fuel has a standard enrichment level (UO_2 4,95%) and can be manufactured by multiple suppliers.

Reactor Type	Number in Operation
Pressurized Water Reactor (PWR)	307
Boiling Water Reactor (BWR)	60
Pressurized Heavy Water Reactor (PHWR)	47
Light Water Graphite Reactor (LWGR)	11
Gas-Cooled Reactor (GCR)	8
Fast Breeder Reactor (FR)	2
High Temperature Gas-Cooled Reactor (HTGR)	1

Figure 3 – Current Global Reactor Fleet by Type

The fuel for the Rolls-Royce SMR is commercially available and currently Rolls-Royce is working with Westinghouse[4] to design and produce the fuel for the Rolls-Royce SMR. Typically fuel in a PWR spends an average of 4 ½ years in the reactor core. Refueling the reactor core happens every eighteen months, but only around one-third of the fuel assemblies are replaced during each refueling outage.

The Rolls-Royce reactor core holds 121 fuel assemblies which is the approximately the same amount as the only operating Dutch NPP at Borssele.

After nuclear fuel has spent its requisite time in the reactor core, it is moved to the spent fuel pool (SFP). Here the fuel is stored in fuel storage racks. Fuel is expected to cool in the fuel storage racks for 6 years before transfer to dry storage casks. The Rolls-Royce SMR has a fuel rack capacity of 548 fuel assemblies, allowing for 10 years of cooling following reactor discharge.

After the fuel has sufficiently cooled, it is transferred to the Cask Loading Pit, located adjacent to the SFP. Also nearby is the Cask Preparation Pit, which is used to prepare the cask before loading, as well as for draining, welding, drying, helium backfilling, and non-destructive testing of the cask after loading. [5]

Once the spent fuel is safely stored in the dry cask it can be removed from the reactor building for storage pending future disposition.

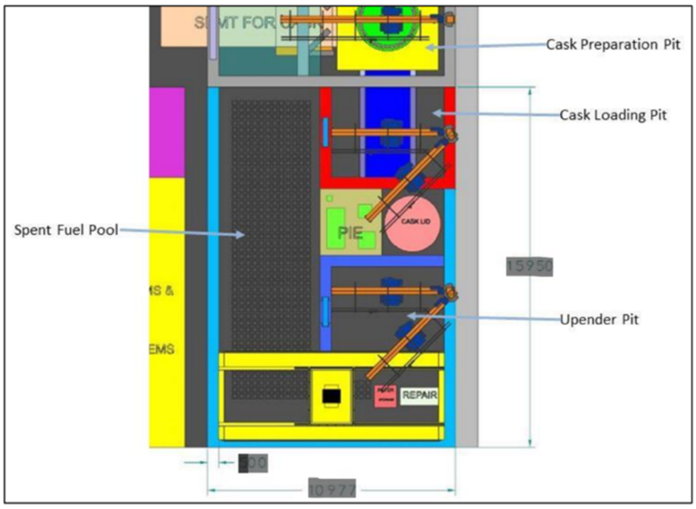

Figure 4 – Spent Fuel Pond and facilities Rolls-Royce SMR

Beside the high radioactive spent fuel, the Rolls-Royce SMR also produces low level (LLW) and intermediate radioactive waste (ILW). This waste comes in two forms which require separate treatment and storage:

- Wet solid radioactive waste including evaporator concentrates, resins and backwashed filter solids coming from Spent Fuel Pool Purification and Cooling System and Liquid Radioactive Effluent Treatment System. Miscellaneous wet waste (such as sludges, oils and solvents) may also arise from the plant.
- Dry solid radioactive waste from the Reactor Island and the rest of the plant, e.g. filter casings and waste produced during maintenance.

A 500 litre drum has been selected as the preferred container for disposal of grouted wet ILW, with 3 m3 boxes or shielded drums options for decay storage [6].

The Rolls Royce SMR has processing and dispatch areas for both LLW and ILW. It also contains temporary storage areas for both types of waste. On the premisses of the Rolls-Royce SMR there is a dedicated storage area for ILW. In the Netherlands however it will be mandatory to transport this waste to the COVRA facility.

5. Current Spent Fuel Process in the Netherlands

In the Netherlands there is currently one NNP in operation for electricity production. This plant is based at Borssele in the southwest of the Netherlands and is operated by EPZ. The Borssele NPP started operations in 1973 and is a PWR. It has a capacity of 485 MWe. The plant is licensed until 2033 but there are plans to extend this license. Both the plant in Borssele and the Rolls-Royce SMR are PWRs of similar size.

The Borssele NPP uses standard LWR fuel, UO_2 4,95%, and the reactor core holds 121 fuel assemblies. The reactor has used both currently uses a 'mix' of new fuel, reprocessed Uranium fuel and Mixed Oxide fuel (MOX). The mix is roughly a 1/3 of each of the fuel types:

- Enriched Natural Uranium (ENU)
- Enriched Recycled Uranium (ERU)
- MOX Fuel, mix of uranium and plutonium

In 2013 Borssele started to use reprocessed fuel, ERU and MOX. Prior to this Borssele has also operated using only ENU. Every eighteen months a third of the fuel in the reactor core gets replaced. The fuel from the reactor will have to cool then and after the cooling down period it is transported to La Hague in France. There, the various component of the fuel, Uranium, plutonium, actinides are separated for further processing. New MOX fuel is fabricated and transported back to Borssele.

Material can be recycled through Borssele multiple times , after that it will be transported back to the Netherlands as waste, for storage at the COVRA facility.

6. Strategy for the Rolls Royce SMR in the Netherlands —Three Pathways

6.1. Direct Disposal

Most NPPs use standard UO_2 fuel. This is fuel which has been newly fabricated and has not yet been irradiated in a reactor. Standard fuel is made by mining uranium (U3o8), converting it to a gas (UF6), enriching the uranium using centrifuges (EUP) and de-converted to make it a solid again (UO2) and finally fabricating in fuel assemblies that contain the enriched uranium. The fuel assemblies containing enriched natural uranium are then placed in the reactor core of a nuclear power plant where they remain, on average, 4 years.

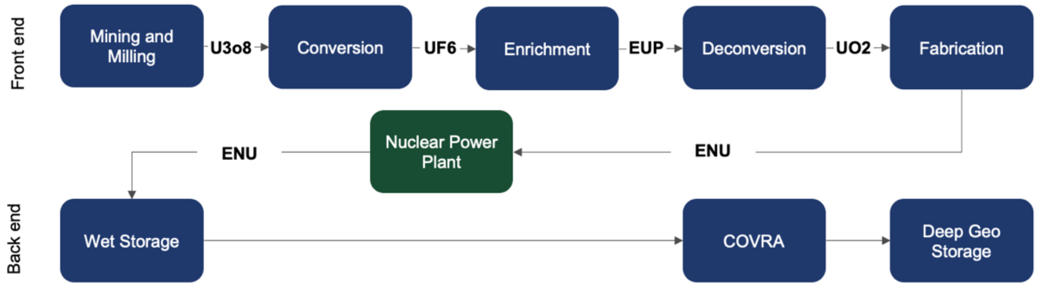

Figure 5 – Front and Back-end Fuel cycle standard UO2 Fuel

This fuel is used in most LWRs, and other conventional nuclear reactors. Typically, the uranium in standard fuel is primarily composed of uranium-238 (~95-97%) and uranium-235 (~3-5%), which undergoes fission to release energy

After fuel is used, it will have to cool down. Cooling down periods vary but take at least 6 years before the fuel could be moved into interim dry storage. There are various commercial canister and cask designs available for this and in the Netherlands the COVRA facility is the place where this material will have to be stored. After a minimum of 100 years in dry storage fuel would move to a permanent repository, typically these are underground facilities. There is no such place yet in the Netherland, but they would have to have one by the year 2130.

6.2. Reprocessing of LWR Fuel

Standard Fuel consist of 96% U-238 Isotope and 4-5% U-235 Isotope. When this standard fuel is irradiated in a reactor, it transforms into three main components:

- unburned U-235,
- plutonium created when U-238 transmutate,
- fission products formed from the U-235 and plutonium that underwent fission.

Because the plutonium also fissions in the reactor it reduces the initial plutonium created and further forms fission products.

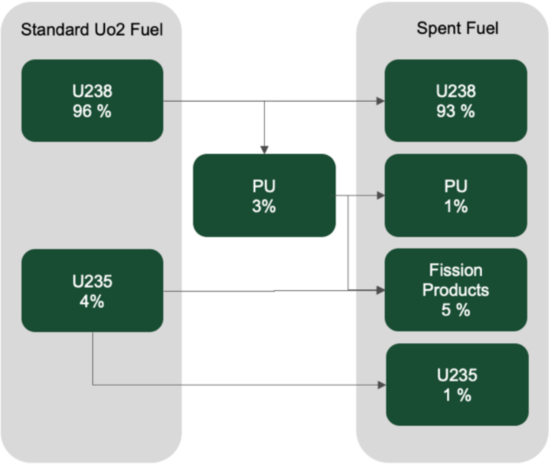

Figure 6 – Reaction of Standard UO2 Fuel [7]

After standard fuel is used in the reactor and has sufficiently cooled the spent fuel pond, it can be reprocessed to recover reusable materials and make 'new' fuel. The reprocessing of spent fuel involves separating the uranium and plutonium that can be reused as fuel from the fission products and minor actinides, which are highly radioactive waste , and must be emplaced in a final disposal. This separation is crucial because the fission products are no longer useful as fuel and create significant heat and radioactivity, while the uranium containing U-235 and plutonium can be recycled to make MOX fuel. Currently there is only one industrial plant in the western world that does have the capacity to reprocess spent fuel. This plant located at La Hague in France is owned and operated by Orano.

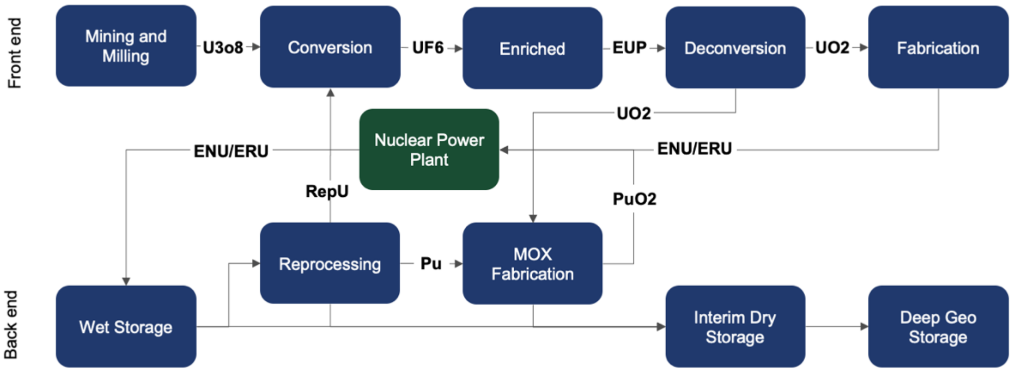

Figure 7 – Front and Back-end Fuel cycle with recycling

MOX fuel is a type of nuclear fuel that blends plutonium oxide (PuO_2) with depleted uranium. Indeed, MOX fuel recycles plutonium, from spent nuclear fuel coming from cicil reactors, and is used as an alternative to uranium-235. Spent nuclear fuel is simply standard fuel after irradiation in a reactor.

The Rolls-Royce SMR is likely capable of using MOX fuel, however, the design currently going through the licensing process in the UK only reflects the use of standard fuel. Additional safety assessment would have to take place before the reactor would be licensed to also use MOX or Reprocessed Uranium (RepU).

Figure 8 – Orano SA reprocessing plant La Hague [8]

6.3. Retain LWR Fuel for future use in Advanced Modular Reactors (AMR).

Currently, several advanced reactor designs are being developed with the specific aim of using material recovered from spent fuel from LWRs as their initial fuel source. Among these designs are certain types of Molten Salt Reactors (MSRs), which differ from conventional reactors in how they handle and utilize fuel. Instead of relying on traditional solid fuel assemblies, MSRs use molten salt containing fissile material, which then flows through the reactor core. Fast neutron reactors also called fast reactors can also use materials recovered from LWR spent nuclear fuel because they operate without a moderator, allowing them to efficiently fission a wider range of isotopes, including plutonium and minor actinides (like neptunium, americium, and curium),. Some types of fast reactors include sodium and lead cooled fast reactors.

These reactors can be designed to extract more energy reusing materials contained in spent LWR fuel thus saving natural uranium resources while reducing long-lived radioactive waste. To preserve the fuel for this type of opportunity it is important that the spent fuel be stored in a retrievable form, choosing casks/canister types that can easily be transported and compatible with the foreseen Reprocessing facilities .

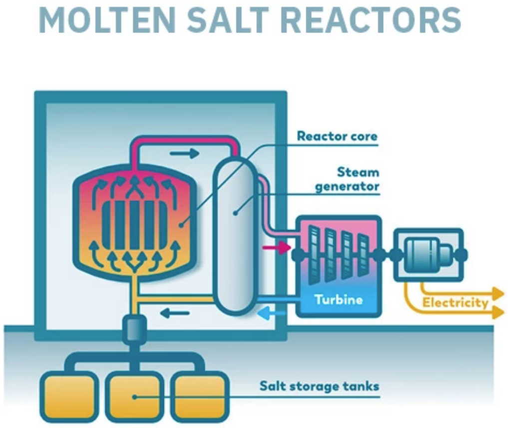

Figure 9 -Molten Salt Reactor [9]

Before this re-use of fuel is achievable, these AMR designs first need to finalise their design, get licensed and build. Most importantly the supply chains for both front-end and back-end fuel cycle need to be in place. Beside the reprocessing/recycling facility that could produce fuel whether Fast reactor MOX or Pu based molten salt, there are also transport systems and other supply chain challenges to overcome. Additional benefit of using these reactors , if minor actinides are also multi-recycled is that they would not only reduce the volume of HL waste but may also significantly reduce the radioactivity levels and years of the remaining waste. This would again require qualification to be achieved and adequate supply chain to be developed.

Appendix - Terms

Term	Explanation
ANVS	Nuclear Safety and Radiation Protection
BWR	Boiling Water Reactor
COVRA	Central Storage for Radioactive Waste
CRP	Common Research Project
ENU	Enriched Natural Uranium
ERU	Enriched Recycled Uranium
EPZ	Elektriciteits Produktiemaatschappij Zuid-Nederland
EUP	Enriched Uranium Product
FR	Gas-Cooled Reactor
GCR	Gas-Cooled Reactor
HTGR	High Temperature Gas-Cooled Reactor
IAEA	International Atomic Energy Agency
LEU	Low Enriched Uranium
LLW	Low Level Waste
LWGR	Light Water Graphite Reactor
MSR	Molten Salt Reactor
MOX	Mixed Oxide Fuel
NPP	Nuclear Power Plant
NPRA	Dutch national radioactive waste program
OPERA	Research Program for Final Disposal of Radioactive Waste
PHWR	Pressurized Heavy Water Reactor
PU	Plutonium
PWR	Pressurized Water Reactor
RepU	Reprocessed Uranium
SFP	Spent Fuel Pool
SMR	Small Modular Reactor
U-235 / U- 238	Uranium isotope 235 / 238
U3o8	Triuranium octoxide
UF6	Uranium hexafluoride
UO2	Uranium Dioxide
WNA	World Nuclear Association

Appendix - References

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