# Mini-project report

# Life Cycle Analysis of the Nuclear Fuel Cycle

## Sellafield High Level Waste Plants 2010/11

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# 1 Introduction

## 1.1 Aim

The aim of this report is to provide a life cycle analysis of the embodied energy and carbon dioxide emissions from high level waste plants at the Sellafield nuclear site in the United Kingdom.

## 1.2 The Nuclear Fuel Cycle

In order to limit the impact of anthropogenic effects on the Earth's climate humanity needs to limit the use of carbon intensive fuel and energy sources for production of electricity and heat.

Bodies such as the World Nuclear Association (WNA) advocate the use of nuclear power for meeting our energy demands [1] due the generally held belief that it produces lower carbon dioxide equivalent ($CO_2e$) emissions than fossil fuels. [1, 2] However, due to limited fuel reserves [3] the potential reduction nuclear power could make to the global carbon footprint is limited. In order to enhance the impact of nuclear power it is possible to recycle spent fuel by reprocessing it, allowing more energy to be extracted from used uranium fuel rods. Reprocessing is also a key technology associated with fast reactor and thorium reactor technologies that are under development. [4]

The International Atomic Energy Authority (IAEA) commissioned a report [4] that states a country operating a fleet of Pressurised Water Reactors (PWRs) could lower the $CO_2e$ footprint of nuclear power if all fuel is reprocessed and used in Mixed Oxide fuel (MOX) reactors.

## 1.3 High Level Waste

Reprocessing of uranium oxide fuels generates a significant quantity of High Active Liquor (HAL). The HAL is produced by solvent extraction of Uranium and Plutonium from fuel which has been dissolved in nitric acid. [5]

The cooling and treatment of HAL is achieved through a variety of processes at a number of different High Level Waste Plants (HLWP). At Sellafield, the world's largest civil nuclear reprocessing facility, [9] the HAL is sent to the High Active Liquor Evaporation and Storage (HALES) plant for conditioning to vitrification. [6] The HAL is vitrified at the Waste Vitrification Plant (WVP); the vitrified product is then transferred to the Vitrified Product Store (VPS) for passive cooling prior to its ultimate disposal. [7] The HAL requires treatment so that it can be disposed of safely with minimal risk to the environment until the radioactivity has decayed sufficiently.

# 2 Method

The LCA described in this report is based on the two stage vitrification process used at Sellafield in the United Kingdom, which is similar to the French AVM (Atelier de Vitrification Marcoule) process used at Marcoule and La Hague. [8] Over 72% of the worldwide civil nuclear fuel reprocessing capacity is at these sites which use the same vitrification technology. [9]

Where possible, data relevant to the Sellafield site was gathered from primary sources including reported usage of electricity and raw materials and from the experience of operational personnel. Additional information from the design basis of plant processes, calculations and assumptions have been used where accurate operational data has proved unavailable.

The LCA has attempted to quantify all direct and indirect energy inputs and emissions where possible in the processes. This includes accounting for disposal of wastes arising from the HLWP and the embodied energy and carbon footprint of process consumables.

## 2.1 Assumptions

The following assumptions have been made in the LCA:

- 25%w/w of the vitrified product consists of fission products from spent nuclear fuel. [10]
- Annual throughput of a vitrification line is 170 canisters, each containing 142.5 litres of product. [11, 12]
- Chemicals are delivered concentrated to the site and then diluted to the required concentration.
- Off gas treatment systems are only running during active plant operation.
- Process effluents are negligible compared to the quantities arising from other operations at Sellafield.

# 3 Results

## 3.1 High Activity Liquor Evaporation and Storage

HAL is evaporated to obtain the correct concentration of solids and stored in actively cooled tanks at HALES to maintain a safe temperature. [6] The evaporation and storage of HAL utilises 4.00MWh/canister of vitrified product. An additional 0.06MWh/canister accounts for stack ventilation at building B204 which is linked to HALES. This figure is based on 1% of B204 electricity use.

The only major consumable at HALES is cooling water; it is assumed in this LCA that cooling water is provided by the Wastwater supply used throughout the Sellafield site. This water supply is provided from a local lake and undergoes minimal treatment and conditioning, [13] therefore the embodied energy of this supply is considered negligible.

## 3.2 Vitrification

Following cooling HAL is immobilised by vitrification at WVP. This process begins by a calciner evaporating the liquor from the HAL and denitrating the remaining solids. The solids, known as calcine, are fed into an induction melter with borosilicate glass to mix before being poured into a stainless steel container; [14, 15] see Figure 1.

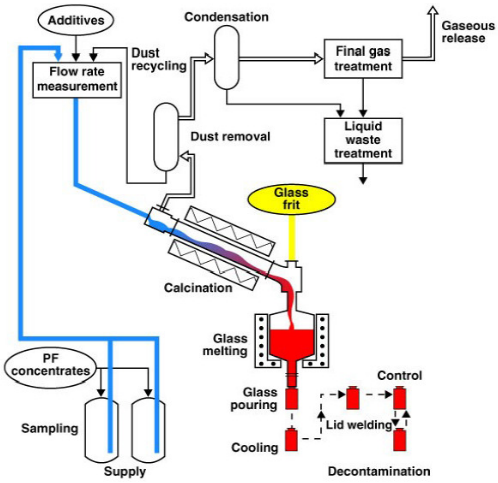

**Figure 1: The two step vitrification process [8]**

Each canister of vitrified product is produced by two pours from the melter. [14] The charge time to fill the melter with glass and calcine is approximately 7 hours 30 minutes and the pour time is approximately 30 minutes. Therefore the vitrification process takes approximately 16 hours to fill a canister. [14]

The vitrification processes consumables account for 5.31MWh/canister of embodied energy and 1.75te$CO_2$e/canister. Direct energy use accounts for 20.3MWh/canister.

## 3.3 Vitrified Product Storage

The vitrified product canisters are passively cooled by natural air convection in VPS. [7] The cooling is required for the product to reach a suitable temperature prior to ultimate disposal. VPS is designed to hold all waste canisters produced at WVP for a minimum of 50 years. [12] No regular consumables are used at VPS and the direct energy use is 1.58MWh/canister of vitrified product.

## 3.4 Disposal

UK policy states vitrified waste is to be disposed of in a deep geological facility. [16] Vitrified product canister will be encased in copper vessels with cast iron shielding inserts. [16] Each of these vessels contains two canisters and embodies 20te$CO_2$e/canister and 87.6MWh/canister.

## 3.5 Steam

Across the Sellafield site much of the process heating is provided by steam from a 168MWe gas fired combined heat and power plant at the site border. [17] Whilst the majority of this steam is used for reprocessing operations it is also used for domestic heating within many of the older plants across the site. The LCA assumed domestic heating is provided electrically at the HLWP due to the age of WVP and VPS. Additional heating may be provided by steam; however the LCA process was unable to confirm any use of steam at the HLWP.

## 3.6 Low Level Wastes

The operation of HALES, WVP and VPS produce regular volumes of Low Level Waste (LLW) estimated to arise at 900$m^3$ per year over the remaining operational lifetime. [18, 19] This equates to 1.8$m^3$ of LLW per canister. The LLW is encapsulated in a cement grout inside a half height ISO freight container before disposal. [18, 19] The LCA assumes that the waste produced is 60% PVC, 40% paper board and the grout is 25% Ordinary Portland Cement (OPC) and 75% fly ash. [19] The manufacture and disposal of equipment as LLW equates to 42.8MWh/canister and 12.8te$CO_2$e/canister.

## 3.7 Summary of Results

The results from the LCA are detailed in Figure 2 below. The total embodied energy is 165.1MWh/canister and the total embodied $CO_2$e is 35.76te$CO_2$e/canister.

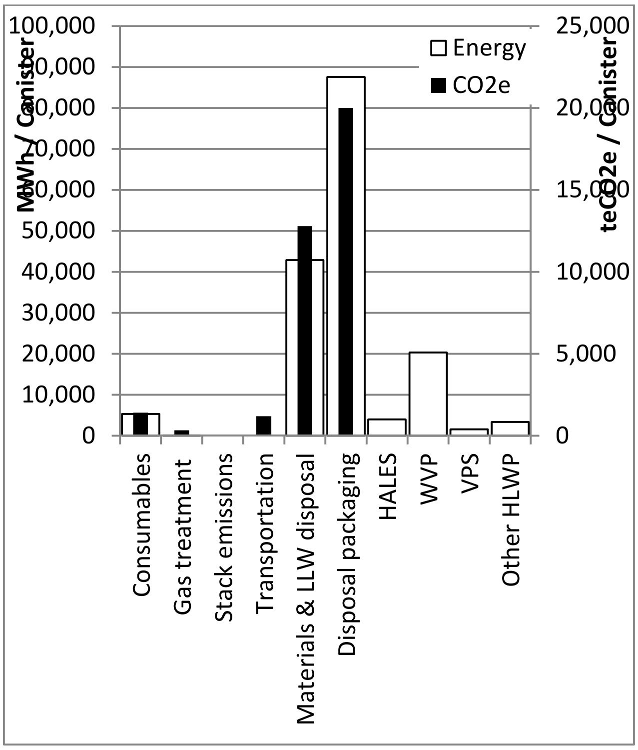

**Figure 2: Summary of LCA findings**

- Consumables include raw materials such as glass frit, stainless steel canisters and sugar used in the vitrification process and regular replacement of melter crucible and rabble bar.
- Gas treatment includes the use of water and nitric acid employed in cleaning off gases at the HLWP
- Stack emissions are the emissions of $NO_X$ gases from HLWP converted to $CO_2$e.
- Transportation includes transfer of materials from location of manufacture to the Sellafield site.
- Materials and LLW disposal includes use of protective materials, and minor items that are disposed from contaminated areas. This includes both their manufacture and disposal when encased in grout.

- Disposal packaging covers copper and iron containers that vitrified product canisters are disposed in.
- Remaining entries in Figure 2 cover the direct energy use at the different HLWP.

# 4 Discussion of Results

The LCA on the HLWP indicates that the greatest contributor to the embodied energy and carbon cost is the manufacture of disposal packaging, followed by the production and disposal of materials as LLW. These account for 79% of the embodied energy and 92% of the embodied $CO_2e$.

## 4.1 Disposal Packaging

An analysis of how the HLWP processes compare to disposal of a PWR fuel arrays was undertaken as disposal packaging materials are the greatest contributor to both energy and carbon cost. The direct disposal of spent fuel in the UK follows a similar philosophy to vitrified waste, in that the fuel assembly is placed into a copper container with cast iron shielding around the fuel.

For typical spent PWR fuel 3% of mass consists of fission products that are vitrified when reprocessed. As one canister of vitrified product contains ~95kg of solid waste materials, each disposal package contains waste from 6.3te of spent fuel.

In contrast 2.8te of PWR fuel are disposed of in a single waste package which contains more copper and iron due to a greater length. 70% of the PWR fuel assembly is uranium. [21]

Therefore comparative costs are:

| | |
|---|---|
| PWR fuel: | 105kWh/kgU |
| (Packaging only) | $24kgCO_2/kgU$ |
| Vitrified waste: | 52kWh/kgU |
| (Full HLWP LCA) | $11kgCO_2/kgU$ |

This is an increase of 53kWh/kgU and $13kgCO_2/kgU$ for direct disposal of spent fuel, compared to the HLWP processes.

Despite the apparent decrease in energy and carbon costs the other costs of fuel reprocessing have not been accounted for. For example reprocessing of oxide fuels at Sellafield directly consumes up to 350kWh/kgU, and the disposal of fuel cladding as Intermediate Level Waste (ILW) has not been accounted for, see Section 4.4 below.

## 4.2 Low Level Waste

LLW disposal contributes a significant environmental cost to many areas of operating nuclear power facilities from mining and fuel fabrication through to the ultimate decommissioning of facilities.

The figures for LLW disposal are based on the Nuclear Decommissioning Authority (NDA) waste stream data sheets, [18, 19] which indicate the average gross waste loading of a LLW package for HLWP is 16.5% volume. It is believed that this figure is pessimistic as operational experience from alternative facilities across the Sellafield site indicates that gross waste loadings of up to 95% are achievable. [20] The achieved waste loading will significantly affect the embodied carbon and energy content of LLW disposal as higher loadings result in less grout and fewer LLW containers being used.

Resultantly to balance the waste loading the LCA does not account for the excavation costs in disposal of LLW to provide a more realistic figure. It is however recommended that a full LCA of LLW disposal should be undertaken to improve the accuracy of this process due it's importance across the nuclear sector.

## 4.3 Process Electricity Use

Use of electricity is the third major contributor to embodied energy costs for the HLWP processes. Over 50% of electricity is used at WVP in the heating processes. The remaining significant use of electricity across the HLWP is accounted for by plant ventilation and pumping of fluids.

## 4.4 Qualitative Analysis of LCA

Due to the overall complexity of reprocessing operations and the utilisation of reprocessed fuel and treatment of wastes a number of omissions were made in conducting the LCA that will contribute both positively and negatively towards the footprint of HLWP. These include:

Construction and decommissioning costs: The facilities detailed in this report require significant radiation shielding which is achieved with thick concrete walls, the concrete and structural steel used in construction may be a significant contributor to the embodied energy and carbon of fuel reprocessing. However, decommissioning of these plants has not been fully quantified and so this has been omitted from the LCA.

Treatment of effluents: The effluents arising from the treatment of off gas at WVP are considered be negligible in comparison to quantities arising from reprocessing and legacy clean-up operations at the Sellafield site. These effluents are routed to the same treatment plants at Sellafield, therefore the net contribution of the HLWP to energy use at effluent treatment plants is insignificant.

Utilisation of waste heat: High level radioactive wastes and spent fuel produce significant quantities of low grade heat as radioactive materials decay. While this heat is currently wasted, and energy actively expended to cool these materials it may be possible to effectively utilise the waste heat in an efficient manner.

Overall the analysis of the HLWP at Sellafield provides an analysis of one aspect of reprocessing spent fuel, and aids determining the effective energy and carbon cost of reprocessing nuclear fuel. Further work should be undertaken in determining the remaining energy and carbon costs for reprocessing operations to provide an accurate view of the impact spent fuel reprocessing has on the environment.

## 5 Conclusions

The LCA of the Sellafield HLWP has produced the following conclusions:

- The most significant impact is caused by the manufacture of copper canisters and the cast iron inserts that the vitrified product is disposed in. This is followed by the use of and disposal of protective equipment as LLW. These two processes account for 80% of the embodied energy and 87% of the embodied carbon content.
- Further work should be undertaken in determining the footprint of LLW disposal to provide an accurate figure for the impact on various aspects of the nuclear fuel cycle.
- Further work should be undertaken to determine the full embodied energy and carbon content in other areas of nuclear fuel reprocessing to determine how it compares with direct disposal of spent fuel and mining of uranium ore.
- The majority of electricity use at the Sellafield HLWP is due to electrical furnaces used at WVP, followed by providing ventilation and pumping of fluids.
- Minimal contributions to the overall LCA totals are the use of electricity for operator facilities and ancillary processes along with gas treatment and stack emissions.

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