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GENIORS

Report on ?Sim-Plant? Methodology and flowsheet comparison

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Summary

Final REport in Geniors on SimPlant

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GENIORS

GEN IV integrated oxide fuels recycling strategies

Deliverable 8.4 – Report on "Sim-Plant" Methodology and flowsheet comparison

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EXEC SUMMARY

Building on past phases of Sim Plant, an assessment of a Euro-GANEX flowsheet has been carried out utilising two fuel cases, namely a 50 GWd/tHM MOx fuel, and a 65 GWd/tHM UOx fuel. These cases were chosen to give a like for like comparison to previous assessments carried out on the Advanced PUREX flowsheet [1]. Using the Sim Plant tool, Euro-GANEX has been successfully assessed for waste arisings, reprocessing plant footprint and waste treatment plant footprint. This has then been directly compared to Advanced PUREX and a Thorp PUREX baseline case.

The concept Euro-GANEX flowsheet performs well compared to Thorp PUREX and Advanced PUREX assessments, with normalised (per TWh_e) data reflecting improvements similar to the Advanced PUREX flowsheet over Thorp PUREX. However, the Sim Plant tool has outlined a number of key areas for improvement to the flowsheet in its current form as it has done previous with Advanced PUREX.

The following recommendations have been made as a result of the work performed for this report and support the development of wate treatment processes, advanced reprocessing and the Sim Plant tool itself:

1. Future development of the Euro-GANEX flowsheet should be focused on the following key areas:
    - Identification of a suitable solvent wash process for DEHiBA and DMODHEMA/TODGA solvents, and optimisation of this process.
    - Optimisation of the routing of non-Ln/An fission product species within the Chemical Separations area of the Euro-GANEX flowsheet, particularly co-extraction into the solvent phase, and optimising the back-extraction of these co-extracted species.
    - The flowrates utilised throughout the Chemical Separations area should be optimised for a larger scale process, as currently the volumes processed lead to significant demands on a HALES system.
2. Building on previous recommendations from the previous phase [1], it is recommended here that the development of Sim Plant continues with the integration of more advanced reprocessing flowsheets to provide insights into the volume, footprint and downstream requirements. This holistic view of a reprocessing and effluent treatment system should continue to establish Sim Plant as the leading platform for strategic plant modelling.

In summary, using the Sim Plant tool to assess a concept Euro-GANEX flowsheet has been successful in that a direct comparison has been obtained against Advanced PUREX and Thorp PUREX, and key areas have been identified for further development of the flowsheet. These key areas have been identified using the Sim Plant tool due to the ability to assess the downstream requirements of a reprocessing flowsheet.

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1. GLOSSARY

AFCP	Advanced Fuel Cycle Programme
AHA	Acetohydroxamic Acid
An	Actinides
AP	Aqueous Product
AR	Aqueous Raffinate
BEIS	UK Government Department of Business, Energy and Industrial Strategy
BTP	2,6-bis(1,2,4-triazin-3-yl)pyridines
CDTA	Cyclohexanediaminetetraacetic Acid
CFT	Centrifuge Feed Tank
CFA	Conditions For Acceptance
DEHiBA	N,N-di-2-ethylhexyl-isobutyramide
DF(s)	Decontamination Factor(s)
DMDOHEMA	N,N'-dimethyl-N,N'-dioctyl-2-(2-hexyoxy-ethyl)-malonamide
EARP	Enhanced Actinide Removal Plant
EPR	European Pressurised Water Reactor
ExAm	Extraction of Americium
FISPIN	Fission Product Inventory (Software which calculates the composition of spent fuel)
FP(s)	Fission Product(s)
GDF	Geological Disposal Facility
GENIORS	Generation IV Integrated Oxide fuels Recycling Strategies
GWd	Gigawatt days
HA	Highly Active
HAL	Highly Active Liquor
HALES	Highly Active Liquor Evaporation and Storage
HAN	Hydroxylamine nitrate

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HAR	Highly Active Raffinate
HAST	Highly Active Storage Tank
HASW	Highly Active Solvent Wash
HASWAE	Highly Active Solvent Wash Aqueous Raffinate
HBU	High Burn-up
HEPA	High Efficiency Particulate Filters
HIP	Hot Isostatic Pressing
HLW	High Level Waste
HM	Heavy Metal (fissile components of fuel)
ILW	Intermediate Level Waste
I-SANEX	Innovative Selective Actinide Extraction
LA	Low Active
LLW	Low Level Waste
Ln	Lanthanides
LWR	Light Water Reactor
MA	Minor Actinide
MASFE	Medium Active Salt Free Evaporator
MOx	Mixed Oxide
NAR	Nitric Acid Recovery Stream
NDA	Nuclear Decommissioning Authority
NIP	Nuclear Innovation Programme
NNL	National Nuclear Laboratory
OK	Odourless Kerosene
OML	Oxalate Mother Liquor
ORION	Fuel Cycle Modelling Software
PPE	Personal protective Equipment
PPSW	Plutonium Purification Solvent Wash

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PUREX	Plutonium Uranium Extraction
PWR	Pressurised Water Reactor
R&D	Research and Development
SANEX	Selective Actinide Extraction
SE	Salt Evaporator
SEC	Salt Evaporator Condensate
SETP	Segregated Effluent Treatment Plant
SNF	Spent Nuclear Fuel
STP	Solvent Treatment Plant
SX	Solvent Extraction
TBP	Tributyl phosphate
TDN	Thermal Denitration
teU	Tonne of equivalent U (pre-irradiation)
tHM	Tonne of heavy metal (fissile components of fuel)
Thorp	Thermal Oxide Reprocessing Plant
TODGA	N,N,N',N'-Tetraoctyl Diglycolamide
TPH	Hydrogenated Tetrapropene
TRU	Trans-Uranic Element
TWh_e	Terawatt hours (electric)
UOX	Uranium Oxide
UPSW	Uranium Purification Solvent Wash
WEP	Waste Encapsulation Plant
WPEP	Waste Package Encapsulation Plant
WO	Waste Oxide

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2. INTRODUCTION

Nuclear fuel reprocessing in the UK is due to complete as the two plants, Thorp and Magnox, come to the end of their operational lifetimes [2]. With no current plan to replace this capability, the UK will move to interim store all of its spent fuel prior to the completion of a Geological Disposal Facility (GDF) designed for the long-term disposal of un-reprocessed spent nuclear fuels and high level waste (HLW) containers (produced from reprocessing operations). In Europe, there is further uncertainty on the part nuclear will play in a carbon-free energy mix. Many scenarios have been considered for the future, from nuclear power as a baseline power generation method to complete phase out.

To complement some of these scenarios, actinide and waste recycling has been identified as a method to reduce demands on the GDFs and improve sustainability in the nuclear fuel cycle. It is, however, recognised that despite the success of the existing Plutonium-Uranium Extraction (PUREX)-based reprocessing plants such as Magnox reprocessing and Thorp, the technology they employ was developed during the 1950s-1980s and improved processes will be needed for any successful future deployment within Europe.

It is, therefore, necessary to focus research and development (R&D) on advanced reprocessing processes such as Euro-GANEX, which demonstrate enhanced benefits in the areas of proliferation resistance, process safety, flexibility of fuel feed, economics, environmental impact, and waste production. There is also a need to enhance our understanding of the performance of advanced solvent extraction equipment such as centrifugal contactors, which offer reduced residence times whilst also reducing plant size and cost.

Progress has been made at a global level towards the development of advanced aqueous recycle processes which offer enhanced benefits compared to current industrialised reprocessing technologies. As a result, multiple options exist at the laboratory level which could be adopted into the next generation of reprocessing plants. To complement scenario analyses and down-selection of processes (to identify the most suitable technology on which to focus development efforts), tools and techniques which quantify the benefits of advanced reprocessing flowsheets over current technologies should be developed. This will allow advanced reprocessing flowsheets to be evaluated in terms of the key drivers such as economics, safety, proliferation resistance, environmental impact, and waste production.

This document provides a comparison of the HLW, intermediate level waste (ILW) and effluents arising from a Euro-GANEX flowsheet, and providing a comparison against a baseline Thorp PUREX process and leveraged previous Advanced Fuel Cycle Programme (AFCP) reference Advanced PUREX process [3] flowsheets. The data obtained regarding the Thorp PUREX process and AFCP reference Advanced PUREX process is a result of previous work comparing the two [4]. Calculations developed through NNL's Sim Plant tool are applied to the outputs of the Euro-GANEX flowsheet to provide a detailed comparison of the composition of the waste and incorporation into waste containers, from which the number and size of waste treatment plants can be inferred. The output of these calculations highlights the impacts of changing from the baseline Thorp process, to either an Advanced PUREX or Euro-GANEX process on the waste treatment processes and contributes to the overall goal of the Sim Plant tool, which is to model the macro-scale (plant and site scale) effects of proposed changes to the reprocessing flowsheet.

In the first phase of Sim Plant work, the primary focus was placed on detailed assessments of HLW, whilst ILW arising from both flowsheets was evaluated on a volume-only basis [5]. As a result of that work, several recommendations were made, of these, a number have since been progressed:

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- Streams for processing the ILW into their final waste forms have been added to the model, allowing for the detailed assessment of ILW to the same degree as HLW, for a more complete overview and comparison between the two reprocessing flowsheets.

- A front-end interface for the Sim Plant tool has been developed which partially interfaces with Fission Product Inventory (FISPIN) software output data. This allows the user to utilise the outputs of FISPIN directly with a simple copy-paste of the data from FISPIN for a particular fuel, burnup time and cooling time etc. Then with “click a button” ease the calculation of the various flowsheets is performed and the results sent to the same interface for display. The potential for further integration with FISPIN or the fuel cycle modelling code ORION could be explored.

- This interface also allows the user to modify key design parameters of the reprocessing process, such as throughput, operating days, size of evaporators, as well modify Conditions for Acceptance (CFA) for the final waste forms – which as default are the same as current values for Sellafield operations. An investigation could be made into understanding the effect of changing these parameters have on results such as the incorporation rates of waste oxides in the HLW.

After the issue of our previous report [1], a series of workshops were held with subject matter experts to assess and refine various aspects of the basis of the flowsheets and assumptions made in the creation of the Sim Plant models. A separate series of workshops with the NNL Design team were carried out to underpin plant sizing, footprint and costing calculations. As a result of this work, the prior results have been updated and the following recommendations made in [1] have been completed:

- The Sim Plant calculations have been extended to investigate the effects on other key criteria such as plant footprint, process unit sizing and the costing requirements of individual processes and plants in a comparison of PUREX reprocessing, Advanced PUREX reprocessing and Euro-GANEX reprocessing.

- A complete set of comprehensive Basis and Assumptions documents for Sim Plant and the accompanying flowsheets have been generated.

A detailed overview of the final waste forms produced by both flowsheets, and the estimated footprints and volumes of the reprocessing plants themselves, will be the primary subjects of this report.

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3. BACKGROUND

1.1. REPROCESSING FLOWSHEETS

Aqueous reprocessing plants generally comprise of three main areas:

- **Head End** – Fuel is removed from its cladding and dissolved into concentrated nitric acid. It is clarified to remove solids and conditioned for downstream processes.
- **Chemical Separation** – liquid-liquid solvent extraction techniques are used to extract and separate desirable chemical species from the bulk of the fission products.
- **Product Finishing** – Solutions rich in product are converted to powders of specific chemical and physical properties.

Although there have been significant advances in head end and finishing technologies, the major differences between advanced reprocessing flowsheets lie within the chemical separation section. Changes can take the form of different contactor bank arrangements (to influence the order in which species are extracted), the number of contactor cycles required to perform the separations, the chemicals used to perform the extractions and the solvent extraction equipment chosen (e.g. mixer-settler, pulsed column or centrifugal contactor). Changes to the head end and finishing sections tend to be incorporated into a reprocessing flowsheet design due to other considerations such as the input fuel (type, burnup, and cooling time) or the type of fuel the product is to be manufactured into (and its associated product specification).

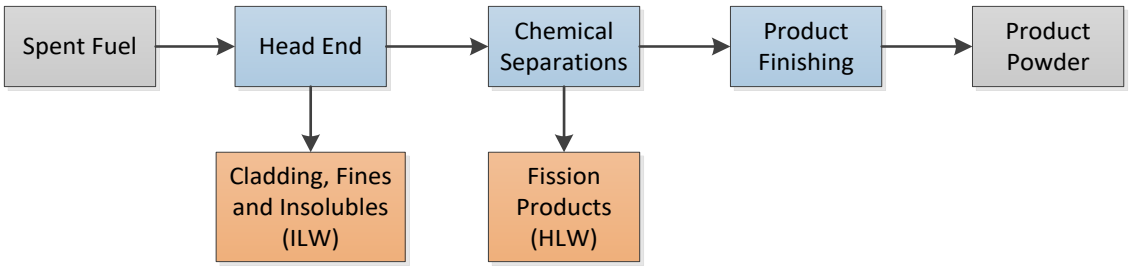

Figure 1 - High-level reprocessing overview [4].

1.1.1. EURO-GANEX

Euro-GANEX (Grouped Actinide Extraction) utilises a significantly different methodology compared to the widely used PUREX process, using different chemicals within solvent extraction to extract a transuranic product rather than a pure plutonium product. The benefits of this type of extraction are two-fold: the absence of pure plutonium in the product increases its proliferation resistance and the smaller quantities of actinides sent to high level waste (HLW) significantly reduces the heat loading of waste packages. Full recycling of actinides results in a reduction in the time required for high level waste to reduce to background levels from ~100,000 years to ~500 years. This increases the quantity of waste that can be incorporated per HLW container, reducing overall strains on storage facilities.

The chemical separation section of a Euro-GANEX process can be split into two cycles: a uranium extract cycle, and a TRU extraction cycle.

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The uranium extraction cycle utilises a DEHiBA solvent dissolved in TPH to extract uranium from the FPs, lanthanides and other actinides into the DEHiBA-TPH solvent stream. The uranium loaded DEHiBA solvent stream is then contacted with a weak nitric acid stream within a uranium strip, which selectively strips the uranium back into the aqueous phase, where it undergoes onward processing into an oxide powder product. The UOx powder production is based upon well-established technology used within Thorp.

The aqueous stream leaving the uranium extract passes to the second cycle, which contains FPs, Ln and remaining An. Prior to entering the second cycle, the aqueous raffinate is conditioned using CDTA to suppress extraction of Zr and Pd into the solvent phase.

The CDTA-conditioning raffinate then enters a TRU extract-scrub unit, where the Ln and remaining An are extracted into the solvent phase, using a TODGA/DMDOHEMA solvent dissolved in OK. The FPs remain in the aqueous phase and are sent for onward treatment as HLW. The An/Ln-loaded solvent stream is contacted with an aqueous stream of HNO_3, SO_3-Ph-BTP and AHA which selectively strips the An species (Pu, Np, Am, Cm) into the aqueous phase. This An stream can be then used to create a mixed actinide powder product, using an oxalic acid precipitation process similar to Advanced PUREX. The solvent stream, loaded with Ln, is then contacted with a weak nitric acid strip within a Ln Strip unit. The Ln stripped into the aqueous stream are then mixed with the FP containing aqueous raffinate from TRU Extract-Scrub and sent as HLW to HALES.

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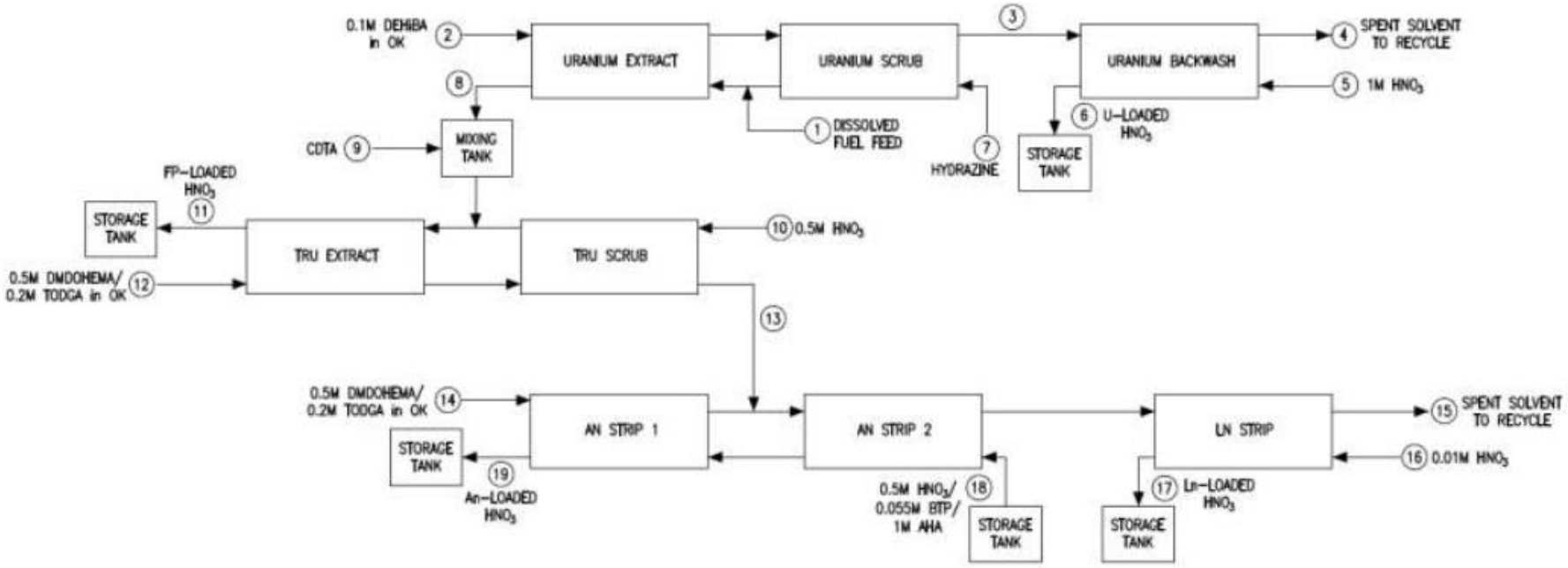

Figure 2. Euro-GANEX Chemical Separation Flowsheet [6].

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1.1.2. PUREX

The PUREX (Plutonium Uranium Extraction) process (Figure 3) is a hydrometallurgical (aqueous) process first adopted in the 1950s [7] for the recovery of Pu from spent fuel. The process involves the use of solvent extraction to separate reusable U and Pu from fission products (FPs) which are removed as highly active waste.

Typically, fuel is mechanically chopped into short lengths and dissolved in nitric acid. Cladding and other insoluble materials are removed as ILW (as it contains activation products and insoluble FPs). The dissolver liquor then passes to the chemical separation stage of the reprocessing plant where it undergoes solvent extraction through contacting the aqueous nitric acid phase with an organic phase comprising tributyl phosphate (TBP) in an odourless kerosene (OK) diluent. U and Pu are extracted into an organic phase which is then backwashed with clean acid to produce two aqueous product streams. The product streams undergo finishing processes to produce oxide powder products (PuO_2 and UO_3 or U_3O_8) which are placed into containers suitable for storage. The Pu is stored pending potential reuse in a mixed oxide (MOX) fuel. The reprocessed U is stored indefinitely for eventual re-use or disposal.

The PUREX process is very technologically mature and is adopted by all current commercial scale reprocessing plants [7]. The process chemicals used have a good selectivity for U and Pu resulting in a high purity product. Other advantages of the process include the ability to operate at relatively low temperatures, the solvent and acid can be cleaned and recycled to reduce operational costs and scale up is relatively easy. Whilst the PUREX process has proved successful, the process does have its drawbacks. For example, solvent degradation via radiolysis can become a safety hazard if degradation products are permitted to accumulate within the process. In addition, the separation of pure plutonium is perceived to present a proliferation risk – that is, the diversion of fissile material for non-civil purposes – that must be carefully managed by a range of safeguards.

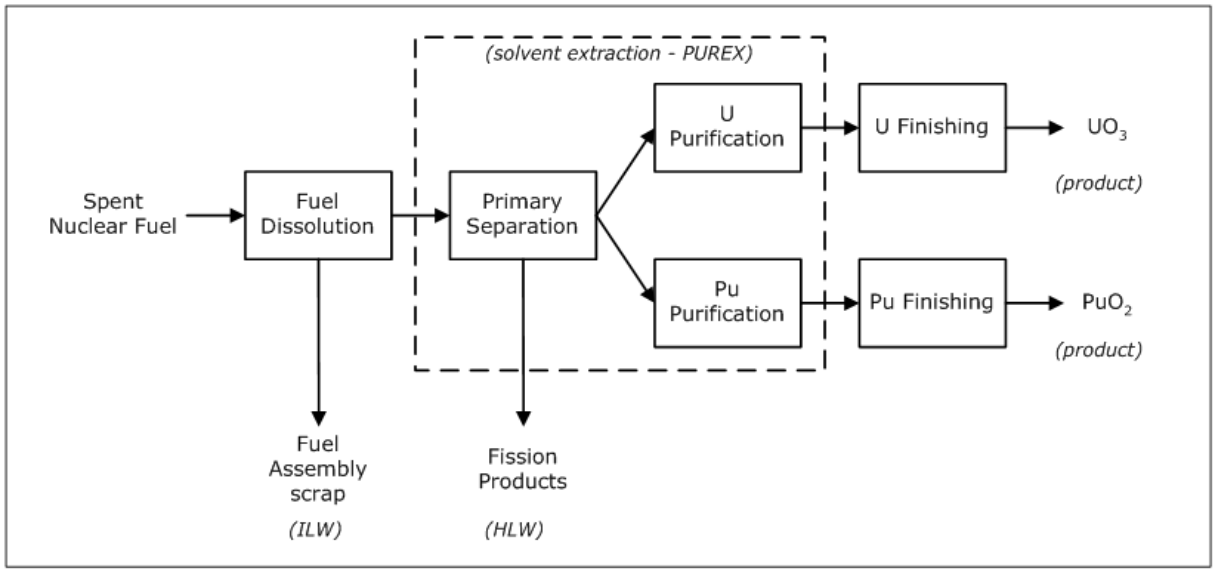

Figure 3 - Overview of the PUREX process [1].

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1.1.3. ADVANCED PUREX

Advanced PUREX (Figure 4) is a flowsheet developed by NNL as an enhancement to the traditional PUREX process. The principles which have driven the development of this flowsheet are: reduction in cost, reduction in waste, increased proliferation barriers, enhanced process safety, increased HLW repository capacity, and increased flexibility of reprocessing (i.e. to be able to cope with high burnup UOX and MOX fuels).

Progressing to a fully closed fuel cycle, whereby the fresh fuel input to the system is minimal, requires an interstitial phase of reactor operation. This phase will likely involve the use of thermal reactors utilising UOx to high burnups (to increase fuel utilisation efficiency) and MOx fuels (in an attempt to partially close the fuel cycle). The operation of thermal reactors is required to generate enough fissile material for the initial cores of fast reactors. Fast reactor cores need to operate in a "burner" configuration, whereby the fuel consumed is greater than the fuel produced, prior to switching to the desirable "iso-breeder" configuration where fuel is produced at the same rate of consumption.

Parallel R&D NNL is undertaking has produced a reprocessing flowsheet for Advanced PUREX [3]. The Advanced PUREX process closely resembles that of the PUREX process in that, fuel is mechanically chopped, dissolved and conditioned to be fed into the chemical separation stage.

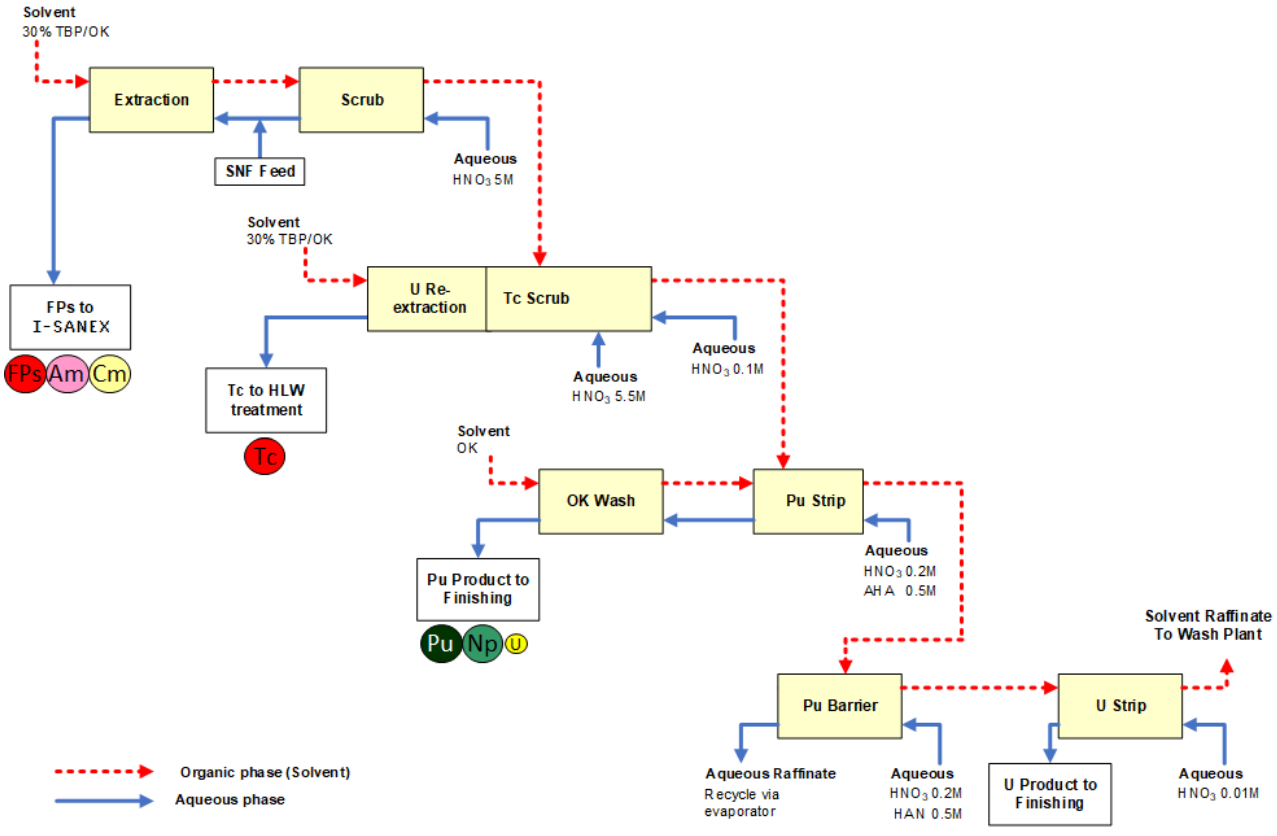

Figure 4 - Overview of the Advanced PUREX solvent extraction process [1].

The chemical separation section of Advanced PUREX firstly separates U, Pu and Np from the bulk of the FPs using a 30 v/v% TBP/OK solvent. A scrub section reduces the amount of residual FPs carried over with the U and Pu in the organic phase. The solvent passes to a Tc strip section where an acid stream contacts and removes Tc (which

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is currently routed to the HLW). Note that this differs from the previous version of the flowsheet [5] where the Tc rejection stage was *after* the U/(U, Pu) separation.

Next, the Pu, Np and some U are back-extracted (stripped) from the solvent stream into an aqueous phase using acetohydroxamic acid (AHA). This aqueous stream will then pass to product finishing whereby an oxalic acid precipitation finishing process (similar to that already employed at Thorp) will co-precipitate U, Pu and Np to form a mixed oxide product. The remaining U rich stream then undergoes another wash with hydroxylamine nitrate (HAN) or AHA to prevent any residual Np and Pu from reaching the U product; this wash is concentrated and recycled. The U is finally stripped from the solvent using a dilute acid and sent to a conventional thermal de-nitration finishing process.

Innovative SANEX (I-SANEX) is then used as a bolt-on chemical separations unit for the Advanced PUREX, to separate out a MA product. Recycling of the MA product, similarly to Euro-GANEX allows a significant reduction in the time taken for HLW packages to decay to background levels.

The stream from the first extract containing FPs and minor actinides (MA) passes to the I-SANEX process which extracts out the MA and some lanthanides (Ln) using a solvent made up of 0.2 mol/L N,N,N',N'-tetraoctyl diglycolamide (TODGA), 5% 1-octanol in an aliphatic diluent.

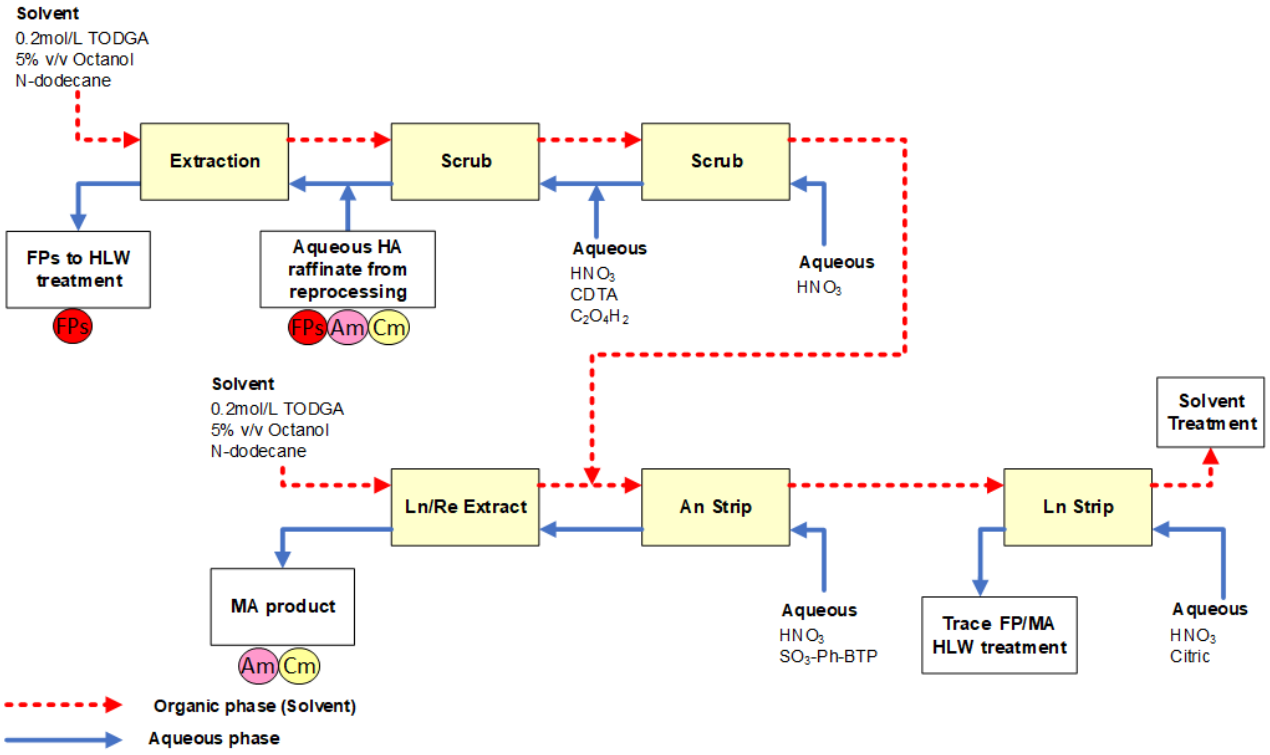

Figure 5 - Overview of the I-SANEX MA extraction process [1].

A series of scrubbers using an acidic stream containing HNO_3, oxalic acid and cyclohexanediaminetetraacetic acid (CDTA) reduce the downstream carry over of FPs to the solvent stream. Subsequently, the MA are removed from the solvent stream by an An strip by another series of extractors using SO_3-Ph-2,6-bis(1,2,4-triazin-3-yl)pyridine (BTP), then purified of remaining lanthanides with fresh solvent. The resultant aqueous stream rich in Am and Cm heads to a precipitation finishing process which forms a dry oxide product (assumed to be a $(U,MA)O_2$ product).

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The solvent stream is cleaned of residual Ln with a further acid scrubber before heading to solvent treatment, the aqueous wash from this Ln strip heads to HLW treatment along with the first extract FPs. A specific solvent treatment process for the solvent from I-SANEX is the subject of ongoing R&D work, but for the purposes of sizing and footprint estimates it is assumed to utilise the same technology as the solvent treatment for Advanced PUREX solvent.

1.1.4. KEY DIFFERENCES BETWEEN FLOWSHEETS

The main differences between the three flowsheets lie within the chemical separation section. Unlike PUREX which operates three solvent extraction cycles, Euro-GANEX requires two cycles, namely GANEX-1 (bulk uranium separation) and Euro-GANEX cycle (separation of An/Ln and remaining fission products). Advanced PUREX is able to perform all the necessary separations within a single cycle.

Whilst the basic Advanced PUREX flowsheet does not account for minor actinide (MA) recovery, a "bolt on" process, effectively a second solvent extraction cycle, in the form of I-SANEX has been added to remove MA from the fission products HLW stream [8]. Doing so greatly reduces the long-term heat loading of the vitrified HLW on the GDF and allows a far higher incorporation of fission products in a smaller volume of glass. Euro-GANEX's 2nd cycle strips Pu alongside minor actinides and as such does not require this additional bolt-on process, giving the same benefit as the inclusion of i-SANEX within Advanced PUREX as standard.

The Am/Cm product stream from i-SANEX could be incorporated into new fuel or utilised for other purposes (e.g. the heat released in their decay can serve as a heat source in radioisotope thermoelectric generators to power spacecraft).

Pu is deliberately not fully separated from other species at any point in the Euro-GANEX process and exits the process with Np, Am and Cm. This increases the proliferation resistance of the product by adding another barrier (defence in depth). This co-extraction within the Euro-GANEX process also reduces HLW package heat loading.

Euro-GANEX has two finishing lines, a U product aligned with those used in PUREX and Advanced PUREX processes, and a Pu/MA finishing line that produces a mixed actinide product consisting of Pu, Np, Am and Cm which delivers the benefits outlined above. PUREX also has two finishing lines: a U product, and a Pu product, Advanced PUREX plus I-SANEX has three: a U product, a U/Pu/Np product, and the Am/Cm MA product.

Euro-GANEX is optimised for fast reactor fuel which has the advantage of being able to use the mixed oxide product in fuel and reduce the amount of long-lived isotopes entering waste forms by recycling them through the process. The PUREX process used at Thorp is optimised for UOx fuels of burnups up to 48 GWd/te. Fuels with increased burnup contain a larger proportion of FPs and, therefore, are associated with higher heat loads and radioactivity levels. Attempting to process high burnup fuels in process plants not designed to cope with them could result in radiation shielding not being sufficient to protect workers; ineffective chemical separation (as the feed will be different to the norm); increased risk of a criticality (if additional Pu has been formed); and the heat load and activity due to HLW will be increased which may be unacceptable. Additionally, the use of MOx fuels, which contain a significant amount of Pu pre-irradiation, will compound the effects of higher burnup fuels by increasing the proportion of transuranic actinides in the spent fuel. Advanced PUREX and Euro-GANEX have been developed with high burnup and MOx fuels in mind, making it more suited to next generation fuels.

One of the technological advantages proposed for the Euro-GANEX and Advanced PUREX flowsheets is the incorporation of centrifugal contactors as the solvent extraction equipment of choice. These units would offer a

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more compact, more intense alternative to the current pulsed column and mixer settler technologies which take up a lot of headroom and plant area respectively.

In addition to the differences in chemical separation, the head end of both Euro-GANEX and Advanced PUREX has also been modified to cope with high burnup MOx fuels through the addition of a secondary Ag(II) dissolver to dissolve Pu-rich fines which remain after the conventional dissolution of MOx fuel. The product liquor from the secondary dissolver also undergoes clarification and conditioning and is mixed with product from the main acid dissolver prior to passing to chemical separations.

1.2. REPROCESSING WASTES

The reprocessing of nuclear fuel generates a variety of different waste streams, each requiring its own waste treatment and disposal route. In addition to conventional chemical and pollutant hazards, radioactivity and radiotoxicity pose a major challenge to the safe disposal of these wastes. In principle, waste is categorised depending on its radioactive inventory and heat generation, it is then concentrated and immobilised in a matrix such that it is completely isolated from the environment. The following is a description of the main waste categories as defined by the Nuclear Decommissioning Authority (NDA) [9].

1.2.1. LLW

Low Level Waste (LLW) contains low levels of radioactivity not exceeding 4 GBq per tonne of alpha activity and/or 12 GBq per tonne of beta/gamma activity [9].

LLW comprises approximately 94% by volume of the radioactive waste generated in the UK, with less than 0.001% of the activity as a % of the total contained within SNF entering the process [10]. It typically consists of items such as paper, plastics, personal protective equipment (PPE) and other scrap materials. Most nuclear facilities generate LLW from everyday operations of the facilities. Items with very low activities may be considered as Very Low-Level Waste (VLLW), this typically consists of building rubble and soil (with regards to nuclear facilities). VLLW can be disposed of as landfill.

In the UK solid LLW is compacted, grouted into metal containers and then stacked into concrete-lined engineered vaults dug into shallow trenches. As the vaults are filled they are capped and buried under topsoil. In the UK, LLW is stored within the Low-Level Waste Repository in Cumbria.

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Figure 6 - UK Low Level Waste Repository [11]

1.2.2. ILW

Intermediate Level Waste (ILW) is classed as waste which exceeds LLW radioactivity limits but is not significantly heat-generating. Approximately 6% by volume of radioactive waste falls into this category, and accounts for around 0.1% of total activity as a percentage of that contained within SNF [10]. In terms of reprocessing, many wastes from the processes fall into this category, including fuel cladding and hulls, insoluble FPs and fine particulates, spent liquors from off gas scrubbing, wash liquors from solvent washes and various evaporator condensates (overheads).

ILW is placed into 500L steel containers or $3m^3$ steel boxes and encapsulated into a grout matrix tailored for the specific type of ILW. Most ILW will require some sort of pre-treatment prior to encapsulation e.g. size reduction, chemical conditioning or drying. Many waste liquor streams that arise from reprocessing will be treated at other plants prior to encapsulation to remove any traces of actinides or specific radioactive species. The drums are then capped, lidded and stored in bespoke ILW drum storage facilities.

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Figure 7 - 500 L ILW drum [11]

1.2.3. HLW

High Level Waste (HLW) is classed as radioactive waste which has a significant heat-generating capability and as such storage facilities need to be engineered to take this into consideration. HLW is generated through nuclear fuel reprocessing and consists of the FP-bearing aqueous raffinate from chemical separations. In terms of volumes, HLW makes up less than 1 v/v% of the radioactive waste inventory in the UK, and containing over 99.7% of the activity contained within SNF [10].

HLW treatment involves vitrification; that is the immobilisation of the waste into a borosilicate glass waste form. Highly Active Liquor (HAL) from the reprocessing plant is first concentrated via evaporation, buffer stored in Highly Active Storage Tanks (HAST) and then calcined to produce a waste oxide powder. This powder is mixed with glass and additives before being melted and poured in 400kg batches into steel waste containers. These containers are lidded and welded, tagged for identification and then stacked in a HLW storage facility designed to provide adequate cooling.

1.3. FUEL

Fuel burnup is effectively a measure of the energy extracted from a fuel whilst in the reactor and as such is an indication of the extent to which a fuel has been irradiated. Typical LWR burnups are in the region of 30-40 GWd/tU [12] with initial U^{235} enrichments of 3-5 %. Future trends are towards increased burnups with the potential for the addition of Pu (to form MOX fuels) to increase the energy extracted from each fuel pellet.

High burnup and MOX fuels can have dramatic effects on the characteristics of spent fuels which need to be considered in the management and reprocessing of the spent fuel.

High burnup fuels typically exhibit higher heat loads and higher radioactivity levels. They often have higher initial enrichment levels compared to lower burnup fuels and as such pose a greater criticality concern. Assuming the fuel is discharged at its design burnup, residual enrichment (i.e. the U235 enrichment in spent fuel) should be similar to fuel designed to reach lower burnups. However, there could be situations where the fuel is discharged from the core prematurely (due to fuel failure) or used inefficiently in-pile. In these situations, given the initial enrichment is higher, the residual enrichment would be higher than usual, resulting in greater criticality risk

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during spent fuel operations– even in that in this particular case the fuel is not considered high burnup. Thus, these non-typical fuels need to be considered when selecting a reprocessing method.

As the burnup of a fuel increases, the following trends can be observed, which has implications on reprocessing schemes:

- The mass of U decreases but the mass of Pu increases initially due to neutron capture of U^{238}
- The quantity of transuranic isotopes of higher mass (Pu and MA) increase, though the individual isotopes have different tendencies.
    - The mass of Np increases in amount to up to half the total mass of the MA
    - The mass of Cm increases with burnup
    - The mass of Pu decreases over longer periods of time, however with lower burnup the Pu content is increased.
    - The proportion of Pu and Am (compared to the total mass of An) decreases with burnup
- The total alpha activity increases, mainly due to the Cm and Am
- The neutron radiation increases, mainly due to the Cm
- The heat released from the fuel increases, mainly due to the increase in proportion of heat-generating fission products (Cs, Sr, Y and Ba in particular).

The effects of MOX fuels greatly exacerbate these characteristics with higher initial Pu content. Therefore, for the same burnup, a MOX fuel will contain a higher proportion of An resulting in significantly higher alpha and neutron activity.

All of the above considerations make the design of equipment, processes and facilities more onerous in terms of cooling, radiation shielding and criticality control. The benefit is reuse of streams that would otherwise be wastes and so increased electricity production per unit of mined uranium.

1.4. SIM PLANT

Sim Plant is a tool currently under development at the National Nuclear Laboratory to compare the effects of changing the chemical separation flowsheet on a reprocessing facility, or even the whole recycling site, at an engineering-scale, including the consequent economic impacts. The tool, which will ultimately take the form of a software package, will in future reference a library of spent fuel inventories and reprocessing flowsheets to produce visual representations of the advanced facility. Sim Plant will benefit both the technical and non-technical communities through the provision of high-level information whilst also demonstrating the real-world effects of technological advances in an easy to understand way.

Sim Plant is being developed as part of both the European Union GENIORS (Generation IV Integrated Oxide fuels Recycling Strategies) project and the BEIS funded AFCP and is currently in the intermediate stages of development with work focussing on the construction of the main engine and the provision of input data (e.g. flowsheet modelling).

This work, taking place under the GENIORS programme includes the construction of a flowsheet for a full-scale reprocessing plant operating the EURO-GANEX process and this report outlines the development of the overall plant sizing methodology calculations. Both the Advanced PUREX and EURO-GANEX flowsheets are benchmarked against the existing Thorp PUREX plant at Sellafield in this report.

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Work undertaken as part of the AFCP has provided some of the underlying methodology and calculations of Sim Plant, with a focus on process wastes. This phase of work assessed the waste that will arise from an Advanced PUREX flowsheet, and what impact the quantity of subsequent waste packages have on long term storage requirements relative to existing oxide fuel reprocessing in the UK, as well providing a preliminary assessment of the footprint of an Advanced PUREX based reprocessing plant [1].

In the longer term, it is intended that Sim Plant be extended to other processes, including molten salt pyrochemical reprocessing, and to include fuel fabrication and other site facilities needed for the full recycling capability.

The final product will be a tool that provides meaningful data that can inform high-level decision making and which could contribute to the progression of advanced reprocessing to the industrial scale.

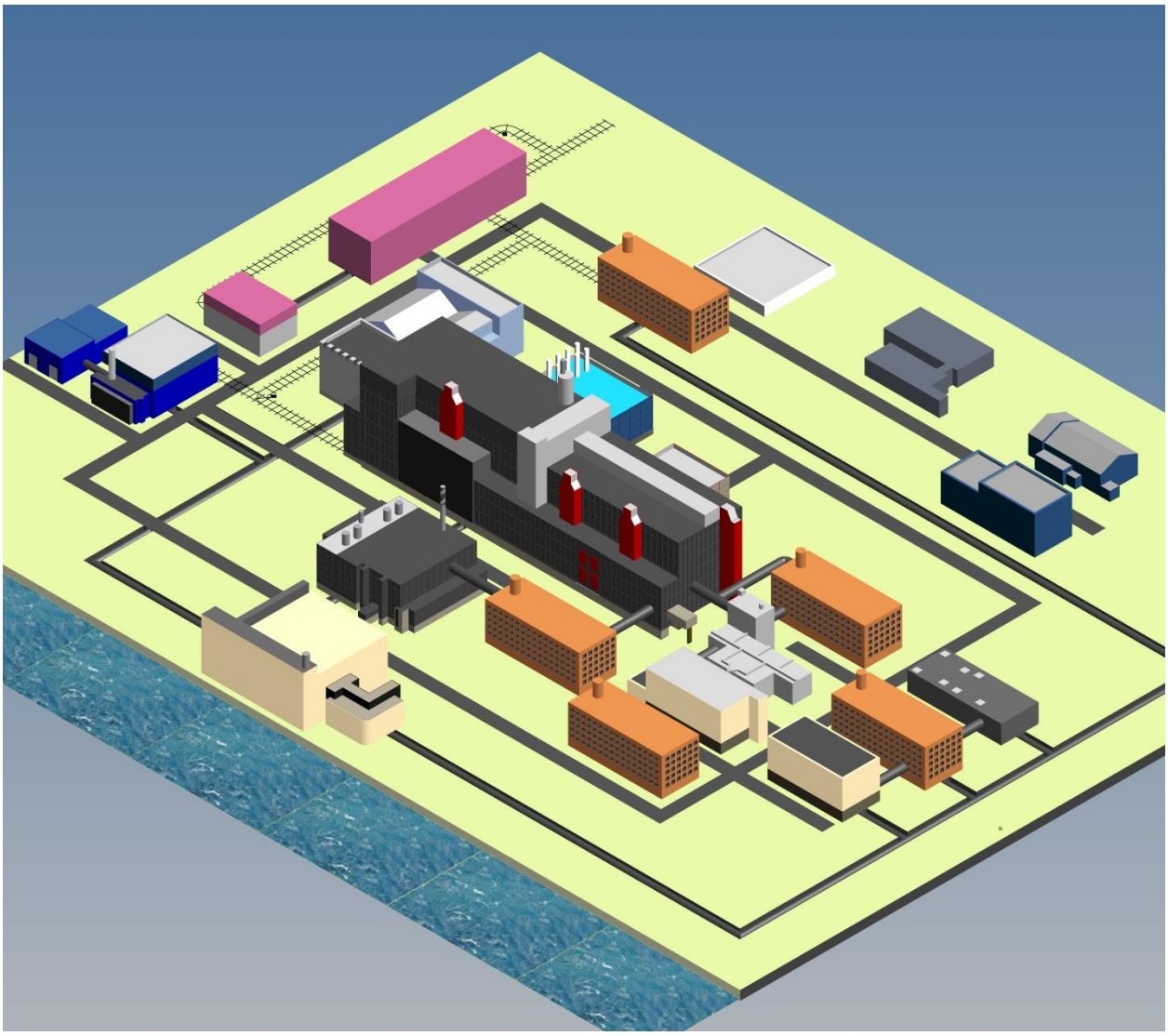

Figure 8 - Concept Sim Plant Representation.

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4. SCOPE

The scope of this report is to provide further analysis of waste arisings and footprint assessments of a Euro-GANEX flowsheet against other nuclear fuel reprocessing schemes. As mentioned previously, work has been done to create a comparison of the baseline Thorp reprocessing plant, and that of an Advanced PUREX reprocessing facility. Fulfilling wider Sim Plant development goals, a Euro-GANEX flowsheet has been created in the Sim Plant template and a detailed assessment of the waste arisings (LLW, ILW and HLW) along with a high-level footprint assessment. The previous results of these assessments regarding PUREX and Advanced PUREX are also included here as a comparison against the Euro-GANEX process.

The scope of the tool is to assess and compare the volumes and activities of wastes which arise from the Euro-GANEX flowsheet to quantify the effects of an advanced reprocessing flowsheet on the waste produced. In addition to this, a preliminary comparison of the indicative footprint and size of a Euro-GANEX reprocessing facility is made. This data is then compared to previous work undertaken to quantify this information against Advanced PUREX and PUREX facilities also assessed using the Sim Plant tool to give a like-for-like comparison.

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5. METHOD

1.1. FEEDS AND REPROCESSING FLOWSHEETS

The Euro-GANEX flowsheet incorporated into Sim Plant was based on the previous flowsheet developed under GENIORS, with changes to reflect the modifications made under the AFCP programme, mainly regarding the exclusion of the voloxidation step in the head end process [13]. Furthermore, as the technology for the solvent wash processes used within the Euro-GANEX flowsheet are currently unknown, a system was assumed that was similar to the HASW system employed within the PUREX process, which was also assumed within the Advanced PUREX flowsheet. It should be noted that whilst use of these solvent wash cycles allows for a like-for-like comparison in terms of solvent wastes, it should not be assumed that the HASW system is intended to be the chosen technology for solvent washing in the Euro-GANEX process in future. It is recommended further research and development work should be undertaken to develop and optimise a solvent wash process for the solvents used within Euro-GANEX.

The Advanced PUREX flowsheet incorporated into Sim Plant was based on the experimentally tested 'reference' flowsheet being developed in the Aqueous Recycle project [3]. To provide a conservative feed for experimental tests, the flowsheet was developed using an artificial mixture of 50 GWd/tHM burnup MOx fuel and 65 GWd/tHM burnup UOx fuel, both with a 10 year cooling period, as its feed, based on a worst case scenario for heat and activity. This mixture of the two fuels was not strictly a proportional blend; the compositions of each spent fuel were compared for each radioisotope, and the higher mass (g/tHM) and, therefore, activity for each species was selected. The compositions of inactive isotopes for each element were adjusted appropriately so that the total mass of each tracked element and the overall mass of the spent fuel remained representative [1]. To ensure a like for like comparison, the Euro-GANEX flowsheet utilised the same feed fuel burnup inputs as the Advanced PUREX flowsheet.

Although the artificial mixture was used as a baseline in the development of the Advanced PUREX flowsheet, in reality no such artificial "blend" would exist. In Sim Plant, to better reflect reality, these two fuels were modelled in two scenarios separately. Therefore, results will be presented for the two fuels (MOx and UOx) individually. The plant throughput was selected as 5 tHM/day in both cases to provide a direct comparison with the Thorp flowsheets.

The Thorp flowsheets used for this work were based on a 5-year cooled, 40 GWd/tHM pressurised water reactor (PWR) oxide fuel with a 40 MW_{Th}/t power density. The throughput is the design throughput of 5 tHM/d. Thorp is a complex plant comprising of several sections e.g. head end, Chemical Separations, Finishing, and even contains some dedicated waste treatment facilities. Due to the complexity and interconnectivity of the waste treatment plants on the Sellafield site, and to ensure the data being compared was as sensible as possible, the output waste streams for each reprocessing flowsheet were both submitted to the same downstream flowsheet, and therefore subject to the same calculations producing the data presented in section **Error! Reference source not found.**. In r eality, Thorp waste is split into a series of different waste types and sent to separate waste treatment facilities which process that type of waste for the entire site e.g. Thorp HLW is not vitrified in isolation, HAL is mixed from

[1] For 1 tonne of HM (fissile mass comprising U, Pu and other An) the mass of spent fuel is approximately 1.135 tonnes (including O, fuel additives, impurities and activation products).

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Thorp and Magnox reprocessing to achieve a specific HAL blend prior to vitrification. This work, however, considers Thorp HLW, ILW and other effluents in isolation in order to provide a suitable comparison.

Before becoming HLW, spent fuel reprocessed by the PUREX process, under normal circumstances, is given a significantly longer time to cool than the 5 years represented in the Thorp base case – in ponds prior to reprocessing, followed by a further cooling time in Highly Active Storage Tanks (HASTs) prior to vitrification (a total time period of typically 20-30 years). Due to this, calculations will be presented, focusing only on HLW, assuming that the material is stored for 15 years post-reprocessing, before vitrification (a total cooling time of 20 years). This may provide a more realistic representation of the HLW from Thorp.

As a result of the learning gained from Thorp reprocessing, with regard to design versus actual cooling times, not due to technological limitations but due to practicalities involving: building times; transport; reliability and availability of plant; research into likely fuel cycle scenarios and cooling times are recommended for further Advanced PUREX and Euro-GANEX simulations.

In the initial flowsheeting work, the Advanced PUREX flowsheet calculations and accompanying documentation were developed within Microsoft Excel [3], whereas the Thorp flowsheets used as a reference consist of a number of historic models built within Aspen Custom Modeller. Both of these flowsheets were converted to models within the state-of-the-art NNL standard platform; that is the gPROMS ModelBuilder software package, for flexibility, efficiency and future-proofing. The effluents flowsheet, which handles the HLW and ILW wastes from reprocessing, was also written in gPROMS, for compatibility and to integrate Sim Plant into a single tool.

1.2. SIM PLANT CALCULATION METHODS

1.2.1. TRACKING SPECIES

The flowrate of species deriving from the fuel, and any inactive additions to the process (both intentional process additions, such as chemicals during reprocessing and treatment, as well as estimates of metals which enter the streams due to the corrosion of the process infrastructure itself, such as piping) must be tracked within process streams from the initial spent fuel feed all the way to the composition of the final waste forms. This is required not only as calculations to determine the operational performance of unit operations are composition dependant, but also because the composition of key species within incorporated waste packages are factors in their characterisation and CFA [14]. The tracking of the flow and accumulation of radioisotopes through reprocessing models facilitates the calculation of activity and heat generation of streams, tanks, unit operations etc. throughout reprocessing and waste treatment. This informs the calculation of the sizing and shielding requirements of each unit which can be used as a metric for the plant and potentially the entire site.

In order to perform this in an organised and consistent manner, a tool has been created for the front-end interface of Sim Plant, which allows for the pasting in of any set of FISPIN (spent fuel composition modelling software) data. FISPIN data provide a tabled breakdown of the composition of spent fuel on an isotopic basis, for a particular fuel type, reactor, burnup, power density and cooling time. Sim Plant organises all isotopes from the FISPIN data of a given spent fuel feed into their respective elements and calculates the overall weighted average atomic mass, specific activity, specific alpha, beta/gamma and heat rating of each element from atomic number 1-103 using reference data [15], as well as the mass fraction of each radioisotope with respect to its element. Along with a specified throughput this then allows for the feed to reprocessing to be represented as an array of mass flowrates of each element.

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It was assumed that the isotopic composition of each element would remain proportionally the same from the spent fuel to the HLW and ILW wastes due to the fact that the chemical separations operate at the elemental level and also judging that the time required for reprocessing is not long enough to constitute a significant change in isotopic makeup due to radioactive decay. Concentrations of isotopes with short half-lives such as Ba-137m (half-life of 153.12 s) which would effectively disappear quickly in isolation, are sustained by the decay of other isotopes.

Tracking the mass flowrate or mass accumulation of each element derived from the fuel using these assumptions, as well as tracking the mass flowrates or mass accumulation of each element derived from other additions, allows for the consistent calculation of the activity or heat generating power of material at any point in the process, including final wastes.

This preliminary interface allows the user to quickly modify various key parameters governing the design of reprocessing and waste treatment in the models: operating days, size of evaporators, as well modify CFA for the final waste forms, aiding future investigations. In future, it could be possible to provide a user with a drop down list of stored FISPIN data from a range of fuel types, burnups and cooling times to process, while also still allowing the option to submit a novel spent fuel combination for modelling and analysis.

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1.2.2. WASTE TREATMENT

Fundamental work was undertaken which investigated the links between the Thorp reprocessing plant and the plethora of different waste streams it produces, including the primary HLW processing stream. The processes by which key wastes are pre-treated and then encapsulated into ILW at the Sellafield site were mapped out.

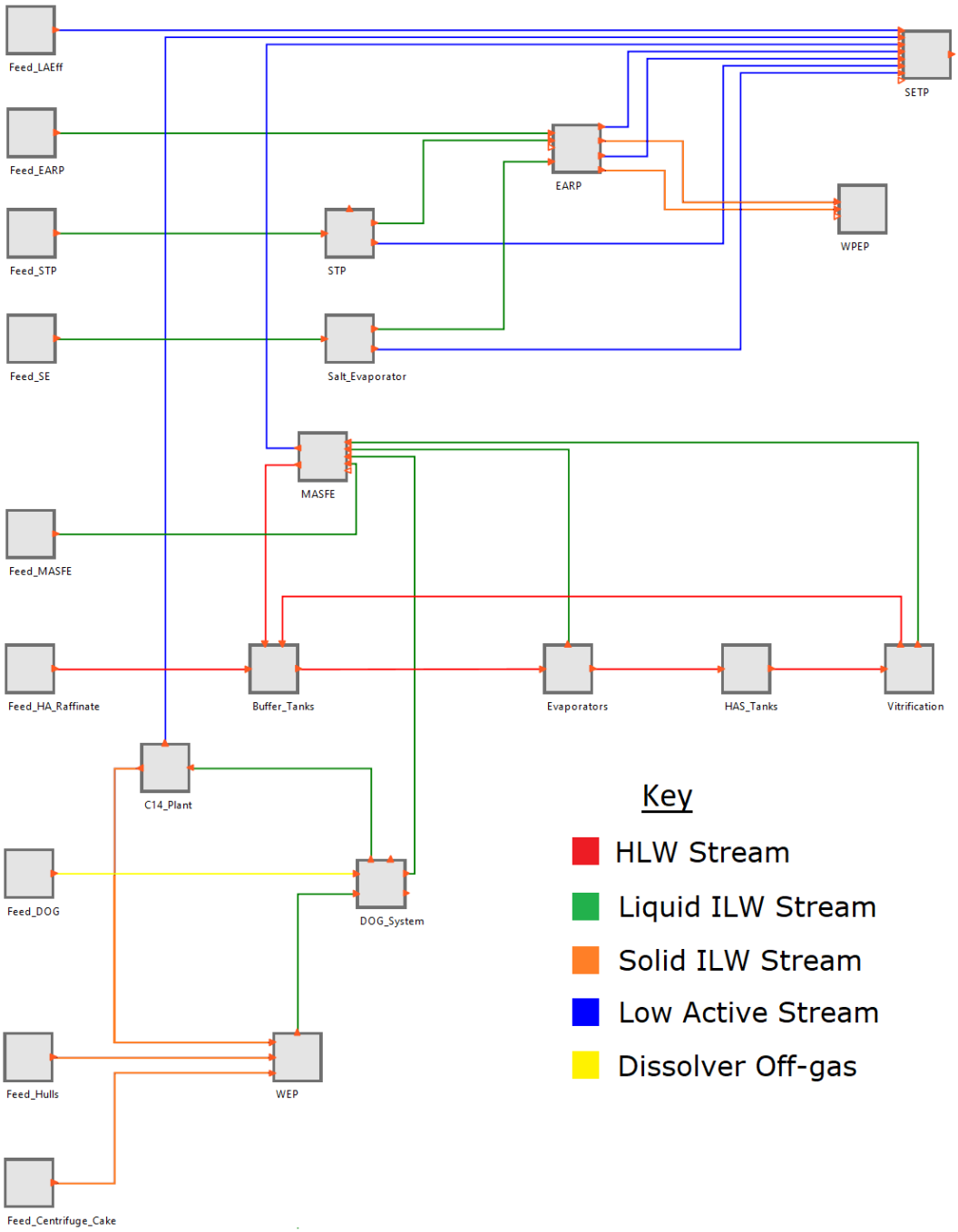

Figure 9 - Topology taken from the Sim Plant Effluents Model.

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The key waste streams known to contribute to HLW and ILW were identified for both reprocessing flowsheets and routed as feeds to the appropriate plants. Within the present version of Sim Plant, Thorp PUREX, Advanced PUREX and Euro-GANEX flowsheets send their wastes to the same Effluents flowsheet which is based on current operations for the routings and treatment of Thorp wastes at Sellafield.

The diagram Figure 9 is a screenshot showing the topology of the current Effluents flowsheet within the Sim Plant tool, displaying the links between the various waste treatment plants.

Essentially, at a high level, the treatment plants are recycling, concentrating, and splitting off active material to be either encapsulated in HLW glass via Vitrification or grouted into drums as ILW in the Waste Encapsulation Plant (WEP) and Waste Package Encapsulation Plant (WPEP). The EARP plant abates liquid effluent, sending the ILW effluent for encapsulation in the aforementioned WPEP. It sends the remaining volumetric flowrate of liquid effluent, which has been thus stripped of almost all of its radioactivity, out to sea via the Segregated Effluent Treatment Plant (SETP).

An analysis of the predicted volume and characteristics of these final waste forms provides an indication of the effects of switching to an alternative (i.e. Euro-GANEX or Advanced PUREX) flowsheet and highlights areas which require further investigation.

In the great majority of cases, these discrepancies are small and may be explained in part due to the activity calculations using the more recent JEF 2.2 database as a source of specific activities, while the original Thorp flowsheets were built using JEF 1 as a source, and otherwise by assumptions made in the construction of the Thorp flowsheets. These small discrepancies can be checked in future, however for the present calculations a set of assumptions were made for consistency:

1. If the mass flowrate of the element is reported, but there is a discrepancy between that value and an inferred value from a particular radioisotope, the reported mass value of the element is the value carried forward.
2. If the mass flowrate of the element is not reported, and there is a discrepancy between values inferred from two or more particular radioisotopes, the largest inferred value for the mass flowrate of the element is the value carried forward.

Also, because the present reprocessing flowsheets do not exhaustively track every element, but only certain key elements, where data is available, then an assumption must be made as to the routing of the elements which are not tracked. Here, an assumption is made that:

- For elements that are not tracked in the reprocessing flowsheet, and which are volatile, they are assumed to entirely exit reprocessing via the Head End Dissolver off-gas.
- For elements that are not tracked in the reprocessing flowsheet, and which are insoluble, they are assumed to entirely exit reprocessing via the Centrifuge Cake (Head End – Feed Clarification).
- For elements that are not tracked in the reprocessing flowsheet, and which are neither volatile nor insoluble, they are assumed to entirely exit reprocessing within the streams being sent to Highly Active Liquor Evaporation and Storage (HALES) as HA raffinate.

The last assumption is justified in that, other than U, Pu, Np, Am and Cm, more than 90% of other non-volatile, soluble elements which are tracked do indeed exit reprocessing via the HA raffinate.

Plant descriptions are contained within the B&A documents for the Euro GANEX and Advanced PUREX process [16, 17].

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1.2.3. ELECTRICITY PRODUCED

To find the electricity produced from each of the two fuels in this work the following assumptions were made.

Thorp PUREX

- PWR reference fuel assumed to be used in Sizewell B reactor
  - Electrical output of reactor 1188 MW_e [18]
  - Thermal output of reactor 3411 MW_{th} [18]

Euro-GANEX and Advanced PUREX Reference MOX fuel to be used within European Pressurised Water Reactor (EPR)

  - Electrical output of reactor 1600 MW_e [19]
  - Thermal output of reactor 4500 MW_{th} [19]

Euro-GANEX was chosen to use the same FISPIN fuel input as Advanced PUREX, as it will allow for a direct comparison of the waste arisings, even though Euro-GANEX is intended for use with fast reactor fuel types, rather than thermal fuel as it is assumed in this report.

The electrical output of each fuel (per tonne of fuel in the reactor) was calculated from the product of thermal efficiency of the intended reactor and the burnup of the fuel. The electrical power produced per tonne of fuel (TWh/tHM) is therefore directly proportional to the burnup of the fuel.

$$Thermal\ Efficiency\ (\%) = \frac{Electrical\ output}{Thermal\ output} \times 100$$

Burnup is a function of the thermal power released from the fuel per tonne of heavy metal. Burnup, usually expressed as GWd/t, is dependent on the thermal power density of the fuel and the length of time spent in the reactor. Therefore, higher burnups can result from either a high-power density fuel, a fuel that has been irradiated for a longer period of time, or a combination of the two.

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1.2.4. KEY ASSUMPTIONS

1.2.4.1. FLOWSHEET

This list details key, high-level assumptions made to enable the Sim Plant flowsheet calculations.

- The isotopic composition of the material derived from the fuel in the entire process remained constant from the spent fuel to the final waste outputs.
- All additions are non-active.
- A zero-accumulation basis was assumed to calculate the stream flows and final wastes (no mass was accumulated at any point of the process).
- The buffer storage and treatment solutions currently used on the Sellafield site were adequate in design to cope with both types of HAL discussed in this investigation.
- 200 operational days were assumed for the reprocessing plants and effluent treatment except the HALES evaporators.
- Buffer storage was available 100% of the time, as and when required, to prevent bottlenecking
- The fuels were utilised in the Sizewell B and EPR reactors, these were assumed to be typical of the reactors in which the two fuel types would be used.

A full and comprehensive overview of the basis and assumptions governing the flowsheets and individual units are laid out within the following documents:

- EU10320/06/70/01 – Basis and Assumptions for the Sim Plant Euro-GANEX flowsheet [20].
- NNL 15306 - Basis and Assumptions for the Sim Plant Input model [21]
- NNL 15307 - Basis and Assumptions for the Sim Plant Advanced PUREX flowsheet [16]
- NNL 15308 - Basis and Assumptions for the Sim Plant Effluents flowsheet [22]

1.2.4.2. SIZING CALCULATIONS

This list details key, high-level assumptions made to enable the new Sim Plant sizing, footprint and costing calculations made during this latest stage of Sim Plant development.

NOTE: Indicative costing calculations are included within Sim Plant but not presented quantitatively within this report.

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- These calculations result in indicative footprints for a reprocessing plant.
- The plant is constructed on a greenfield site with appropriate utilities (steam supply, electricity supply, cooling water supply, compressed air supply) in place, so large extra costs associated with construction around existing operational nuclear facilities is avoided.
- Sizing calculations are based primarily on Sellafield architecture and technology, unless otherwise stated.
- The annual throughput of the reprocessing facility chosen for evaluation is within reasonable bounds around 1000 tHM of spent fuel per year.
- There are no step changes in technology occurring when scaling up or down in throughput.
- Fuel receipt ponds, other fuel stores and product stores are not considered [2]. Fuel refabrication, necessary for recycle, is not included at this stage.

A full and comprehensive overview of the basis and assumptions governing the sizing and costing calculations are laid out within the following document:

1. NNL 15472 - Basis and Assumptions for the Sim Plant Sizing and Costing Calculations [23].

[2] Some scenarios will require more fuel ponds than others (e.g. deliberate delay storage). It is recommended that fuel ponds be looked at later when required.

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6. RESULTS AND DISCUSSION

This section presents and assesses the significance of the results from processing the waste outputs from the Euro-GANEX simulations. These outputs are then benchmarked against previously calculated data regarding Advanced PUREX and Thorp PUREX [1]. Sim Plant produces a lot of data, including hundreds of individual stream flowrates and compositions from reprocessing and waste treatment, and full breakdowns of every isotope contained in waste packages. It would be exhaustive and cumbersome to present such a vast quantity of data in this report – so therefore the key results are summarised instead.

The results presented in this report are broken down as follows:

- Electricity Produced
- Total Waste Arisings - These are normalised against the electricity generated (per TWhe) to allow for clearer comparison of the results.
- Detailed HLW Results – HLW containers produced
- Detailed ILW Results – WEP & WPEP ILW drums produced
- Liquid Effluent Results – discharges from site
- Aerial Effluent Results – discharges from the Dissolver Off Gas (DOG) System, Solvent Treatment Plant (STP) and Vitrification stacks
- Sizing, and Footprint Results

The references for the data presented within this section are contained within [21].

The results are broken down into the 6 cases investigated:

1. Euro-GANEX (50 GWd/tHM MOx Case, 10-year cooled)
2. Euro-GANEX (65 GWd/tHM UOx Case, 10 year cooled)
3. Thorp base case (5 year cooled)
4. Thorp (total 20 year cooled, only displayed for Vitrification)
5. Advanced PUREX (50 GWd/tHM MOx Case, 10 year cooled)
6. Advanced PUREX (65 GWd/tHM UOx Case, 10 year cooled)

The results presented aim to be indicative of the overall waste arisings from and footprint of a Euro-GANEX reprocessing flowsheet and provide a normalised comparison to the historically implemented Thorp-PUREX, and alternative reprocessing scheme Advanced PUREX. The Thorp PUREX 20-year cooled case is only displayed for comparison in the vitrification results, to give a comparison as to Thorp operations.

As the models are based on the existing waste treatment processes located on the Sellafield site, UK, where Thorp does not operate in isolation – these processes also have to serve Magnox reprocessing and fuel storage - then the waste treatment technologies are not optimised directly to serve any of the cases specified.

As such, the comparison being made is not between the reprocessing schemes. Rather, within Sim Plant, the waste arisings and footprint are based on utilising the same waste treatment processes as those utilised by a hypothetical Thorp PUREX plant, where both are limited by the same basis and assumptions as laid out in the

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documents referenced section 5.1. Sim Plant is therefore also a platform on which to evaluate future advances in waste treatment processes against the existing Sellafield baseline.

1.3. ELECTRICITY PRODUCED

Table 1. calculated electricity produced from Euro-GANEX, Thorp PUREX and Advanced PUREX reference fuels.

Parameter	Units	Euro-GANEX MOx Case 1	Euro-GANEX UOx Case 2	Thorp PUREX[3]	Advanced PUREX MOx Case 1[4]	Advanced PUREX UOx Case 2[4]
Fuel Burnup	GWd/tHM	50	65	40	50	65
Fuel Thermal power	MW_{th}/t	50	50	40	50	50
Electrical output of reactor	MW_e	1600	1600	1190	1600	1600
Thermal output of reactor	MW_{th}	4500	4500	3410	4500	4500
Thermal efficiency	%	35.6	35.6	34.8	35.6	35.6
Electrical output /t fuel	TWh_e/tHM	0.43	0.55	0.33	0.43	0.55

Error! Reference source not found. illustrates the difference between the performance of the two fuel types w ithin reactors typical of the types in which they would be irradiated. As anticipated, the HBU fuels produce significantly more electricity per unit mass than the Thorp reference UOx (an increase of 28% and 66% respectively for 50 GWd/tHM MOx and 65 GWd/tHM UOx). These are the cases that were used to produce the total waste arising results.

1.4. TOTAL WASTE ARISINGS

This phase of work continues upon previous work, by calculating total waste arisings as a result of reprocessing streams for a Euro-GANEX process. The table below presents the normalised outputs of HLW, ILW, liquid and aerial discharges as a result of the Euro-GANEX reprocessing scheme for the defined fuel cases. It further compares this to previously calculated data for Thorp PUREX and Advanced PUREX.

[3] Assuming fuel used in Sizewell B reactor [18]
[4] Assuming fuel used in EPR reactor [19]

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Table 2 - Total Overall Wastes.

Waste Type		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Thorp PUREX (20 year cooled pre-Vitrification)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Total Solid HLW	containers/TWh	1.4	1.4	2.8	1.8	1.6	1.6
	kg/TWh$_e$	556	568	1120	719	634	643
	m^3/TWh$_e$	0.24	0.24	0.47	0.30	0.27	0.27
Total Solid ILW	drums/TWh$_e$	1.5	1.2	2.2		1.5	1.2
	kg/TWh$_e$	2040	1570	2890		2070	1590
	m^3/TWh$_e$	0.85	0.65	1.23		0.86	0.66
Total Liquid Effluent (Sea discharge)	m^3/TWh$_e$	465	355	354		281	209
	TBq	1.96	0.85	0.36		0.064	0.021
	TBq Alpha/TWh$_e$	1.02	0.20	0.0052		0.0032	0.00068
	TBq Beta/TWh$_e$	0.94	0.66	0.36		0.061	0.020
Total Aerial Effluent	m^3/TWh$_e$	34800	29480	30400		25600	22700
	TBq	376	611	1080		376	611
	TBq Alpha/TWh$_e$	0.014	0.016	0.003		0.014	0.016
	TBq Beta/TWh$_e$	376	611	1080		376	611

Note 1: Thorp PUREX 20 year cooled only assessed for HLW. Other streams would be expected to be similar to 5-year cooled case.

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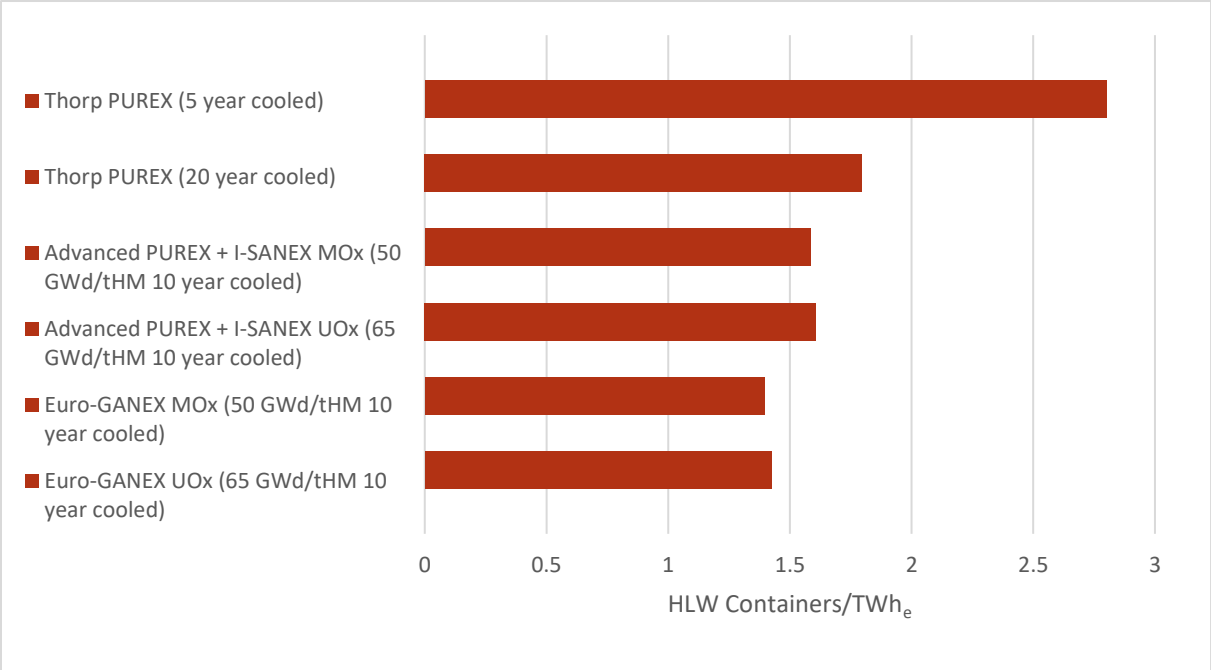

Figure 10. Comparison of HLW production, normalised to electricity generated.

Overall, against the Thorp PUREX and Advanced PUREX, Euro-GANEX deliver reductions in HLW produced as shown in Figure 10. Comparison of HLW production, normalised to electricity generated.Figure 10. Against Thorp PUREX 5 year cooled, Euro-GANEX reduces the number of HLW containers produced by 50.2% and 49.1% for the MOx 50 GWd/tHM and UOx 65 GWd/tHM cases respectively. Against Advanced PUREX, Euro-GANEX delivers a reduction of 11.9% and 11.5% of HLW containers produced for the MOx 50 GWd/tHM and UOx 65 GWd/tHM cases respectively. This shows that both Euro-GANEX and Advanced PUREX are able to process fuels with a higher burn-up and still deliver benefits against even a 20-year cooled Thorp reprocessing flowsheet.

For ILW from WEP and WPEP, Euro-GANEX and Advanced PUREX generate ILW waste reductions of 71.4% and 54.9% against the Thorp PUREX baseline, for the MOx 50 GWd/tHM and UOx 65 GWd/tHM cases respectively.

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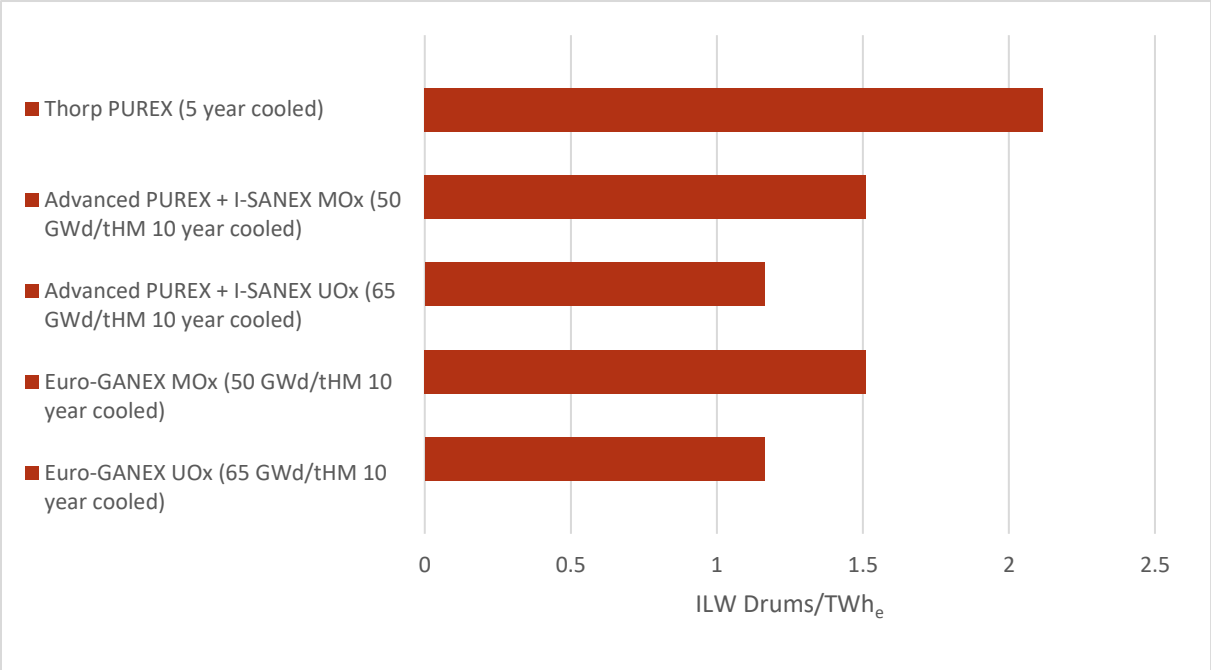

Figure 11. Comparison of ILW production, normalised to electricity generated.

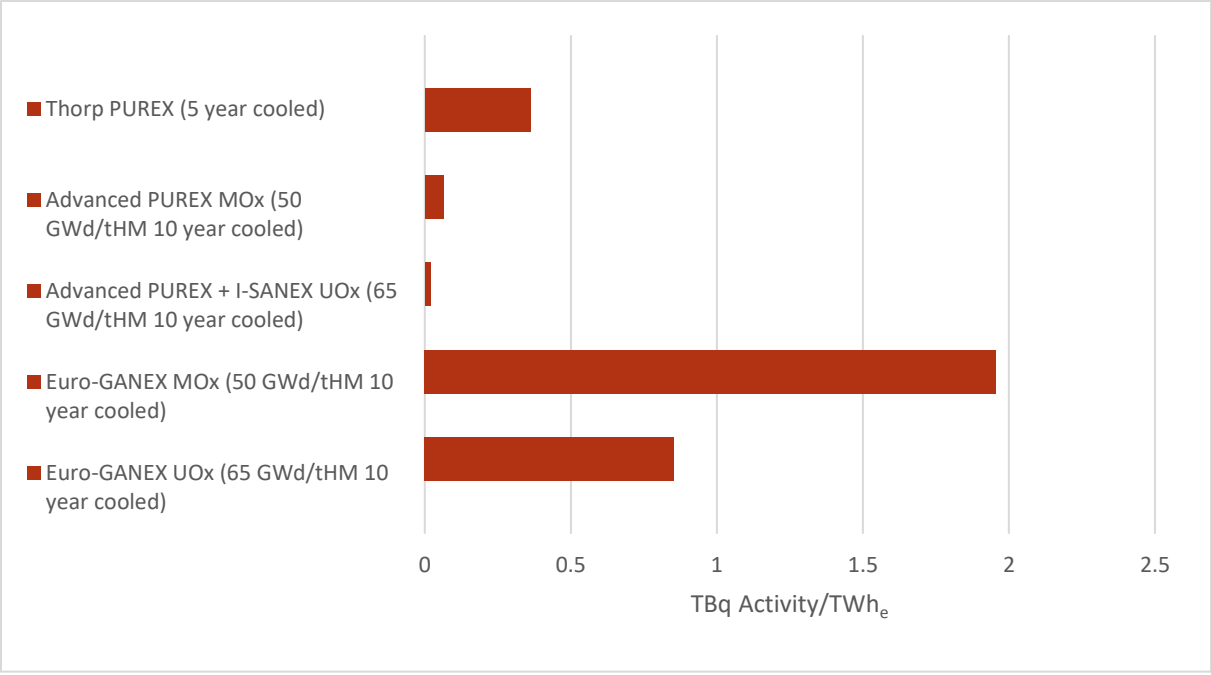

Figure 12. Comparison of TBq per TWh$_e$ of LLW Liquid Effluent Arisings.

For LLW liquid effluent routing via SETP, Euro-GANEX shows a significant increase compared to that of Advanced-PUREX and Thorp PUREX. The majority of this increase arises from the non-optimised nature of the routings of active species through chemical separations. Table 3 highlights the main contributing species that cause this increase in activity via LLW liquid effluent. Significant amounts of these and residual contributing

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species tend to remain in the solvent that is sent to solvent washing. The solvent washing process then cleans the solvent, removing these species to effluent treatment which is unable to abate these species effectively.

The solvent wash system assumed for the Euro-GANEX cases are based on the HASW systems used in Thorp and Magnox reprocessing. This technology is assumed due to the lack of an appropriate alternative technology, and as such introduces significant uncertainty to the performance of the solvent wash processes. As such, the combination of the arbitrary performance of the solvent washing processes, along with the non-optimised routing of fission products in the solvent phase highlights that the experimental work done to date requires further optimisation of these species' routings. This would ensure they are well back-extracted from the solvent to prevent large activity arisings from LLW liquid effluent. Further, development of a suitable technology for solvent washing of the DEHiBA and DMDOHEMA/TODGA solvents would potentially deliver other advantages, such as solvent volume requirements, and solvent washing cell footprints.

Table 3. % Contribution to total activity discharged from SETP for both Euro-GANEX cases.[5]

Species	% Contribution to total activity discharged from SETP (MOx 50 GWd/tHM)	% Contribution to total activity discharged from SETP (UOx 65 GWd/tHM)
Am	17.7	0.7
Cm	36.7	2.2
Eu	18.0	4.1
Pu	5.6	0.3
Sb	6.8	0.1
Tc	1.3	22.9
Ru	0.3	66.0

Aerial arisings, namely three off-gas systems from Dissolver off-gas (DOG), STP Stack and Vitrification off-gas for Euro-GANEX are markedly higher in alpha activity compared to Advanced PUREX and Thorp PUREX. The main contributors to this increase is the presence of the species outlined in Table 13 and Table 3 and their increased presence in the solvent compared to the other reprocessing schemes. This leads to discharge of these species through off-gas systems. Optimising for these species would bring the results of the aerial effluent in-line with that of Advanced PUREX, which reflects a decrease in volumetric flowrate and total activity discharged via aerial effluent.

[5] Note, this table represents only a selection of the primary species that are contributors to the activity present in LLW liquid effluent discharged via SETP

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1.5. DETAILED HLW RESULTS

The HLW results for Euro-GANEX are based on arisings from HALES and Vitrification processes similar to those that are present at the Sellafield site, UK. The results describe the main comparisons that can be made between the Euro-GANEX in each step, benchmarked against the Advanced PUREX and Thorp cases, if the Sellafield process is applied, from the HA raffinate stream exiting the reprocessing flowsheets through to vitrification of the final waste form. In the earlier Sim Plant work [5], a hypothetical scenario was presented which indicated the effects of including an MA removal process on the output of Advanced PUREX. In this case, the flowsheet contains a fully described I-SANEX process for Advanced PUREX.

The processing requirements analysed here (buffer tanks, evaporators, HASTs) are not intended to reflect how the Euro-GANEX or Advanced PUREX process would be implemented (or even how Thorp was actually implemented). Rather, the intention is to highlight sensitive areas in the processing of HLW, or upstream in the separation process, to reduce the HAR burden to HLW plants, where future R&D is required. Understanding the impacts on the current (Sellafield) technologies is, therefore, the starting point for R&D to develop advanced processing strategies and technologies that will reduce costs, wastes and hazards.

1.5.1. HALES BUFFER TANKS

Table 4. Comparison of Buffer Tank Results.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
No. Buffer Tanks	-	6	6	1	4	4
No. Yearly Tank Fills	Fills/yr	59.4	59.7	5.1	31.6	31.9
Total Buffer Time	d	20.2	20.1	39.6	25.3	25.1
Total Buffer	m^3	7500	7500	1250	5000	5000
Activity	TBq/tank	2.4E+05	3.6E+05	4.4E+06	4.5E+05	6.8E+05
Alpha	TBq/tank	4.0E+01	1.1E+01	2.5E+04	1.3E+02	4.2E+01
Beta/Gamma	TBq/tank	2.4E+05	3.6E+05	4.3E+06	4.5E+05	6.8E+05
Heat Generation	W/tank	1.8E+04	3.0E+04	4.2+05	3.5E+04	5.6E+04

The required buffer storage volume for Euro-GANEX is significantly higher than that of the Thorp PUREX baseline. Similarly, Advanced PUREX requires a higher volume of buffer storage of the HA raffinate. This is due to both flowsheets sending high volumes of a lower activity concentration to HA treatment. The heat loading and activity contents are around twenty times less than that of Thorp PUREX for Euro-GANEX, and around a

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ten-fold reduction for Advanced PUREX. This has implications on the footprint and sizing of the downstream facilities in the HA treatment process, which is discussed in the following sections.

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1.5.2. HALES EVAPORATORS

Following the buffer tanks, the HA raffinate is evaporated to reduce the volume. Table 5 highlights the main results for the HALES evaporators.

Table 5. Comparison of HALES Evaporators Results.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
No. Evaporators	-	7	7	1	4	4
Operating Days	d	177	178	105	165	166
Number of Batches per day per Evaporator		0.03	0.04	0.28	0.07	0.09
Campaign Time	d	2.98	2.98	20.8	5.21	5.21
Float Time	d	0.39	0.38	18.71	1.12	0.90
Total Activity	TBq/batch	3.3E+05	4.1E+05	7.5E+05	3.1E+05	3.7E+05
Alpha	TBq/batch	5.7E+01	1.2E+01	4.3E+03	9.2E+01	2.3E+01
Beta/Gamma	TBq/batch	3.3E+05	4.1E+05	7.5E+05	3.1E+05	3.7E+05
Heat Generation	W/batch	2.6E+04	3.4E+04	7.3E+04	2.3E+04	3.1+04
Volumetric Flowrate to HALES	m^3/day	362	362	26.4	189.4	189.4

Due to the increased volumetric flowrate through HALES, the evaporative demands also increase substantially for both Euro-GANEX and Advanced PUREX, which is further investigated in section 0. Euro-GANEX requires the most evaporators as the flowrate issue outlined in the previous section is the most prominent. The activity per batch is reduced for both Euro-GANEX and Advanced PUREX, which means that these two processes produce HAL that is less active per unit mass of waste oxides. The activity and heat generation data in Table 5 is representative of the batch at the outlet condition. The evaporators follow the same limits of 13.7 m^3 batch volume, with a 100 kg WO/m^3 limit for a total of 1370 kg WO/batch. The differences in activities is due to the different radionuclide composition of the fuel in each case.

The evaporators are required to run for increased operating days for Euro-GANEX and to a slightly lesser extent Advanced PUREX due to the reduction of activity concentration in the feed to HA treatment processes.

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1.5.3. HASTS

Table 6. Comparison of HAST Results.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
No. HASTs	-	14	17	10	15	19
Tanks Filled per Year	Fills/yr	4.4	5.6	3.1	4.9	6.1
Total Buffer Time	d	560	541	341	509	514
Total Buffer Volume	m^3	1820	2210	1300	1950	2470
Total Activity	TBq/tank	3.2E+06	3.9E+06	7.1E+06	2.9E+06	3.6E+06
Alpha	TBq/tank	5.4E+02	1.2E+02	4.1E+04	8.7E+02	2.2E+02
Beta/Gamma	TBq/tank	3.2E+06	3.9E+06	7.1E+06	2.9E+06	3.6E+06
Heat Generation	W/tank	2.5E+05	3.2E+05	6.9E+05	2.3E+05	2.9E+05

If we apply the layout, processing envelopes and CFA used for the HLW processes at Sellafield, the Euro-GANEX cases require 40-70% more HASTs than Thorp PUREX, and Advanced PUREX requires 50-90% more than Thorp PUREX. The increased footprint of the HA treatment processes is, as described earlier, due to the increased flowrates which leads to the requirements for increased buffer storage, evaporative and HAL storage capacities. In the case of Euro-GANEX, it is understood that the flowrates utilised in the current conceptual flowsheet do not scale well from the current scale and as such highlight a recommended direction of optimisation in further development of the Euro-GANEX flowsheet. The aims will be to reduce the evaporation and interim storage requirements to as low as is reasonably practical from operational, safety and cost perspectives. Changes in technologies, plant designs and upstream separation processes should all be investigated to achieve these aims.

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1.5.4. VITRIFICATION

Table 7. Comparison of Vitrification Results.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Thorp PUREX (20 year cooled pre-Vitrification)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Number of Vitrification Lines	-	4	6	7	5	5	6
Operating Capacity	% of max production rate	99.2	87.9	89.2	80.1	90.1	99.1
Total Production Rate	Containers/year	595	791	937	601	676	892
Containers per Vitrification	Containers/year	149	132	134	120	135	149
Incorporation	w/w% waste oxides	23.7	22.6	10.5	20.4	23.0	22.0
Total Activity	TBq/container	2.3E+04	2.652E+04	2.278E+04	1.7E+04	2.0E+04	2.4E+04
Alpha	TBq/container	3.99	0.83	1.3E+02	156	6.26	1.51
Beta/Gamma	TBq/container	2.3E+04	2.652E+04	2.2E+04	1.7E+04	2.0E+04	2.4E+04
Total Heat	W/container	1.8E+03	2.194E+03	2.2E+03	1.5E+03	1.6E+03	2.0E+03

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Table 7 highlights the impact of each reprocessing case on the vitrification process. The key basis behind the calculation of the container production rate is that there is a certain flowrate of HAL containing a certain mass flowrate of waste oxides to be vitrified. The maximum mass of waste oxides that could form the glass to be contained within a single container before it would break any of the CFAs, such as the maximum heat loading per container, or the maximum alpha content, the maximum allowed content of curium, etc. is found. A single vitrification line can produce a maximum volume of HAL per year and produce a maximum number of containers per year[6].

For Advanced PUREX, the I-SANEX process is used in this phase and proves its merit in terms of achieving high waste oxide incorporation of 23% and 22% by mass in the glass for the HBU 50 and 65 GWd/tHM cases respectively, instead of the ~2% achievable without I-SANEX due to the presence of MA. In both of these cases with I-SANEX the CFA which is limiting the incorporation is now the proportion of FP+An (19% w/w) in the glass, see [22]. Euro-GANEX achieves broadly similar results to Advanced PUREX.

The result for the Thorp PUREX base case is a 10.5% w/w incorporation. This is due to using the initial Thorp PUREX base case of 5-year cooled fuel. This is colloquially referred to as “hot” fuel, and it is indeed the heat loading which is limiting the incorporation in this case (total heat per container hitting the max of 2.2 kW in the Thorp 5 year cooled case: again, see [22]). Such low incorporation may be detrimental to glass quality if not specifically designed for.

In reality the normal total cooling time for waste vitrified in Thorp is greater than 20 years. Hence, the models correctly predict that Thorp is able to get ~20% w/w incorporation of WO when a more realistic feed is simulated. This is now limited by the quantity of Sr-90 in the glass.

Sellafield’s Vitrification Plant typically achieves WO incorporations of 30-35% w/w, however these are for blends of Magnox and UOx fuel raffinates containing >50% WO derived from inactive additions [24]. The greater the proportion of UOx in the blend, the lower the total incorporation achieved, as less additions arise during UOx reprocessing in Thorp, down to ~25% WO w/w derived from inactive additions in a pure UOx raffinate. In the theoretical Thorp expressed by the Thorp flowsheet in Sim Plant, only ~9% w/w of the WO incorporated is derived from process additions. This discrepancy is due to the real Thorp adding larger quantities of Gd to the head end dissolver than the design value, also there are far larger quantities of Fe, Cr and Ni arising due to the corrosion of the dissolver basket and other components which is not fully captured in Sim Plant. A recommendation may be to add these empirically to the dissolver stage of the flowsheets, as the quantity of inactive additions in the Euro-GANEX and Advanced PUREX flowsheet may also be an underestimate, causing the incorporation predicted to appear lower than recent Thorp values and therefore unreasonably pessimistic when in reality the same mass of waste deriving from spent fuel is being incorporated.

The total activity and heat loading per container is approximately equivalent in terms of magnitude; however, the alpha content is an order of magnitude lower, even comparing with the 20-year cooled Thorp case.

[6] Containers per Vitrification Line and Operating Capacity are using the current operating capacity of 150 containers/year as the maximum production rate that has been achieved over time. This is far below the original design specification but due to unreliability 150 containers/year is a realistic operating capacity, this was debated and agreed in the Basis and Assumptions Document.

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The number of vitrification lines required, containers produced per vitrification line per year and resulting operating capacity of each vitrification line is not indicative of a plant designed for Euro-GANEX or Advanced PUREX. These values only show what would be the effect of attempting to run these throughputs through the system currently used at Sellafield. A truer indication of throughput is the Total Production Rate, the values for these final waste outputs when normalised for electricity are shown in Table 2. Effects of HA Raffinate Volume

Table 8. Comparison of HA Raffinate flows to HALES.

Reprocessing Case	Origin	Volumetric Flowrate (m^3/d)
Euro-GANEX	HAL from TRU Extract-Scrub	181
	HAL from Ln Strip	181
Thorp PUREX	HAL from Chemical Separations	26.4
Advanced PUREX	HAL from I-SANEX	116
	Tc Strip	73.4

There have been marked effects on HALES in terms of buffer storage requirements and the demand on evaporation in the Euro-GANEX case, even increase compared to assessments carried out on Advanced PUREX. This is to be expected due to the poor scaling of experimental scale flowrates applied to a process scale flowsheet. Table 8 highlights that the HA raffinate flows are almost double that which are provided to HALES by Advanced PUREX, and a 1370% increase in HA raffinate flowrate compared to Thorp PUREX. A large benefit can be delivered by better scaling of these flows in future iterations of the conceptual Euro-GANEX flowsheet. Utilising different technologies in the evaporative stages, such as a thermosiphon system or wiped film for the HA evaporators may be of use in this optimisation of the process for downstream processing. The Sim Plant tool can aid in HA treatment optimisation and optioneering due to the modular nature of the effluents flowsheet [22].

1.6. DETAILED ILW RESULTS

The two solid ILW streams arising from the reprocessing cases are processed by plants: WPEP and WEP:

- WPEP grouts the iron-based flocculate from EARP into drums.
- WEP takes fuel Hulls and Ends (primarily the fuel cladding), centrifuge cake from feed clarification, BaCO3 slurry from the C-14 plant, as well as miscellaneous scrap waste, and similarly grouts them into drums.

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1.6.1. WPEP

WPEP handles two types of waste floc from EARP – bulks and SEC (Salt Evaporator Concentrate). The two are blended together before being encapsulated with cementitious grout. As they are blended, the calculations and thus arisings do not consider the bulk and concentrate flocs separately. Table 9 shows the differences between Euro-GANEX, Advanced PUREX and Thorp. Euro-GANEX shows an increased rate of drum production compared to Thorp and Advanced PUREX. However, what is more significant is the activity loading of WPEP ILW drums. WPEP drums from a Euro-GANEX flowsheet have a markedly higher amount of activity and heat generation compared to Thorp and Advanced PUREX cases. This increase is mainly due to poor optimisation of species that remain in the solvent that are routed to the Salt Evaporator and STP, which increases the activity of the floc from EARP sent to WPEP for encapsulation. Future work should look to optimise the back-extraction of fission products from the solvent phase during the Euro-GANEX chemical separations area.

With Advanced PUREX, there is a significant reduction of ILW arisings from WPEP, in terms of drums produced, as well as the total activity and heat generation rates per drum, due to Advanced PUREX not sending any effluent directly to EARP, and all EARP feeds in the Advanced PUREX case being secondary streams from other plants (SE and STP) which are less active.

Table 9. Comparison of WPEP Arisings

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Drum Production Rate	drums/day	0.15	0.15	0.08	0.05	0.05
	kg/day	172.4	172.4	99.8	59.4	59.4
	m^3/day	0.08	0.08	0.05	0.03	0.03
Total Activity	TBq/drum	200	44.0	11.6	0.50	0.17
Total Alpha	TBq/drum	14.9	4.0	0.08	0.02	0.006
Total Beta/Gamma	TBq/drum	185.511	40.017	11.5	0.478	0.159
Total Heat	W/drum	13.9	4.05	0.09	0.02	0.005

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1.6.2. WEP

WEP handles four solid/slurry ILW streams which are grouted into ILW drums for storage. Table 10 highlights the overall arisings from WEP in each case. Broadly, there is a slight decrease in ILW arisings with increasing burnup for the same throughput of fuel to reprocessing, this translates, referring back to the Total Waste Arisings Table 2, to a great reduction in ILW arisings from WEP per TWh_e when normalised for the amount of electricity produced.

Table 10 - Comparison of Overall WEP Arisings.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Drum Production Rate	drums/day	3.2	3.2	3.5	3.2	3.2
	kg/day	4360	4360	4725	4360	4360
	m^3/day	1.8	1.8	2.0	2.8	1.8

The production of each type of drum and associated activity and heat content are given individually.

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Table 11 - Comparison of WEP Arisings (Hulls and Ends).

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Drum Production Rate	drums/day	2.6	2.6	2.6	2.6	2.6
	kg/day	3630	3630	3630	3630	3630
	m^3/day	1.4	1.4	1.4	1.4	1.4
Total Activity	TBq/drum	30	29	29	25	22
Total Alpha	TBq/drum	0.70	0.18	0.16	0.70	0.18
Total Beta/Gamma	TBq/drum	29.7	29.0	29.0	24.2	21.9
Total Heat	W/drum	3.3	4.7	1.6	2.7	3.9

The hulls and ends wastes are shown in Table 11. As the amount of fuel processed is the same in each case (5 tHM/day) then the throughput of cladding, hulls and ends is identical. The results for Euro-GANEX and Advanced PUREX are identical due to the same fuel types being used for each case.

The volumes of waste remain similar; however, the amount of activity and heat loading per drum changes. While the Beta/Gamma values are lower for both the Euro-GANEX and Advanced PUREX cases because the spent fuel has been cooled for longer, the alpha activity and the heat generation are increased with Euro-GANEX and Advanced PUREX due to the greater presence of heat generating radionuclides in the HBU fuel.

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Table 12 - Comparison of WEP Arisings (Centrifuge Cake).

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Drum Production Rate	drums/day	0.21	0.21	0.51	0.21	0.21
	kg/day	208	208	503	208	208
	m^3/day	0.12	0.12	0.29	0.12	0.12
Total Activity	TBq/drum	14060	4495	898	2433	647
Total Alpha	TBq/drum	674	187	0.06	157	43
Total Beta/Gamma	TBq/drum	13400	4310	898	2280	604
Total Heat	W/drum	1050	531	1.67	148	47.3

Table 12 shows that the Euro-GANEX and Advanced PUREX centrifuge cake waste drums are orders of magnitude more heat generating than their PUREX counterparts, the MOx case also generates significantly more Beta/Gamma radiation. A significant increase would be expected due to the processing of MOx and HBU fuels, however the extreme magnitude of the increase warranted further investigation.

Whilst Advanced PUREX and Euro-GANEX may produce the same amount of ILW, Euro-GANEX is disadvantaged by the level of activity that is routed to ILW waste streams. For the MOx 50 GWd/tHM case, the amount of activity per drum is 14058 TBq, compared to 2433 TBq per drum for Centrifuge Cake ILW drums for Advanced PUREX. This gives a 6.9-fold increase in the heat generation of the Centrifuge Cake ILW drums. The increase in activity is due to the routing of insoluble species such as Rh, Te, Pu and lanthanides such as Eu. These species relative activity contribution of the total to centrifuge cake ILW drums is given below in Table 13.

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Table 13. % Contribution to total activity of Centrifuge Cake ILW drums.

Species	% Contribution to total activity of Centrifuge Cake ILW drums
Pu	52.1
Rh	17.1
Te	9.6
Eu	14.6
Ba	1.9
Cs	2.2

The IFP dissolver in the flowsheet is assumed to be 99% efficient, this, at the moment is not based on a detailed experimental program, it is only based on simple assumptions which are believed possible in this type of dissolver. These assumptions are probably pessimistic and realistic values underpinned by experimental studies are needed.

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Table 14 - Comparison of WEP Arisings ($BaCO_3$ Slurry).

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Drum Production Rate	drums/day	0.28	0.28	0.29	0.28	0.37
	kg/day	294	294	308	294	387
	m^3/day	0.16	0.16	0.16	0.16	0.21
Total Activity	TBq/drum	0.66	0.88	0.45	0.66	0.66
Total Alpha	TBq/drum	5.1E-03	1.4E-03	9.8E-04	5.1E-03	1.0E-03
Total Beta/Gamma	TBq/drum	0.65	0.87	0.45	0.65	0.66
Total Heat	W/drum	8.7E-03	7.3E-03	3.8E-03	8.7E-03	5.5E-03

Table 14 highlights the increased drum activity in the Euro-GANEX and Advanced PUREX processes from $BaCO_3$ waste slurry. As this slurry comes from the C-14 plant, this can be attributed to an increased activity in the aerial effluent streams from the Dissolver off-gas system.

Scrap metal waste production outlined in Table 15 is assumed to be independent of activities of streams within the flowsheet and is simply based on the throughput of HM.

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Table 15 - Comparison of WEP Arisings (Scrap Waste).

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Drum Production Rate	drums/day	0.16	0.16	0.16	0.16	0.16
	kg/day	233	233	233	233	233
	m^3/day	8.7E-02	8.7E-02	8.7E-02	8.7E-02	8.7E-02

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1.7. LIQUID EFFLUENT

The liquid effluent waste streams are accumulated within SETP for neutralising and sampling (if required) prior to sea discharge. These streams originate from throughout the entire process such as evaporator overheads from reprocessing and MASFE and the SE and also supernates from EARP, STP and the C-14 plant. The results presented are the overall arisings of low-level liquid effluent accumulated within SETP. Table 16 shows that the volumes of LLW discharged to sea are broadly similar for Advanced PUREX and Thorp PUREX, yet again are markedly increased for Euro-GANEX cases. The amount of activity is orders of magnitude larger for both Euro-GANEX cases compared to the other reprocessing flowsheets. This is due to previously discussed issues surrounding the retention of active species within the solvent phase, which are then routed to SE and STP and then to SETP. Optimisation of the back-extraction of co-extracted species in the Euro-GANEX chemical separations would decrease the amount activity released to sea discharge via SETP.

To the advantage of the Advanced PUREX process, the normalised waste arising per unit electricity generated is lower than that of the PUREX process. Furthermore, 5-10 times less activity is released to sea in the Advanced PUREX cases. This low activity opens the possibility for increased reuse of effluent. This is being considered by other projects in AFCP.

Table 16 - Comparison of SETP Arisings.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Volumetric Flowrate	m^3/day	992	985	592	599	580
Total Activity	TBq/day	4.17	2.37	0.61	0.14	0.057
Total Alpha	TBq/day	2.17	0.54	8.6E-03	6.8E-03	1.9E-03
Total Beta/Gamma	TBq/day	2.00	1.82	0.60	0.13	0.06

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1.8. AERIAL EFFLUENT

Aerial effluent streams from the STP, DOG and the Vitrification Off-Gas systems are modelled. Table 17 and Table 18 show the results for the aerial effluents arising from the STP and Vitrification plant stacks respectively.

Table 17 - Comparison of STP Stack Arisings.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Volumetric Flowrate	m^3/day	3.3E+04	3.3E+04	1.7E+04	1.0E+04	1.0E+04
Total Activity	TBq/day	6.9E-03	1.4E-03	2.1E-05	3.4E-06	7.4E-07
Total Alpha	TBq/day	3.9E-04	1.1E-04	1.6E-07	1.9E-07	5.3E-08
Total Beta/Gamma	TBq/day	6.5E-03	1.3E-03	2.1E-05	3.2E-06	6.8E-07

The STP stack releases a small amount of activity, with a high volumetric flowrate due to the large volumes of air provided to the stack.

The references used to construct the model assumed that the HEPA filters captured all of the activity before release [20], this leaves the NOx produced as the most notable component for comparison between processes. It is concluded that the increase in NOx produced is not significant because the mass flow is low.

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Table 18 - Comparison of Vitrification Off-gas System Stack Arisings.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Volumetric Flowrate	m^3/day	2.9E+04	3.6E+04	2.0E+04	3.1E+04	4.0E+04
NOx Released	kmol/day	0.04	0.05	0.03	0.04	0.05

The complete abatement of every elemental species, bar NOx, in the WVP stack outlet is known to not represent reality – with a significant proportion of Sellafield site's overall discharge of key isotopes coming from this stack. This includes around 80% of the release of Ru-106 and between 10-20% of the site's release of C-14 (in the years 2016 and 2017).

Table 19 - Comparison of DOG System Stack Arisings.

Parameter		Euro-GANEX MOx (50 GWd/tHM) (10 year cooled)	Euro-GANEX UOx (65 GWd/tHM) (10 year cooled)	Thorp PUREX (5 year cooled)	Advanced PUREX + I-SANEX MOx (50 GWd/tHM) (10 year cooled)	Advanced PUREX + I-SANEX UOx (65 GWd/tHM) (10 year cooled)
Volumetric Flowrate	m^3/day	1.3E+04	1.3E+04	1.3E+04	1.3E+04	1.3E+04
Total Activity	TBq/day	802.9	1695	1806	802.9	1695
Total Alpha	TBq/day	0.03	0.05	4.8E-03	0.03	4.6E-02
Total Beta/Gamma	TBq/day	802.9	1695	1806	802.9	1695

Table 19 shows the data for the DOG system stack, which has a notably high activity. The activity of beta/gamma is dominant in the stream and this is almost entirely from Kr-85. Kr is a chemically unreactive noble gas which is unaffected by the off-gas system for the dissolver (with no abatement). The quantities released in each case is due to increased or decreased presence of this radioisotope within the fuel. There are 11.057 g of Kr-85 /tHM within the 50 GWd/tHM fuel, and 23.345 g of Kr-85 /tHM in the 65 GWd/tHM fuel, which correlates to the roughly doubled amount of beta/gamma activity discharged from the DOG stack.

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However, there is an important caveat in that although almost all of the total activity is from Kr-85, its radiotoxicity is very low and a calculation of either the collective dose or the critical group dose uptake is recommended for future updates. The critical group dose may be highly sensitive to relatively small quantities of alpha and beta emitters, in particular C-14 and I-129. The composition of the stream is already modelled in Sim Plant, so along with an assumption on the location of the plant, this can be completed easily.

Present aqueous effluents flowsheeting is thought to be broadly satisfactory. However, the model excludes consideration of aerial effluents in most locations. This is, in part, because operational plant data on which to base such flowsheeting is not always present. However, this is an omission from Sim Plant which we should look to address in later phases of work. In particular, the lack of the inclusion of vent streams and a central off-gas system should be addressed.

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7. SIZING AND FOOTPRINT RESULTS

1.9. SCOPE

The sizing calculations have focused on the main reprocessing plant and waste treatment facilities, but has not included fuel receipt and storage, or product and waste stores.

The design and size of both fuel ponds for receipt and storage in the Head End and stores for products and wastes post-reprocessing, depend on the fuel cycle strategies adopted, most obviously the holding time before reprocessing and fuel refabrication.

1.9.1. FUEL RECIEPT AND STORAGE

Some scenarios will require more fuel storage than others (e.g. deliberate delay storage). It is recommended that fuel ponds be looked at later when required. Dry storage could also be considered.

1.9.2. PRODUCT AND WASTE STORES

Product Stores would be required to house:

- The U product.
- The mixed oxide product.

Waste Stores are required for:

- HLW canisters.
- ILW drums.

1.9.3. SALT EVAPORATOR PLANT

There was some difficulty obtaining design records of this legacy plant in order to form enough information to confidently estimate the effects on sizing. Although shortly before the issuing of this report, leads have been discovered, this plant is very unlikely to be a significant differentiator between the reprocessing regimes and has been ignored within this phase of work. It should be added later once sufficient supporting data are located.

1.10. REPROCESSING

The changes which will lead to significant differences in sizing and cost lie within the differences in cell volumes required for the key unit operations noting that these cells make up only a fraction of the volume of the building, and are surrounded by supporting infrastructure, ancillary rooms as well as personnel rooms and corridors which would take up a comparable space in the building as on Thorp. So, what will be highlighted are the key differences between Euro-GANEX, Thorp PUREX and Advanced PUREX.

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For context, Sellafield's Thorp, excluding fuel receipt and storage, has a building volume of 921,400 m^3. Out of that total volume of 921,400 m^3, the key cell and plant envelope volumes which are being compared amount to 85,000 m^3, i.e. under 10% of the building volume.

1.10.1. HEAD END

The head end of reprocessing is in most ways similar to THORP, however, Euro-GANEX and Advanced PUREX requires a second dissolution stage using a silver (II) process to aid in the dissolution of Pu rich particles. This is required since Euro-GANEX and Advanced PUREX will be used to process FR and MOx fuels respectively, the aqueous stream from this secondary dissolver will then undergo a second centrifugation stage to remove any fine fines.

This is a batch process that handles specific quantities of fuel, and the required size of the operation for handling one unit of fuel would not be particularly sensitive to changes in throughput. Significantly increasing the throughput more than the current basis of 5 tHM/day may require a parallel line.

Table 20 – Head End Sizing.

	Dissolver and Feed Clarification Cells						
	Footprint (m^2)	**Height (m)**	**Volume (m^3)**	**% Footprint vs Advanced PUREX**	**% Volume vs Advanced PUREX**	**% Footprint vs Thorp PUREX**	**% Volume vs Thorp PUREX**
Cells	887	21.5	19100	100	100	200	200

The main difference within the Head End of Euro-GANEX and Advanced PUREX reprocessing is that in comparison with Thorp PUREX, the cell volume doubles – simply due to the dissolution and clarification steps being repeated. This assumes that the second dissolver cell is the same size as the first – there may be scope to have a smaller 2^{nd} cell, but such detail could only come from more focused engineering design.

1.10.2. SOLVENT EXTRACTION AND WASHING

This constitutes the main process within the Chemical Separations section of reprocessing where the PUREX process has been replaced by GANEX-1 and Euro-GANEX solvent extraction cycles. The Advanced PUREX and I-SANEX cycles are used for the Advanced PUREX comparison. Solvent washing also occurs within these cells. Euro-GANEX cycles both use differing solvents, namely DEHiBA for GANEX-1 and a DMDOHEMA/TODGA solvent for the Euro-GANEX cycle. Thus, two solvent wash cycles are required for both Euro-GANEX and Advanced PUREX in comparison to the three cycles used by Thorp PUREX (HASW, PPSW, UPSW).

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Table 21 – Sizing of Solvent Extraction and Solvent Washing.

	Solvent Extraction and Solvent Washing (Referring here to the Exterior Footprint and Volume of the Cells – see below for internal Footprints)						
	Footprint (m^2)	**Internal Height (m)**	**Volume (m^3)**	**% Footprint vs Advanced PUREX**	**% Volume vs Advanced PUREX**	**% Footprint vs Thorp PUREX**	**% Volume vs Thorp PUREX**
Cells	921	5	4610	126	126	35.2	12.4

These calculations indicate that the Euro GANEX process achieves a substantial reduction in cell footprint and volume by using centrifugal contactors. Similarly, Advanced PUREX and I-SANEX processes find the same reductions in footprint and volume by utilising centrifugal contactors. Around 40% of the Euro-GANEX solvent extraction process' footprint is utilised by the solvent wash process, with 72% of the footprint arising due to the combined Euro-GANEX 2nd cycle and accompanying solvent wash. The increased footprint of the Euro-GANEX cycle is due to the large flowrates utilised by this cycle and by consequence the solvent wash process leading to larger size process units required.

It is worth noting that the solvent wash processes assumed by the Euro-GANEX are based upon the HASW process utilised by Thorp PUREX, due to the lack of suitable process available. Thus 40% of the volume taken by the solvent wash can be reduced by developing and implementing a more optimised process for solvent washing of the particular solvents used in Euro-GANEX. Further, optimising the flowrates through the Euro-GANEX cycles will allow for smaller centrifugal contactor sizes, which take up the remaining 60% of the processes' footprint. The flowrates are increased in the Euro-GANEX process due to the poor scaling of flowrates from a concept flowsheet at a low TRL. With further trials it would be expected that these flowrates would be optimised such that the results of the Sim Plant analysis would give a smaller footprint for solvent extraction and washing [25].

Compared to Advanced PUREX, Euro-GANEX shares similar outcomes in terms of the optimisation of solvent washing processes, and increased flowrates. Solvent washing also takes up around 40% of the footprint of Advanced PUREX. This indicates that a focus of R&D on the optimisation of solvent washing could be very significant in terms of footprint and could now be considered as in the limiting factor in the reduction of the size of the cell volume within the Chemical Separations section of reprocessing. Furthermore, I-SANEX and its solvent wash take up approximately 30% of the footprint of the cells, indicating the importance of knowing whether MA separations are needed.

In terms of the individual cells:

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Table 22 – Individual Sizing of Solvent Extraction and Solvent Washing Cells.

Footprint taken up by:	Internal Cell Footprint (m^2)	External Cell Footprint (m^2)
Euro-GANEX 1st Cycle (GANEX-1) and DEHiBA Solvent Wash	158	189
Euro-GANEX 2nd Cycle and DMDOHEMA/TODGA Solvent Wash	669	732
Advanced PUREX First Extraction (Extract, Scrubs and Tc Strip)	107	133
Rest of Advanced PUREX and its Solvent Wash	326	370
I-SANEX and I-SANEX Solvent Wash	195	230

In addition to the more compact technology when utilising centrifugal contactors, a significant fraction of the volume reduction in the case of Euro-GANEX Advanced PUREX is due to the removal of the Plutonium Purification plant - it is no longer required because the chemical separation process produces the target concentrations by design.

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1.10.3. MASFE

The MASFE plant which concentrates medium active effluent is housed within the main reprocessing plant:

Table 23 – MASFE Sizing.

	MASFE and NAR Cells						
	Footprint (m^2)	**Height (m)**	**Volume (m^3)**	**% Footprint vs Advanced PUREX**	**% Volume vs Advanced PUREX**	**% Footprint vs Thorp PUREX**	**% Volume vs Thorp PUREX**
Cells (MOx 50 GWd/tHM case)	2230	27.5	61300	154	192	193	269
Cells (UOx 65 GWd/tHM case)	2210	27.4	60600	159	200	192	266

The estimated size for a MASFE plant to treat effluent arising from the combined PuMA finishing lines is significantly higher than that required for a Thorp PUREX process, being close to two times the footprint, and 270% of the volume compared to a Thorp PUREX baseline. Comparing to Advanced PUREX, the process also requires a larger MASFE plant compared to Thorp, however it is significantly smaller.

1.10.4. STP

Table 24 – STP Sizing.

	Solvent Treatment Plant		
	Volume (m^3)	**% Volume vs Advanced PUREX**	**% Volume vs Thorp PUREX**
Cells	5490	323	88.6
Building Envelope	30100	323	88.6

For Euro-GANEX, a reduction in size for an STP plant is reduced by around 10% compared to a baseline Thorp PUREX process. The STP is greatly reduced in volume for an Advanced PUREX process, scaling down to only around 25-30% of the size of the plant required to serve the equivalent Thorp-PUREX case. The increased size of a Euro-GANEX STP compared to an Advanced PUREX is due to an increase in flowrate and activity contained

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within the effluent routed to this process, which is spent solvent from the solvent wash cycles of Euro-GANEX. The increased activity is due to the use of the experimental data in the flowsheet to calculate routings of individual species. Due to the low TRL of the Euro-GANEX flowsheet, it is expected in further trials the optimising of species routings will occur. In this case it can be seen from the results that the increased size due to the activity is primarily due to the contributions of Pu and Ru which making up 72% and 23% of the activity sent to STP respectively.

1.10.5. COMBINED EARP AND SETP PLANT

Sellafield's EARP employs flocculation in order to entrain active species from effluent streams before they are sent directly to the sea discharge tank, floc is sent for encapsulation in WPEP. However, in the cases of Euro-GANEX and Advanced PUREX, there is no need for WPEP as a separate, dedicated plant, in fact the floc would be sent to be handled by WEP instead; in these two cases, the demand on this process is much reduced (only approximately 9 m^3 per day) – as without Magnox, and with the fact that Euro-GANEX/Advanced PUREX does not, in their current arrangement, send any effluent directly to EARP, that leaves the only feed to EARP being concentrate from the Salt Evaporator and Washings from Solvent Treatment Plant.

It would be justified in proposing that for the purposes of sizing, the function of EARP would be carried out within a combined EARP-SETP plant. This removes the need of a separate, dedicated EARP (Sellafield's EARP cost £172 million at the mean base date of 1991, when it was constructed.

An alternative solution could be to send the flow that would be treated by an EARP plant or an EARP-like section of a combined EARP-SETP plant to HALES instead.

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1.10.6. WEP

This plant would also serve as the WPEP plant, as a dedicated WPEP plant would only be processing around 10 drums per year. The throughput of a separate WPEP plant is so low in the Euro-GANEX and Advanced PUREX cases in comparison to WEP (approx. 1-2%), that the stream from EARP (or a combined EARP-SETP) to be encapsulated can be sent to WEP for in-line mixing without making a significant difference to the overall throughput of WEP. This decision is supported by [26] which gives some details about the origins of WEP and that it was originally intended to take EARP floc as part of its feed.

Table 25 – WEP Sizing.

	WEP Plant						
	Footprint (m^2)	**Height (m)**	**Volume (m^3)**	**% Footprint vs Advanced PUREX**	**% Volume vs Advanced PUREX**	**% Footprint vs Thorp PUREX**	**% Volume vs Thorp PUREX**
Cells	4510	23	104000	100	100	100	100
Building Envelope	6540	35	210000	100	100	100	100

Sellafield WEP operates at far below its design capacity, processing around 3-4 drums per day, relatively close to the same magnitude required by Euro-GANEX and Advanced PUREX at a spent fuel throughput of 5 tHM/day, in comparison to a hypothetical 9 drums/day maximum [27]. Therefore, there is a large degree of flexibility in the current design of Sellafield WEP which should be able to handle roughly more than double to triple the throughput, and so the size will not be varied.

The size of a WEP plant would be the same in the equivalent Thorp-PUREX and Advanced PUREX and I-SANEX cases as Sellafield's WEP.

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1.10.7. HAAR BUFFER TANKS

Table 26 – Sizing of the HAAR Buffer Tanks.

	HAAR Buffer Tanks		
	Volume (m^3)	**% Volume vs Advanced PUREX**	**% Volume vs Thorp PUREX**
Cells	48700	150	600
Building Envelope	155000	150	600

The number of HAAR Buffer Tanks required in the Euro-GANEX cases rose from 1 to 6, and so the volume of cells and the building to house them also has increased by a factor of 6. Advanced PUREX requires a lower number of HAAR buffer tanks, rising from 1 to 4 compared to Thorp PUREX. As discussed in previous sections, this increase is due to the poor scaling of flowrates from the current state of the concept flowsheets and would be expected to be reduced with further optimisation. The increased flowrates leave the buffer tanks with roughly a 10-fold reduction in activity compared to the Thorp base case. The optimising of flowrates to increase the activity concentration of the buffer tank feed would enable a reduction in the sizing of this portion of plant.

1.10.8. HALES EVAPORATORS

Table 27 – HALES Evaporator Plant Sizing.

	HALES Evaporators						
	Footprint (m^2)	**Height (m)**	**Volume (m^3)**	**% Footprint vs Advanced PUREX**	**% Volume vs Advanced PUREX**	**% Footprint vs Thorp PUREX**	**% Volume vs Thorp PUREX**
Cells	672	30	20200	175	175	700	700
Building Envelope	3650	30	110000	175	175	700	700

For Euro-GANEX, the number of HA evaporators is 7, compared to 4 for Advanced PUREX and one for the Thorp PUREX baseline. Again, the increase for both Euro-GANEX and Advanced PUREX is due to the dilution of the HA raffinate feed, which requires a higher throughput for the HA effluent treatment systems.

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1.10.9. HASTS

Table 28 – HAST Plant Sizing.

	HASTs						
	Footprint (m^2)	**Height (m)**	**Volume (m^3)**	**% Footprint vs Advanced PUREX**	**% Volume vs Advanced PUREX**	**% Footprint vs Thorp PUREX**	**% Volume vs Thorp PUREX**
Cells (MOx 50 GWd/tHM case)	1140	10.3	11700	93.3	93.3	140	140
Building Envelope (MOx 50 GWd/tHM case)	1880	20	37600	93.3	93.3	140	140
Cells (UOx 65 GWd/tHM case)	1390	10.3	14200	89.5	89.5	170	170
Building Envelope (UOx 65 GWd/tHM case)	2290	20	45700	89.5	89.5	170	170

The number of HASTs required for a Euro-GANEX process rose from 10 in the THORP PUREX case to 14 and 17 for the MOx 50 GWd/tHM and UOx 65 GWd/tHM cases respectively. Thus, the volume of cells and footprint increased by a factor of 1.4 and 1.7 compared to the Thorp PUREX baseline. Similarly, for Advanced PUREX, 15 and 19 required HASTs led to a 1.5 and 1.9 increase in footprint and volume against Thorp PUREX. In both cases, the cascade of higher HA feed flowrates to a HALES process leads to increased footprint.

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1.10.10. VITRIFICATION

Table 29 – Vitrification Plant Sizing.

	Vitrification Plant						
	Footprint (m^2)	**Height (m)**	**Volume (m^3)**	**% Footprint vs Advanced PUREX**	**% Volume vs Advanced PUREX**	**% Footprint vs Thorp PUREX**	**% Volume vs Thorp PUREX**
Cells (MOx 50 GWd/tHM case)	1920	18	34700	80	80	80	80
Building Envelope (MOx 50 GWd/tHM case)	8190	40	328000	85.98	85.98	85.98	85.98
Cells (UOx 65 GWd/tHM case)	2880	18	51500	100	100	120	120
Building Envelope (UOx 65 GWd/tHM case)	10860	40	434000	100	100	114.02	114.02

The number of vitrification lines required for a Euro-GANEX process is reduced to 4 compared to 5 in the Thorp PUREX baseline and increases from 5 to 6 in the MOx 50 GWd/tHM and UOx 65 GWd/tHM cases respectively. For Advanced PUREX, it remains the same at 5 vitrification lines for the UOx case and increases to 6 for the MOx case. The requirements for a Euro-GANEX and Advanced PUREX vitrification process are broadly similar as can be seen – 1 less vitrification line for Euro-GANEX MOx, and the same number of vitrification lines for Euro-GANEX UOx as Advanced PUREX.

While these results show that a Thorp PUREX reprocessing plant requires more vitrification lines than present at Sellafield, this is because of the annual throughput for all cases is 1000 tHM per year, and, under the Sim Plant basis, a vitrification plant is required to keep up with the annual throughput from reprocessing without any accumulation. Whereas at Sellafield, vitrification of Thorp waste will continue for years after Thorp and Magnox reprocessing plants have been closed. The assumed throughput is also based on that achieved using aging facilities.

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1.11. FOOTPRINT AND VOLUME SUMMARY

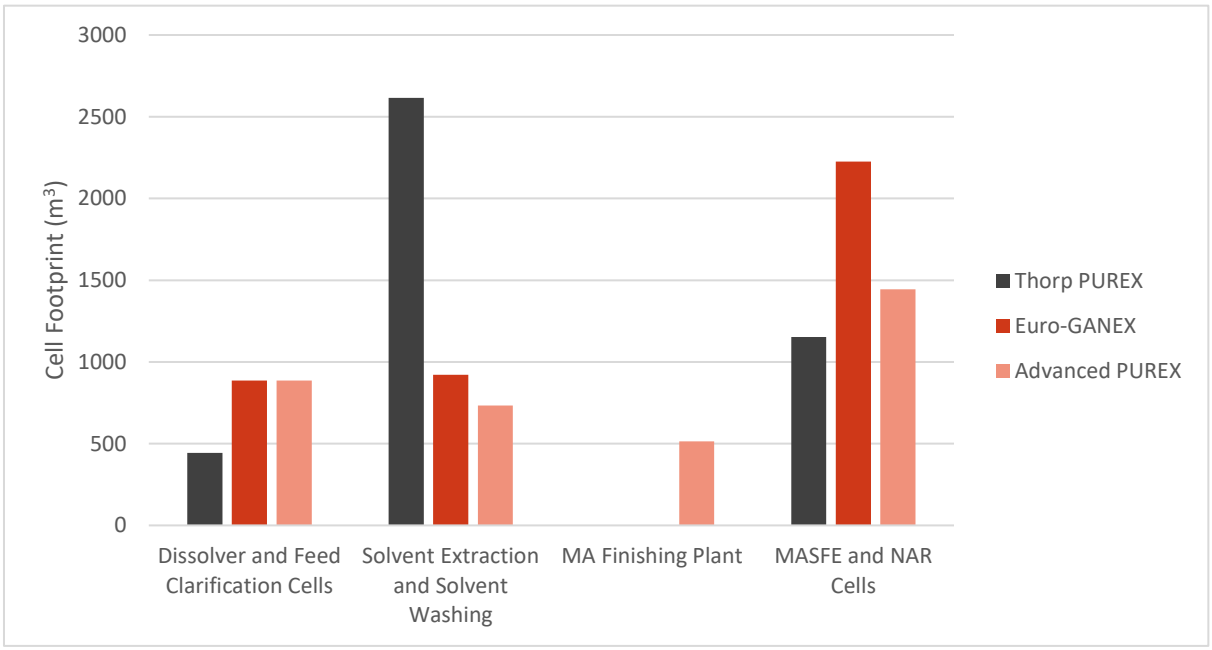

Figure 13. A Comparison of Cell Footprints within Reprocessing.

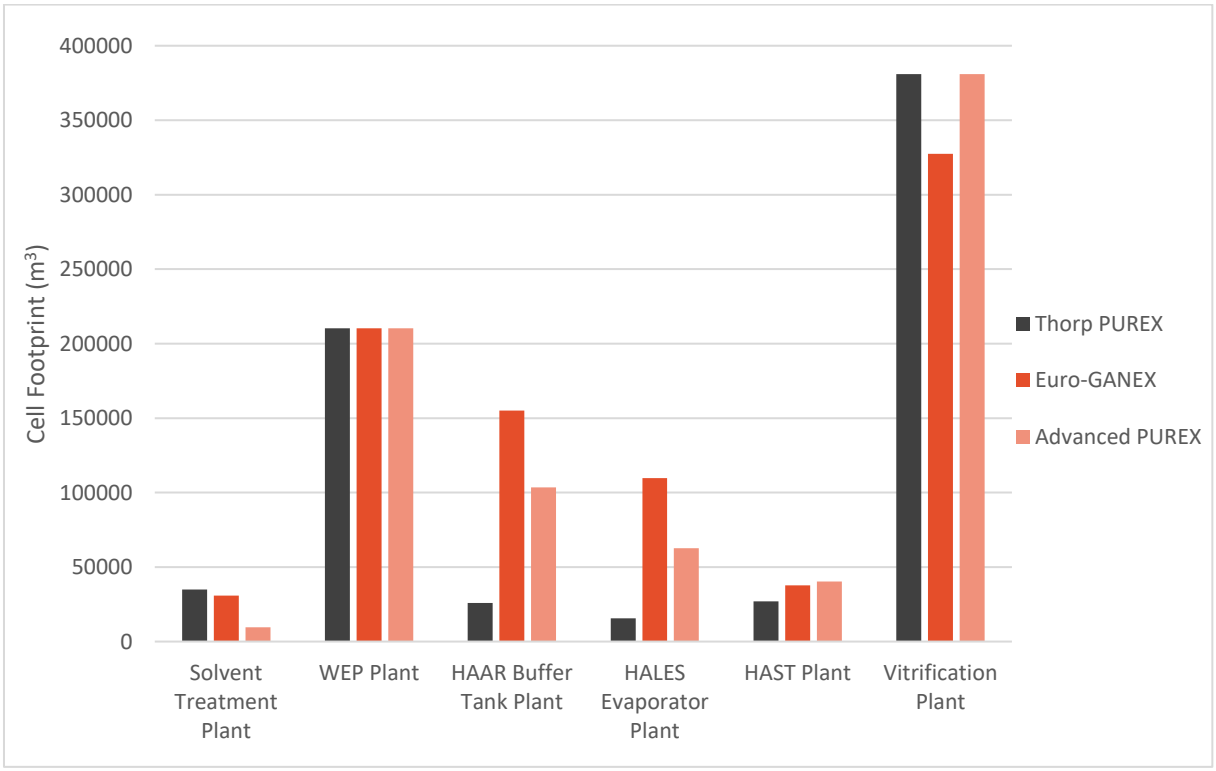

Figure 14. A Comparison of Waste Treatment Plant Volumes.

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8. CONCLUSIONS

Building on past phases of Sim Plant, an assessment of a Euro-GANEX flowsheet has been carried out utilising two fuel cases, namely a 50 GWd/tHM MOx fuel, and a 65 GWd/tHM UOx fuel. These cases were chosen to give a like for like comparison to previous assessments carried out on the Advanced PUREX flowsheet [1]. Using the Sim Plant tool, Euro-GANEX has been successfully assessed for waste arisings, reprocessing plant footprint and waste treatment plant footprint. This has then been directly compared to Advanced PUREX and a Thorp PUREX baseline case.

The concept Euro-GANEX flowsheet performs well compared to Thorp PUREX and Advanced PUREX assessments, with normalised (per TWh_e) data reflecting improvements similar to the Advanced PUREX flowsheet over Thorp PUREX. However, the Sim Plant tool has outlined a number of key areas for improvement to the flowsheet in its current form as it has done previous with Advanced PUREX.

The key areas are the optimisation of the suppression of co-extracting non-An/Ln fission products in the Euro-GANEX 2nd cycle, and the ensuring of back extraction of these co-extracted species prior to the Solvent recycle. Further, as was found with Advanced PUREX, the Euro-GANEX performs with need for improvement with regards to HA treatment, with 5% of the activity per buffer tank compared to Thorp PUREX which has downstream implications of needing 7 HA evaporators to provide the evaporative capacity needed. By optimising the flowrates across the chemical separations area, the footprint of the process would be further reduced, and the downstream implications for the HA raffinate would be more practicable. Further, both the Euro-GANEX and Advanced PUREX flowsheets require roughly 40% of the footprint of the entire chemical separations area for the purpose of solvent washing, which is based on the HASW system used in Thorp PUREX. This process was used for the Euro-GANEX flowsheet in the absence of any other alternative suitable technology and should not be assumed that it would be intended to use this technology in future. Thus, by investigating and optimising alternative technologies available for solvent washing of the DEHiBA and DMDOHEMA/TODGA solvents used in Euro-GANEX would not only reduce the footprint taken up by this process, but also reduce the requirements of a STP and a Salt Evaporator plant downstream, leading to reduced aerial and liquid effluent activities.

In summary, using the Sim Plant tool to assess a concept Euro-GANEX flowsheet has been successful in that a direct comparison has been obtained against Advanced PUREX and Thorp PUREX, and key areas have been identified for further development of the flowsheet. These key areas have been identified using the Sim Plant tool due to the ability to assess the downstream requirements of a reprocessing flowsheet.

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9. RECOMMENDATIONS

The following recommendations have been made as a result of the work performed for this report and support the development of wate treatment processes, advanced reprocessing and the Sim Plant tool itself:

1. Future development of the Euro-GANEX flowsheet should be focused on the following key areas:
    - Identification of a suitable solvent wash process for DEHiBA and DMODHEMA/TODGA solvents, and optimisation of this process
    - Optimisation of the routing of non-Ln/An fission product species within the Chemical Separations area of the Euro-GANEX flowsheet, particularly co-extraction into the solvent phase, and optimising the back-extraction of these co-extracted species.
    - The flowrates utilised throughout the Chemical Separations area should be optimised for a larger scale process, as currently the volumes processed lead to significant demands on a HALES system.
2. Building on previous recommendations from the previous phase [1], it is recommended here that the development of Sim Plant continues with the integration of more advanced reprocessing flowsheets to provide insights into the volume, footprint and downstream requirements. This holistic view of a reprocessing and effluent treatment system should continue to establish Sim Plant as the leading platform for plant modelling.

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