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Radwaste Treatment Options Study Report

Radwaste Treatment Options Study Report, Aker Solutions Document Number 63000333-000-000-181-K-0001, provides information supporting the UK Generic Design Assessment of the Westinghouse Electric Company AP1000.

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Radwaste Treatment Options Study Report

Westinghouse AP1000 Radwaste

AKER SOLUTIONS PROJECT NO: 63000333

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Contents

Glossary of Terms

ALARP - As Low As Reasonably Practicable
BAT – Best Available Techniques
CFA – Conditions For Acceptance
EA – Environment Agency
GDA - Generic Design Assessment
GWPS – Generic Waste Package Specifications
HAL – Highly Active Liquor
HEPA - High Efficiency Particulate Absorption
HLW - High Level Waste
HSE – Health & safety Executive
HVAC - Heating Ventilation Air Conditioning
ILW – Intermediate Level Waste
IX – Ion Exchange
LLW - Low Level Waste
LoC – Letter of Compliance
MCDA – Multi Criteria Decision Analysis
NII - Nuclear Installations Inspectorate
NRC Nuclear Regulatory Commission
PPE – Personal Protective Equipment
RWMD Radioactive Waste Management Directorate
WETOX – Wet Oxidation
WEC - Westinghouse Electric Company

1 Executive Summary

This report is produced in support of Westinghouse Electric Company's application to licence their AP 1000 Reactor design for use in the UK and documents the work done in a study to address the pre-disposal treatment of radwaste.

The report is one of a suite of documents that describe how it is proposed that radwaste will be produced, managed and disposed of. It considers all radwaste in general however focuses in the main on the treatment of solid waste specifically ILW Ion Exchange resins, ILW filter bed media and LLW mixed general wastes.

In the course of the study, an extensive search was conducted to identify all available treatment process options for the relevant waste streams. The report documents all options considered and describes a systematic approach taken to then produce a shortlist of viable candidate options and ultimately through a detailed analysis to arrive at the recommended reference design option. The analysis was conducted against a carefully developed set of selection criteria that reflect all areas of key stakeholder interest including regulators and potential owner/operators. All reasons for selection/de-selection of options are recorded for auditability.

The selected option for LLW treatment was compaction.

After consideration of all factors, the prime process technology selected as the optimum for treatment of the ILW streams was Cement Encapsulation. A major factor in the consideration was the current status of technology availability within the UK. However a significant opportunity was identified for reduction in waste volume with consequential reduction in environmental impact and waste disposal costs through adoption of developing technologies should they become available at a future stage.

It is recommended that:

- Compaction is adopted as design option for the treatment of LLW.
- Cement Encapsulation is adopted as the reference design for predisposal treatment of ILW.
- A plan is developed to undertake development work during the post GDA design stage to address the particular issues associated with dimensional stability of organic resins and thereby underpin the acceptability of the cemented ILW product for long term disposal.
- The design proposals are to be flexible where possible to maximise the potential to accommodate a change in process technology in the event that techniques that are more beneficial in waste volume reduction performance e.g. Vitrification or Controlled Oxidation become proven for application to the waste streams considered.

2 Introduction

In January 2008, the UK Government invited energy companies to put forward plans to build and operate new nuclear power stations on a commercial basis in the UK. The Environment Agency (EA) as a nuclear regulator along with the Health & Safety Executive (HSE – including the Office for Civil Nuclear Security) are working together to assess the proposed nuclear power station designs. EA and HSE have set up a Joint Programme Office in order to administer the assessment of the proposed designs using a Generic Design Assessment (GDA) process.

Aker Solutions (AS) is acting in support of Westinghouse Electric Company (WEC) and their submission of the AP1000 generic reactor design for UK licensing. The AP1000 is a USA-market compliant design which has US Nuclear Regulatory Commission (NRC) approval. However, this design has not yet been licensed for use in the UK and there are several areas specifically relating to waste treatment, storage and disposal where the Regulators' response to the GDA submission requests further information to demonstrate consideration of Best Available Technique (BAT) principles during development of the design.

The AP1000 design includes process routes for several significant wastes – notably gaseous and liquid radioactive wastes and WEC have been advised to consider producing a history of the development of the AP series design showing the design options considered and the reasons for those adopted. However with regard to solid radioactive and non-radioactive wastes the design of the waste treatment facilities are usually developed during the licence application stage and not at this early stage of pre-licensing. Also the development of the Radwaste Treatment Plant design will need to show how these waste arisings will be dealt with within the UK regulatory framework.

Therefore this options study was conducted to support the development of the front end engineering design for a Radwaste Treatment Plant to support a UK new-build AP1000 power station.

Absolute transparency is an overriding requirement of the study and whilst the need to demonstrate consideration of BAT principles is a key driver for the study, it is also necessary to demonstrate ALARP (As Low As Reasonably Practicable) principles. Furthermore it is recognised that the product of any chosen process technology option needs to satisfy the Conditions for Acceptance (CFA) for disposal in UK ILW (ref 2) and LLW repositories. Naturally there will also be economic factors to be considered.

The different requirements may place conflicting demands on the design solution that then compete in the final analysis, therefore the solution needs to balance all pertinent factors.

3 D_2O Process

D_2O is a systematic and rigorous optioneering process which has been used on many engineering and non-engineering tasks and which allows the identification and evaluation of options to seek the solution to complex problems. It is particularly powerful where there is a high level of stakeholder interest or influence and where there may be conflicting requirements that need to be balanced and is therefore an appropriate choice in the AP1000 application.

Implementation of the process is supported by the use of powerful software tools that enable multiple evaluations to be undertaken with relative ease. Different modelling tools are available; typically ‘Pro 1’ and ‘Pro 2’. Pro 1 lends itself to evaluation of options as complete stand alone solutions whereas Pro 2 is best suited to applications where the solution can be comprised of multiple component parts with different options available under each component.

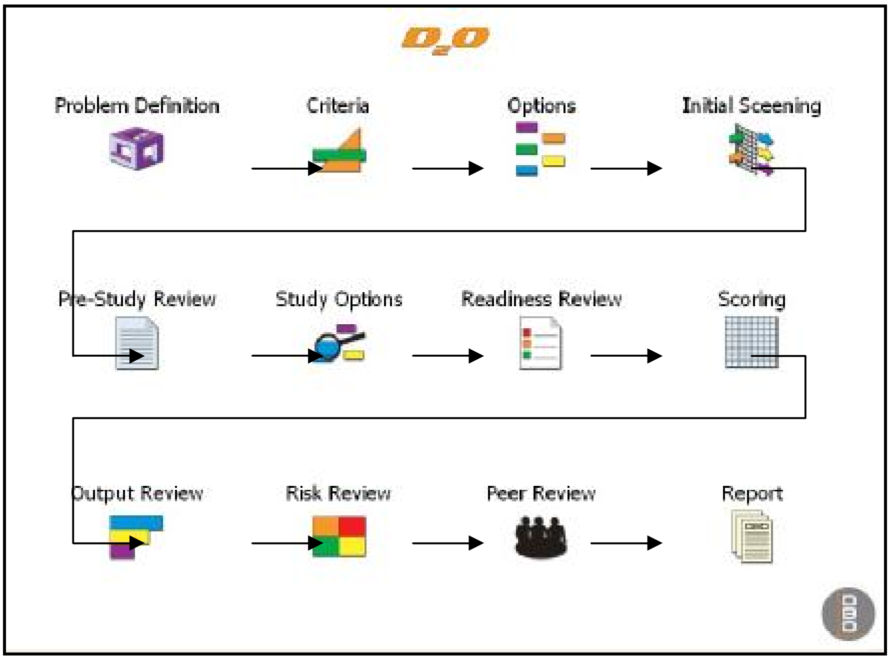
The D_2O process provides:

- Consistency and rigor
- Transparency and auditability
- Opportunity for Stakeholder input and ownership
- The ability to undertake multiple evaluations

The process is structured and comprehensive but remains flexible in order to meet the specific needs of individual clients.

The process constitutes up to12 steps; although all are not always required depending on the nature of the study. The 12 steps are shown pictorially in the figure below, with a brief description of each step in the following text:

Fig 31 D_2O Process



3.1 D_2O Process Steps

1) Problem Definition

This step aims to achieve clarity on the overall objectives together with associated drivers, constraints assumptions and key success criteria. A stakeholder analysis would also be undertaken to identify the key influencers; this leads to identification of areas of interest which can help in development of selection criteria.

2) Criteria Selection

Criteria are selected that reflect the aspects of importance that represent the benefits of a particular option choice. They must be capable of measurement and act as discriminators between options. The approach to weighting of criteria would be agreed.

3) Option Generation

Options may be derived by a number of methods including brainstorming, literature search and known best practice. They may represent complete solutions to a specific strategic objective or for detailed engineering problems may be derived against specific design features or unit operations.

4) Initial Screening

This is the initial evaluation of options against relevant benchmarks or constraints (e.g. legal or technical), to effectively identify and eliminate any options that are immediately apparent as unworkable i.e. ‘non-starters’. Options that survive initial screening go forward to the main option study stage of ‘Option Scoring’

5) Pre-Study Review

This step is undertaken to confirm the remaining options that will go forward to scoring and also the criteria that will be used to evaluate the options. The scope of the scoring study is also determined at this point along with the definition of the level of information on each option required to allow scoring to take place. The choice of software to support the evaluation would be confirmed at this point.

6) Study of Options

The objective during this stage is to produce sufficient relevant information on each option to allow objective and representative scoring against the criteria.

7) Readiness Review

This is an intermediate step to confirm sufficient information to the required standard is in place to allow option scoring.

8) Option Scoring

Options are scored against the criteria and the data is entered into an appropriate software tool. Criteria may be weighted to reflect a group view, views of particular stakeholders or neutral weighting.

9) Output Review

The model output is analysed to identify the favoured solution(s). Further work is then undertaken to test sensitivity to specific weightings and to understand the specific criteria, which are driving the solution choice.

10) Risk Review

A high level review of risks to assumptions and specific option risks to further evaluate the robustness of specific solutions.

11) Peer Review

Independent review to confirm the robustness of the process and the decision reached. This is normally an internal review by senior personnel who are independent of the case under consideration

12) Study Report

Presents the outcome of the study and provides the audit trail.

The following sections of the report present the outcome of each of the key steps of optioneering process.

4 Problem Definition

4.1 Objectives

4.1.1 Overall Objective

To underpin the selection of the fundamental process design concept for radioactive waste treatment and storage in support of Westinghouse Electric Company in their application to supply the AP1000 to the UK.

4.1.2 Specific Objectives

To define the design concept for the treatment, immobilisation and storage of solid ILW waste in line with RWMD specifications

To develop the design for the treatment of solid LLW waste in line with the UK practice of transfer of LLW to the UK disposal site (currently Drigg)

4.2 Scope

The Scope of Work of this study is to address waste activities from transfer / transport from the 'Nuclear Island' (i.e. the reactor complex) through to despatch to ILW store prior to disposal or to LLW disposal as appropriate. To deliver the overall objective detailed above, this study applies the D_2O optioneering process to a set of radwaste treatment options. This process utilises MCDA techniques as a tool to inform decision making. The overall process underpins the selection of a suitable treatment option whilst demonstrating consideration of BAT and ALARP principles.

The studies consider solid LLW and solid and liquid ILW wastes and any secondary waste arisings associated with them. Spent Fuel and Decommissioning Wastes are not included within the scope of this report.

Solid wastes are as defined in table 5.3 of the Basis of Design document (ref 1) and comprise:

- Wet ILW spent ion exchange resins and deep bed filtration media –11.3 m^3/yr
- Spent filter cartridges (ILW) – 0.6 m^3/yr.
- LLW solid wastes – 135 m^3/yr general trash and mixed wastes as a result of normal plant operation e.g. used PPE, wipes and other consumables.

4.3 Drivers

As a result of the Regulatory Issue (RI-AP1000-0001) raised by the EA in response to the GDA submission, WEC are required to provide more information on waste management and environmental discharges in order to demonstrate compliance with UK regulations and specifically to demonstrate compliance with Best Available Techniques (BAT) principles.

Definition of BAT

“Best” – means the most effective techniques for achieving a high level of protection of the environment as a whole.

“Available” – means techniques developed on a scale which allows them to be used in the relevant industry sector, under economically and technically viably conditions taking account of the costs and advantages.

“Techniques” includes both the technology and the way the installation is designed, built, maintained operated and decommissioned.

4.4 Constraints

The following constraints apply to the potential design solution
:

- Waste must be packaged and sentenced in accordance with current LLW and ILW repository Conditions for Acceptance
- ILW and LLW containers must comply with existing agreed specifications

-

4.5 Assumptions

These assumptions have been made in order to define the boundary of the scope of the study:

- Any laundry or laundry wastes will be treated off site and are excluded from the scope of this study. The reasons are presented in Reference 1
- Waste oils will be treated off site and are excluded from the scope of this study. The reasons are presented in Reference 1,
- Solid ILW waste includes spent resins plus zeolite and activated charcoals from guard beds and cartridge filters
- ILW resins are organic
- ILW resins and filter bed media are to be conveyed to the radwaste treatment facility hydraulically and will therefore include cover / transport water to be removed and / or recycled. The reasons are presented in Reference 1
- Solid LLW includes HVAC filters, gloves, respirator cartridges, used tools, PPE, consumables, rags and tissues etc.

4.6 Stakeholders

The following stakeholders have an interest in the outcome of this options study:

- Regulators - EA, HMNII
- Repository: RWMD
- Reactor manufacturer – Westinghouse Electric Company
- Utility Companies - E.ON, RWE, Endesa, Iberdrola, Suez and Vattenfall

5 Criteria

5.1 Evaluation Criteria Generation

Criteria are generated to enable the evaluation and comparison of options. They reflect the attributes that are important in the final solution and therefore should reflect all relevant issues and stakeholder views which may impact on option choice. Options are scored on a scale of One to Five, therefore ranked descriptions are prepared that map each score against a given criterion and describe the extent to which a given option might satisfy that criterion.

By defining the criteria early in the process a clear picture is given as to what information is required to describe the options to allow them to be evaluated on an informed basis. A basis is also provided for the initial screening of options where certain criteria are deemed to be mandatory i.e. options would not be considered further unless the criteria were met.

In total, 12 criteria were developed under headings of Technical, Safety, Environmental and Economic as follows:

Technical

- Technology Availability
- Operability / Maintainability

Safety

- Dose Uptake
- Hazard Potential (Radiological)
- Hazard Potential (Non-Radiological)

Environmental

- Primary Waste Management
- Secondary Waste Management
- Planning Issues
- Product Quality
- Resource Usage

Economic

- Implementation Time
- Process Technology Costs

Appendix 1 records the complete details for each criterion including the calibration descriptions.

5.2 Initial Screening Criteria Generation

In order to filter out clearly unworkable or unsuitable options at an early stage; initial screening criteria were set of:

- Process/Waste Compatibility
- Technology Availability

5.3 Criteria Weighting

Weighting of the criteria allows the relative contribution of each criterion to the total score of each option to be made more or less significant than the other criteria. As such it reflects the relative importance of different criteria and views on weighting inevitably vary between stakeholders.

A set of weights was agreed at a workshop on 4th June 2008 at which representatives from AKER Solutions, WEC, RWE, Rolls Royce, Vattenfall, Endessa and Iberdrola were present. The attendees represented a wide range of expertise and experience with all relevant disciplines present including designers, operators, environmental and safety practitioners. The agreed weights represent the full range of stakeholder interest and hence were used in the analysis.
The set of weights produced and agreed at the workshop were as follows:

Criterion	Relative Weight
Technology Availability	4
Operability / Maintainability	4
Dose Uptake	4
Hazard Potential (Radiological)	4
Hazard Potential (Non-Radiological)	3
Primary Waste Management	5
Secondary Waste Management	4
Planning Issues	2
Product Quality	5
Resource Usage	1
Implementation Time	2
Process Technology Costs	3

6 Option Generation

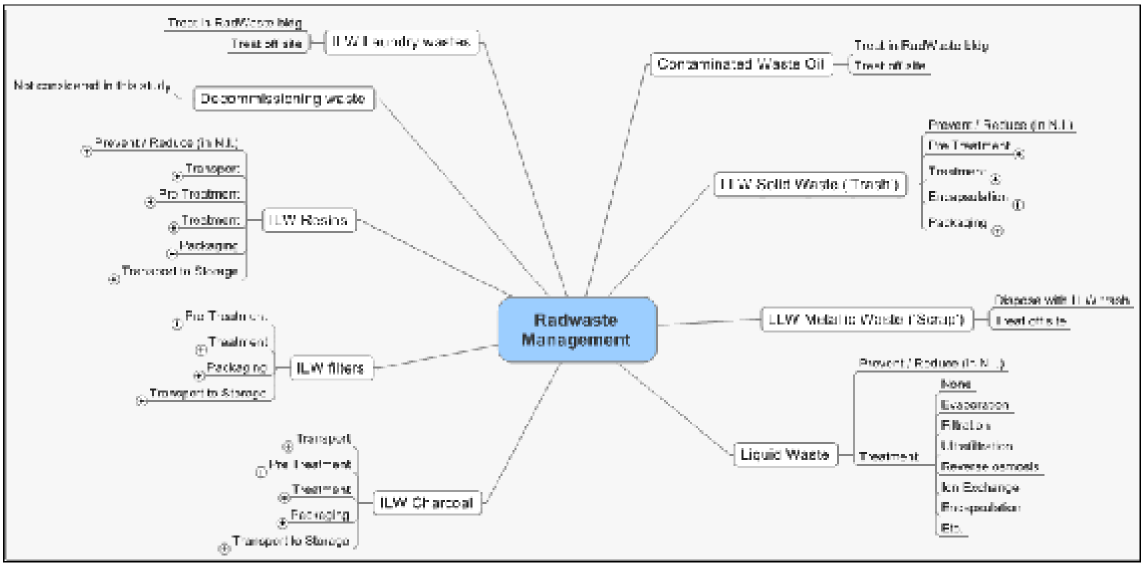
6.1 Waste stream Identification

The first step is to capture the full suite of wastes streams generated by AP1000, then to consider the candidate treatment options for the various waste streams. These were identified as follows:

- ILW Ion Exchange resins
- ILW filters
- ILW charcoal
- Metallic waste, i.e. scrap components LLW
- LLW Liquid waste
- LLW mixed solid waste
- ILW laundry wastes
- Decommissioning waste
- ILW Contaminated waste oil

These are represented pictorially below in the Radwaste strategy mind map prepared by DBD

Fig 6.1 Radwaste Management Strategy options



6.2 Process Options Generation

The first step was to gather all potentially viable process technology options and then to generate sufficient information for the options to be scored against the evaluation criteria on an informed basis. To that end, brief process descriptions supported by schematics where appropriate were compiled in addition to information regarding safety, environmental, technical and economic issues this information was compiled into a document (Appendix 3) and distributed prior to the workshop to all participants to inform their views. The option list was compiled through a combination of brainstorming, literature plus internet search also by drawing on the extensive prior knowledge of SQEP individuals within AKER Solutions and DBD. For convenience the options are summarised below:

6.2.1 Minimisation & Segregation

i. Minimisation

Prevent the production or reduce the amount of waste generated by application of the generic waste management hierarchy principles of; prevent; reduce; reuse; recycle; recover; dispose. The principle of minimisation will be addressed within the Nuclear Island

ii. Segregation

Waste is sorted into types or classes at source to allow for a more appropriate treatment and / or disposal route.

6.2.2 Storage as raw waste

i. Solids

Solid waste is stored in packaging designed to suit the type of waste, any handling requirements, duration of storage and environmental conditions.

ii. Liquids

Issues surrounding storage of raw liquid waste are similar to those of solid waste with more rigorous requirements due to increased mobility and volatility of the waste.

iii. Solid / Liquid Mixtures

Requirements set out for 2.1 and 2.2 apply with additional requirements such as agitation mechanisms for sludges.

6.2.3 Treatment

6.2.3.1 Non-destructive methods

i. Drying / Evaporation

The process removes liquid from wastes as a vapour in order to reduce the storage volume and / or risk of seepage / leakage, occasionally using heat or reduced pressure to do so.

ii. Settling / Decanting

Solids are allowed to settle at the bottom of a tank and the surface liquid is decanted off in order to reduce the storage volume and / or risk of seepage / leakage.

iii. Physical Conditioning / Separation

The waste stream is separated into two or more components or is conditioned by means such as shredding for certain types of solid waste. Liquids may be separated by phase separation.

iv. Filtration

Solid bearing fluids are passed through a porous medium such as a sieve, strainer or screen to remove solids, the size or nature of which can be tailored by the type of filter used.

v. Reverse Osmosis

A solution is forced through the use of pressure through a semi-permeable membrane which prevents the passage of the solute.

vi. Ion Exchange

A solution is passed through the ion exchange medium which is tailored to selectively bind the desired ionic species.

vii. Decontamination of Solids / Liquids

Radioactive contamination is removed by methods such as solvent cleaning or surface washing with water or supercritical CO_2, thereby allowing the waste to be placed in a lower waste category, reused / recycled, or free released.

viii. Absorption

An absorbent, such as a clay or polymer, is used to soak up liquid waste which results in a solid product.

ix. Size Reduction

Processes including cropping, sawing, shredding and crushing are used to reduce the size of large solid wastes such as filters and metallic components.

x. Compaction

Compaction of solid waste employs large forces of up to 50 MN to eliminate voids and cavities present in the waste. Supercompaction employs forces up to 2000t

xi. Direct Immobilisation (Encapsulation)

Solid or liquid waste mixed with an encapsulant such as cement or polymer material are immobilised within the solid matrix formed by the encapsulant. Commonly used in the UK to immobilise ILW, where the encapsulant used predominantly is cement although there have been isolated examples of the use of polymer resins. There are examples of the use of Bitumen overseas e.g. Belgium, however not in the UK.

6.2.3.2 Destructive methods

i. Conventional Incineration

Conventional incineration employs high temperatures to destroy the organic component of solid or liquid wastes through combustion in air to produce inorganic solid and / or gaseous products.

ii. Controlled Oxidation

Controlled Oxidation processes e.g. pyrolysis degrade organic solid or liquid wastes into inorganic and gaseous species under an inert or reduced oxygen atmosphere at a lower temperature than conventional incineration. Reagents can be added to prevent the formation of undesirable products. Combustible off-gas species are burnt off in an afterburner. Examples of large scale application of different proprietary variants on the process occur in the US (Studsvik THOR process) and several instances across Europe (Nukem pryolyser).

iii. Vitrification

The waste is mixed with glass and melted at very high temperature to form an encapsulated monolith. Organic materials are destroyed by the temperatures involved. One major UK application exists at Sellafield for the treatment of liquid HLW although is also used overseas for treatment of LLW and ILW.

iv. Plasma

An electric arc is used to break the waste down into its constituent atoms, melt metal components and vaporise organic materials which are burnt in an afterburner. The resultant ash or slag product is allowed to cool and solidify and then can be encapsulated; alternatively addition of glass frit to the feed stream will produce a vitrified product. Although well developed commercially, it is still in the developmental stage for nuclear application in the UK.

v. Geomelt®

GeoMelt® process uses an electric current to convert contaminated soil and waste into a stable, glass-like product. Organic materials are destroyed by the temperatures involved. Known large scale applications in treatment of LLW and ILW occur in USA, Australia and Japan.

vi. Synroc

Typically applied to HLW, the process converts waste into ‘Synthetic Rock’ by employing geochemically stable minerals instead of glass to create the crystalline matrix within which the waste is bound. Its main applications are for treatment of military wastes; few are known outside of USA and Australia.

vii. Molten Salt Oxidation

A bath of molten alkaline salts warmed to temperatures ranging from 500 - 900 C is used to oxidise combustible organic materials in the waste. Inorganic waste is isolated as a residue and subsequently encapsulated. Applications are believed to be in USA and Korea and mainly lab scale.

viii. Chemical Oxidation

An aqueous solution containing sodium or ammonium peroxydisulphate at relatively low temperature is used to oxidise organic species with no requirement for catalyst use. It is at a developmental stage in the US for treatment of organic liquid wastes.

ix. Wet Oxidation (WETOX)

This process uses soluble salts of redox sensitive elements with hydrogen peroxide, oxygen or air and sometimes using heavy metal catalysts to oxidise the organic content of waste materials. A process developed and licensed as a mobile plant by Winfrith has been deployed for the treatment of ILW resins.

x. Advanced Oxidation

Similar to Wet Oxidation, this process uses oxidants such as hydrogen peroxide, ozone or ultraviolet light, often including a catalyst, to oxidise organic species within the waste. Used to treat liquid streams containing small amounts of organic wastes

xi. Supercritical Water Oxidation

This is another variation on Wet Oxidation where water above its critical temperature and pressure is combined with air to oxidise organic species within the waste. Inorganic species form insoluble precipitates and metal waste forms insoluble oxides.

6.3 Option Configuration

It was recognised that of most the options individually do not offer a complete solution and a combination of at least two techniques as discrete process stages is desirable if not essential. The following mind maps were prepared in advance of the workshop by DBD to indicate how the options may be configured for each of the waste streams. For completeness, the mind map displays all the waste management steps from origin to storage (i.e. ‘cradle to grave)’ although not all would be decided within this report.

<u>Fig 6.2 ILW Resins and Charcoal Option Map</u>

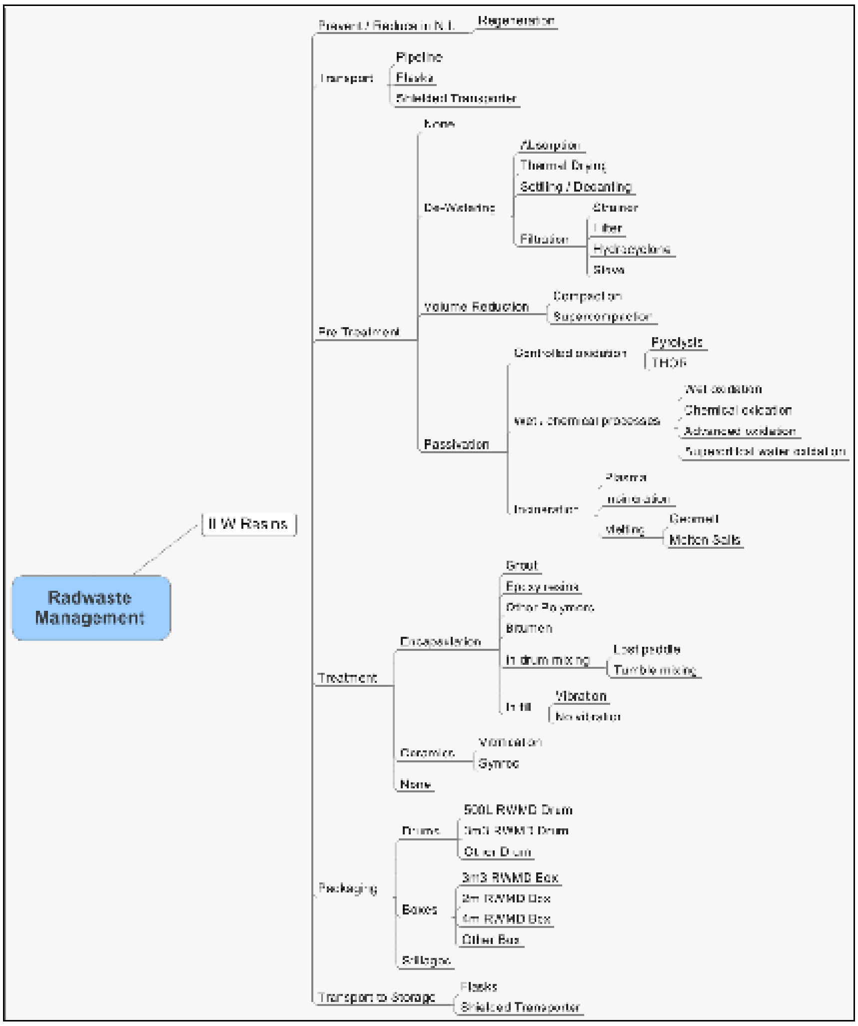


Fig 6.3 ILW Filters Option Map

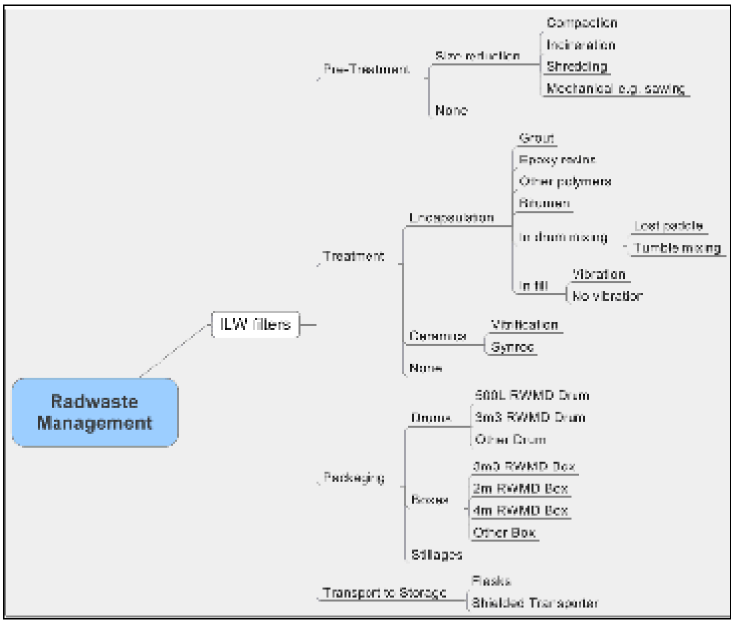
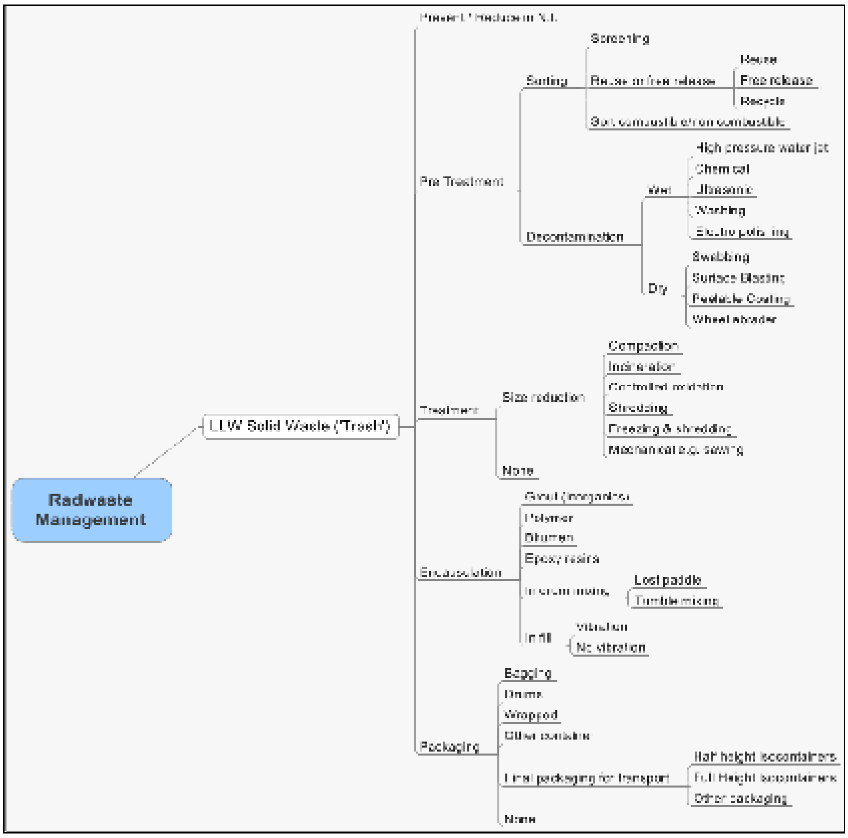


Fig 6.4 LLW Mixed Waste Option Map



7 Initial Screening

To eliminate non viable options, the following initial screening criteria were chosen:

- **Process /Waste compatibility** i.e. assesses if the processing option is suitable for treatment of the waste stream and if the waste stream is compatible with the process.
- **Technology availability** i.e. addresses the maturity and therefore the readiness of the technology to be applied in the AP1000 application.

Against the *Waste /Process compatibility* question, a straightforward 'Yes/No' answer was required.

However for *Technology Availability*; a simple Yes/ No would not the capture the varying degree of maturity exhibited by the options. It was recognised that the definition of '*Available'* within BAT is not necessarily limited to its being available within the UK, however the screening needed to consider that a option that is not tried and tested in the UK would be unlikely to yield a licensable design solution within a timetable that is commensurate with that of the GDA submission. Therefore it was decided to score options on a scale of 1 to 5 using the same calibrations as the Evaluation Criteria template (appendix 1), where 1 represents a completely novel technology with no full scale application to 5 for a fully tried and tested, UK licensed, widely applied technology, 3 would be a widely available, fully mature but non UK example.

The initial options were screened at a workshop by a combined AKER/DBD team and later reviewed and endorsed at the scoring workshop with WEC and Utilities present.

The initial screening results are shown in the following table. This is colour coded to aid visualisation, a 'YES' in the Waste/Process Compatibility column has been coloured in *Green* and a 'NO' in *Red*. Under Technology Availability; a score of 4 or 5 is coloured *Green*, a score of 1 - 2 in *Red* and 3 in *Amber*. For an option to survive initial screening a *Green* in the relevant column under Waste /Process Compatibility is required **PLUS** a *Green* or *Amber* under the Technology Availability column. An *Amber* score would indicate significant uncertainty over the option's technical readiness in time for the reactor design and build schedule, therefore that option would only be considered if other fully mature options were not available that provide the same functionality or benefit.

Table 7.1 Initial screening Results

	Process/Waste Compatability						Technology Availability		
Processing Options	**ILW Resins (organic)**	**ILW Resins (inorganic)**	**ILW Charcoal**	**ILW Filters**	**ILW Metal scrap**	**Mixed LLW**	**ILW**	**LLW**	**Comments**
Prevent / Reduce	Y	Y	Y	Y	Y	Y	5	5	Essential component in waste management strategy. To be performed at source of waste. Partial solution - waste consigned to radwaste requires further treatment.
Segregate	N/A	N/A	N/A	N/A	Y	Y	5	5	Assumptions are: 1 Sorting of mixed LLW waste allows for selection of the appropriate treatment(s) for constituent waste streams, 2 Charcoal and resin streams will be treated via the same processes therefore segegation is not required other than dewatering - covered later.
Store as Raw Waste									
- Solids	N/A	N/A	N/A	Y	Y	Y	5	5	Unacceptable for disposal. However may be a contingency option if CFA cannot be determined
- Solid / liquid mixtures	Y	Y	Y	N/A	N/A	N/A	5	5	As for solids above
Volume/Size Reduction									
- Size Reduction	N	N	N	Y	Y	Y	5	5	Partial solution only - requires further treatment
- Compaction/supercompaction	Y	Y	Y	Y	Y/N	Y	5	5	Final treatment for LLW. ILW would require overpacking. Is a potential viable process for hollow items e.g tubes, canisters but not for valves & solid items.
Non-destructive Treatment									
- Drying	Y	Y	Y	N	N	N	5	N/A	Partial solution only - requires further treatment
- Evaporation	N	N	N	N	N	N	5	5	Applicable to liquid wastes only
- De-watering (Settling / Decanting)	Y	Y	Y	N	N	N	5	N/A	Partial solution only - requires further treatment
- Filtration	Y	Y	Y	N	N	N	5	N/A	Partial solution only - requires further treatment
- Decontamination	N	N	N	Y	Y	Y	5	5	Partial solution - creates secondary waste, requires further treatment
- Absorption	Y	Y	Y	Y	Y	N	5	N/A	Partial solution - requires further treatment. For metal wastes is limited to swabbing to remove surface water dependant on downstream process selection
- Direct Immobilisation	Y	Y	Y	Y	Y	Y	5	5	May require pre-teatment to passivate organics
Destructive Treatment									
- Conventional Incineration	Y	Y	Y	Y	N	Y	2	5	Partial solution passivates waste - requires further treatment to immobilise. No known applications for ILW resins
- Controlled Oxidation	Y	N	Y	Y	N	Y	3	3	Partial solution - requires further treatment to immobilise. Could be used on inorganic IX resin however provides no benefit. No UK applications, several in US & Europe
- Vitrification	Y	Y	Y	N	N	Y	4	2	Single UK application on liquid HLW, several application world wide inc. other wastes, limited use for LLW
- Synroc	Y	Y	Y	N	N	Y	2	2	Developed for liquid HLW, mainly used for High Pu military wastes. No UK application
- Plasma Arc	Y	Y	Y	Y	Y	Y	2	2	Either with frit to form glass or without - without requires further treatment of ash (i.e. encapsulation). No full scale nuclear application UK or elsewhere
- GeoMelt	N	Y	N	N	N	N	2	N/A	Only known applications are in the ground and non UK
- Molten-salt Oxidation	Y	Y	Y	N	N	Y	2	2	Partial solution only - requires further treatment. Emergent technology - lab scale only
- Wet Oxidation	Y	N	Y	N	N	N	4	N/A	One UK licensed mobile plant. Partial solution only - requires further treatment

Notes

1 Wet Oxidation is taken as a generic category to represent all Wet /Chemical Oxidation processes that includes Advanced and Supercritical Water variants as all are essentially sub options on a common process. Screening was carried out using the Winfrith process as the benchmark as the known UK licensed process.

2 Controlled Oxidation is taken as a generic term that includes the various proprietary pyrolysis sub options.

Should either generic process be selected, further optioneering may be necessary to select between the sub options.

The screening did not consider the means of transport from the Nuclear Island to the Radwaste treatment process nor the packaging for disposal. Transport from the Nuclear Island has been determined to be hydraulic methods for practical reasons and is justified in Reference 1. The selection of the storage/disposal package is not a fundamental process technology issue but a downstream consideration that is determined on pragmatic grounds and cost/benefit analysis following technology selection.

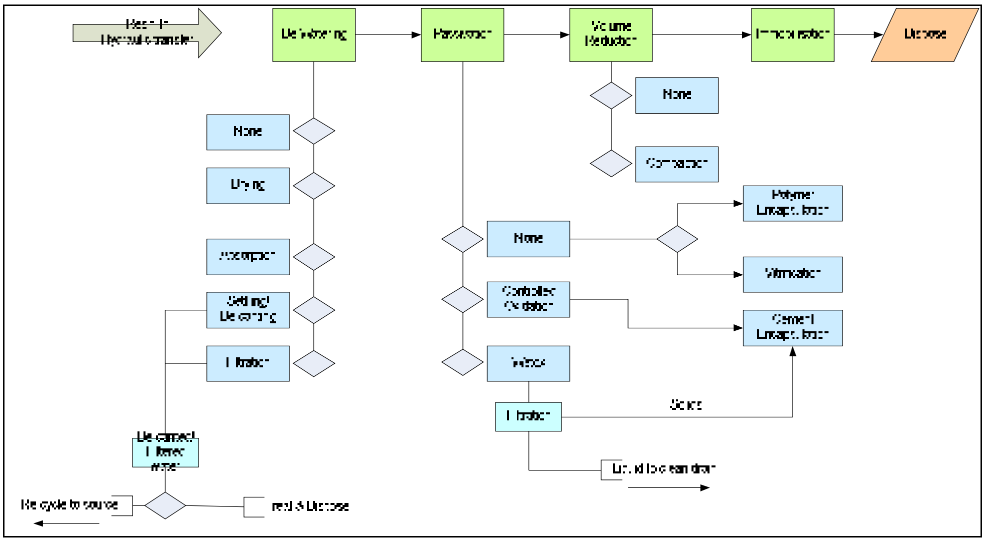
8 Study of Options

The options that were considered in initial screening would not all necessarily constitute a complete treatment process individually; therefore it may be necessary to combine complementary techniques to form an overall solution. The options that survived initial filtering were arranged into potential process configurations.

8.1 ILW Ion Exchange Resin Treatment Options

The candidate options for the treatment of ILW resins were configured under headings that represent the key process stages of: *De-Watering, Passivation, Volume Reduction and Immobilisation* as illustrated in Figure 7.1 below. A complete solution for treatment of a given waste stream would then consist of one option from under each process stage heading (shown in green). A diamond indicates a choice: arrows between categories from one option to another indicate where the choice of a latter option is dependent on a previous choice.

Fig 8.1 ILW Organic Resin Treatment Options



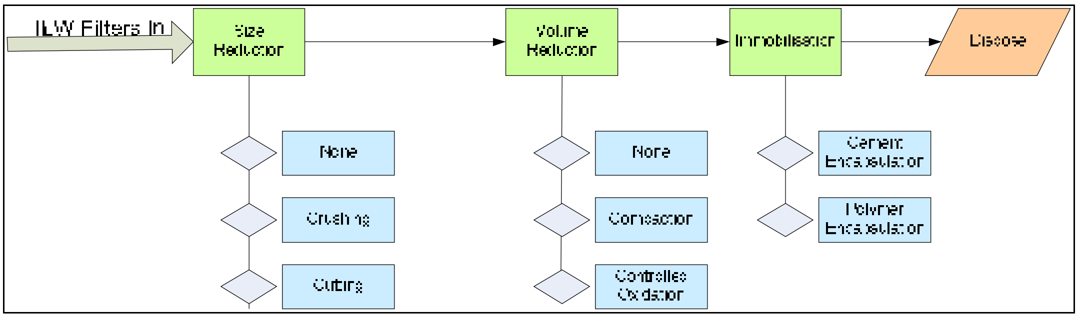
These options were agreed and confirmed as the options to take forward to the scoring workshop.

Note
1 Zeolite and charcoal will be received via the same route and can be treated via an identical process; however the *Passivation* stage will have little/no effect on any inorganic materials.

8.2 ILW Filters Treatment Options

The surviving candidate options for the treatment of ILW filters were configured as shown below:

Fig 8.2 ILW Filters treatment Options



The very low, almost negligible annual arising renders any investment for additional treatment facilities over and above those required for treatment of resins difficult to justify.

Therefore it is reasoned that no size or volume reduction technology is selected (other than taking advantage where appropriate of any provided for treatment of other streams) on the assumption that the filters can be accommodated within the disposal package without size reduction.

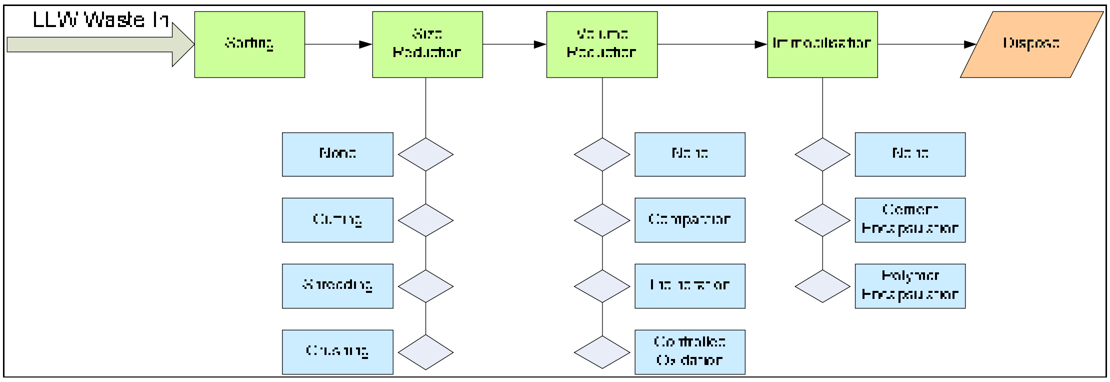
There are no issues surrounding the choice of the immobilisation option for this stream versus the resin stream, therefore the selection can follow the outcome of the resin study.

The only residual issue would be the selection of in drum mixing versus grout infill methods; this is a downstream engineering issue to be determined later.

8.3 LLW Mixed Waste Treatment Options

The surviving candidate options for treatment of LLW were configured under headings of *Sorting, Size Reduction, Volume Reduction and Immobilisation*

Fig 8.3 ILW Filters treatment Options



Sorting

Sorting may be necessary to allow waste to be segregated according to its suitability for the processes that are selected downstream e.g. into *Compactable* vs, *Non – Compactable* or *Combustible* vs, *Non - Combustible* Wastes.

Size Reduction

LLW will be mixed material and difficult to specify exactly what the nature will be therefore the provisions need to be flexible to deal with various types on an ad –hoc basis. The selection may be conditional on downstream choices. The options are *Shredding* (potentially for plastics and rubber), *Cutting* (i.e. mechanical) and *Crushing* (in this context, crushing means on an individual item basis e.g. a can crusher potentially for filter cartridges etc). All are low cost industrial technologies that cannot be precluded at this stage and are therefore potential options.

Volume Reduction

Volume reduction has an important role to play in reducing environmental impact and waste disposal costs. The options considered here are bulk volume reduction technologies of *Compaction* (i.e. in the form of a large hydraulic press as opposed to the can type crusher considered under Size Reduction)*, Incineration and Controlled Oxidation* (i.e. a form of incineration).

Whilst *Incineration* survived the initial screening against the screening criteria, adverse public perception of incinerators would be likely to lead to delays to licensing through planning issues that would place it outside of the AP1000 timetable. Therefore it is suggested that conventional *Incineration* be discounted. *Controlled Oxidation* addresses many of the issues that make conventional *Incineration* unacceptable however has not yet been licensed in the UK and would probably also be subject to the same planning issues. Therefore it is reasoned that both the foregoing techniques are discarded for the purposes of this GDA submission leaving *Compaction* as the only remaining option. However, *Controlled Oxidation* presents a substantial opportunity for huge savings in waste volumes and disposal costs should it be possible to allay the public's fears. Hence it is recommended that design proposals are flexible where possible to accommodate a later change in process technology in the event that techniques that are more beneficial in waste volume reduction performance become proven.

Immobilisation

The options here are *None, Cement or Polymer Encapsulation*. However Immobilisation, whilst feasible is not a requirement of the CFA for the LLW Repository, also it would increase transport weights and potentially the number of transfers and hence fuel consumption. Therefore it is argued that *None* is the logical selection.

9 Option Scoring

9.1 Scoring Process

The options that were confirmed to go forward to scoring were evaluated and scored at a workshop held on 4th June 2008. These were the options for treatment of ILW resins noting that the results would also apply to charcoal and other ILW streams.

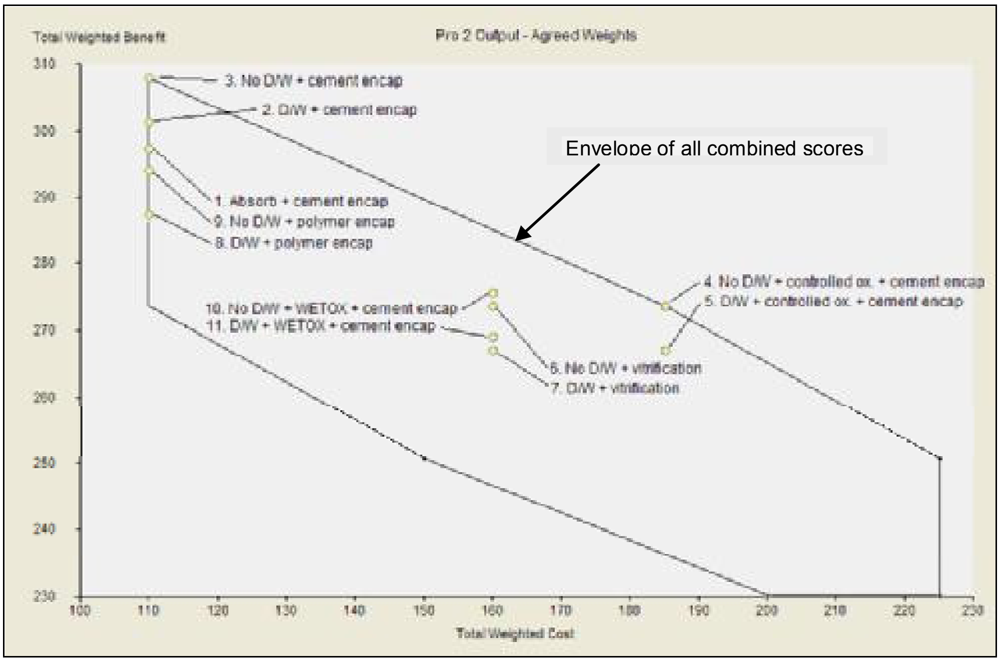
The process involved reviewing each option individually and scoring against each criterion in turn. The scores were agreed by consensus amongst the workshop participants.
A complete illustration of the individual scores that each option received against the criteria is given in Appendix 2. These tables also include documented reasoning behind each score.

The ‘Pro 2’ modelling software was then used to analyse the options. It produces an overall score for every potential combination of options so that not only can complete solutions for radwaste treatment can be assessed but also allows the contribution from individual options to be analysed.

9.2 Scoring Results

The ‘Pro 2’ modelling software used to analyse the option scores combines the scores of the individual options to create overall scores for every possible solution (i.e. combination of options). It displays the output in the form of a *benefit – cost* graph, where for each complete solution *cost* is the sum of the relative cost scores awarded in the scoring session and *benefit* is the sum of all the scores against the weighted criteria. It should be noted in this context that *cost* represents an assessment the cost of providing the technique and does not include at this stage any consequential costs of choosing any given technique.

Fig 9.1 Pro 2 Output: Benefit vs. Cost Curve



All possible combination of options that form complete solutions are bounded within the envelope described by the black line, with the optimum solutions lying towards the top Left Hand corner. The leading solutions plus others that provide a representative selection of the key process choices have been picked out for illustration and comparison purposes.
Note: The solution process description summarises the component options from each process stage that makes up the solution. The *DW* indicates whether or not a *De-watering* option has been chosen or not. For the sake of clarity, the scores for the *Settling / Decanting* option for dewatering was used as the benchmark as it received equal to or higher scores relative to the other dewatering options. The *Absorption* option has been considered separately as the volume of waste generated by this dewatering option differs from those of the other dewatering options. Having taken these simplifying assumptions into account, the eleven process solutions assessed represent all of the remaining combinations of options.

From the model output and analysis of the scores:

Dewatering

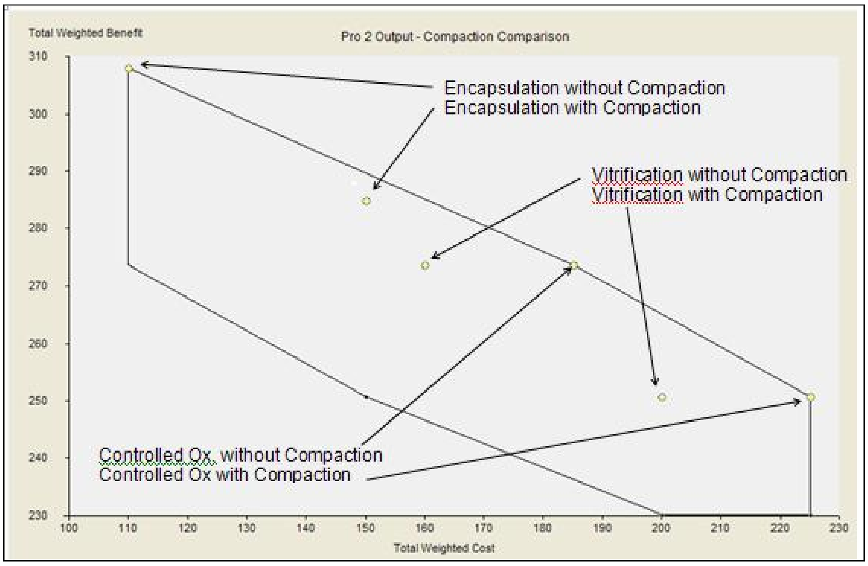
There is little difference between the *De-watering* options, all are similar cost but provide slightly different benefit. Out of the options; *No De-watering* emerges marginally (by 7 pts out of 308 or 2%) highest on benefit overall although scoring joint worst with *Absorption* on waste management principles. Of the remainder; *Settling/Decanting* has the highest benefit and is therefore the natural choice for the De-watering step.

Volume reduction

Comparison of results for options including *Compaction* with *No Compaction* shows that *Compaction* introduces additional cost whilst providing a net overall negative benefit. The reasons for the reduction in benefit are that it introduces additional safety hazard and operability issues.

This is illustrated in the following plot from the Pro 2 Model that compares option combinations with and without *Compaction*. In each case, it can be seen that options including *Compaction* represent higher cost and lower benefit than the corresponding option with *No Compaction.* The plot shows selection option combinations for illustration purposes, the same shift in cost benefit was exhibited in all cases.

Fig 9.2 Comparison of Compaction with No Compaction options



The only possible benefit of *Compaction* and therefore reason for its consideration as a candidate treatment option would be in waste volume reduction. Due to the nature of the material and its inherent lack of voidage; the scoring exercise concluded that Compaction would provide an insignificant reduction in volume reduction. As *Compaction* introduces additional cost and hazard potential with no benefit in volume reduction it is discarded from further discussion.

Passivation

Solutions comprising Controlled Oxidation and Wetox technologies score similarly in benefit terms, both introduce higher cost and safety considerations however provide some considerable additional benefit in waste reduction. Controlled Oxidation also scores low, specifically on technology availability in the UK and is assessed to be more costly than Wetox.

Immobilisation

Solutions comprising Cement and Polymer Encapsulation options without any passivation are equal lowest cost and yield significantly higher benefit than Vitrification. Of the two, Cement Encapsulation provides higher benefit overall and specifically in terms of meeting CFA for the repository. Therefore it is suggested that Cement Encapsulation is selected.

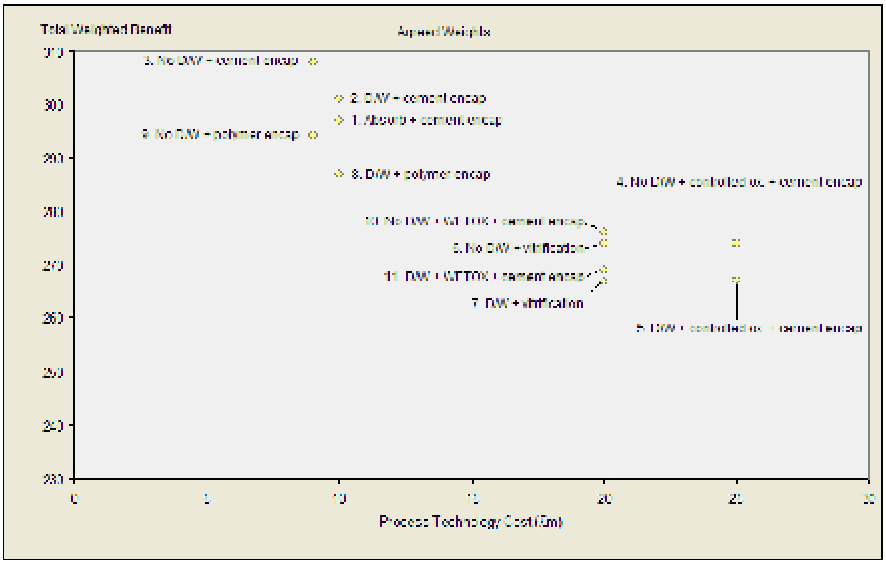
Vitrification emerges at higher cost and also scores less well overall, specifically on technology availability (for the GDA submission stage), reliability and safety considerations.

From the above, *Cement Encapsulation* without and with *De-watering* emerge as the two leading option combinations respectively.

9.3 Further Cost /Benefit Analysis

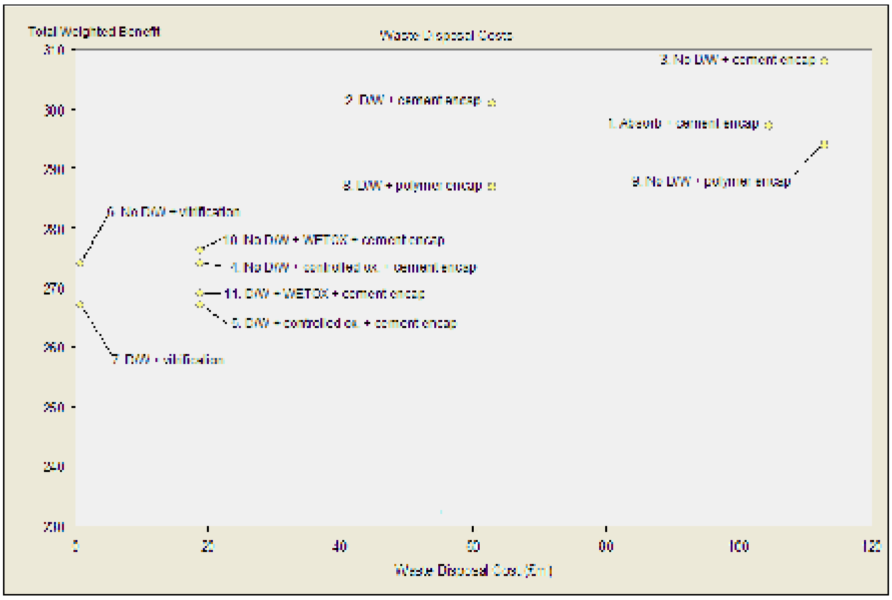
Until this stage the cost data used in analysis has been an assessment of the cost of a given technology option relative to another based on the estimated scope and complexity.
Now that a relatively small number of ‘joined up’ option combinations are emerging, it is possible to conduct further analysis by looking at the cost implications of the complete solutions; not only in terms of capital cost to provide the technology but also in Waste Disposal costs. As the waste disposal cost is directly relative to the waste volumes, it can also be taken as a measure of the environmental impact.
In the following analysis, the waste disposal volumes were estimated for each solution; the calculations forming the basis for these can be found in Appendix 4. Waste disposal cost was based on an assumption of disposal in 3m^3 drums/boxes at 2.7 m^3 per package with £100K disposal cost per package plus £25K for the container itself. The process technology costs were based on experience of the cost of similar plants and reasoned judgement and reflect the additional cost of engineered protection to manage the safety hazards associated with deployment of the techniques. The capital cost estimates include the associated civil structure, services etc.

Fig 9.3 Benefit vs. Process Technology (Capital) Cost



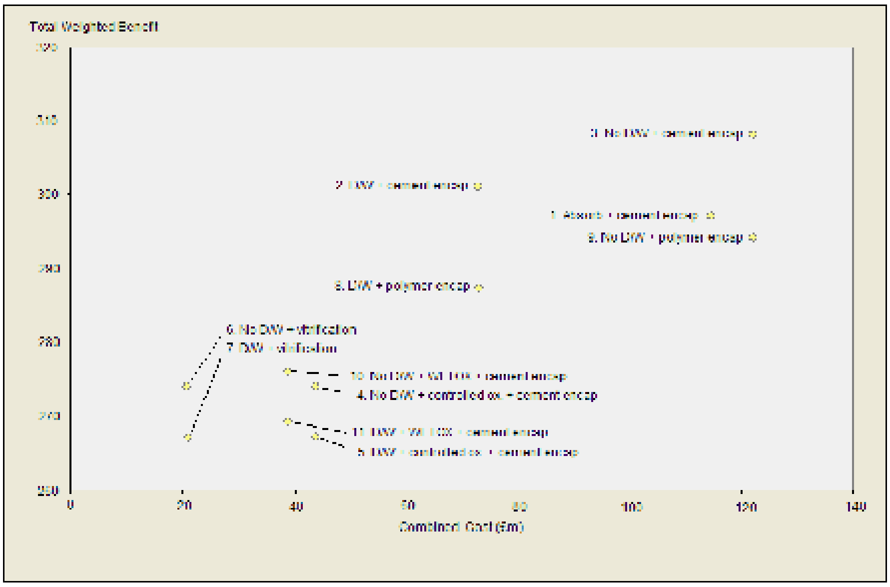
The plot shows the high initial investment costs of Vitrification (6&7), Wetox and Controlled Oxidation (4 & 5) against which the simple encapsulation options appear very attractive.

Fig 9.4 Benefit vs. Waste Disposal Costs



This plot shows the low disposal costs of Vitrification (6&7) and Controlled Oxidation (4 & 5) or WETOX (10 & 11), and also shows the high cost penalty of no dewatering or absorption coupled with encapsulation. The encapsulation options now look much less attractive.

Fig 9.5 Benefit vs. Combined Waste Disposal and Process Technology Costs



This shows the overall low Combined Capex and Waste Disposal Cost of Vitrification (6&7) followed by WETOX with encapsulation (10 &11) and Controlled Oxidation plus encapsulation (4 & 5). The simple encapsulation options still appear less attractive.

9.4 Discussion

Analysis of the overall waste volumes and disposal costs shows:

1 A strong argument for Dewatering in view of the major saving in waste disposal volumes, environmental impact and costs

2 A substantial incentive to reduce the waste disposal volumes and disposal costs through development of either Oxidation or Vitrification techniques. The development of the technology or demonstration of its transferability to the AP1000 application is unlikely to occur before the next GDA submission stage, however later submissions should take cognisance of any developments in these technology areas.

3 The high investment costs may not make the development of alternative technologies attractive on a case by case basis, however on the basis of a fleet of stations there may be justification maybe for a centralised or mobile facility.

4 Furthermore controlled oxidation in tandem with cement encapsulation would address the residual issue of concerns over CFA for disposal by passivation of the organic content in addition to waste volume reduction.

10 Output Review

10.1 Sensitivity Analysis

Sensitivity analyses allow the robustness of the scores and weights to be tested. This is particularly important when the solutions are close together; the sensitivity check will reveal if slight changes in weights and/or scores cause a change or reversal the ranking of results.

One simple test of the weight set used was to apply a set of neutral weights to the options where all criteria were given the same weighting. The impact of doing so can be seen by comparison of the figures below showing weighted results (Fig. 10.1) and equally weighted results (Fig 10.2).

Fig 10.1 Weighted Results (Agreed weightings)

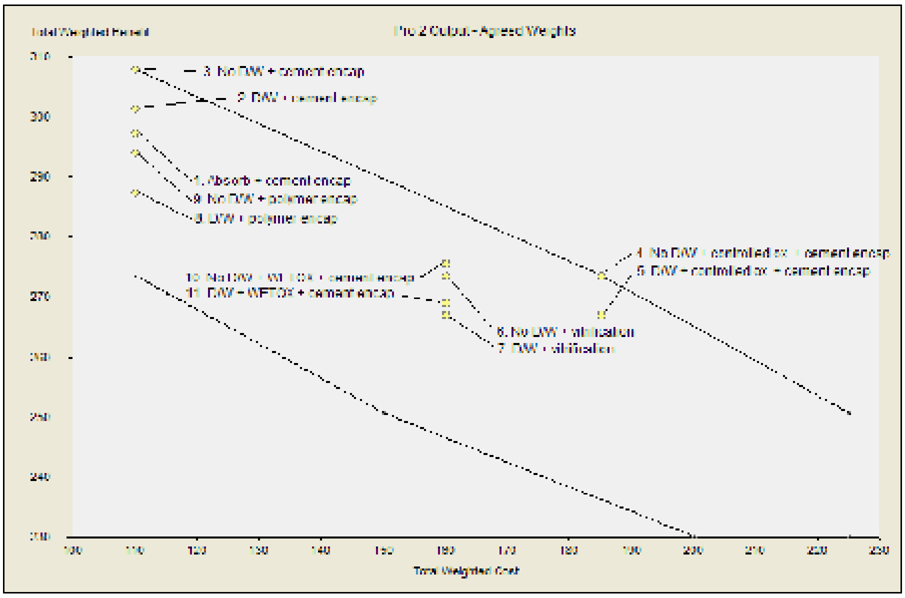
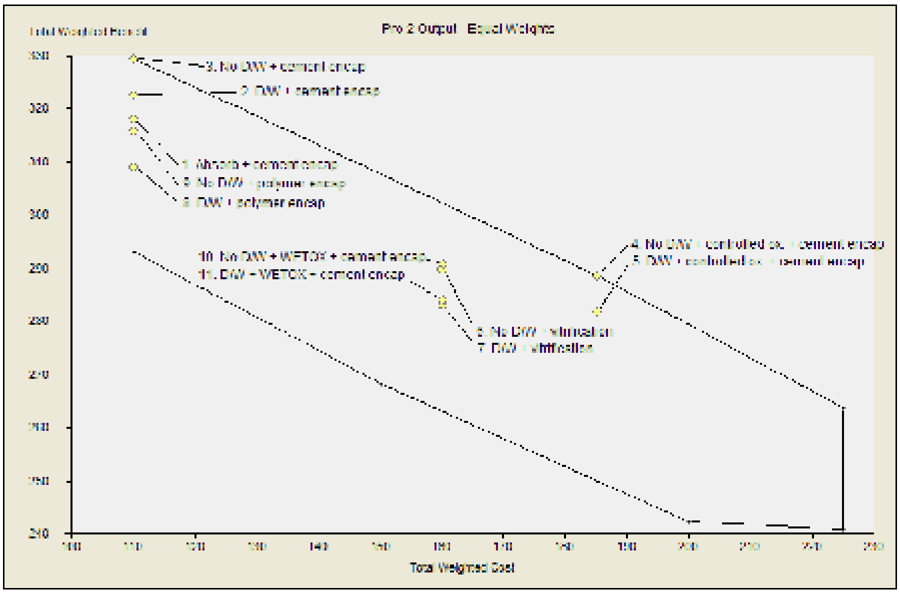


Fig 10.2 Equally Weighted Results



The results do not change significantly from Figure 10.1to fig 10.2; although it can be seen that the relative benefit of each solution is slightly influenced by the application of different weights, the overall shape of the curve and the ranking of the solutions within it are unchanged. This and other similar checks i.e. changing individual weightings demonstrated that the results are not sensitive to change in weightings in so far as the front runner simple encapsulation options are concerned. This is not the case with the more exotic options and further analysis could be required to choose between them.

Similarly the positioning of the leading solutions with respect to the others is immune to small changes in scoring. Due to the vertical distance between the cement encapsulation solutions and the Oxidation and Vitrification techniques; a significant shift in scores would be required to overturn the rankings.

In conclusion the modelling results are considered to be robust.

11 Risk / Uncertainty/Opportunity Review

The risk/uncertainty review is to assess the high level risks and uncertainties that may affect the outcome of the optioneering study and also to identify any opportunities that may be presented say, by relaxation of any constraining assumptions. The major threat to the outcome rests with the assumptions made either as base assumptions at the outset of the study or in the evaluation and downstream analysis.

The base assumptions were reviewed and it was concluded that a change in assumptions e.g. a change in waste volumes would not change the outcome. The logic behind the scores was sound and evidence to support the scoring was robust, therefore it was concluded that there are no major risks to the findings.

A degree of uncertainty surrounds the choice of organic resins and the acceptability in the ILW Repository as a cemented product if not passivated. The potential for degradation, shrinkage and consequential voidage leads to some uncertainty in meeting the CFA for the Repository. The degree of uncertainty depends on the exact behavioural characteristics of the specific resins proposed, the cement formulation as well as the ratio of organic content to cement. In the AP1000 application, blending of the resin with the inorganic filter bed media may help in diluting the organic content. RWMD has previously considered and endorsed proposals based on the immobilisation of organic IX resins in cement; therefore it is likely that an application for a Letter of Compliance (LoC) will be successful. However, in all cases it was necessary to address particular issues arising from the behaviour and evolution of the resins, with respect to dimensional stability when designing formulations. Further development and interaction with RWMD would be required to demonstrate the acceptability of any specific proposal. Hence it is recommended a programme of development work and dialogue with RWMD is formulated in the post GDA design stage is established to support the LoC application process

A major opportunity was identified in that relaxation of the time constraint regarding the Technology Availability criterion would improve the ranking of the Oxidation and Vitrification techniques in the analysis thereby allowing benefit of reduced waste volumes to be realised

12 Conclusions and Recommendations

12.1 Conclusions

1 The main treatment option for LLW is Compaction

2 The only prime process options for treatment of ILW resin and ILW filters to go forward with to the next stage GDA submission as demonstrable technologies are variations on the Encapsulation option.

3 Of the Encapsulation options, cement provides the higher benefit overall and particularly in terms of meeting the CFA for disposal. However this carries some residual concerns over the long term stability of organic resins in cement. There may be a benefit in changing to inorganic Ion Exchange media or in blending inorganic filter bed media with organic resins to dilute the organic content in any given package. In either case development work to underpin the acceptability of the cemented product will be required.

4 There are major waste minimisation benefits to be gained through De-Watering prior to Encapsulation. Of the De- Watering options, Settling and Decanting is the optimum choice

5 Compaction of the ILW resins and filter bed media provides no benefit and can be discarded as an option. Compaction of cartridge filters would provide some volume reduction however for the low volume of filters arising; the investment would not be justifiable.

6 There is a substantial environmental and economic incentive to reduce the waste disposal volumes and disposal costs through development of either Oxidation or Vitrification techniques. However the development of the technology or demonstration of its transferability to the AP1000 application is unlikely to occur within the GDA timetable.

12.2 Recommendations

It is recommended that:

1. Compaction is adopted as the design option for the treatment of LLW.

2. Cement Encapsulation preceded by Settling and Decanting is adopted as the reference design for predisposal treatment of ILW.

3. A plan is developed to undertake development work during the post GDA design stage to address the particular issues associated with dimensional stability of organic resins and thereby underpin the acceptability of the cemented ILW product for long term disposal.

4. The design proposals to be flexible where possible to accommodate a change in process technology in the event that techniques that are more beneficial in waste volume reduction performance e.g. Vitrification or Controlled Oxidation become proven for application to the waste streams considered.

13 References

1. Basis of Design 63000333-001-111-S-008. AKER Solutions 2008
2. Generic Waste Package Specifications NIREX N104 June 2005
3. Application of Thermal Technologies for Processing of Radioactive Waste. IAEA-TECDOC-1527. December 2006
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5. Pyrolysis of Radioactive Organic Waste. NUKEM Technologies GmbH. January 2007
6. IAEA-TECDOC-427, Predisposal Management of Organic Radioactive Waste, July 2004
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Acknowledgements

The following organisations' websites were accessed for information in the compilation of this report:

NDA – Generic Waste Package Specifications
Studsvik – *THOR* process
JGC Corporation *WETOX* process
AMEC – *Geomelt* Process
ANSTO – *Synroc* Proces

Appendices

Appendix 1 - Criteria

Appendix 2 - Scoring Information

Appendix 3 - Detailed Option Descriptions

Appendix 4 - Waste Volume Calculations

Appendix 1 – Criteria

1.1 Technical Criteria

			Mapping of Scoring Requirements against Criteria					
		Score:	1	2	3	4	5	
	Criterion	**Weight**						Description
Technical	Technology Availability	4	Essentially a completely novel and unproven concept. No evidence of nuclear industrial/commercial application. Considerable fundamental development work anticipated to bring to UK licensable position	Novel concept which has undergone a significant amount of development to underpin its feasibility. Little/no evidence of full scale deployment either in UK or elsewhere although pilot scale plants may exist. Major effort needed to develop to a deployable condition and to establish UK licence position.	Evidence of technology deployment in nuclear industrial/commercial applications overseas. Potentially viable for UK use - however significant effort anticipated to secure UK licensing	Evidence of UK deployment although limited examples exist currently. Licensable technology although a moderate amount of work is anticipated in ensuring its application to this project.	Many examples of technology application in UK industry. Well documented process - little/no problems anticipated with UK licensing.	This assesses the maturity of the technology being considered and reflects the uncertainty of whether the option will be successful and therefore the amount of development required to underpin an option and enable its successful implementation. A low score will be earned where the technology remains to be proven (i.e. will it work?) or developed (how well will it work?). A tool such as the Technology Evolution Index (TEI) can be used as a measure. This attribute is focused on technical confidence. The time to undertake development work is addressed under the implementation time attribute.
	Operability/ Maintainability	4	Highest complexity, highest potential for outages. Lowest overall availability	Highly complex, high potential for outages. Low overall availability	Moderately complex, moderate potential for outages. Moderate overall availability	Low complexity, low potential for outages. High overall availability	Lowest complexity, lowest potential for outages. Highest overall availability	An assessment of the inherent availability, reliability and maintainability. At the stage of development of the option this will be based on a view of the scope and complexity of the envisaged plant a complex heavily engineered plant or one with a large number of process steps will increase the likelihood of maintenance periods reducing the overall availability. Concerned with plant availability as distinct from technology availability.

1.2 Safety Criteria

Safety	Dose Uptake	4	Highest complexity, highest potential for outages and hands on activities. Highest potential for non - routine dose uptake	Highly complex, high potential for outages and hands on activities. Highest potential for non - routine dose uptake	Moderately complex, moderate potential for outages and hands on activities. Moderate potential for non - routine dose uptake	Low complexity, low potential for outages and hands on activities. Low potential for non - routine dose uptake	Lowest complexity, lowest potential for outages and hands on activities. Lowest potential for non - routine dose uptake.	As a new facility built to modern plant standards, routine dose uptake is not likely to be a major discriminator. The potential for radiation exposure will be most likely to occur during periods of manual intervention for maintenance during breakdowns and then will be designed to stay within target levels. However the potential for dose uptake will increase with the frequency and occupancy of maintenance episodes. At a conceptual stage it will be judged as a function of the scope and complexity of the process.
	Hazard Potential (Radiological)	4	High no. of high consequence potential accident scenarios. Very difficult to design out. Very heavy reliance on active engineered protection.	High no. of /or high consequence potential accident scenarios. Difficult to design out. Heavy reliance on active engineered protection.	Medium no. / consequence of potential accident scenarios. Some reliance on engineered protection	Low no. of potential accident scenarios -mostly easy to design out. Low consequence. Minimal engineered protection.	Inherently safe. Very low no. of potential accident scenarios. Very low consequence.	To address the radiological hazard potential (frequency and consequence) from reasonably foreseeable accident scenarios of each option and the confidence that hazards can be managed to achieve national risk criteria. It reflects the option's potential for management of radiological hazards against the Hazard Management Hierarchy of Eliminate, Prevent, Mitigate, Protect- passive means, Protect - active means. i.e. an option that is inherently safe will score more highly than one that places heavy reliance on engineered protection.
	Hazard Potential (Non-radiological)	3	High no. of high consequence potential accident scenarios. Heavy reliance on managerial control and protective measures	High no. of /or high consequence potential accident scenarios. Significant reliance on managerial control and protective measures	Medium no. / consequence of potential accident scenarios. Moderate reliance on managerial control and protective measures	Low no. of potential accident scenarios. Low consequence. Some reliance on managerial control and protective measures	Inherently safe. Very low no. of potential accident scenarios.	A measure of the option's performance in management of conventional safety hazards (temp. pressure, height, confined space, moving machinery etc). An option that is inherently safe will score more highly than one that places heavy reliance on protection measures or managerial/supervisory control. Considers construction, operation and decommissioning.

1.3 Environmental Criteria

Environmental	Primary Waste Management	5	Considerable increase in Primary waste volumes	Significant increase in Primary waste volumes	No or insignificant reduction or increase in Primary waste volumes	Significant reduction in Primary waste volumes	Considerable reduction in Primary waste volumes	A measure of the option's potential performance in the management of primary wastes. Considers Waste Management Hierarchy Principles of Prevent, Reduce, Reuse, Recycle, Recover, Dispose whilst recognising that prevention occurs at source and therefore focuses on reduction or conversely additional waste generation through the treatment process. For the purposes of the scoring exercise Primary waste is classed as the combined volume of resin and water crossing the system boundary into radwaste treatment. Water:solids taken as ~ 1:1 v/v.
	Secondary Waste Management	4	Considerable and/or problematic secondary wastes (solid, liquid, gaseous) generated	Significant amounts of secondary wastes generated requiring secondary/subsidiary process route.	Significant amounts of secondary wastes generated requiring secondary/subsidiary process route.	Moderate amounts of secondary wastes generated requiring secondary/subsidiary process route.	Minimal to no secondary wastes generated as a result of the specific process proposed.	A measure of the option's potential performance in the management of secondary wastes. Secondary wastes to be taken as including S.L.G . waste streams including new liabilities and consumables e.g. filters or other media. Does not consider generic effluents e.g. washdown that are common to all options
	Planning Issues	2	Very high probability of inquiry. Long delays to consent envisaged	High probability of inquiry.	Moderate probability of inquiry.	Low probability of inquiry.	Very low probability of inquiry. No extra ordinary delays to consent envisaged	This reflects the probability of delays through planning issues e.g. with respect to public inquiry and is particularly relevant to options such as incinerators
	Product Quality	5	Very low confidence in meeting current UK specs.	Significant uncertainty regarding whether technology proposed would ever meet UK specs. Meets only isolated conditions or achieves partial compliance on all conditions	Could be made to meet UK specs only by the addition of a complementary process. Meets ~50% of conditions as a standalone process	Nearly meets all requirements e.g. Meets most CFA fully with partial compliance on isolated conditions. May be granted an L.o.C. if it can be demonstrated that all reasonable measures have been taken	Very high confidence in meeting current UK requirements. Fully meets all CFA.	An indication of the option's potential to produce a product that gains a Letter of Compliance from RWMD by meeting their Conditions For Acceptance for the ILW Repository :- immobilised, free of water, homogeneous, radiologically stable, chemically passive (i.e. zero gas generation), characterised, voids minimised (ref 2 - Nirex GWPS vol 2.) Alternatively to meet CFA for LLW repository in the case of mixed waste /trash.
	Resource Usage	1	Very high resource demand	High resource demand	Moderate resource demand	Low resource demand	Very low resource demand	To compare the relative potential consumption of resources (non - human), including raw materials, water, energy. Does not consider demand for human resources which is covered under operational costs.

1.4 Economic Criteria

Economic	Implementation Time	2	Time to develop design to appropriate standard for GDA submission is well beyond deadline	Time to develop design to appropriate standard for GDA submission is behind deadline	Time to develop design to appropriate standard for GDA submission is on deadline	Time to develop design to appropriate standard for GDA submission is within deadline	Time to develop design to appropriate standard for GDA submission is well within deadline	Time to implement the Radwaste Bldg is unlikely to be a factor relative to the time to implement the reactor plant. Therefore the time to submit designs relative to the GDA deadline is used as the benchmark instead.
	Process Technology Costs	3	Highest overall relative cost. Substantial investment anticipated in fundamental research and development. Greatest scope, most complex process. Greatest operator demand.	High relative cost for the technology option. Expected to require significant development cost. High scope, complex process. High operator demand.	Medium relative cost. Moderate scope, moderately complex process. Moderate operator demand.	Low relative cost. low scope, fairly simplistic process. Low operator demand.	Lowest relative cost. Least scope, simplest process. Least operator demand.	A relative assessment of treatment costs includes development, design, capital & operating costs. At an early stage the score will reflect the anticipated scale, scope and complexity of the process plant rather than a full engineering estimate against bill of quantities, rates and norms.

Appendix 2 – Scoring Information

2.1 Option scores against Technology Availability Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	Technology Availability	Essentially a completely novel and unproven concept. No evidence of nuclear industrial/ commercial application. Considerable fundamental development work anticipated to bring to UK licensable position	Novel concept which has undergone a significant amount of development to underpin its feasibility. Little/no evidence of full scale deployment either in UK or elsewhere although pilot scale plants may exist. Major effort needed to develop to a deployable condition and to establish UK licence position.	Evidence of technology deployment in nuclear industrial/ commercial applications overseas. Potentially viable for UK use - however significant effort anticipated to secure UK licensing	Evidence of UK deployment although limited examples exist currently. Licensable technology although a moderate amount of work is anticipated in ensuring its application to this project.	Many examples of technology application in UK industry. Well documented process - little/no problems anticipated with UK licensing.	This assesses the maturity of the technology being considered and reflects the uncertainty of whether the option will be successful and therefore the amount of development required to underpin an option and enable its successful implementation. A low score will be earned where the technology remains to be proven (i.e. will it work?) or developed (how well will it work?). This attribute is focused on technical confidence. The time to undertake development work is addressed under the implementation time attribute.
	Score:	1	2	3	4	5	Comments
De-Water	None					5	Although there are no known examples of this practice on ILW resins in UK plants it was considered that the technology was easily transferable and therefore is a feasible option
	Drying					5	Although there are no known examples of this practice on ILW resins in UK plants it was considered that the technology was easily transferable and therefore is a feasible option
	Absorption					5	Although there are no known examples of this practice on ILW resins in UK plants it was considered that the technology was easily transferable and therefore is a feasible option
	Settling / decanting					5	Although there are no known examples of this practice on ILW resins in UK plants it was considered that the technology was easily transferable and therefore is a feasible option
	Filtration					5	Although there are no known examples of this practice on ILW resins in UK plants it was considered that the technology was easily transferable and therefore is a feasible option
Volume reduction	None					5	Although there are no known examples of this practice on ILW resins in UK plants it was considered that the technology was easily transferable and therefore is a feasible option

		Mapping of Scoring Requirements against Criteria					
Option Set	Technology Availability	Essentially a completely novel and unproven concept. No evidence of nuclear industrial/ commercial application. Considerable fundamental development work anticipated to bring to UK licensable position	Novel concept which has undergone a significant amount of development to underpin its feasibility. Little/no evidence of full scale deployment either in UK or elsewhere although pilot scale plants may exist. Major effort needed to develop to a deployable condition and to establish UK licence position.	Evidence of technology deployment in nuclear industrial/ commercial applications overseas. Potentially viable for UK use - however significant effort anticipated to secure UK licensing	Evidence of UK deployment although limited examples exist currently. Licensable technology although a moderate amount of work is anticipated in ensuring its application to this project.	Many examples of technology application in UK industry. Well documented process - little/no problems anticipated with UK licensing.	This assesses the maturity of the technology being considered and reflects the uncertainty of whether the option will be successful and therefore the amount of development required to underpin an option and enable its successful implementation. A low score will be earned where the technology remains to be proven (i.e. will it work?) or developed (how well will it work?). This attribute is focused on technical confidence. The time to undertake development work is addressed under the implementation time attribute.
	Score:	1	2	3	4	5	Comments
	Compaction					5	As above
Passivation	None					5	As above
	Controlled oxidation			3			Well developed process outside of the UK: Studsvik THOR process in US, Nukem Pyrolysis in Japan & W. Europe
	WETOX				4		Mobile plant developed by Winfrith, Licensed and used at certain UK stations on resins and other ILW
Immobilisation	Polymer encapsulation				4		Many examples outside the UK e.g. polythene in the USA. One known UK example at Trawsfynydd.
	Vitrification		2				One major application in UK i.e. WVP Sellafield on HA liquids, however can be used on ILW & LLW. Cold crucible vit. developed in Korea for use on ILW. Time to develop design to required standard would be outside GDA timescale
	Cement Encapsulation					5	Several UK applications exist mainly on materials other than organic resins however no reason why the technology would not be readily transferable. Proven technique by Tilwisp portable encapsulation plant for resins but concerns surrounding disposability / CFA

2.2 Option scores against Operability / Maintainability Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Operability/ Maintainability**	Highest complexity, highest potential for outages. Lowest overall availability	Highly complex, high potential for outages. Low overall availability	Moderately complex, moderate potential for outages. Moderate overall availability	Low complexity, low potential for outages. High overall availability	Lowest complexity, lowest potential for outages. Highest overall availability	An assessment of the inherent availability, reliability and maintainability. At the stage of development of the option this will be based on a view of the scope and complexity of the envisaged plant a complex heavily engineered plant or one with a large number of process steps will increase the likelihood of maintenance periods reducing the overall availability. Concerned with plant availability as distinct from technology availability.
	Score:	1	2	3	4	5	Comments
De-Water	None					5	No equipment to fail, therefore maximum availability
	Drying			3			More complex than above, includes items that may require maintenance e.g. electrical heaters, circuits and controls systems etc
	Absorption				4		Simple technique, little to go wrong, minimal potential for outage
	Settling / decanting				4		Simple technique, little to go wrong, minimal potential for outage
	Filtration				4		Simple technique, little to go wrong, minimal potential for outage
Volume reduction	None					5	No equipment to fail, therefore maximum availability
	Compaction			3			Compactors, hydraulic circuits, motors, moving parts, electrical circuits and controls etc all simple technology however more to potentially fail and present a maintenance problem
Passivation	None					5	No equipment to fail, therefore maximum availability
	Controlled oxidation		2				Not based on operational experience, a judgement based on complexity of plant as described in the option document
	WETOX		2				As previous
Immobilisation	Polymer encapsulation			3			Moderately complex plant: mixers, powder feeders, load cells, multiple drives & control circuits therefore moderate outage potential
	Vitrification	1					Highly complex plant, high potential for breakdown of plant, poor track record in UK and certain other countries, challenging maintenance regime
	Cement Encapsulation			3			As Polymer

2.3 Option scores against Dose Uptake Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Dose Uptake**	Highest complexity, highest potential for outages and hands on activities. Highest potential for non - routine dose uptake	Highly complex, high potential for outages and hands on activities. Highest potential for non - routine dose uptake	Moderately complex, moderate potential for outages and hands on activities. Moderate potential for non - routine dose uptake	Low complexity, low potential for outages and hands on activities. Low potential for non - routine dose uptake	Lowest complexity, lowest potential for outages and hands on activities. Lowest potential for non - routine dose uptake.	As a new facility built to modern plant standards, routine dose uptake is not likely to be a major discriminator. The potential for radiation exposure will be most likely to occur during periods of manual intervention for maintenance during breakdowns and then will be designed to stay within target levels. However the potential for dose uptake will increase with the frequency and occupancy of maintenance episodes. At a conceptual stage it will be judged as a function of the scope and complexity of the process.
	Score:	1	2	3	4	5	Comments
De-Water	None					5	Scores from O&M criterion used as dose uptake is directly related to complexity of operation and maintenance demands
	Drying			3			
	Absorption				4		
	Settling / decanting				4		
	Filtration				4		
Volume reduction	None					5	
	Compaction			3			
Passivation	None					5	
	Controlled oxidation		2				
	WETOX		2				
Immobilisation	Polymer encapsulation			3			
	Vitrification	1					
	Cement Encapsulation			3			

2.4 Option scores against Hazard Potential (Radiological) Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Hazard Potential (Radiological)**	High no. of high consequence potential accident scenarios. Very difficult to design out. Very heavy reliance on active engineered protection.	High no. of /or high consequence potential accident scenarios. Difficult to design out. Heavy reliance on active engineered protection.	Medium no. /consequence of potential accident scenarios. Some reliance on engineered protection	Low no. of potential accident scenarios -mostly easy to design out. Low consequence. Minimal engineered protection.	Inherently safe. Very low no. of potential accident scenarios. Very low consequence.	To address the radiological hazard potential (frequency and consequence) from reasonably foreseeable accident scenarios of each option and the confidence that hazards can be managed to achieve national risk criteria. It reflects the option's potential for management of radiological hazards against the Hazard Management Hierarchy of Eliminate, Prevent, Mitigate, Protect-passive means, Protect - active means. i.e. an option that is inherently safe will score more highly than one that places heavy reliance on engineered protection.
	Score:	1	2	3	4	5	Comments
De-Water	None					5	No activity to perform therefore zero risk potential
	Drying			3			Thermal energy technique some reliance on control system to protect against hazards from overheating.
	Absorption				4		Low energy process, minimal hazard potential
	Settling / decanting				4		As previous
	Filtration				4		As previous
Volume reduction	None					5	No activity to perform therefore zero risk potential
	Compaction			3			Pressure energy process, use of hydraulic circuits (water/glycol), hazard from burst hoses etc
Passivation	None					5	No activity to perform therefore zero risk potential
	Controlled oxidation		2				High temperature process - explosion risk, heavy reliance on safety mechanisms
	WETOX		2				High temperature process - explosion risk, heavy reliance on safety mechanisms
Immobilisation	Polymer encapsulation				4		Low energy process, risks of splashing or spillage
	Vitrification		2				Very high temperature process - heavy reliance on safety mechanisms
	Cement Encapsulation				4		Low energy process, risks of splashing or spillage

2.5 Option scores against Hazard Potential (Non-radiological) Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Hazard Potential (Non-radiological)**	High no. of high consequence potential accident scenarios. Heavy reliance on managerial control and protective measures	High no. of /or high consequence potential accident scenarios. Significant reliance on managerial control and protective measures	Medium no./consequence of potential accident scenarios. Moderate reliance on managerial control and protective measures	Low no. of potential accident scenarios. Low consequence. Some reliance on managerial control and protective measures	Inherently safe. Very low no. of potential accident scenarios.	A measure of the option's performance in management of conventional safety hazards (temp. pressure, height, confined space, moving machinery etc). An option that is inherently safe will score more highly than one that places heavy reliance on protection measures or managerial/supervisory control. Considers construction, operation and decommissioning.
	Score:	1	2	3	4	5	Comments
De-Water	None					5	No activity to perform therefore zero risk potential
	Drying			3			Thermal energy technique some reliance on control system to protect against hazards from overheating.
	Absorption				4		Low energy process, minimal hazard potential
	Settling / decanting				4		As previous
	Filtration				4		As previous
Volume reduction	None					5	No activity to perform therefore zero risk potential
	Compaction			3			Moving parts and high pressures involved
Passivation	None					5	No activity to perform therefore zero risk potential
	Controlled oxidation		2				High temperature, use of electricity, mechanical handling of ash product, explosion risk
	WETOX			3			Toxic chemicals, hydrogen peroxide used
Immobilisation	Polymer encapsulation		2				Mechanical handling issues, solvent flammability
	Vitrification		2				High temperature, use of electricity, presence of powders, container handling, severe maintenance requirements
	Cement Encapsulation				4		Mechanical handling issues, cement dust

2.6 Options scores against Primary Waste Management Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Primary Waste Management**	Considerable increase in Primary waste volumes	Significant increase in Primary waste volumes	No or insignificant reduction or increase in Primary waste volumes	Significant reduction in Primary waste volumes	Considerable reduction in Primary waste volumes	A measure of the option's potential performance in the management of primary wastes. Considers Waste Management Hierarchy Principles of Prevent, Reduce, Reuse, Recycle, Recover, Dispose whilst recognising that prevention occurs at source and therefore focuses on reduction or conversely additional waste generation through the treatment process. For the purposes of the scoring exercise . Primary waste is classed as the combined volume of resin and water crossing the system boundary into radwaste treatment. Water:solids taken as ~ 1:1 v/v.
	Score:	1	2	3	4	5	Comments
De-Water	None			3			Does nothing therefore excess water left in system, original volume unchanged
	Drying				4		Removes water plus resin beads shrink in volume
	Absorption			3			Although absorption medium remains with the resin, the volume of absorbent is insignificant when compared to the volume of water. Absorption rate = 50:1 typically
	Settling / decanting				4		Removes excess water
	Filtration				4		Removes excess water
Volume reduction	None			3			Volume unchanged
	Compaction			3			Technique considered to give an insignificant (i.e. Less than 10%) reduction in primary waste on materials considered
Passivation	None			3			Volume unchanged
	Controlled oxidation					5	70% reduction in waste volume. Organics combusted in the afterburner producing a minimal volume of solid waste as inorganic ash then requiring encapsulation
	WETOX					5	Volume reductions claimed to range from 5:1 to 100:1
Immobilisation	Polymer encapsulation		2				Encapsulant doubles final waste volume
	Vitrification					5	Organic component of the waste is burnt off leaving activity in the vitrified product. Reduction rates of 50:1 claimed. Filters and maintenance wastes (e.g. scrap melters) also become ILW (secondary waste)
	Cement Encapsulation		2				Encapsulant doubles final waste volume

2.7 Option scores against Secondary Waste Management Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Secondary Waste Management**	Considerable and/or problematic secondary wastes (solid, liquid, gaseous) generated	Significant amounts of secondary wastes generated requiring secondary/ subsidiary process route.	Significant amounts of secondary wastes generated requiring secondary/ subsidiary process route.	Moderate amounts of secondary wastes generated requiring secondary/ subsidiary process route.	Minimal to no secondary wastes generated as a result of the specific process proposed.	A measure of the option's potential performance in the management of secondary wastes. Secondary wastes to be taken as including S.L.G. waste streams including new liabilities and consumables e.g. filters or other media. Does not consider generic effluents e.g. washdown that are common to all options
	Score:	1	2	3	4	5	Comments
De-Water	None					5	
	Drying				4		Drying will produce a vapour that will require treatment.
	Absorption					5	
	Settling / decanting					5	It is assumed that excess water removed is recycled
	Filtration					5	It is assumed that excess water removed is recycled. Assume that filtration technology used will not be of a type that creates significant secondary wastes.
Volume reduction	None					5	
	Compaction					5	
Passivation	None					5	
	Controlled oxidation				4		Off gas typically requires caustic jet scrubber. Relatively small amount of caustic liquor requires disposal adding to ILW volumes.
	WETOX			3			Some scrubber liquor and off-gases for treatment, noxious salts in product require treatment
Immobilisation	Polymer encapsulation				4		Waste encapsulant and washings produce significant amounts of inactive waste for disposal
	Vitrification			3			Off-gases require treatment producing filters. Also waste from maintenance requires disposal
	Cement Encapsulation				4		Waste encapsulant and washings produce significant amounts of inactive waste for disposal

2.8 Option scores against Planning Issues Criterion

Option Set	Planning Issues	Mapping of Scoring Requirements against Criteria					
		Very high probability of inquiry. Long delays to consent envisaged.	High probability of inquiry.	Moderate probability of inquiry.	Low probability of inquiry.	Very low probability of inquiry. No extra ordinary delays to consent envisaged.	This reflects the probability of delays through planning issues e.g. with respect to public inquiry and is particularly relevant to options such as incinerators
	Score:	1	2	3	4	5	Comments
De-Water	None					5	No issues envisaged
	Drying					5	No issues envisaged
	Absorption					5	No issues envisaged
	Settling / decanting					5	No issues envisaged
	Filtration					5	No issues envisaged
Volume reduction	None					5	No issues envisaged
	Compaction					5	No issues envisaged
Passivation	None					5	No issues envisaged
	Controlled oxidation			3			Regulatory concerns over high temperature process
	WETOX				4		Use of hazardous chemicals
Immobilisation	Polymer encapsulation					5	No issues envisaged
	Vitrification			3			Regulatory concerns over high temperature process
	Cement Encapsulation					5	No issues envisaged

2.9 Option scores against Product Quality Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Product Quality**	Very low confidence in meeting current UK specs.	Significant uncertainty regarding whether technology proposed would ever meet UK specs. Meets only isolated conditions or achieves partial compliance on all conditions.	Could be made to meet UK specs only by the addition of a complementary process. Meets ~50% of conditions as a standalone process.	Nearly meets all requirements e.g. Meets most CFA fully with partial compliance on isolated conditions. May be granted an L.o.C. if it can be demonstrated that all reasonable measures have been taken.	Very high confidence in meeting current UK requirements. Fully meets all CFA.	An indication of the option's potential to produce a product that gains a Letter of Compliance from RWMD by meeting the Conditions For Acceptance for the ILW Repository :- immobilised, free of water, homogeneous, radiologically stable, chemically passive (i.e. zero gas generation), characterised, voids minimised (ref Nirex GWPS vol 2.) Alternatively to meet CFA for LLW repository in the case of trash.
	Score:	1	2	3	4	5	Comments
De-Water	None						Processes that do not alter the quality of the final product have not received a score.
	Drying						
	Absorption						
	Settling / decanting						
	Filtration						
Volume reduction	None						
	Compaction						
Passivation	None						
	Controlled oxidation		2				Process passivates the organic component of the waste
	WETOX		2				Process passivates the organic component of the waste
Immobilisation	Polymer encapsulation		2				Concerns about lifetime stability of organics.
	Vitrification	1					Waste form has no risk of weepage, cracked but solid structure. Significant doubts about compatibility of glass waste form in cement-containing stores
	Cement Encapsulation				4		Concerns about lifetime stability of cement encapsulated organics therefore does not meet the 'passive' CFA. Provided that organic resin is typical of UK power stations, concerns surrounding product quality will be shared.

2.10 Options scores against Resource Usage Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Resource Usage**	Very high resource demand	High resource demand	Moderate resource demand	Low resource demand	Very low resource demand	To compare the relative potential consumption of resources (non -human), including raw materials, water, energy. Does not consider demand for human resources which is covered under operational costs.
	Score:	1	2	3	4	5	Comments
De-Water	None					5	No process activity therefore no resource demand
	Drying			3			Requires heat so low energy demand
	Absorption				4		Absorbant medium required
	Settling / decanting					5	No process activity therefore no resource demand
	Filtration				4		Possible need for filter medium
Volume reduction	None					5	No process activity therefore no resource demand
	Compaction				4		Energy required for high pressures employed
Passivation	None					5	No process activity therefore no resource demand
	Controlled oxidation			3			Induction heating requirements
	WETOX			3			Requires heavy metal catalysts
Immobilisation	Polymer encapsulation			3			Chemicals used associated with encapsulation process
	Vitrification		2				Heating requirements and additional materials for maintenance
	Cement Encapsulation				4		Some use of electricity and cement

2.11 Option scores against Implementation Time Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Implementation Time**	Time to develop design to appropriate standard for GDA submission is well beyond deadline	Time to develop design to appropriate standard for GDA submission is behind deadline	Time to develop design to appropriate standard for GDA submission is on deadline	Time to develop design to appropriate standard for GDA submission is within deadline	Time to develop design to appropriate standard for GDA submission is well within deadline	Time to implement the Radwaste Bldg is unlikely to be a factor relative to the time to implement the reactor plant. Therefore the time to submit designs relative to the GDA deadline is used as the benchmark instead.
	Score:	1	2	3	4	5	Comments
De-Water	None					5	Simple/ no process therefore minimal time to develop
	Drying					5	Simple/ no process therefore minimal time to develop
	Absorption					5	Simple/ no process therefore minimal time to develop
	Settling / decanting					5	Simple/ no process therefore minimal time to develop
	Filtration					5	Simple/ no process therefore minimal time to develop
Volume reduction	None					5	Simple/ no process therefore minimal time to develop
	Compaction			3			Uncertainty in application of process to organic resins
Passivation	None					5	Simple/ no process therefore minimal time to develop
	Controlled oxidation			3			Regulatory issues concerning application of a high temperature process
	WETOX		2				Relatively novel application of the process, process currently presents issues that would have to be addressed such as incomplete oxidation.
Immobilisation	Polymer encapsulation				4		Nature of polymer to be used currently unknown but could probably be proposed in time (whether suitable or not). Based on US experience.
	Vitrification	1					Regulatory issues concerning application of a high temperature process, product quality issues, design of plant would require significant investigation
	Cement Encapsulation				4		Issues regarding product quality of cement encapsulated organic resins

2.12 Option scores against Process Technology Costs Criterion

		Mapping of Scoring Requirements against Criteria					
Option Set	**Process Technology Costs**	Highest overall relative cost. Substantial investment anticipated in fundamental research and development. Greatest scope, most complex process. Greatest operator demand.	High relative cost for the technology option. Expected to require significant development cost. High scope, complex process. High operator demand.	Medium relative cost. Moderate scope, moderately complex process. Moderate operator demand.	Low relative cost. Low scope, fairly simplistic process. Low operator demand.	Lowest relative cost. Least scope, simplest process. Least operator demand.	A relative assessment of treatment costs includes development, design, capital & operating costs. At an early stage the score will reflect the anticipated scale, scope and complexity of the process plant rather than a full engineering estimate against bill of quantities, rates and norms.
	Score:	1	2	3	4	5	Comments
De-Water	None				4		Score reflects the knock on cost associated with carrying additional water through the subsequent processes
	Drying				4		Simple process therefore costs are very insignificant
	Absorption				4		Simple process therefore costs are very insignificant
	Settling / decanting				4		Simple process therefore costs are very insignificant
	Filtration				4		Simple process therefore costs are very insignificant
Volume reduction	None					5	No process therefore no cost
	Compaction			3			Moderately complex process therefore medium cost
Passivation	None				4		Score reflects the knock on cost associated with carrying more waste through the subsequent processes
	Controlled oxidation	1					Most complex process and greatest scope
	WETOX		2				Less complex than above but more than compaction
Immobilisation	Polymer encapsulation			3			Moderately complex process therefore medium cost
	Vitrification	1					Most complex process and greatest scope
	Cement Encapsulation			3			Moderately complex process therefore medium cost

2.13 Attendees

AkerSolutions (*AS*)
Mike Peach
Colin Fuller (p/t)
Richard Carr
Darren Morris
Gavin Marsden
Dave Thompson
Richard Hunter-Smith
Sylviane Bartkowiak (p/t)
Different By Design (*DBD*)
Ron Howarth
John Lomax
Hugh Allen
Westinghouse Electric (*WEC*)
Larry Eisenstatt
Tim Meneely
Geoffrey Anderson
Peter Kerry
Rolls Royce (*RR*)
Keith Plamping
Vattenfall
Ann McCall (SKB)
RWE
Gail Donaldson
Peter Barlow
Ulecia Endessa
Mariano Carreter
Iberdrola
Alicia Gonzalez)

Appendix 3 – Detailed Option Descriptions

CONTENTS:

1. Minimisation & Segregation

1.1. Minimisation

Following the generic waste management hierarchy principles of; Prevent; reduce; reuse; recycle, recover, dispose: minimisation of waste volumes is an essential prime component that needs to be demonstrated in any waste management strategy. Although in many cases the intrinsic value of the materials themselves is limited, the costs of treating and storing these materials, once they become 'RadWaste', can be very significant.

Examples of this approach are;

- Use reusable, washable items in place of single use items
- Filter contaminated oils to remove sludges / particles
- Washing of items to remove surface contamination

This type of process may also allow wastes to be put into a different category, or potentially even re-classified as non-nuclear waste.

1.2. Segregation

This is an important principle that may remove some of the difficulties associated with the treatment and storage of heterogeneous wastes. Segregation of wastes at source, where practicable, will allow consideration of a greater range of treatment processes and may also reduce the complexity of those processes by allowing the targeting of treatment to suit the materials in question.

2. Storage as raw waste

One strategy is to store the waste in the form in which it is generated – "raw waste". This should be undertaken as a positive decision to maintain the waste in this condition, rather than simply as a default 'do nothing' option.

By evaluating the hazards associated with the wastes, along with the planned storage time and arrangements, the half-life of the activity present in the waste, etc. the conclusion may be reached that continued storage of the raw waste is appropriate.

In addition, in cases where no disposal facility is available, or where Conditions For Acceptance (CFA) or Waste Acceptance Criteria (WAC) are uncertain, such storage may be logical rather than undertaking treatment that may subsequently prove less than ideal and potentially require re-work.

2.1. Solids

Waste packaging should be suitable for the type of waste held, any handling / transport envisaged (including foreseeable hazards encountered during such activities), the planned duration of storage and the expected environmental conditions in which it will be stored.

Where it cannot be guaranteed that the stored solid waste is free from liquids, a controllable drainage system should be fitted including, possibly, a monitoring and alarm system to indicate if liquids are draining from the stored waste.

The waste store should maintain the packages in a consistent environment, preventing exposure to undue variations in temperature, humidity, etc.

In addition, the waste store and the packaging should exclude access by animals to prevent uncontrolled spread of activity and / or damage to the waste packages.

2.2. Liquids

The increased mobility of liquid wastes imposes more rigorous requirements on packaging and storage of liquid wastes. Waste containers / vessels should be selected to suit the nature and quantity of liquid waste to be stored. In addition, storage facilities for liquid waste will need collection / drainage systems to mitigate against leakage or, in some cases, double containment and leakage detection.

The same general comments on fire prevention / mitigation apply to organic liquid wastes as organic solid wastes. However, in many cases requirements will be more rigorous due to the increase in mobility and volatility of liquids compared to solids.

2.3. Solid / liquid mixtures

Where the waste form, or other constraints, lead to the requirement to store a mixture of solid and liquid wastes together, the requirements set out in sections 2.1 and 2.2 above apply, along with some additional requirements.

Unintentional phase separation (settling) of sludges (solids held in suspension in liquids) can result in additional challenges both to storage and later retrievals. This can result in uneven radioactive inventory distribution within the storage vessel and may impose specific access requirements, either to ensure that the sludge is agitated to maintain suspension, or to allow for more aggressive retrievals methods should settling occur. The risk of settling is dependant upon the nature of the sludge, the storage conditions (including physical geometry) and length of storage.

3. Treatment

Some wastes may pose a challenge to long term storage and disposal. Wastes that are chemically active or not radiation tolerant may degrade in storage evolving gases that are potentially hazardous and also may have other undesirable characteristics e.g. that lead to expansion of the waste package.

Other wastes may also pose significant hazards due to their; volatility; flammability; toxicity; chemical instability; etc. It may be possible to reduce the storage challenge by treatment or conditioning thereby allowing continued storage in a reduced state of risk.

Such processes can be broadly categorised as

- Non-destructive – techniques or processes which primarily involve a physical change to the properties of the material to allow additional treatment, storage or disposal, but which do not destroy organic components or change chemical characteristics of those materials.
- Destructive – techniques or processes involving a chemical change in the waste material.

In general, the purpose of treatment and conditioning techniques is to allow for the waste product to be stored or disposed of more safely.

3.1 Non-destructive methods

i) Drying / Evaporation

Drying techniques are typically used for solid wastes that contain significant quantities of free water.

Evaporation techniques are typically used for liquid waste streams containing suspended or dissolved solids.

In either case, the aim is to remove liquid in order to either reduce the volume to be stored or to reduce the risk associated with leakage of liquid from the waste whilst leaving the major part of the contamination in the resulting dried / evaporate concentrate.

As a general rule, drying techniques are relatively simple and result in small quantities of secondary waste. Evaporation techniques tend to be more complex and may result in secondary waste streams, such as off-gases, of significant volumes.

Heat can be used with either technique in order to accelerate the process.

Examples;

- Ion exchange resins may be dried prior to encapsulation in a monolithic solid matrix.
- CFA / WAC dictate that wastes for disposal contain negligible free liquid, so such materials must be dried prior to disposal.
- Evaporation may be used to concentrate Highly Active Liquor (HAL) as a pre-treatment prior to further processing (e.g. vitrification). It should be noted that this technique may lead to the generation of secondary wastes such as filters, etc. which will also require treatment / storage / disposal.

ii) Settling / Decanting

Solids held in suspension in liquids will, in general, settle to the bottom of the container if the solid / liquid mixture is left undisturbed. The speed and degree of settling will depend upon the natures of both the liquid and the solid, including the conditions in which they are held.

Once settled, the liquid phase will sit on top of the layer of settled solids and can then be removed or ‘decanted’. This process provides a simple way of reducing the liquid content of solid / liquid mixtures. It should be noted that the remaining ‘solid’ phase will still contain some of the liquid and, likewise, the decanted liquid may require further processing, such as filtration, to remove any remaining solid content.

This process has the advantage that it requires a very low energy input and typically works at ambient conditions. The main requirement is for a suitable vessel or container to hold the mixture that allows the liquid phase to be decanted and the solid phase to be recovered. The low temperature, low energy nature of this process means that there is little, if any, off-gas processing required and that the process is inherently safe.

One disadvantage is that some settled solids may be difficult to retrieve and handle, in some cases forming thick, sticky sludges. With increased settling time and / or depth of settled solids the degree of consolidation of the resulting sludge may increase, making retrieval and handling more difficult still.

Other disadvantages of this process are that it may be slow, depending upon the nature of the solid / liquid mix and that it may require a number of large tanks or vessels. In some cases it may be necessary to re-add liquid to the settled solids for subsequent handling or processing operations.

This process is well proven however, and has been widely used in the nuclear industry. It does not, however, result in a waste product suitable for final disposal. Typically the settled solids will be immobilised in a grout or other binding matrix to form a waste product suitable for final disposal.

iii) Physical Conditioning / Separation

These techniques are defined as the segregation of a waste stream into two or more components.

For solid wastes this would typically involve mechanical means such as shredding and sorting. Such techniques may be employed as a pre-treatment prior to encapsulation (3.1.11, Direct immobilisation, below) or incineration (3.2, Destructive methods, below). For encapsulation, the aim is generally either size reduction or to allow a better inclusion of the waste in the encapsulant. For incineration, shredding allows a smaller, more even feed to be produced. It should be noted, however, that such techniques can create considerable volumes of dust / small particles and will therefore require enclosure to prevent the spread of contamination, thereby driving up the level of complexity and cost of the facility.

For liquid wastes this may include the phase separation of solid bearing liquids – i.e. the settling of solids from a sludge allowing liquid to be removed. As noted above (2.3, Solid / liquid mixtures), settled sludges may pose significant challenges for future retrievals and / or handling.

iv) Filtration

Solids held in suspension in fluids (either liquids or gases) may be removed by filtration. Filtration is defined as the process of passing the solid bearing fluid through a porous medium that allows the fluid to pass through but that acts as a barrier to a greater or lesser proportion of the solid particles.

There are many different methods of filtration, all aiming to attain the separation of substances. This is achieved by some form of interaction between the substance or objects to be removed and the filter media. In addition the substance that is to pass through the filter must be a fluid, i.e. a liquid or gas.

The simplest method of filtration is to pass a solution of a solid and fluid through a porous interface so that the solid is trapped, while the fluid passes through. This principle relies upon the size difference between the particles making up the fluid and the particles making up the solid. Alternate methods often take the form of electrostatic or chemical attraction between the filter media and the particles to be removed from the fluid.

There are a wide range of filtration media and techniques available and the overall process can be tailored to suit the specific waste stream and the output requirements. Multi-stage filtration may be used to either target a wider range of particles for removal or to ensure a higher degree of filtration compared with single-stage processes.

Many filtration processes are well developed and well proven in service in the nuclear industry. Disadvantages are that the filtration media have a finite service life (which may be extended by cleaning) requiring periodic maintenance and / or replacement and become a secondary waste to be treated and disposed of once that service life is exhausted.

For the purposes of the radwaste treatment optioneering study; filtration is taken as a generic separation process that includes filters, simple sieves, screens and strainers that would achieve a simple, single step stage of segregation.

v) Reverse Osmosis

This process uses pressure to force a solution through a semi-permeable membrane. The membrane allows the passage of the solvent but not the solute and the solvent therefore passes from a region of high solute concentration to a region of lower solute concentration, thereby separating the solvent from the solute.

This is the reverse of the natural osmosis process (i.e. solvent passing from a region of low solute concentration, through a membrane to an area of higher solute concentration) and pressure is required in excess of the osmotic pressure in order to reverse the natural flow. The natural tendency for solvent to flow through the membrane is described as the 'osmotic pressure', since it is analogous to flow caused by a pressure differential.

When two solutions with different concentrations of a solute are mixed, the total amount of solutes in the two solutions will be equally distributed in the resulting, combined solution.

Instead of mixing the two solutions together, they can be put in two compartments where they are separated from each other by a semi-permeable membrane which does not allow the solutes to move from one compartment to the other, but does allow the solvent to move. Since equilibrium cannot be achieved by the movement of solutes from the compartment with high solute concentration to the one with low solute concentration, it is instead achieved by the movement of the solvent from areas of low solute concentration to areas of high solute concentration. When the solvent moves away from low concentration areas, it causes these areas to become more concentrated. On the other side, when the solvent moves into areas of high concentration, solute concentration will decrease. This process is termed osmosis.

In reverse osmosis, in a similar setup as that in osmosis, pressure is applied to the compartment with high concentration. In this case, there are two forces influencing the movement of solvent: the pressure caused by the difference in solute concentration between the two compartments (the osmotic pressure) and the externally applied pressure.

The membranes used for this process typically have a dense barrier layer in the polymer matrix.

This process has many, well established commercial and industrial applications, such as desalination of sea water. In nuclear applications, the process can be applied liquid wastes to concentrate the un-wanted solute prior to further treatment and recover the solvent for re-use or disposal.

vi) Ion Exchange

Ion exchange is a process to carry out an exchange of ions between two electrolytes or between an electrolyte solution and a complex. In most cases the term is used to denote the processes of purification, separation, and decontamination of aqueous and other ion-containing solutions with solid polymeric or mineralic 'ion exchangers'.

Typical ion exchangers are ion exchange resins (functionalised porous or gel polymer), zeolites, montmorillonite, clay, and soil humus. Ion exchangers are either cation exchangers that exchange positively charged ions (cations) or anion exchangers that exchange negatively charged ions (anions). There are also amphoteric exchangers that are able to exchange both cations and anions simultaneously. However, the simultaneous exchange of cations and anions can be more efficiently performed in mixed beds that contain a mixture of anion and cation exchange resins, or passing the treated solution through several different ion exchange materials.

Ion exchangers can be unselective or have binding preferences for certain ions or classes of ions, depending on their chemical structure. This can be dependent on the size of the ions, their charge, or their structure.

It is common for medium active wastes in the nuclear industry to be treated with ion exchange or other means to concentrate the radioactivity into a small volume. For instance, it is possible to use a ferric hydroxide floc to remove radioactive metals from aqueous mixtures. After the radioisotopes are absorbed onto the ferric hydroxide, the resulting sludge can be placed in a metal drum before being mixed with cement to form a solid waste form. In order to get better long-term performance (mechanical stability) from such forms, they may be made from a mixture of fly ash, or blast furnace slag, and portland cement, instead of normal concrete (made with portland cement, gravel and sand).

vii) Decontamination of solids / liquids

This type of technique is widely used to remove the radioactive contaminants from solid or liquid wastes, thereby allowing the waste to be placed in a lower waste category, re-used / recycled, or free released.

Such techniques are typically mechanical processes, although there are chemical decontamination processes in use.

Typical techniques include;

- Solvent cleaning
- Surface washing with water
- Surface washing with supercritical CO_2

Uses of solvent cleaning and surface washing with water for solid wastes typically include; laundering / dry cleaning of clothing, rags, etc. (probably the most common application of the decontamination techniques); the washing of surfaces to remove loosely held contaminants. Such processes will result in secondary wastes requiring treatment.

The use of supercritical CO_2 for surface washing has been applied to the removal of oils / greases from cutting swarf / sludges resulting from the cutting of metals and glass using CO_2 in Germany.

Liquid-liquid extraction has been used to decontaminate oils in Czech nuclear facilities. In this process an oil and water mixture is pumped into a closed 1 m^3 tank (mixture containing 500 litres of oil and 100 – 200 litres of demineralised water). Following circulation for 1 – 3 hours, phase equilibrium is established and the water is discharged from the lower part of the tank. This water contains the radioactive contaminants and is passed for treatment in a water purification system. The cleaned oil may be treated as free release waste.

By their nature, all decontamination techniques produce secondary wastes, the types and volumes depending upon the technique and its application.

The general advantage of these techniques is that they allow for the re-use, re-categorisation and / or free disposal of the decontaminated waste.

viii) Absorption

Liquid wastes can be absorbed into various materials – when the liquid is brought into direct contact with the absorbent the two combine to form a solid product. These are typically very simple techniques and, due to no need for elevated temperatures and little or no mechanical mixing, offer relatively little in the way of potential process hazards, such as splashing or dust generation, when compared with other processes.

Various absorbent materials are available, ranging from clays and minerals to special polymers and result in waste products ranging dry granules to gels to relatively dry, hard solids.

There are a number of question marks over the performance of such techniques, especially over their use to pre-treat liquid wastes prior to long term storage. These include:

- The ability of the liquid to be fully integrated and held in the absorbent matrix such that it cannot be released.
- The long-term stability and resistance of the resulting product to degradation.

ix) Size Reduction

Large solid waste items, such as filters, metallic components and general LLW trash may need to be size reduced prior to further processing. Such processes are generally classified as 'non-destructive' waste treatment techniques since although they change the physical size of the waste they do not change the nature or chemical make-up of the items. In particular, the organic or volatile constituents of the waste are not destroyed.

The requirements to size reduce from simply making the items smaller and easier to handle, to allow better packing density or simply to fit into waste containers, or to increase the surface area of the waste material in order to improve the efficiency of destructive waste treatment processes such as oxidation (including incineration) or other chemical reactions.

There are a wide range of size reduction processes available and the appropriate selection will depend upon the nature, size and geometry of the waste material and what subsequent processing is planned for the waste.

Typical size reduction processes include:

- Cropping
- Sawing
- Shredding (very flexible items, such as rubber gloves, may benefit from freezing prior to shredding)
- Crushing (Compaction (see 3.1.10, below) is a variation of crushing)

Advantages of these processes are that they are typically simple and well established mechanical techniques. Disadvantages include safety issues associated with aggressive, mechanical operations, dust and swarf generation and the reliability and maintenance issues associated with nuclearised mechanical equipment.

x) Compaction

The general aim of compaction techniques is to reduce the volume of solid wastes to the practical minimum by the elimination of voids and such techniques are well established and widely used in the nuclear industry around the world. Compaction equipment in the UK includes facilities at Sellafield and Dounreay. Mobile compaction facilities have been used in countries including the UK, the USA, Germany and Italy.

Compaction is normally carried out by placing raw waste into thin-walled, sacrificial steel drums before placing them within a hydraulic press to form a compacted waste 'puck' which may then be placed or grouted into an additional, larger container.

Volume reduction is directly dependant upon the type of waste to be compacted, how it is loaded into the sacrificial drum and the compaction force applied. Compaction forces have increased greatly from less than 1MN initially, through the development of 'supercompactors' in the 1980s using forces in excess of 10 MN, to forces in the 20 – 50 MN range with the latest equipment.

Wastes must be compatible with the compaction process if it is to be applied successfully. For example, powders or bulky metallic items will not give useful volume reductions or form cohesive compacted 'pucks'. Also, compressed gases, significant volumes of free liquid and explosive materials should be removed from the waste prior to compaction. Where wastes for compaction contain free liquid, the compaction facility will need to be equipped to capture liquid that is pressed out during the process and pass this liquid on for separate treatment. Likewise, systems may need to be in place to deal with airborne effluent arisings (dust, aerosols, etc.).

Supercompaction has been used in the UK for LLW prior to disposal at Drigg and at Sellafield for ILW, where 200 litre drums containing PCM are subjected to a compaction force of 2000t prior to being grouted into 500 litre stainless steel drums.

The advantages of compaction are that for suitable solids waste forms it will maximise the density of the waste for subsequent disposal and that it is a simple process that uses relatively simple and inexpensive equipment. However, as the compaction force increases the cost and complexity of that equipment rises, as does the level of skill required in the operators.

xi) Direct Immobilisation (Encapsulation)

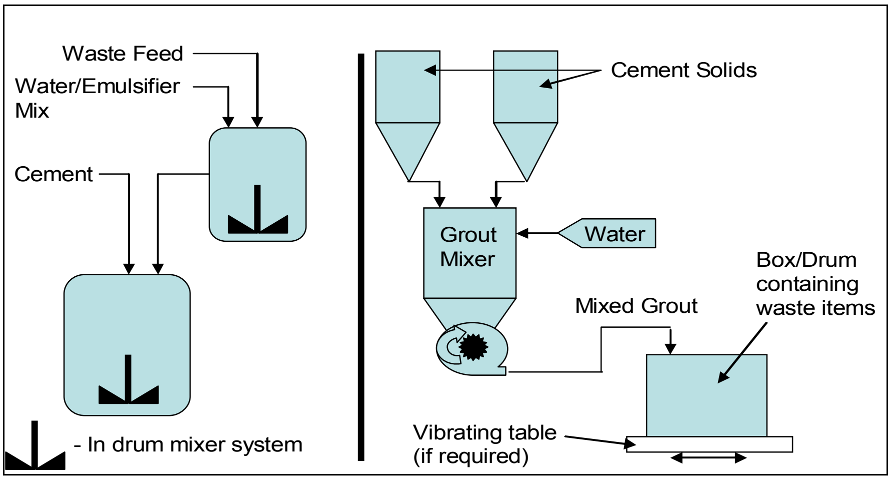
This group of processes involve the immobilisation of raw waste into a solid matrix formed from a binding material to form a cohesive monolith. Direct immobilisation by encapsulation is used in many applications in the nuclear industry for a variety of wastes. No novel technology is required from an equipment point of view and the process is well established. The use of polymers for encapsulation has only been employed at the Trawsfynydd site within the UK although it is much more developed in the US and elsewhere.

The nature of the raw waste itself is not changed by the process, but it becomes embedded into the encapsulant and is therefore secured from the environment.

Typical immobilisation processes use physical mixing of the waste with the encapsulant. This may lead to hazards associated with aerial discharges such as dust, splashing and spillages of the mixture prior to completion of curing of the matrix.

One advantage of the process is that raw waste may be transformed into a form suitable for disposal in a single step and that the equipment, and therefore the processing of waste, can be located near to the source of waste generation. The equipment used is generally simple and widely available in both the nuclear and non-nuclear industrial world.

Figure 3.1.11.1 Encapsulation techniques



This type of process is widely used for a range of solid and liquid waste forms and a diverse range of encapsulants have been used around the world, including:

- Cements / grouts
- Bitumen
- Epoxy resins / Polymers

Historically in the UK there has always been concern over organic materials in encapsulated products either as the waste to be immobilised or as the encapsulant itself, with the regulators typically preferring inorganic materials for encapsulation. For example, it may be difficult to justify the use of bitumen as an encapsulant in the UK, which is both an organic material and represents a fire risk (bitumen fires are known to have occurred in nuclear facilities outside the UK). Additional factors counting against organic materials include the potential for solubility of the fixed radioactive species and possible transfer into the environment,

3.2 Destructive methods

i) Conventional incineration

Incineration is an exothermic reaction (oxidation) process which involves the application of heat at temperatures in excess of 600 C to break down organic components of the wastes by combustion, while melting its inorganic components by reaching and exceeding their melting temperatures. Pre-treatment of the waste is usually not required although aqueous waste requires emulsifying.

In most cases, the combustion of the waste stream itself is sufficient to provide the heat required to maintain the reaction. However, in cases where this is not sufficient (i.e. where the inorganic content of the waste stream is high) a supplemental fuel source can be added to the reaction – typically natural gas or oil.

Incineration is a simple concept and a well proven technology and the combustible nature of organic waste materials makes it a good solution for the complete destruction of the organic content of waste materials.

The process is continuous, has a high throughput and can handle mixtures of solid and liquid wastes simultaneously.

Incineration of radioactive organic waste is commonplace and the versatility of acceptable waste feeds is often cited as an advantage.

Another advantage is that it offers a very significant reduction in waste volume and mass compared with techniques such as immobilisation or encapsulation. All organic materials are incinerated and the final products are off-gases and an inorganic ash.

The clean up associated with the ventilation systems is usually expensive but capable of being tailored to meet gaseous discharge regulations. However the limited public acceptability of the fumes produced has often been highlighted as an argument against using incineration technologies [Ref 3].

However, incineration of radioactive ILW has proven to be a costly means of waste disposal. The Controlled Incineration Facility at the Savannah River Site cost $102 million to build and $19 million/year to operate. Its capacity however allowed for 2.4 million lbs of organic liquid to be incinerated in addition to other wastes [Ref 4].

Further problems associated with incinerator operations have been experienced with operational reliability and maintenance. Such problems include frequent replacement of off-gas treatment system filters, plugging of heat exchangers, incomplete incineration, and accumulation of residual ashes in systems and components not designed for ash removal. Such problems have also resulted in higher operating costs.

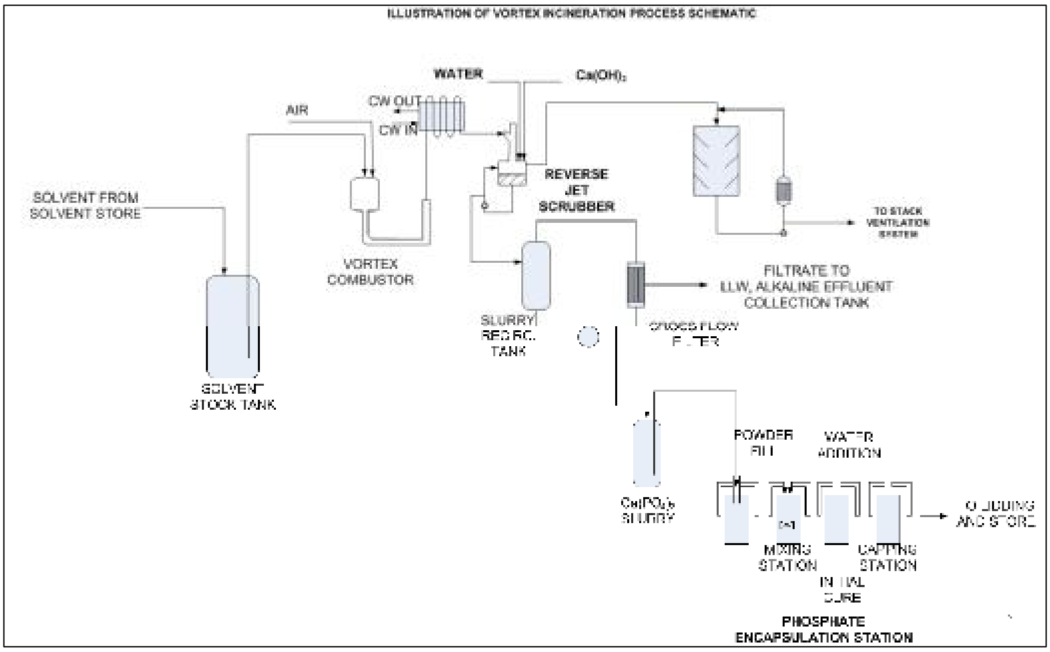


Figure 3.2.1.4 Schematic of a vortex combustor system

There are a number of different incineration technologies in use worldwide;

- Excess air incineration – a one-step process where significant excess air beyond that required for complete combustion is added to the combustor (typically 50 – 75%). This results in considerable volumes of particulate matter being entrained in the off-gas, which is of relatively low quality.
- Controlled air incineration – a multi-step process where stochiometric air:fuel ratios are used in the primary combustion chamber (combustion temperature 600 – 800 C) followed by excess air combustion in a secondary chamber (combustion temperature 1000 – 1200 C). The resulting off-gas is of good quality.
- Starved air combustion – 'Pyrolysis', see Section 3.2.2, below.
- Fluidised bed incinerators – generally single chamber, excess air systems, where the waste is injected directly onto a bed of heated granular material. The air used to fluidise the granular bed is usually heated by the exhaust gases. This type of incinerator can be used for liquid, solid or slurry wastes.
- Slagging incinerators – multi-chamber systems, similar in principle to controlled air incinerators. The waste feed is formed by a combination of flammable and non-flammable materials. The waste feed is passed through the first chamber, where it is combusted under stoichiometric conditions prior to being passed to a

second, higher temperature chamber to melt the non-flammable materials. The melted material is quenched in a further chamber to form a highly insoluble slag.

- Slagging kiln incinerators – a variation of slagging incinerators where the primary chamber operates at a high enough temperature to melt the non-flammable material. The second chamber is used to ensure destruction of remaining hazardous materials.
- Rotary kiln incinerators – this type of incinerator uses a large tubular hearth, slightly inclined from the horizontal, rotating slowly. The rotation agitates the waste material and ensures mixing with air, whilst gravity pulls the remaining waste along the inclined hearth to the lower end of the kiln. Exhaust gases are passed through a secondary combustion chamber to ensure that any residual organic material is oxidised.
- Agitated hearth incinerators – generally used for homogenous waste streams that either have high water content (e.g. ion exchange resins and filters) or which are difficult to oxidise.
- Multiple hearth incinerators – constructed from a vertical series of circular hearths, with air-cooled rabble arms to move the waste between the hearths. As the waste moves downwards from the uppermost hearth it is; heated; dried; combusted; cooled. This type of incineration is especially well suited to waste forms which generate relatively little heat as they combust, such as tar, sludge and certain types of solid material.
- Cyclone incinerators – a single hearth, vertical cylindrical combustion chamber. This type of incinerator is best suited to sludges, slurries and liquids and the high-shear, cyclonic flow of air through the combustion chamber ensures mixing and complete combustion.

With all of these processes, the main challenge is to manage emissions in the off-gas resulting from combustion. Depending upon the waste materials that are incinerated, the systems required to capture and deal with the contaminants (e.g. dioxins; furans; radioactive materials; etc.) in the off-gas can be complex and expensive to build and operate. In addition, certain waste materials (e.g. those containing; chlorine; phosphor; sulphur; etc.) can resulting highly corrosive off-gas, which can lead to operational and maintenance problems.

It is also worthy of note that public opinion is generally negative to incineration facilities.

References;

3 Application of Thermal Technologies for Processing of Radioactive Waste. IAEA-TECDOC-1527. December 2006

4 Waste Incineration at the Savannah River Site. Audit Report. DOE/IG-0453. October 1999

ii) Controlled Oxidation

Controlled oxidation is related to incineration (see 3.2.1, above) and is in effect combustion starved of oxygen, so that thermal decomposition destroys the waste, driving off organic content as a gas and converting the remaining waste into an inorganic residue. A typical technique for controlled oxidation is the pyrolysis process. The temperatures used for pyrolysis are lower than those used in other incineration processes, typically in the 500 – 600C range. The gas resulting from pyrolysis is removed from the reaction chamber, mixed with excess air and burned in a simple combustion chamber, the off-gas then being passed for cleaning prior to discharge.

The lower temperatures and oxygen levels employed in the reaction chamber allow for volatile species, such as caesium (Cs) and ruthenium (Ru), to be mostly retained within the waste residue generated in the reaction chamber rather than being carried away in the off-gas and thereby requiring capture later in the process. Likewise, corrosive species, such as phosphoric oxides are converted into stable inorganic phosphates rather than phosphoric acid. This gives reduced operation and maintenance challenges when dealing with the process off-gas when compared to conventional incineration techniques.

Pyrolysis can be used to treat a wide range of solid and liquid wastes and give a great reduction in waste volume and mass for a similar capital outlay and operating costs to more conventional incineration techniques. Some waste types (e.g. PCM and high dose-rate ion exchange resins) do, however, require pre-treatment which involves the use of specialised equipment and this can result in a significant increase in costs. In general, pyrolysis plants are very expensive to construct, operate and maintain and require large input volumes to be cost effective.

The resulting waste residue may not, however, be as homogeneous as that from conventional incineration. The inorganic ash product is stable enough to allow storage for many years before encapsulation. This allows the encapsulation of the waste product to be delayed until waste disposal criteria are established.

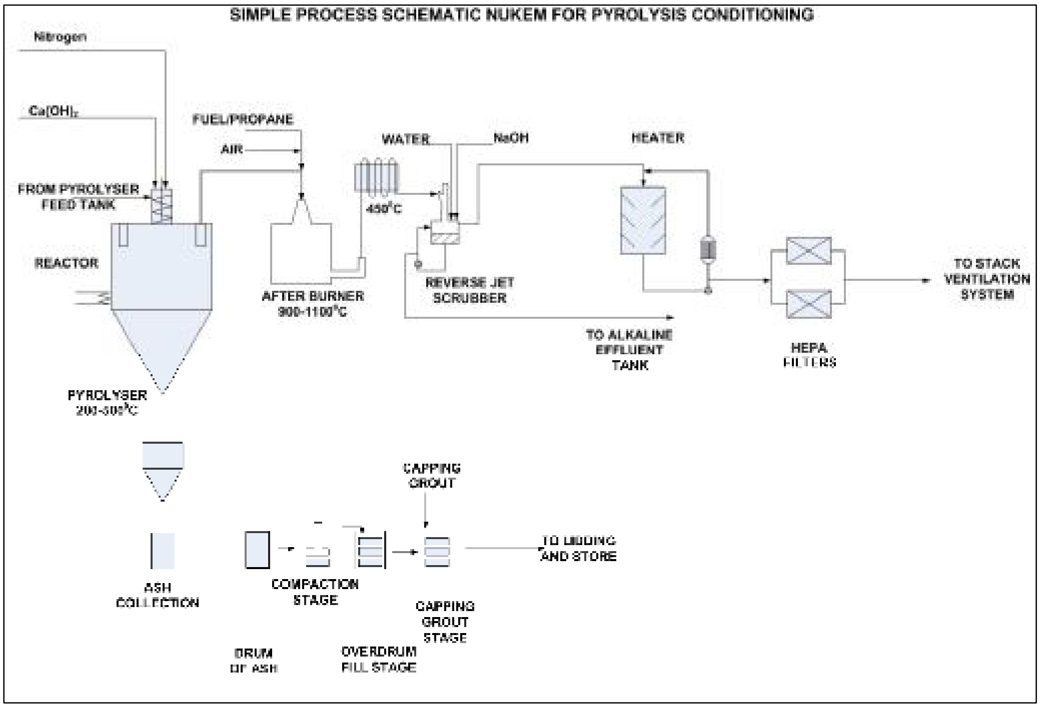


Figure 3.2.2.2 Schematic of a conventional pyrolyser system

Examples of commercially operating controlled oxidation processes are as follows;

NUKEM Pyrolysis - NUKEM brochure [Ref 5] suggests pyrolysis as a preferable waste treatment method for ILW over incineration. The pyrolyser top section is designed as a pebble bed reactor with agitated ceramic or metal balls where the waste is pyrolysed. The solids formed in pyrolysis are removed at the bottom of the pyrolyser – the lower part of the pyrolyser is the filtration section where the solid particles settle. The light particles are retained over sintered metal filter candles which are regularly blown back with nitrogen. These separated solids are collected into the conical bottom and periodically drawn off, through a discharge sluice, under and nitrogen atmosphere. Pyrolysis gases at around 400 – 600C, flow into the combustion burner where it is ignited. Combustion is completed in the after burning chamber where the temperature is 900 – 1100C. The after burning chamber is cylindrical and lined with refractory material. Combustion air is supplied through an air filter by a fan. The oxygen concentration in the combustion chamber is adjusted to 6% minimum. Propane is fed to the burner only during start-up or shut down. The flue gas contains only small quantities of radio-nuclides and other materials which have to be reduced to a level to permit emission. Typically, the hot gases leave the after burning chamber at around 1050C cooled to around 700C by mixing with fresh air in a static mixer. Hot gases leaving here are further cooled to 450C in a double tube gas cooler which is cooled by fresh air supplied by a blower. The gas is then washed in a reverse jet scrubber to remove dust particles, any NOx. The pH value of the scrubber solution is adjusted by means of caustic soda solution. The gases are finally treated by HEPA filter; the off-gas temperature is controlled to maintain a minimum of 30C above its dew point. A NUKEM pyrolysis plant is in full-scale operation at La Hague (active) and a half scale pilot plant is also in operation (inactive) La Hague. NUKEM have also built pyrolysis facilities in Belgium and Japan. The reactor can be operated as a pyrolyser, as an evaporator, or dryer. This versatility makes it possible to treat all types of liquid waste as well as organic solids, such as spent ion exchange resins, and either reduce them in volume or convert them to a chemically inert form. The dried product, or the solids formed, can be either directly stored in suitable containers or immediately immobilised. The volume reduction factor, expressed in the number of cemented final containers produced, either with wet resins or with pyrolysed resins, is greater than 5 for bead resins and greater than 9 for powder resins.

Studsvik THOR Steam Reformation process - the THOR process includes two main reaction stages followed by processes of off-gas treatment. The initial stage decomposes organic materials into simple combustible gases using superheated water oxygen and nitrogen addition. The waste is reacted in a fluid bed operating at about 600C. In the second stage the combustible gases are oxidized at around 750C in order to generate CO_2 and H_2O products that pass to the off-gas treatment process. Temperatures of up to 1100C are sometimes necessary. THOR systems can accept solid, liquid, slurry or gaseous feeds with high water, organic or sulphur content and facilities can accept high throughputs over a small footprint. The THOR process has been used to convert organic ion exchanger from power station water conditioning systems to a form suitable for storage and disposal. The process has a track record in converting organic wastes into a stable product compliant with USDOE disposal regulations. The THOR process tailors the process ingredients (mainly inert inorganic material) so that the waste products produced at the end of the process produce a stable waste product. This process can be considered excessive for a LLW that conforms to the disposal criteria. However there may be other reasons to consider this process. The THOR process is able to handle a wide variety of challenging wastes and may offer opportunities to manage other wastes. A granular waste product can be obtained from the THOR process with zero liquid discharges, as water is disposed of as vapour through the stack. This granular product can be packaged into waste containers suitable for disposal to an appropriate waste repository. Commercial radioactive applications include THOR facility in Erwin, TN to treat waste from nuclear power plants and USDOE treatment of sodium bearing wastes as part of the Idaho Cleanup Project.

References;

5 Pyrolysis of Radioactive Organic Waste. NUKEM Technologies GmbH. January 2007

iii) Vitrification

This process forms a glass matrix containing the radionuclides from the waste stream by combining the waste with glass-forming compounds at high temperature, which is then allowed to cool in a container into a monolithic block. The high temperatures involved in the process destroy any organic materials present preventing the discharge of volatile gaseous species that would require off-gas treatment prior to discharge.

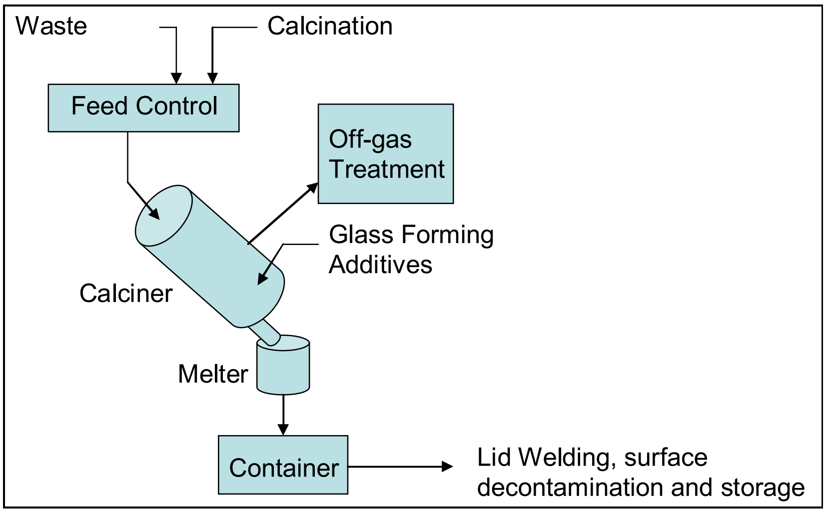


Figure 3.2.3.1 Schematic of a conventional vitrification system

A variation of the vitrification process is molten glass incineration. In this process, solid LLW (usually shredded to a small, regular size) is fed directly into a bed of molten glass. Any organic material contained in the shredded waste combusts in the molten glass leaving a residue encapsulated in the resulting glass matrix. It should be noted that the resulting waste product from this process is not as homogeneous as that from true vitrification.

Cold-crucible vitrification is another alternative to the standard technique which uses a cooling circuit around the melter to mitigate against corrosion. This allows for an almost unlimited reactor lifetime with no upper limits on reaction temperatures.

Vitrification processes are in wide use for the immobilisation of HLW in the UK, France, Russian Federation and the USA. For this type of use, it is important that the waste stream is fully calcined and the radionuclides contained in the waste are dissolved into the glass matrix.

Use of this type of process for other waste forms, such as sludges containing organic species has been investigated. The Russian Joule melting process allows for the direct introduction of organic aqueous waste into the glass making crucible without calcination.

Pilot plants for the vitrification of LLW have been built in France, the USA and the Republic of Korea. Claims of volume reduction factors up to 200:1, mass reduction factors of up to 10:1 and processing rates of up to 70kg/hr have been made for these facilities.

The main advantages of the vitrification process are that the resulting waste form is very robust and therefore suitable for long-term storage / disposal with a total destruction of all organic material. It can be used for a wide range of solid and liquid waste forms.

The main disadvantages are that it is a complex process with expensive equipment and plant, including the use of exotic materials in order to operate at the high temperatures associated with this process. It is typically applied, therefore to HLW and other specialised wastes that are difficult to treat with other processes. High temperature vitrification processes are known to be problematic from a reliability perspective.

iv) Plasma

Plasma treatment is an extreme high temperature process where an electric arc is used to generate temperatures in excess of 20,000C in the waste, breaking down its molecular structure into its constituent atoms. The arc is typically generated by either one or more graphite electrodes or by use of a conventional, industrial plasma torch, with power ratings from hundreds of kW to several MW. This is a multi-stage process that aims to eliminate chemical and radioactive content in the resulting off-gas to levels complying with regulations for both radioactive and conventional emissions.

This process vaporises organic and other volatile elements and melts metallic or inorganic constituents in the waste feed. Vaporisation can be carried out in either a reducing plasma gas (i.e. argon or nitrogen) or an oxidising gas (i.e. air or oxygen).

The vapour phase generated by the electric arc is passed to an afterburner or catalytic converter in order to ensure complete oxidation takes place and is then treated in an off-gas treatment system suitable to the waste type. The molten metal and / or slag residue formed by the electric arc contain most of the radioactivity from the waste and are transferred from the plasma chamber into an external vessel for cooling / solidification. In most cases, these residues form solid and stable wastes which are suitable for long-term storage or disposal. A modification to the process is to add glass frit to the plasma crucible along with the waste feed, resulting in vitrification of the waste residue, leading to a final waste form with enhanced stability.

The off-gas treatment system will result in the creation of some secondary waste, such as HEPA filters, sludges, aqueous solutions, etc. These secondary wastes may themselves require subsequent treatment as radioactive wastes.

Various forms of this process have been used, typically for the destruction of wastes that are difficult to treat by other means and latterly for the incineration or melting of LLW.

An example of the use of plasma arc for the treatment of LLW is the Plasma Arc Centrifugal Treatment plant (PACT) at ZWILAG in Switzerland. This facility uses a feed system, where LLW contained in drums (which are sliced into sections to reduce their size prior to treatment) is fed into the plasma crucible. The final waste form from this facility is a vitrified slag.

The KAERI waste treatment centre in the Republic of Korea has a system using graphite electrodes to generate the plasma arc.

In general, the advantages of plasma arc treatment processes are similar to those of vitrification – it results in a robust and stable final waste form that is suitable for long-term storage or disposal. Organic contents are completely destroyed and the process is suitable for a wide range of solid and liquid waste forms. It differs from most other thermal processes in that it does not require pre-sorting of the waste feed – entire drums of waste material, the drum included, can be fed directly into the process. However, also like vitrification processes, plasma arc treatment systems are expensive to construct and operate. As yet, there is only pilot-scale experience with treatment of LLW.

v) GeoMelt®

This process uses an electric current to melt a mixture of soil and waste material, using temperatures typically in excess of 1500C and has been used in various countries around the world on a wide range of waste, hazardous and toxic materials including explosives. The high temperatures generated by the electric current result in the waste / soil mixture melting to form a glass-like solid mass. The organic constituents are destroyed, with very high efficiency rates quoted, whilst any inorganic materials present are retained in the resulting vitrified product.

GeoMelt is a patented process with AMEC currently holding the world-wide licence for its application. The process essentially vitrifies waste materials, using the soil associated with buried waste materials as the glass-forming matrix. AMEC have applied the process in the USA and Japan for the treatment of various difficult to treat wastes using mobile equipment. Two variations of the process are offered by AMEC;

- Subsurface Planar Melting – used to treat buried materials in-situ (i.e. without needing to dig the waste materials back out of the ground, or otherwise disturb them). This minimises the contact and exposure of the buried materials with the surrounding environment and is typically used to treat historic or legacy wastes on contaminated sites. Electrodes and a ‘starter-path’ are installed into the ground in order to initiate the melting process. Current is passed through the electrodes until all waste has been treated. A containment hood is erected over the area to be treated to collect any gases or vapours generated during the treatment process and direct them to off-gas treatment. The ‘starter-path’ is vertical planes of material between the electrodes, positioned at the required depth and separation to capture the waste material to be treated.
- In-Container Vitrification (ICV) – an AMEC-developed, ex-situ (i.e. above-ground) variation of the GeoMelt process. Again, this is a mobile process and is used for batch melting of contaminated materials, typically including contaminated soils from wastes recovered from burial. AMEC have used ICV in Australia, the USA and Japan and are further developing the process for use in US Department of Energy (DoE) projects. Low-cost, refractory-lined steel containers are used to hold and treat the batches of waste material. These can vary in size from 55 gallon drums up to ISO-freight containers. The waste material is melted and allowed to cool within the container, which can then either be re-used or disposed of with the waste contents.

The two variations of the process use essentially the same equipment and create effectively the same conditions within the waste material being treated. In both cases, the principal of operation is that a vitrified product is formed by the electric melting of a soil and waste mixture – soil must, therefore, be a major constituent of the waste being processed. Soil is predominantly silica and alumina which are the glass-formers for the process. Soil is not a conductor of electricity at ambient temperature and therefore requires the conductive ‘starter-path’ to raise the temperature in the surrounding soil until it melts and becomes electrically conductive. Convective currents in the molten waste ensure good mixing of heterogeneous wastes and the resultant vitrified product has the appearance of volcanic obsidian rock. Claims are made that the vitrified product is between 10 and 100 times more durable and leach resistant that the borosilicate glasses used in conventional nuclear vitrification processes.

Secondary waste materials (e.g. filters, PPE, etc.) can be mixed into the waste being treated by the process, so the process can treat its own waste by-products.

vi) Synroc

Synroc (‘Synthetic Rock’) was developed at the Australian National University in the 1970’s and is an advanced ceramic comprising geochemically stable natural titanate minerals. These minerals are naturally occurring and retain uranium and thorium in the ground. The crystal structures of these minerals will incorporate most of the elements found in HLW and will effectively immobilise them. The process is, therefore, typically applied to HLW and was originally developed to immobilise liquid HLW arising from the reprocessing of light water reactor fuel.

By 1980 vitrification with borosilicate glass had become the standard process for dealing with HLW arising from nuclear fuel reprocessing due to its technical maturity, Synroc being less well developed at that time. In recent years, Synroc has been developed in Australia and the USA to deal with military radioactive waste materials, typically with high plutonium content.

A pilot Synroc plant treating HLW was jointly developed between the Australian Nuclear Science and Technology Organisation (ANSTO) and the US DoE in 1997. This also used hot isostatic pressing (temperature in excess of 1200C, pressure 150MPa within an inert argon atmosphere) to ensure the density and stability of the resulting product. In 1998, the US DoE selected a pyrochlore-rich form of Synroc from around 70 competing processes for HLW management with the aim of having a plutonium immobilisation facility operational at Savannah River by 2007. Based on this decision, ANSTO set up a joint venture with Cogema of France to bid for the contract to build this plant. The bid was submitted in 2000, but in April 2001 DoE announced that is would be deferring immobilisation plants in favour of the production of MOX (Mixed-Oxide) fuel as a policy for plutonium disposition.

Advantages quoted for the pyrochlore-rich form of Synroc over the alternative (borosilicate glass) are that it is more chemically insoluble, it is more easily and safely processed, it contains neutron absorbers and is therefore criticality-safe, higher loadings of actinide wastes are possible resulting in lower (approx’ half) final waste volumes, reduced neutron dose-rate to workers.

vii) Molten Salt Oxidation

This process has been developed as an alternative to conventional incineration processes for the treatment of organic waste materials. Combustible organic species contained in the waste feed are oxidised in a bath of molten alkaline salts at a temperature in the range 500 – 950C. The organic constituents of the waste react with oxygen producing water and CO_2, the inorganic constituents form residues that are retained in the molten salts. These inorganic residues include actinide species. Acid gases formed during the oxidation (e.g. hydrochloric acid) are scrubbed by the alkaline salt. The salts are recycled to remove the waste residues from the bath, the residues then being passed for immobilisation.

This process is generally used for mixed wastes and the spent salts from the bath can be converted into ceramics as part of the process cycle. The process off-gas requires extensive treatment, thereby producing secondary wastes, typically in the forms of scrubber liquors and / or salts.

This type of process has been applied to radioactive wastes in a number of locations, including military waste treatment facilities in the US and the Republic of Korea and a laboratory-scale facility at the Lawrence Livermore Laboratories in the US.

One of the main advantages of this process is that it results in the complete destruction of organic content in the waste, including complex poly-aromatic compounds that are very difficult to deal with using other processed. It also operates at lower temperatures than other thermal processes (such as incineration, vitrification or plasma arc), produces negligible dioxins and furans in the off-gas and the alkaline salt bath both traps the radioactive content of the waste and scrubs acid gases from the process off-gas.

The disadvantages of the process are that it has not been widely used on a large-scale, other than in development facilities, requires high capital cost equipment and specialised techniques to condition the salt product.

viii) Chemical Oxidation

This process was developed at the Lawrence Livermore Laboratories in the US in order to exploit the benefits of an aqueous system (i.e. retaining dust whilst the waste products are held in a liquid medium) whilst increasing the efficiency of oxidation of organic wastes in an aqueous process. This is done through the use of sodium or ammonium peroxydisulphate – the peroxydisulphate ion is a very strong oxidant and the reactions using this ion do not require the use of catalysts.

This process operates at a low (80 – 95C) temperature. The resulting bisulphate ion can be recycled in order to produce new oxidants by conventional electrolysis.

The organic waste material is converted into CO_2 and inorganic residue products, the latter being collected and passed for immobilisation by encapsulation.

The process is developmental and has been tested on a number of organic materials including fuel reprocessing solvents.

Advantages of this process are that it is a low temperature and pressure technique. It is suitable only for liquid, organic waste materials.

ix) Wet Oxidation

This process uses soluble salts of redox sensitive elements with hydrogen peroxide, air or oxygen to oxidise the organic content of waste materials. The products of the reaction are CO_2, water and inorganic salts and the reaction is exothermic.

Through a series of reactions the original, organic carbon structure in the waste is completely converted in a similar manner to incineration.

Wet oxidation is used at low temperatures and pressures, generally with hydrogen peroxide, with or without a catalyst, or at higher temperatures and pressures using oxygen or compressed air as the oxidant. The process can be used for liquid wastes or small, particulate solid wastes such as ion exchange resins or sludges.

In applications for ion exchange resins, wet oxidation has been used with either iron or copper as the catalyst, achieving organic carbon reduction by up to 99% and volume reduction in excess of 75% when treating spent cation resins. A mobile treatment plant, housed in a single ISO-freight transport container, has been developed in the UK, designed to treat up to 100 litres of organic ion exchange resin per day, with the resulting slurry residue being encapsulated in cement. This mobile demonstration plant was built and operated under UK regulations and treated 360 litres of ion exchange resins, contaminated with in excess of 100 MBq of radioactivity.

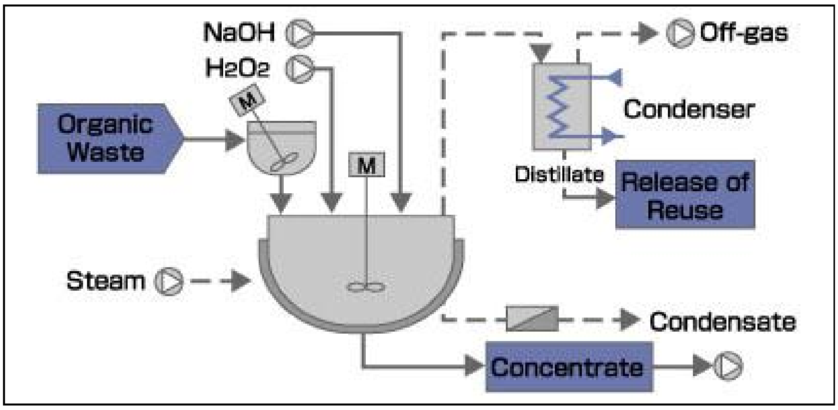


Figure 3.2.9.1 Simple schematic for the WETOX process

A variation of the process using chromium as the catalyst was patented by BNFL. However, the disposal of large volumes of aqueous waste containing chromium, a highly toxic material in hexavalent (chromium IV) form, by methods including immobilisation may pose challenges which outweigh any potential benefits of the process.

A form of WETOX technology developed by JGC Corporation (Japan) has been implemented with the United States (system illustrated above) that does not make use of catalysts (REF JCG corporation website)

Advantages of this technique are that it uses degradable oxidising agents (such as hydrogen peroxide) and is suitable for use in mobile treatment facilities. It can be undertaken with simple equipment and at low pressures and temperatures and is suitable for low-concentration water miscible, organic waste feeds.

However, frequently heavy metal catalysts (such as chromium) are needed and the process can result in incomplete oxidation leaving behind alcohols in the waste product.

Safety concerns limit the hydrogen peroxide content to around 6%. Also, when high temperatures are used, special alloys are required in the equipment to resist corrosive attack.

There are also reports of this process requiring high levels of maintenance. Gaseous emissions have also been reported as being problematic.

x) Advanced Oxidation

This is a class of waste treatment methods that include the use of oxidants, such as hydrogen peroxide or ozone, or ultraviolet (UV) light to destroy organic materials. Often catalysts are used in combination with the oxidants. The resulting products are CO_2 and water and, if catalysts are used, inorganic salts.

This type of process is similar to wet oxidation (see 3.2.9, above) and is used in various industries to treat waste water containing small amounts of organic materials.

When using UV light, the waste stream must be maintained with a minimum of turbulence in order to allow the UV light to fully penetrate.

Applications for radioactive waste streams include the removal of the organic component of a liquid waste prior to treatment by another method such as flocculation.

These techniques cannot deal with high concentration wastes and dilution of a radioactive waste stream prior to treatment by this method is not likely to be practical due to the subsequent volume increase.

A variation of this process is to use UV to cause photochemical decomposition of hydrogen peroxide, resulting in strong oxidants that can then be used to oxidise the organic material in a waste stream to CO_2 and water.

Another advanced oxidation technique is catalytic chemical oxidation with alumina coated in platinum as a catalyst to promote the decomposition of organic waste materials in a high temperature (450 – 750C) without ignition. However, this requires complex and expensive equipment, including off-gas treatment to reduce aerial emissions and, as yet, has not been demonstrated on a large scale. While catalytic chemical oxidation is a non-flame process that allows the catalysts to be recycled, it is not therefore ready for commercial use.

Advanced oxidation techniques have been used in the US to treat halogenated solvents. It has also been demonstrated at laboratory scale to oxidise oxalic acid and TBP in nitric acid.

A pilot-plant has been built in the Republic of Korea using advanced oxidation for treating wastes arising from a radioactive laundry.

Advantages of this technique are that it uses degradable oxidising agents (such as hydrogen peroxide) and is suitable for use in mobile treatment facilities. It can be undertaken with simple equipment and at low pressures and temperatures and is suitable for low-concentration water miscible, organic waste feeds.

Safety concerns limit the hydrogen peroxide content to around 6%. Also, these types of process require dilute, aqueous waste solutions and there is only very limited experience of their application to radioactive wastes worldwide.

xi) Supercritical Water Oxidation

This process, essentially an advanced form of wet oxidation (see 3.2.9, above), uses the properties of water above its critical temperature and pressure (374 C and 22 MPa, respectively) combined with air to oxidise the organic content of waste materials. The products of the oxidation are CO_2, water and the remaining inorganic components in the form of insoluble precipitates. Metals contained in the waste material are generally converted into their oxides and precipitated out of the supercritical water. The inorganic precipitates form a concentrated sludge which will then require further treatment in order to immobilise it.

In the supercritical condition, water behaves as a non-polar fluid in which all organic materials are soluble. Oxygen can be added to supercritical water in any proportion. By further increasing the temperature and pressure of the supercritical water (beyond 400C and 25 MPa) all organic matter present will become unstable.

This process has been applied to non-nuclear industrial wastes such as chemical wastes, military toxic wastes and explosives in the USA with some success and modular, transportable treatment units have been developed to deal with small volumes of waste. In addition, this process has been applied to municipal sewerage in a number of countries. The process has been investigated in Japan for the treatment of nuclear LLW and mixed wastes. At Los Alamos National Laboratory in the USA, this process has been used on α contaminated waste materials, including solvents, rags, filters and ion exchange resins.

One advantage of the process is that it provides rapid and efficient oxidation of organic waste materials without the generation of NO_x of SO_x. It is also an efficient method of separating dissolved heavy metals and fission products from dilute aqueous solutions and is suitable for use in mobile treatment plants. However, a disadvantage is that the process plant required to create the supercritical conditions in the process water is substantial, operating at elevated temperatures and pressures and is typically limited to treating slurry wastes containing 2 – 25% organic material with particulate sizes less than 100 μm in diameter. Also, the chemical environment in the reaction chamber forms mineral acids (e.g. from the Cl or F content in the waste) which may require the addition of strong alkalis to the waste feed in order to prevent corrosion. The oxidation process is exothermic, meaning that the process needs to be controlled in order to prevent excessive temperature increases.

xii) Conditioning of treated & secondary wastes

As noted in the descriptions of the various waste treatment processes above, many of these processes result in waste forms that require further treatment before they are acceptable for disposal or long-term storage. Many of the processes also generate secondary wastes, which in turn also require processing.

The waste forms created, either as a direct result of processing the original waste material, or as a secondary waste, are generally inorganic in content and include materials such as ash, salt residues, liquids, sludges, fused solids and compacted solids. Conditioning of these materials is generally via ‘conventional’ techniques such as direct immobilisation (see section 3.1.11, above).

In some cases, however, special considerations may be necessary, as described below.

Solid waste & residues

A number of the waste treatment processes discussed above result in a solid waste product that is acceptable for final disposal or long-term storage, such as direct immobilisation (3.1.11), vitrification (3.2.3) or plasma arc (3.2.4). In these cases, the waste product requires no further conditioning.

However, many of the other processes described, whilst they may or may not immobilise the waste, do not result in a form that is ready for disposal or long-term storage.

In the case of the former, for example a stable waste ‘puck’ produced by compaction (3.1.10) may be made ready for final disposal by grouting it into an overpack container using cement.

In the case of the latter, dry ash or salt residue may also be conditioned by direct immobilisation into monolith by mixing with a binding agent such as cement, polymer or bitumen. However, the waste form may need a special formulation of binding agent tailored to the nature of that waste.

Finally, substantial waste items such as mechanical components resulting from maintenance are often conditioned by direct encapsulation into a binding agent.

Appendix 4 – Waste Volume Calculations^(Note 1)

Throughput:

400 ft^3 resin / year = 11.3 m^3/year

Over 60 years this corresponds to 678 m^3 of resin

Assuming the resin arrives as 50% by volume slurry there will also be 678 m^3 of transport water over 60 years

Tested Processes:

	De-Watering	Passivation	Volume Reduction	Immobilisation	Waste Disposal Volumes (m^3/60 yr)	No. of Lifetime Products
1	Absorption	None	None	Cement Encapsulation	2256	835
2	Settling / Decanting	None	None	Cement Encapsulation	1356	502
3	None	None	None	Cement Encapsulation	2440	903
4	None	Controlled Oxidation	None	Cement Encapsulation	406	15
5	Settling / Decanting	Controlled Oxidation	None	Cement Encapsulation	406	15
6	None	None	None	Vitrification	14	5
7	Settling / Decanting	None	None	Vitrification	14	5
8	Settling / Decanting	None	None	Polymer Encapsulation	1356	502
9	None	None	None	Polymer Encapsulation	2440	903

Note: No. Of products assumes 2.7 m^3 actual vol. per nominal 3m^3 package.

Process 1 - Absorption and Cementation
Assuming cemented products are 50% by volume cement and 50% waste product:

678 m^3 raw resin feed will lead to 1356 m^3 cemented product

Assuming that the absorber can absorb 50 times its volume of water:

678 m^3 water will lead to 692 m^3 absorber

Cement consists of 20% (by volume) water and so 1356 m^3 cemented resin contains 678 m^3 cement which itself is made up of 136 m^3 water

By using 136 m^3 of the resin transport water to form the cement for the resin then this will leave:

678 - 136 = 542 m^3 water remaining for absorption

By absorbing approximately 450 m^3 of this water the remaining ~90m^3 could be used to form the cement required to encapsulate the absorber

[Note: 450 m^3 absorber + 450 m^3 cement (made up of 360 m^3 cement solids + 90 m^3 water)]

This leads to 900 m^3 cemented absorber

In total, 1356 m^3 cemented resin + 900 m^3 cemented absorber = **2256 m^3 total solid waste over 60 year lifetime**

Process 2 - Settling / Decanting and Cementation
Assume that all excess water above that necessary removed is returned to the reactor so the resin is essentially dry:

678 m^3 resin leads to **1356 m^3 cemented resin over 60 year lifetime**

Process 3 - No Dewatering and Cementation
678 m^3 resin leads to 1356 m^3 cemented resin

This requires 136 m^3 water which can be used from the transport water

This leaves 678 - 136 = 542 m^3 water to encapsulate

Assuming that a cemented product has a volume equal to 2 times the volume of water used:

542 x 2 = 1084 m^3 cemented transport water

In total 1356 m^3 cemented resin + 1084 m^3 cemented transport water = **2440 m^3 total solid waste over 60 year lifetime**

Process 4 - No Dewatering and Controlled Oxidation
Transport water is assumed to be evaporated as part of the pyrolyser process

Assuming a pyrolyser type process for controlled oxidation and using a volume reduction factor of resin of 70% by volume (reference 5):

678 m^3 resin leads to 203 m^3 ash

Cementation of the ash product will increase the volume by 2:

203 x 2 = **406 m^3 cemented ash over 60 year lifetime**

Process 5 - Settling / Decanting and Controlled Oxidation
Assume that all water removed is returned to the reactor so the resin is essentially dry

Assuming a pyrolyser type process for controlled oxidation and using a volume reduction factor of resin of 70% by volume (ref 5):

678 m^3 resin leads to 203 m^3 ash

Cementation of the ash product will increase the volume by 2:

203 x 2 = **406 m^3 cemented ash over 60 year lifetime**

Process 6 - No Dewatering and Vitrification
Transport water is assumed to be evaporated as part of the vitrification process

Using an approximate volume reduction factor of resin of 2% by volume (refs 6 & 7):

678 m^3 resin leads to **14 m^3 vitrified product over 60 year lifetime**

Process 7 - Settling / Decanting and Vitrification
Assume that all water removed is returned to the reactor so the resin is essentially dry

Using an approximate volume reduction factor of resin of 2% by volume (refs 6 & 7):

678 m^3 resin leads to **14 m^3 vitrified product over 60 year lifetime**

Process 8 - Settling / Decanting and Polymer Encapsulation
Assume that the polymer encapsulation process generates an equivalent volume of product as cement encapsulation so Process 8 generates the same volume of waste as Process 2:

1356 m^3 cemented resin over 60 year lifetime

Process 9 - No Dewatering and Polymer Encapsulation
Assume that the polymer encapsulation process generates an equivalent volume of product as cement encapsulation so Process 9 generates the same volume of waste as Process 3:

2440 m^3 total solid waste over 60 year lifetime

Process 10 - No Dewatering and Wet Oxidation
Assume similar volume reduction to Controlled Oxidation

406 m^3 cemented residue over 60 year lifetime

Process 11 - Dewatering and Wet Oxidation
As Process 10 above

406 m^3 cemented residue over 60 year lifetime

References

5 Pyrolysis of Radioactive Organic Waste. NUKEM Technologies GmbH. January 2007
6 IAEA-TECDOC-427, Predisposal Management of Organic Radioactive Waste, July 2004
7 IAEA-TECDOC-1504, Innovative Waste Treatment and Conditioning Technologies at Nuclear Power Plants, May 2006

H.Allen Jun 2008, (chkd T. Conboy)

Note 1 – Since the preparation of this report (July 2008), the waste arisings figures have been revised with improved data from Westinghouse. In addition revised resin/cement ratio data has been incorporated into the ILW encapsulation plant designs. These changes are captured in the Process Basis Of Design, 63000333-001-111-S-008 [Reference 1].