Dounreay Site Restoration Ltd

ISSUE SECTION	MARKING	DOCUMENT REF:
Waste Services	None	DEC(09)P175
Title: **A Review of National and International Best Practice on Waste Minimisation**		**Issue:** 2 **Date:** March 2009 **Page:** 1 of 60
Purpose: For Issue		**File No:**

A review has been undertaken to identify best practice techniques for the minimisation of waste disposals. The review concluded that there are many techniques available and these techniques can be grouped under a number of options against the various forms of waste i.e. solids, liquids and gases.

A review was then undertaken of the application of the techniques both nationally and internationally. This has shown that although many techniques are established and proven they have not been used extensively in the nuclear industry up until now. However, there are a number of innovative projects on-going which are investigating primarily high temperature processes for the minimisation of solid and liquid wastes.

The results of this review have been compared with the current and planned waste management strategies at Dounreay to identify any areas for potential improvement. The Dounreay site waste management strategies are largely compliant with best practice, however, a number of waste streams have been identified where there is scope for further assessment or consideration of the waste strategy, and these waste streams will be taken forward for further review by the BPEO assessment process.

The Dounreay Environment Committee (DEC) has endorsed the following:

- The report fully covers the requirement under Schedule 11 (Item 2) of Dounreay Site Restoration Ltd's regulatory authorisation granted under the Radioactive Substances Act 1993.
- The report should be submitted to the Scottish Environment Protection Agency (SEPA) as DSRL's response to Schedule 11 (Item 2) of the aforementioned Authorisation.

Issue	Date	Author Name Signature	Checked by Name Signature	Endorsed by Name Signature	Accepted by DEC
1	January 2009	Submitted to the Dounreay Environment Committee for comment			
2	March 2009	G Beaven	E Mackenzie	A Anderson	S Middlemas

Distribution:

Standard DEC, G Beaven, E Mackenzie, SEPA

Contents

1. INTRODUCTION

The purpose of this report is to identify national and international best practice for minimising waste disposals and to compare this with current and planned strategies at Dounreay to identify any potential for improvements to feed into the Dounreay Site Best Practicable Environmental Option Assessment.

A new Dounreay Site Waste Best Practicable Environmental Option (BPEO) assessment is to be completed for submission to SEPA in June 2009. This is a requirement under Schedule 11 of Dounreay Site Restoration Ltd's (DSRL's) regulatory authorisation granted under the Radioactive Substances Act 1993 (Item 1).

A further requirement of Schedule 11 (Item 2) is to: 'provide SEPA with a full report of a comprehensive review of national and international developments in best practice for minimising all radioactive waste disposals, together with a strategy for achieving reductions in such disposals.' DSRL undertook this review as the first step in the BPEO assessment so that it would provide input to the identification of relevant options for further investigation.

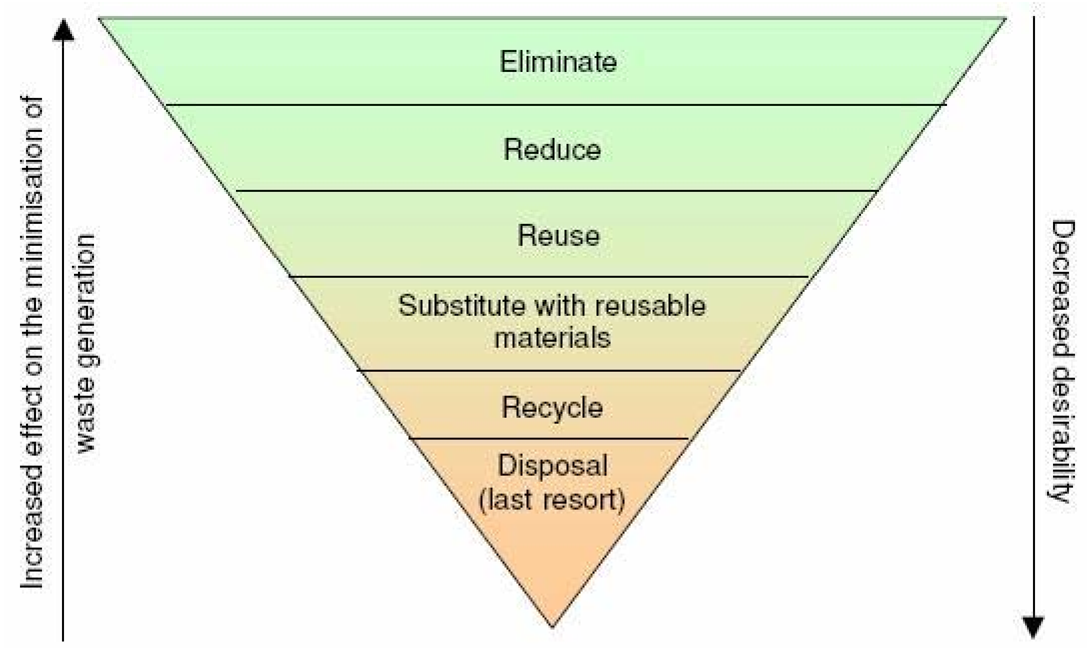
This report provides the results of the review into best practice developments, briefly comprising:

- Identification of best practice technologies for waste minimisation
- Identification of best practice or new developments in waste minimisation in the UK
- Identification of international waste minimisation best practice or developments
- Summary of the Dounreay approach to the application of waste minimisation
- Comparison of best practice with current site practice and the waste management strategies at Dounreay to identify any gaps that will require further work
- Proposal of possible options for further consideration and analysis

1.1 Waste Minimisation Review

To provide a clear basis for the study it is important to clarify what is encompassed by waste minimisation. In its simplest form, this requires avoidance of waste in the first instance and reducing as far as possible the volume requiring disposal once the waste has been produced.

SEPA's National Waste Strategy for Scotland [1] and National Waste Plan [2] identify that use of the waste hierarchy is one of the key principles for sustainable waste management. The waste hierarchy gives an order of preference to options for waste management to minimise the volume for disposal. The hierarchy is generally given in the following form, with the higher options being preferred:



For radioactive waste, minimising both the activity and volume of waste as far as reasonably practicable is important. The International Atomic Energy Agency (IAEA) has defined a set of principles underpinning the strategy for managing radioactive waste, the seventh of these principles relates to waste minimisation and outlines the measures which may be considered to minimise waste generation:

> *'The generation of radioactive waste shall be kept to the minimum practicable, in terms of both its activity and volume, by appropriate design measures and operating and decommissioning practices. This includes the selection and control of materials, recycle and reuse of materials, and the implementation of appropriate operating procedures. Emphasis should be placed on the segregation of different types of waste and material to reduce the volume of radioactive waste and facilitate its management.'*

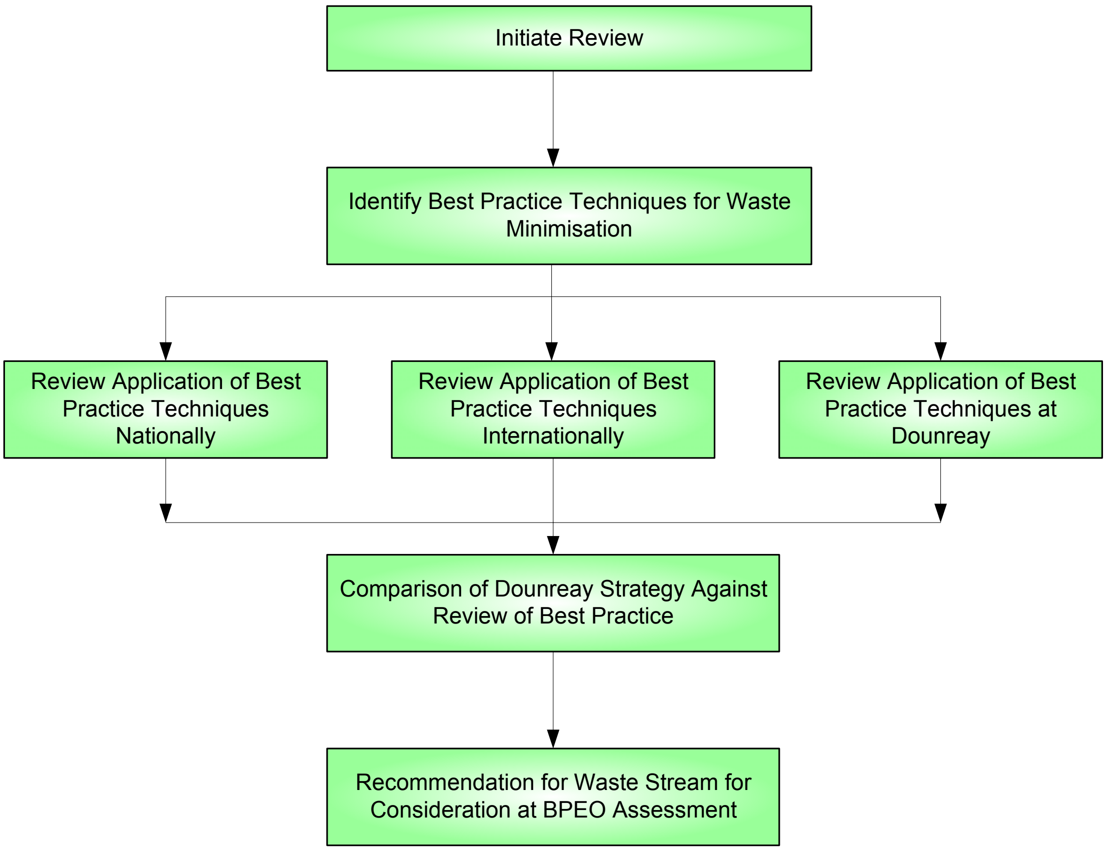
Waste minimisation is a requirement under a variety of legislation, including the Radioactive Substances Act 1993 and Nuclear Installations Act. Under the Nuclear Site Licence, site Licence Condition 32 requires arrangements for minimising the rate of production and total quantity of radioactive waste accumulated on site. The HSE provides guidance on the management of radioactive waste on nuclear licensed sites which spells out their expectations for the application of waste minimisation [3]. This includes:

- Avoidance of the production of secondary waste
- Segregation of waste streams (by waste category, physical and chemical properties)
- Preventing the spread of contamination
- Recycling and reuse of material
- Waste clearance
- Decontamination
- Volume reduction
- Disposal

As well as methods chosen to avoid the generation of waste this review has considered where each of the above practices are applicable and what has been selected as best practice.

1.2 Approach to the Review

The first stage in this review was to collect information on national and international developments in best practice for minimising radioactive waste disposals as relevant to the wastes arising at Dounreay. The prime source of information for this review was the Environment Agency Requirements Working Group (EARWG) waste minimisation best practice database. The EARWG database contains a wealth of information on abatement technologies which is the result of an ongoing review of national and international best practice and emerging technologies.



The information from the EARWG database was supplemented by reviews of IAEA, US DoE and UK nuclear site Integrated Waste Strategy and Lifetime Plan Documents. The SEPA requirement was to study radioactive waste disposals but for the purposes of the BPEO study it is appropriate to look at the management of all gaseous, liquid and solid waste at nuclear licensed sites, whether it is radioactive, exempt or radiologically clean.

The various different waste streams expected to arise at Dounreay can be grouped into a number of broad waste categories, largely dependent on the waste activity. Best practices or developments were identified for each of these main waste categories with any differences related to the actual wasteform (e.g. solid, liquid, gas) highlighted where relevant. The complete list of Dounreay waste types with waste stream specific examples is given in Table 1.

The Dounreay waste categories for use in the BPEO assessment are summarised below:

- Remote Handleable ILW
- Contact Handleable ILW
- Low Level Waste
- High Volume Low Activity
- RSA Exempt Non-Hazardous Waste
- RSA Exempt Inert Waste
- RSA Exempt Hazardous Waste
- Clean Non-Hazardous Waste
- Clean Inert Waste
- Clean Hazardous Waste
- Gaseous and Airborne Waste

Table 1: Summary of Waste Categories and Waste Streams for DSRL Site Wide BPEO

Waste Category	Waste Form	Waste Type
Remote Handleable ILW	Solid	Other (operational and decommissioning wastes), Special Nuclear Materials Declared as Wastes, ion exchange resins
	Liquid	Reprocessing liquors (from PFR, DFR and MTR), ADU floc supernatant, Special Nuclear Materials declared as wastes
	Sludge	Sludge
Contact Handleable ILW	Solid	Special Nuclear Materials declared as wastes, plutonium contaminated wastes, uranium contaminated wastes, thorium contaminated wastes, irradiated graphite
	Liquid	Special Nuclear Materials declared as wastes, contaminated solvents and oils (from fuel reprocessing)
Low Level Waste	Solid	Compactable, bulk and spoil
	Liquid	Effluent for discharge and solvent & oils
	Sludge	Sludge/ granular media, putrescible wastes from millscreens and LSA scale
High Volume Low Activity Low Level Waste	Solid	Construction & demolition material, and spoil
	Liquid	Contaminated groundwater
RSA Exempt non-Hazardous Waste	Solid	Construction & demolition materials, Soil, Recyclable (other) materials, Non recyclable (other) materials
	Liquid	Recyclable, non recyclable

Waste Category	Waste Form	Waste Type
RSA Exempt Inert Waste	Solid	Construction & demolition materials, Soil, Recyclable (other) materials, Non recyclable (other) materials
	Liquid	Recyclable, non recyclable
RSA Exempt Hazardous Waste	Solid	Construction & demolition materials, Soil, Recyclable (other) materials, Non recyclable (other) materials
	Liquid	Recyclable, non recyclable
	Sludge	Putrescible
Clean Non-Hazardous Waste	Solid	Construction & demolition materials, Soil, Recyclable (other) materials, Non recyclable (other) materials
	Liquid	Recyclable, non recyclable
Clean Inert Waste	Solid	Construction & demolition materials, Soil, Recyclable (other) materials, Non recyclable (other) materials
	Liquid	Recyclable, non recyclable
Clean Hazardous Waste	Solid	Recyclable, non recyclable
	Liquid	Recyclable, non recyclable
	Sludge	Putrescible
Gaseous and Airborne	Gas	Routine gaseous discharges

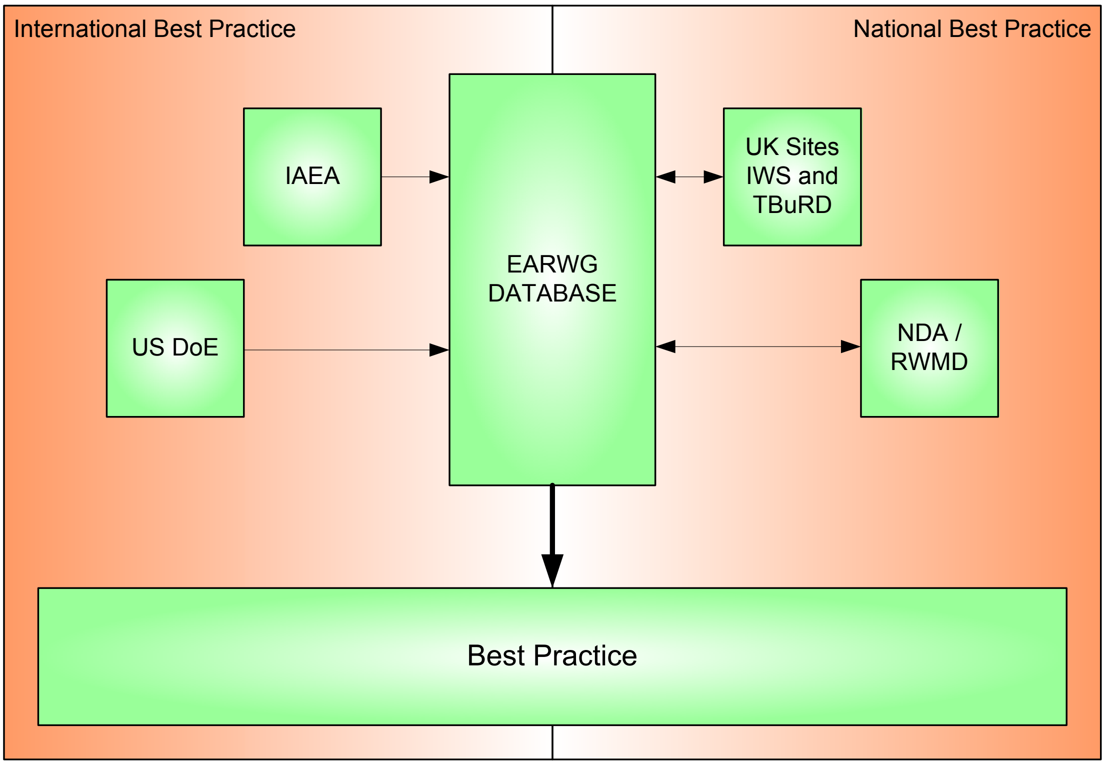
To provide a basis for comparison with best practice, a summary of the current approach to waste minimisation at Dounreay was compiled. This comprises the overarching objectives for site waste management together with how these objectives are enacted for the individual waste types. This data was largely taken from the Site Interim Integrated Waste Strategy [4] supplemented by waste stream specific data where relevant.

The Dounreay approach and strategies were then compared with the results of the review of best practice and any gaps or inconsistencies identified. These gaps and inconsistencies, and any potential revised strategies that have been identified, will be taken forward for further assessment by the BPEO process.

2 REVIEW OF BEST PRACTICE TECHNIQUES

A detailed review has been undertaken of the techniques available for the minimisation of waste arising from operational and decommissioning activities on the Dounreay site.

The basis for this review was the Environment Agency Requirements Working Group waste minimisation best practice database. The EARWG database contains a wealth of information on abatement technologies which is the result of an ongoing review of national and international best practice and emerging technologies. The information from the EARWG database was supplemented by reviews of IAEA, US DoE and UK nuclear site Integrated Waste Strategy and Lifetime Plan Documents.



The review concentrates on tried and tested techniques; reference is made to some new and developing technologies, but the references are qualified by statements of experience. With regards to decommissioning methodologies: *'Most decommissioning tasks can be accomplished with well established and proven techniques. If new techniques appear to offer some advantage, then their use should be recognised for research and development, so as not to rely too heavily on reported results'.* However, some techniques described in this review, although established and proven in various applications, have not been used extensively in the nuclear industry up until now.

There is a large inter-relationship between different waste minimisation techniques. For example, the technique used for the dismantling of solid waste items may have an impact on the generation of secondary wastes such as aerosols which may increase gaseous waste arisings. The decontamination of solid waste items may give rise to significant quantities of liquid wastes which will also need to be managed and disposed of. Therefore, before a strategy is developed and a process implemented, a full lifecycle environmental assessment should be undertaken to assess the secondary waste implications.

Limiting waste generation from decommissioning is important but a decommissioning strategy needs to optimise the balance of costs, time schedule, worker doses and waste minimisation. The development of the strategy requires decisions to be made regarding:

- The reduction of hazard and achieving passive safety;
- The need to decontaminate or fix contamination;
- Where to decontaminate or fix contamination – in situ or in a workshop at the facility, or use other facilities on or off site;
- The amount of size reduction done in situ;
- Handling wastes on site or in a centralised facility;
- Cutting under water or in air;
- Access modes and contaminated material routing;
- Manipulation and handling equipment - robots, etc;
- Methods of protection, safety and security.

Many of these have a direct impact on key issues relating to waste minimisation – source reduction, prevention of contamination spread, recycling and reuse, and waste management optimisation.

Options for reuse of materials, particularly metals and concrete rubble have been proposed but many have not yet been adopted commercially. The main factors which affect the attractiveness of recycling and reuse are:

- Quantity - processes are more likely to be developed for large quantities than small quantities of waste;
- Technical feasibility – of both decontamination and characterisation methods;
- Ability to release from regulatory control - different standards are used in different countries;
- Cost benefit – linked to resale values;
- Availability of disposal facilities;
- National policy e.g. the Government, in the new national LLW Policy, has relaxed the restrictions on transboundary transfer of LLW wastes for treatment when the required options are not currently available in the UK;
- Public acceptance of the recycling of materials from the nuclear industry and its reuse.

Decontamination can be effective at reducing dose rates associated with waste, to allow manual operations and reducing the volume of higher activity wastes requiring storage and disposal, but care must be taken to limit the quantity of secondary waste generated.

This section provides a summary of the techniques that can be used for waste minimisation. Table 2 provides a high level summary of the different options available against the different forms of waste. The application of a technique would be identified by a Best Practicable Means process and is outside the scope of this review.

Further detailed information on each technique is provided in Appendices 1 to 3.

Table 2: Overview of Radioactive Waste Treatment Options from EARWG Best Practice Database

Waste Types	Option	Examples
Solids	Sorting/segregation	Manual, Automated
	Dismantling	Dismantle
	Volume reduction	Compaction, Incineration, Oxidation, Biodegradation, Cracking / pyrolysis, Melting, Shredding, Thermochemical conversion (reaction), Freezing and crushing
	Physical decontamination	Waster flushing, Strippable coatings, Steam cleaning, Jet washing, Grinding / shaving, Milling, Drilling, Jackhammer, Ultrasonic, Melting, Thermal degradation, Abrasion, Wiping, Vacuuming / dusting, Scabbling, Laser, Vacuum desorption, Microwaves, Cryocleaning
	Chemical decontamination	Acids, bases / alkali, Complexing agents, Bleaching, Detergents, Surfactants, Organic solvents, Foam decontamination, Gels / pastes, Chemical fog / gas phase, Exothermic metalised powders (thermite), Low oxidation metal ion reagent, Microbial degradation, Dissolvable clothing, Supercritical fluids, Ice-pigging
	Electrochemical decontamination	Electropolishing / electrodeplating, Decontamination for decommissioning ion exchange, Electrokinetics / electromigration
	Encapsulation / immobilisation	Ceramic encapsulation, Bituminisation, Cementation, Polymer immobilisation, Mineral matrices (synroc), Vitrification
	Storage	Stainless Steel containers, Mild steel containers, Concrete containers, Nirex approved containers, Solid holdup containers
	Direct disposal	LLWR near Drigg[1]
Liquid	Filtration	Simple, Pre-coat filters, Cross flow, Microfiltration / ultrafiltration, Reverse osmosis
	Precipitation / flocculation	Co-precipitation, Precipitation, Polyelectrolyte bases precipitation
	Treatment of non-aqueous liquids	Biodegredation, Incineration, Conversion to solid by absorption, Encapsulation
	Chemical separation technologies	Ion exchange, Solvent extraction, UV ozonolysis
	Electrochemical separation technologies	Electroflotation / electrofloculation, Electrochemical ion exchange, Electrodeposition, Electrodialysis, Plasma mass filter
	Physical separation technologies	Evaporation, Centrifuge / hydrocyclone, Delay / hold-up / outgassing, Freeze crystallisation, Calcinations, Immobilised moss, Steam reforming

[1] For Dounreay LLW, disposal to Drigg has been ruled out by a Holyrood Direction (2005)

Waste Types	Option	Examples
Airborne Gaseous	Condensers	Condensation of vapours
	Particulate removal	Filtration, Cyclones / centrifuge
	Separation of components	Delay beds, Cryogenic separation
	Decay tanks	Decay tanks
	Gas scrubbers / absorbers	Charcoal filters, Iodine absorbers, Tritium absorbers

2.1 Solid Waste

This section contains a brief summary of the options available for the processing and storage of solid radioactive waste streams. The following processes are reviewed because they are all undertaken on the Dounreay site:

- Dismantling
- Decontamination
- Encapsulation of liquid wastes
- Volume reduction of solid wastes
- Waste storage

2.1.1 Overview of Dismantling

This is the process of actually removing and dismantling the items that are to become waste. Although not strictly a volume reduction technique, the easiest and best way to reduce active waste volumes is to ensure that all wastes are properly segregated, and that non-active wastes cannot become classified as active wastes through mismanagement.

Generally, some form of material containment must be in place to prevent any escape of particulate materials to atmosphere or the surrounding ground during dismantling/disassembly. When cutting small diameter pipes, crimping shears can be considered good practice, as they produce no secondary wastes, and prevent the escape of loose contamination into the environment. This has the added benefit of also being safer for the operator. Of the dismantling methods reviewed, mechanical cutting is the most environmentally acceptable, due to the lower energy consumption, lower waste generation and easier containment of dust and aerosols, compared to hot cutting techniques.

Details on the various technologies available for disassembly are provided in Table 7 of Appendix 1.

2.1.2 Overview of Decontamination

Generally the techniques used for decontamination of solid waste items should be kept as simple as possible to minimise environmental risks. Single stage processes should be adopted wherever practicable, as they produce lower secondary waste arisings. The technologies applicable will vary with each waste type and type/level of contamination. Combinations of technologies may often be the best option.

Owing to the unique nature of each application, good practice cannot be identified for the technologies available, with respect to minimising radioactive releases into air and water. Whichever is chosen, it is important to provide systems for dust suppression and containment and for the control of the disposal of decontamination liquors.

Generally it can be said that good practice involves:

- Minimising the requirement for decontamination by 'good housekeeping' – cleaning up any spills quickly to prevent spread and/or surface penetration
- Regular and frequent cleaning to ease decontamination requirements in the future
- Designers and operators recognising decommissioning as a key part of the facility's life cycle from the outset
- The management of decontamination procedures should ensure that areas of high contamination are dealt with first, and the procedures should ensure that recontamination is not possible. For example a component should be cleaned from the top down.

There are pros and cons to various decontamination techniques and the following key lessons have been learned from historical UKAEA experience:

- The contamination needs to be characterised and the work planned thoroughly
- The techniques used should be kept simple
- Liquids should not be used to wash down a contaminated building unless the floor and other surfaces are impermeable
- Chemicals such as chelating agents should be avoided where downstream processing can be compromised
- Where remote operations are required, test them in a mock-up facility
- Cross-contamination should be avoided

Decontamination techniques can be considered under the headings – chemical, electrochemical, mechanical, melting and other. The choice of the appropriate technique for a particular task depends largely on the material to be decontaminated and the type of contamination present.

Many chemical reagents have been developed; some are non-corrosive reagents such as detergents, complexing agents and dilute acids and alkalis, and others are aggressive chemicals including strong acids and alkalis. Whilst high decontamination factors can be achieved, high volumes of liquid secondary wastes are generated and the process is not usually effective on porous surfaces.

Electrochemical decontamination (also known as electropolishing) can be used to remove surface contamination from conducting surfaces. The process offers high decontamination factors and lower secondary waste volumes than chemical decontamination but is not suited to large items and those with complex geometries.

Mechanical decontamination can involve surface cleaning or surface removal. The most effective method depends on many variables such as the contaminants, surface material and cost. Selection of the process will also need to consider the management of the surface contamination (solid or liquid) that is removed. The techniques are usually quite versatile and there could be benefits in establishing a centralised decontamination facility on a site in which a selection of technologies could be used. Wet abrasive techniques are used in many nuclear facilities to remove smearable and fixed contamination from metal surfaces. Dry abrasive blasting can also be used although care is needed to control dust and airborne contamination. Unless the abrasive medium is recycled, large amounts of waste can be produced. For buildings; scarifiers, needle scalers, scabblers, concrete shavers and hydraulic hammers are used to remove surface contamination. These tools can be used with dust collection equipment to minimise the spread of contamination.

Metal melting is being undertaken by Studsvik in Sweden where by contaminated metals are melted and the activity remains with the slag. The recovered metals are recycled and the slag is returned to the customer for management and disposal.

Details on the various technologies available for decontamination are provided in Table 8 of Appendix 1.

2.1.3 Overview of Waste Encapsulation

Cementation is the most commonly used approach for the immobilisation and encapsulation of liquid and solid wastes. Cementation has the advantage of being much cheaper than other potential processes. However, where the waste contains substances which may react with a cementitious grout e.g. aluminium, uranium metal, salts or ion exchange resins then the use of polymer as an encapsulant may be employed.

Vitrification processes can produce an extremely stable wasteform. However, economics may prevent this option being justifiable for small inventories of waste. Vitrification has been the preferred method for immobilisation/encapsulation of HLW, although encapsulation in “Synroc” (a synthetic mineral matrix) may be better in some cases.

The potential waste strategies of high temperature processes, such as pyrolosis and geomelt, are currently being considered by a number of the Nuclear Decommissioning Authority sites in the UK. Many of the processes claim to reduce waste volumes but the processes have yet to be demonstrated on the large-scale in the UK. Internationally they tend only to be applied to low level wastes and contaminated land.

Further details on the technologies available for waste encapsulation are provided in Table 9 of Appendix 1.

2.1.4 Overview of Volume Reduction

There is some discussion as to whether volume reduction brings any real benefit, as the hazardous waste becomes more concentrated, hence the waste may become more hazardous and the techniques involve the use of energy. Full environmental impact assessments should be performed before making a decision to reduce the volume of waste by the methods listed in Appendix 1.

When procedures have been properly used to segregate wastes into combustible and non-combustible materials, incineration can be considered for combustible LLW. The incinerator must minimise active gaseous effluent, hence it should be fitted with scrubbers to remove acid gases, and filters to remove particulates.

Slagging incinerators have the advantage of producing a solid waste stream that is not dusty.

Physical compaction should be used where appropriate for solid ILW and non-combustible LLW. This both reduces storage and disposal costs.

Further details on the technologies available for volume reduction are provided in Table 10 of Appendix 1.

2.1.5 Overview of Storage of Unconditioned Waste

Although not strictly waste minimisation, the storage of unconditioned wastes can have an effect on overall waste volumes. From an environmental viewpoint:

- Long term surface storage of liquid and sludge wastes in their original form is generally not considered to be good practice because of the higher potential hazard;
- Waste must be retrievable from the store during the entire planned storage period;
- Waste packaging, repacking or over-packing must meet requirements for future storage / transport and disposal;
- Wastes should be sampled and characterised before storage and records kept for the lifetime of the storage facility;
- Before commitment to storage, waste should be segregated to simplify retrieval for later processing/disposal;
- Dusty wastes should be sealed in bags prior to placing in storage containers and confirmation that outer surfaces of wastes are free from loose contamination must be obtained before placing in a store;
- Storage of unconditioned waste does not preclude consigning unencapsulated waste for disposal. This is beneficial as there is no inactive encapsulant so it may be possible to increase the loading of waste in the packages.

2.1.6 Overview of Storage of Conditioned Solid Waste

The choice of the specific type of waste container is likely to be dependent upon local arrangements and advice given by site experts such as the area waste officer and RAM transport, therefore the following section provides an overview.

Further details on the technologies available for waste storage are provided in Table 11 of Appendix 1.

2.2 Liquid Waste

This Section provides a review of the available literature on the abatement of process releases into the water environment. It covers the technologies available for the removal of both suspended and dissolved radionuclides from aqueous process waste streams.

If solids are present in the waste stream, settling should be considered for the first stage followed by filtration. Generally filtration can be considered good practice for the removal of suspended solids. It may be more practical to include several stages of filter, with each successive stage using a smaller mesh and the final stage being a membrane system. This staging of the filtration system would prevent frequent blinding of fine (and more expensive) meshes. To improve efficiency, a pre-treatment stage of flocculation followed by settling could be used, if the chemistry allows. Electrically enhanced filtration could also be used, but the increase in cost and complexity may not be justified.

Evaporation produces a clean aqueous stream for direct disposal into the aqueous environment and a concentrated waste stream containing both solids and soluble species for disposal by cementation or another acceptable disposal route. In some cases horizontal wiped film evaporators are endorsed as good practice for concentrating liquid wastes. There are some concerns over the reliability of the equipment, and some form of reliability/operability assessment should be performed before installation. Evaporation is also energy intensive, and thus relatively expensive when compared to most standard abatement methods. It also does not help much with the reduction of tritium and carbon-14.

Precipitation/flocculation tends to be more established as a treatment method for removal of radionuclides from intermediate level aqueous waste streams; however this will need to be followed by membrane filtration to obtain the low levels of discharge now required.

Membrane (micro or ultra) filtration, involving the addition of flocculants to the waste stream, is increasingly used for the treatment of low level liquors containing a range of contaminants. If the concern is just a small number of contaminants, radionuclide-specific ion exchange should also be considered.

A detailed review of the following technologies is provided below in Table 12 to Table 17 in Appendix 2:

- Filtration;
- Precipitation and flocculation;
- Evaporation;
- Other physical, chemical and electrochemical miscellaneous technologies.

2.2.1 Overview of Storage of Liquid Waste

General considerations for the temporary storage of liquid and sludge wastes are outlined below. It is considered good practice to keep stored volumes of radioactive liquors to an absolute minimum to reduce the consequences arising from leaks.

Storage of large volumes of liquid generally involves the use of storage tanks. Sludges, resins etc. can be stored in steel or steel-lined concrete tanks with secondary containment capable of holding the entire inventory. Radiolytic production of gases and heat generation should be accounted for, and the storage facility must be designed to handle these factors safely.

Liquid storage systems should include secondary containment designed to hold at least 110% of the contents of the largest inventory, and preferably the entire inventory. Storage tanks should be designed to the relevant standards for the fluid handled and the tank wall thickness should be based on assuming water as the fluid contained, unless the fluid is denser than water.

Liquid wastes of differing activity and/or which could react chemically should be stored separate from one another.

Provision should be made to detect any leaks into a bund, and for pumping out the bund into a tank. Bunds should not contain drain valves, and should be hydraulically impermeable. The bunds should be equipped with sumps and these provided with level indicators, fitted with visual and audible high level alarms.

The storage tanks should have adequate capacity for normal, shutdown, maintenance and accident conditions and should be provided with high and low level alarms and overflow connections to another tank. Spare tank capacity should ideally be provided for use in the case of maintenance or emergencies. Tanks should be adequately vented to allow breathing in and out when liquid levels change. Underground tanks should be avoided if possible.

Tanks located in cells require measurement systems that are maintenance free, and the traditional method of measurement is with an air reaction system. Equipment that meets these criteria can require a flow of gas (usually air or nitrogen) through the process liquor to determine level and active species can be carried over in the off-gas stream. An alternative method is to use ultrasonic measurement and this is increasingly being installed for level detection in preference to the above system.

This has the advantages of being non-invasive, it does not produce a potentially active gas stream and can detect phase boundaries instead of level. However, ultrasonics cannot be used for foaming liquors. Microwave, nucleonic, and radar level sensing have the same advantages of ultrasonic level detection, but can also be used effectively where there is foaming liquors or varying vapour densities. However, these two methods are likely to be more expensive than ultrasonics.

High activity wastes (heat generating) require provision for monitoring and cooling to prevent excessive temperatures.

2.3 Gaseous and Airborne Waste

This Section provides a summary of the review of the available literature on the abatement of process releases into air, covering the technologies available for the removal of particulates from both ventilation systems and process systems. It also covers the technologies available for the removal of gaseous and entrained liquid based radionuclides from process gas streams.

HEPA filters are generally considered to be industry good practice for the abatement of particulate emissions in ventilation streams, with double filtering for some applications. Decontamination levels of 99.95 to 99.99% can be achieved for systems which are correctly installed and maintained. Of the different types of HEPA filter available, the best available technology for particulate removal is considered to be circular HEPA filters as replacement is easier to seal as there are no corners, the circular/cylindrical filter can provide an effective filter surface that is greater for a smaller volume and provide a more readily compactable item consistent with other waste containers.

Process gas streams tend to be more heavily contaminated than ventilation systems, and therefore HEPA filters would need more frequent replacement in such systems. Hence HEPA filters tend to be used downstream of the primary particle removal equipment, such as electrostatic precipitators or cyclones, in process systems to remove those particles not removed by a primary system, i.e. as ‘polishing units’.

For removal of soluble gases from process off-gas streams, wet scrubbers are generally the most effective method. For iodine removal from gas streams, iodine absorbers are the most widely used technology, and the most effective.

For short-lived radionuclides, delay beds are the most cost-effective method, and good practice for reducing radioactive contamination. Decay tanks tend to be only suitable for a limited number of relatively short half life noble gases.

A detailed review of each technology identified in the literature is provided in Table 18 to Table 21 in Appendix 3. They cover:

- Particulate removal from gas streams
- The removal of gaseous contaminants from gas streams
- Gas scrubbing
- Gas condensers

3 REVIEW OF THE NATIONAL APPLICATION OF BEST PRACTICE IN WASTE MINIMISATION

Information on national best practice for the application of waste minimisation techniques has been identified largely from individual site Integrated Waste Strategy documents and individual site Technical Baseline and Underpinning Research and Development documents. These have been compared against the baseline strategies for the waste categories identified for use in the Dounreay site wide BPEO assessment. The proposed best practice techniques for waste minimisation being applied by each site for each waste category are summarised in Appendix 4.

Some general guidelines on waste minimisation best practice were identified in the summary Magnox South Integrated Waste Strategy [5]. This sets down the following preferred practices for minimising waste at Magnox South sites:

- Segregation of radioactive and potentially clean waste;
- Only necessary items to be taken into controlled areas;
- No packaging to be taken into controlled areas;
- Use of incinerable materials in controlled areas, where possible;
- Prior consideration of the amount of material required for a job in a controlled area;
- Decontamination, where possible, to allow disposal as exempt waste;
- Volume reduction techniques such as in-drum compaction and shredding;
- Exclusion, where possible, of plastics, rubber, solvents and aerosol cans within controlled areas;
- Plant walkdowns and surveys to refine waste volume estimates.

At the waste category level the current waste management strategy at other licensed sites was examined for techniques utilised to minimise waste arisings and disposal. The findings from this review are presented below against each of the main Dounreay waste categories.

3.1 RHILW Solids

Current national best practice is to segregate wastes at source as far as possible to separate out ILW and LLW. The remaining ILW is then further minimised where possible by:

- Dry, wet or thermal decontamination techniques to convert ILW to LLW. Recommended techniques include chemical decontamination, abrasion techniques, and heat treatment, respectively;
- Further segregation of ILW by material type during dismantling e.g. concrete, steel, aluminium, lead, organics, graphite etc. to allow bespoke treatment by material type;
- Co-packaging of waste streams offers waste minimisation opportunities as waste streams are generally reported singly at the national Inventory level and co-packaging can give better utilisation of waste container capacity;
- Volume reduction by dismantling, cutting, shredding, crushing etc. to improve packing efficiency;
- Decay storage to allow time for a natural reduction in activity of the wastes.

Following waste minimisation the current baseline approach at all sites is encapsulation and storage of the remaining RHILW pending the availability of a National ILW Repository. In the past the encapsulant has generally been a cementitious material however this tends to lead to large increases in volume of the conditioned waste. Alternative treatment processes are now being considered such as thermal treatment which will produce a vitrified wasteform and the use of polymer is now becoming more extensive. Waste can also be disposed of unencapsulated as long as it meets RWMD guidance for the disposal of unencapsulated waste.

Many of the Magnox sites are looking for innovative methods for waste minimisation. Hinkley Point A is leading on the trials for thermal treatment processes. Bradwell plans to follow the Dungeness process and has undertaken a BPEO Study for the management of its Fuel Element Debris (FED) which has determined dissolution to be the preferred strategy. By this method the Magnox components are dissolved and discharged with aqueous effluent (following ion exchange), leaving the majority of radioactive components as sludge that can be encapsulated. This method offers significant volume reduction compared to the baseline strategy which specifies prompt encapsulation. Bradwell's plan is to develop agreement to make dissolution the baseline strategy [6]. Sizewell A is also considering the same process.

A summary of the baseline and new potential developments is presented below.

Baseline Solid RHILW Strategy/Practice	**New/Potential Developments Being Explored**	**Site**	**Reference**
Decontamination to LLW	None identified.	Hunterston A	[7]
		Hinkley Point A	[8]
Encapsulate in cement	Encapsulation in polymer	Harwell	[9]
	Dissolution	Bradwell	[6]
		Sizewell A	-
	Thermal treatment	Hinkley Point A	[8]
	Decontaminate ILW pond skips to LLW to allow prompt disposal. Successful operation of the Aqueous Decontamination Facility (ADF) has allowed ~350 of ~1734 pond skips to be decontaminated.	Hinkley Point A	[8]
	Decontamination of aluminium pond skips using nitric acid.	Hunterston A	[7]

3.2 RHILW Sludges and Liquids

The current baseline approach for RHILW sludges and liquids is immobilisation in a cementitious matrix followed by storage pending the availability of a National ILW Repository.

In order to minimise disposals Bradwell and Hunterston are planning to co-package and blend sludges and IX resins to maximise waste loading prior to encapsulation [10].

Hinkley Point A has recently completed an assessment of options for the management of its Wet ILW that identified immobilisation in glass (thermal vitrification) as an alternative to immobilisation in cement. This offers greater long term stability and substantial reduction in packaged volume [8, 11]. A Conceptual Letter of Compliance (CLoC) has been obtained for the vitrified product and the site is currently engaged with NDA and Regulators to take this forward. Glass formulation trials are currently underway at Sheffield University using simulants to help develop the technology [12]. Drying and supercompaction was identified as the next highest ranking and is therefore still under consideration. Other potential techniques which were assessed included polymer encapsulation, strong acid decontamination/regeneration and thermal treatments such as Molten Salt Oxidation and Steam Reformation [11].

A summary of the baseline and new potential developments is presented below.

Baseline RHILW Sludges and Liquids Strategy/Practice	New/Potential developments being explored	Site	Reference
Co-packaging and blending sludges and IX resins to maximise waste loading prior to encapsulation	None identified	Bradwell	[10]
Immobilisation in a cementitious matrix followed by storage pending the availability of a National ILW Repository	Thermal vitrification	Hinkley Point A	[8] [11] 12]
	Drying and supercompaction	Hinkley Point A	[12]

3.3 CHILW Solid

Current best practice is to segregate wastes to separate out ILW and LLW. The remaining ILW can then be further minimised by:

- Dry, wet or thermal decontamination techniques to convert ILW to LLW. Recommended techniques include abrasion techniques, chemical decontamination and heat treatment, respectively
- Dismantling, cutting, shredding, crushing etc. to improve packing efficiency and hence reduce the number of waste disposal packages
- High force compaction of compactable wastes
- Pu/U recovery whereby Pu/U is extracted from waste to allow it to be re-used. The remaining waste would then be conditioned for disposal

Following volume reduction the current baseline approach at all sites is encapsulation and storage of the remaining CHILW pending the availability of a National ILW Repository. However a potential alternative to encapsulation is thermal treatment which, depending on the technique chosen, can potentially achieve high volume reduction factors. There are a number of thermal treatment processes which could be suitable for processing of CHILW including Plasma, Metal Melting and GeoMelt. Although these processes are currently untested for CHILW, RWMD is currently undertaking a Conceptual LoC assessment for a glassy slag produced from the plasma process [13].

A summary of the baseline and new potential developments is presented below.

Baseline Solid CHILW Strategy/Practice	New/Potential developments being explored	Site	Reference
CHILW inventory has been shredded prior to packaging in 200 litre drums	None identified.	Harwell	[9]
PCM waste is high force compacted through the Waste Treatment Complex	Under review.	Sellafield AWE	[14]
Immobilisation in a cementitious matrix followed by storage pending the availability of a National ILW Repository	Thermal treatment. Plasma, Metal Melting and GeoMelt.	Sellafield	[13]

3.4 CHILW Liquids and Sludges

The current baseline approach for CHILW sludges and liquids is immobilisation by encapsulation in a cementitious matrix followed by storage pending the availability of a National ILW Repository (i.e. the same approach as for RHILW). However, thermal treatments such as plasma, pyrolysis or GeoMelt may be suitable for such wastes albeit some type of pre-treatment such as drying or adsorption may be required for high volumes of liquid [9].

A summary of the baseline and new potential developments is presented below.

Baseline Liquid and Sludge CHILW Strategy/Practice	New/Potential developments being explored	Site	Reference
Immobilisation in a cementitious matrix followed by storage pending the availability of a National ILW Repository	Thermal treatment. Plasma, Metal Melting and GeoMelt.	Magnox Sites	[13]

3.5 LLW Solids

The current practice in the UK for the disposal of solid LLW is to consign the waste to the LLW Repository in Cumbria (except for Dounreay, which is awaiting approval for its own LLW Facility). The waste consignments must comply with the LLWR conditions for acceptance. Waste consigning sites are required to use Best Practicable Means to minimise the volume of waste transferred. Current developments and best practice include:

- Only taking necessary items into controlled areas.
    - At Sellafield recent site initiatives have focussed on reducing the amount of material which is taken into active areas and hence becomes potentially contaminated [14].
- Segregation of waste.

    - At Sellafield the formation of a new clearance and characterisation team has enabled a reduction in LLW arisings by providing a centralised pre-demolition characterisation assessment profile which then informs segregation in order to maximise clean/exempt and lower category waste yields [14].
    - Bradwell has recently obtained consent from the Environment Agency (EA) to employ 'activity averaging' for consignments of non-contaminated asbestos and asbestos contaminated with low levels of tritium. This has reduced the consignments of contaminated waste that are sent to the LLW repository [10].

- Decontamination where possible.
    - At Winfrith metal LLW is decontaminated to exempt levels using the Winfrith Abrasive Cleaning Machine (WACM) [15].
    - At Sellafield surface contaminated LLW metals that are suitable for abrasive decontamination are currently processed through either of the two site "wheelabrators" [14].
    - A facility has recently been built at Bradwell incorporating blast cleaning, vacuuming, strippable coatings, scarifying/scrabbling and grinding/shaving/polishing [6].
    - Trials for acid decontamination of filters are currently being carried out at Sizewell A [16].
- Segregation of combustible wastes (e.g. oils, solvents, graphite etc.) followed by incineration. This primarily represents a volume reduction treatment as the majority of the radioactivity remains in the ash.
    - At the Magnox South Sites combustible LLW is incinerated where possible either on or off-site. Depending on the source and type of waste, ash may be consigned for disposal at the LLWR or returned to the originator for further processing e.g. high force compaction, and potential recovery of materials [5].
    - At Harwell plans are being developed to incinerate woodwork, such as doors arising from decommissioning that cannot be consigned as exempt waste [9].
- High force compaction of non-combustible solid wastes where possible, to effect volume reduction.
    - At Dounreay compactable LLW is supercompacted in the Waste Receipt, Assay, Characterisation and Supercompaction facility (WRACS) [17].
    - At Sellafield compactable LLW is supercompacted in the Waste Monitoring and Compaction Plant (WAMAC) [14].
- Size reduction of non-combustible wastes which are not suitable for high force compaction.
    - A facility has recently been built at Bradwell incorporating size reduction techniques such as power nibblers, saws, shears and shredding, in order to improve packing efficiency and hence reduce the number of waste packages sent for disposal [6].
- Segregation of metal followed by melting.

    - Hinkley Point A has taken the lead in considering alternatives to disposal of pond skips to the LLWR near Drigg. Trial transfer of contaminated pond skips to the United States for recycling by metal melting, for reuse in the nuclear industry, has underpinned this approach as the BPM solution for contaminated metals over the current baseline [8].

- Clearance of asbestos wastes
    - Greater use has been made of exemption procedures which has reduced the requirement for managing large volumes of asbestos as radioactive waste [18].

New initiatives by the LLW Repository (LLWR) are also aimed at significantly reducing the volume of waste for disposal at the Repository. The LLWR is now offering ‘Segregated Waste Services’ for metallic, combustible and Very Low Level Waste (VLLW). Subject to prior approval the aim is for these wastes to be segregated at source and then dispatched to the LLWR for onward treatment or disposal. The LLWR is responsible for the provision of the new routes and for gaining regulatory approval and it is anticipated that the metallic wastes and combustible wastes routes are to be available from the end of 2008. The LLWR Conditions for Acceptance specify the requirements for materials to be accepted via each of these routes, e.g. “*reasonable means shall be used to …segregate metallic waste into the following waste categories: stainless steel, carbon steel, aluminium, brass, copper and lead*”.

In addition to the above waste minimisation practices Hinkley Point A is taking the lead in developing a design for an on-site LLW disposal facility. However, such a facility is unlikely to be available at any site before 2010. If realised, this could offer a significant opportunity to reduce the amount of LLW transferred to the LLWR near Drigg [11].

A summary of the baseline and new potential developments is presented below.

Baseline Solid LLW Strategy/Practice	**New/Potential developments being explored**	**Site**	**Reference**
Segregation of LLW and potentially clean waste	None identified	Sellafield	[14]
		Bradwell	[10]
Segregation of (HVLA) LLW	None identified	Capenhurst	[17]
Decontamination to exempt levels	None identified	Winfrith	[15]
		Sellafield	[14]
		Bradwell	[15]
Consignment to LLWR	The strategy for the demolition of the pond and bunkers is scabbling to variable depths which has the ability to remove known contamination levels greater than LLW	Hunterston A	[7]
		Sizewell A	[16]
Incineration of combustible wastes	None identified	Magnox South Sites	[5]

Baseline Solid LLW Strategy/Practice	New/Potential developments being explored	Site	Reference
Consignment to LLWR	Incineration of woodwork	Harwell	[9]
Supercompaction	None identified	Dounreay	[4]
		Sellafield	[14]
Size reduction (cutting, shredding)	None identified	Bradwell	[6]
Consignment to LLWR	Segregation of metal followed by melting	Hinkley Point A	[8]
Dewatering of LLW sludges	None identified	Berkeley	[19]
		Trawsfynydd	[8]
Clearance of asbestos waste	None identified	All	[18]
Consignment to LLWR	Segregation by material type	LLWR	[18]
Consignment to LLWR	On-site LLW disposal facility	Dounreay	[4]
		Hinkley Point A	[11]

3.6 LLW Liquids and Sludges

There are many different practices in operation on UK sites to minimise the generation of liquid discharges [8, 9, 14]. These are summarised below:

- Liquids are subject to treatment prior to discharge, utilising a range of effluent treatment techniques e.g. separation using ion exchange beds, filtration, precipitation and flocculation etc. This adjusts the chemical content and removes sufficient radioactivity to discharge the resulting effluent.
- Plant, such as ion exchange beds and filters, which is essential to minimising activity levels, is subject to maintenance, inspection and testing regimes to ensure that it is operating correctly.
- The management of discharges of aqueous effluent is subject to the limits and conditions set in the RSA93 authorisation for the site. In particular discharges are subject to the requirement to use BPM to minimise the activity discharged and to exclude all entrained solids.
- Prior to discharge liquids are sampled and analysed to ensure compliance with the limits and conditions of the RSA93 authorisation. Should the effluent in a tank be non-compliant, the tank will not be discharged. In this case, the effluent will be re-treated through the available treatment facilities.

One example of innovative application of these techniques is at Berkeley where they have de-watered aloxite and pond sludge for disposal as LLW direct into HHISO containers without the need to encapsulate in 200 litre drums resulting in a significant reduction in waste volume to the LLWR [19].

An example of flocculation and filtration is the use of the Enhanced Actinide Removal Plant (EARP) as Sellafield for the treatment of bulk liquors using hexacyanoferrate and then ultrafiltration. Any particulate remaining in the liquid is allowed to settle out before the liquid is discharged to sea. This can also include the use of ion exchange resins for the removal of activity prior to discharge of exempt liquid wastes.

A summary of the baseline and new potential developments is presented below.

Baseline LLW Liquid and Sludge Strategy/Practice	New/Potential developments being explored	Site	Reference
Encapsulation in cement	Dewatering of LLW sludges	Berkeley	[19]

3.7 HVLA Waste

High Volume Low Activity (HVLA) LLW is not currently recognised as a specific waste type arising at nuclear licensed sites but is a general term to describe the lower activity LLW which generally arises from decommissioning waste. Harwell are currently looking into the development of a new on-site HVLA waste disposal facility [9]. At Capenhurst HVLA LLW is segregated and disposed under 'controlled burial' arrangements at Clifton Marsh [17].

Whilst such wastes must remain subject to control under RSA 93 and NIA 65, a study conducted by CIRIA in 2005 [20] suggested they may be suitable for re-use or recycling for on-site uses. Thus, mildly contaminated steel may be suitable for the construction of waste containers; mildly contaminated concrete may be suitable for inclusion in grouting material and mildly contaminated rubble may be suitable for infill of voids. Alternatively such wastes could be disposed to off-site landfill facilities.

A summary of the baseline and new potential developments is presented below.

Baseline HVLA Strategy/Practice	New/Potential developments being explored	Site	Reference
Disposal to the LLWR	On-site HVLA LLW disposal facility	Harwell	[9]
	Re-use or recycling for on-site uses or disposal to off-site landfill facilities	CIRIA	[20]

3.8 RSA Exempt and Clean Non Hazardous Waste

Current best practice is to segregate non-hazardous wastes from inert wastes to reduce volume and to segregate the remaining non-hazardous wastes according to their material type to allow maximum re-use/recycling [8, 9, 14].

Capenhurst use a contractor for their non-hazardous waste who operate a local waste segregation and transfer station. Overall, about 47% of site waste is transferred to the recycling market by the main waste contractor [17]. Non-hazardous wastes that cannot be recycled are generally sent to landfill, however, they could potentially be incinerated with energy recovery.

Site Decommissioning Sustainable Practices in the Use of Resources (SD SPUR) has listed the potential applications for high volume low value wastes as:

Material	Potential Applications	Current Practices
Aggregate	Crushed – used as bulk filler	50% use as aggregate, 40% otherwise reused 10% landfill disposal
Excavated soil	Landscaping	On-site applications such as landscaping and ground raising
Road planings	On and off site construction and repair of roads	Nationally most road planings are recycled
Timber	Reused on site or used in chip board manufacture	Unknown amount is recycled, rest sent to landfill
Concrete	Crushed – used as bulk filler	About 90% from building demolition used in some form

And for high value wastes as:

Material	Potential applications	Current practices
Bricks and blocks	Restoration work	Often crushed and used as aggregate
Steel	Recycled off site	Usually recycled if can be separated
Plastics	Remoulded for an alternative use	Processes are being developed and refined
Glass	Specialist reprocessing, Concrete aggregate	Some glass from bottles and containers recycled
Non-ferrous metals	Recycled via scrap metal industry	Unknown amount recycled. Rest sent to landfill

A summary of the baseline and new potential developments is presented below.

Baseline Exempt and Clean Waste Strategy/Practice	**New/Potential developments being explored**	**Site**	**Reference**
Segregation from inert wastes followed by segregation by material type to enable maximum re-use/recycling	None identified	Magnox South Sites	[8]
		Harwell	[9]
		Sellafield	[14]
		Capenhurst	[17]
	Incineration with energy recovery for combustible non-recyclable wastes	Capenhurst	[17]
	Magnox south are proposing a new “yellow box” container for the packaging, storage, transport, and disposal of ILW. This box will be made from recycled lightly activated and contaminated steel from nuclear sites	Magnox South Sites	[21]

3.9 RSA Exempt and Clean Inert Waste

Typical inert waste types include concrete, bricks, soil and stones. It is currently best practice to retain these materials on-site to be recycled as back-fill for voids generated during decommissioning. Excess material that is not used on site can be sold or as a last resort sent to landfill [8, 9, 14].

A summary and the baseline and new potential developments is presented below.

Baseline Exempt and Inert Waste Strategy/Practice	**New/Potential developments being explored**	**Site**	**Reference**
Retain on-site to be recycled as back-fill for voids generated during decommissioning	None identified	Magnox South Sites	[8]
		Harwell	[9]
		Sellafield	[14]
		Magnox North Sites	[12]

3.10 RSA Exempt and Clean Hazardous Waste

Current best practice is to segregate mixed hazardous wastes as far as possible as this may produce a smaller volume of residual hazardous waste, with remaining material classed as non-hazardous. All remaining hazardous wastes are segregated according to their material type to allow maximum re-use/recycling. Hazardous wastes that cannot be recycled are separated into combustible and non-combustible fractions and incinerated or pre-treated for disposal respectively [8, 9, 14].

Volumes of hazardous waste can also be reduced by optimising the waste retrieval process. For example, at Bradwell the replacement of the 'quilling' process, utilising wet shot blasting to remove the remaining ingrained asbestos; with a 'dry ice' cleaning system has removed the need to use absorbent material to soak up the water which was subsequently despatched as hazardous waste to landfill [10].

A summary and the baseline and new potential developments are presented below.

Baseline Exempt and Clean Hazardous Strategy/Practice	New/Potential developments being explored	Site	Reference
Segregation from non-hazardous wastes followed by segregation by material type to enable maximum re-use/recycling	None identified	Magnox South Sites	[8]
		Harwell	[9]
		Sellafield	[14]
		Magnox North Sites	[12]
Incineration of combustible non-recyclable wastes	None identified	Magnox South Sites	[8]
		Harwell	[9]
		Sellafield	[14]
		Magnox North Sites	[12]
Optimisation of waste retrieval process	None identified	Bradwell	[17]
Clearance of asbestos waste	None identified	All	[18]

3.11 Clean and Exempt Liquid Discharges

The current best practice for the management of clean and exempt liquid discharges is the treatment of the liquid waste prior to discharge. This can include separation of organic and aqueous waste streams, filtration to remove particulates to minimise the activity discharged and flocculation using a flocculating agent to remove activity.

A summary of the baseline and new potential developments is presented below.

Baseline Liquid Discharges Strategy/Practice	New/Potential developments being explored	Site	Reference
• Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. • Thorough maintenance of treatment plant • Sampling and analysis of liquids prior to discharge to ensure compliance	None identified	Magnox South Sites	[8]
		Harwell	[9]
		Sellafield	[14]

3.12 Gaseous Discharges

Application of BPEO, BPM, and waste minimisation principles ensure that gaseous arisings are minimised at source and subsequent treatment utilises good design principles to ensure the majority of gaseous contamination is transferred to solid or aqueous form, where it has a lesser impact.

At all sites contamination control procedures are in place and cleaning of equipment is carried out periodically in order to reduce levels of 'loose' surface activity which might become airborne. Containment e.g. tenting is used where necessary to minimise the spread of airborne contamination.

In addition to taking measures to limit the generation of airborne activity, the major discharges of gaseous radioactive waste are treated by various types of effluent control equipment. The most widely used item of pollution abatement equipment is the High Efficiency Particulate in Air (HEPA) filter, as particles are the main source of contamination in most of the gaseous streams. Wet scrubbers are also used, especially on streams where significant volatile activity is present, for example caustic scrubbers are employed to remove iodine and carbon dioxide. Other equipment used includes electrostatic precipitators, packed beds, condensers and pre-heaters (to prevent condensation in the filters). Every building or plant has individual needs, and containment and ventilation systems are designed to ensure the safety of plant operators and to minimise, as far as reasonably practicable, gaseous effluent discharges to the environment [14].

A summary of the baseline and new potential developments is presented overleaf.

Baseline Gaseous Discharges Strategy/Practice	**New/Potential developments being explored**	**Site**	**Reference**
• Periodic cleaning of equipment to reduce levels of 'loose' surface activity which might become airborne. • Use of containment e.g. tenting to minimise the spread of airborne contamination. • Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids, wet scrubbers to remove significant volatile activity, electrostatic precipitators, packed beds, condensers and pre-heaters (to prevent condensation in the filters).	None identified	Sellafield	[14]

Some Magnox sites still have large radionuclide discharge authorisations because they are either still operational or they still have fuel on site.

4 REVIEW OF THE INTERNATIONAL APPLICATION OF BEST PRACTICE FOR WASTE MINIMISATION

This review has considered the application of best practice for the minimisation of wastes arising on international nuclear sites. The techniques used depend on the nature of the waste and the specific regulatory framework of the location (country and site). It has been difficult to identify any innovative waste minimisation techniques applied on international sites which have not already been identified in the review of the national application of best practice.

A very important factor in determining the appropriate waste management method is whether disposal facilities are available in the country of interest. If they are available or if conditions for acceptance have been agreed then treatment technologies will be driven by the constraints imposed by the disposal facility. If there are no disposal facilities then the constraints associated with storage will need to be considered.

There are a number of principles that aim to minimise waste disposal quantities which are generally followed by most nuclear waste producing countries. These are:

- Limit waste production at source
- Understand and characterise the waste stream
- Recycle for reuse whenever possible
- Volume reduce (if not recyclable)

4.1 Best Practice for the Minimisation of Solid Radioactive Wastes

Typical methods of solid ILW and LLW radioactive waste treatment across many countries include compaction, decontamination, incineration and metal melting [22]. The particular method adopted will depend on the waste type and other factors such as the availability of facilities. Concentration of waste management activities may encourage recycle and reuse practices such as segregation and recovery of valuable items (scrap, tools, safety clothing) that could not be justified at dispersed facilities.

4.1.1 Compaction

Compaction is widely used to reduce waste volume. The volume reduction depends on the nature of the waste and the compaction force. Since the 1990s the compaction force used has increased to 20MN or more. Generally the pucks produced are encapsulated by grouting into a larger container. Some wastes such as compressed gas canisters, explosive materials, powders and bulky items are not compatible with the compaction process. In addition wastes that cause reassertion and wet wastes may be excluded unless the plant is designed to accommodate them. Compaction is used for ILW in the Netherlands, France, UK, Germany, Russia, USA, Ukraine and elsewhere. It is also used for LLW in Spain (El Cabril), Italy (Sogin).

Compactors are also used for decommissioning LLW on DoE sites. At East Tennessee Technology Park the compactor’s large compression box allows items up to 26ft long by 14 ft wide by 6 ft high to be size reduced [23].

4.1.2 Incineration

Incineration is used in several countries (Austria, Belgium, Canada, France, the Netherlands, the Russian Federation, Slovakia, the UK and the USA) to reduce the volume of combustible wastes requiring disposal. For high volumes of waste, usually LLW, an excess air incineration process is preferred but pyrolysis (or air starved incineration) can be appropriate for smaller volumes, particularly ILW, to prevent vigorous burning. The primary product of the incineration process is ash which is usually immobilised before storage or disposal. Incineration also produces secondary waste arising from pre-treatment of the waste, scrubber liquids and off-gas filtration wastes. Although incineration can achieve high volume reduction ratios and is able to deal with many different types of waste, the process has relatively high capital and maintenance costs and may produce environmentally damaging by products such as dioxins. Preventing the release of these materials adds to the cost. Also public perception of incineration is often negative.

Incineration Where used (examples)	Start of operations	Product	Comment
Canada - Ontario Power Generation	2003	Solid & liquid wastes	
Belgium – Belgoprocess	1995	Solid & liquid wastes	
Netherlands – Vlissingen -Oost	1994	Organic liquids, solid biological matter	Some operating difficulties

Incineration was used on US Department of Energy sites but the facilities at some sites (INEEL and Savannah River) have been closed.

4.1.3 High Temperature Processing

Pyrolysis with flue gas treatment has been used when corrosive materials such as phosphates are produced by incineration or volatile species such as ruthenium and caesium are present. Pebble bed pyrolysis has been used in France and Belgium to treat organic solvents. Pyrolysis in tandem with steam reforming has the capability of treating a variety of wastes although some wastes require specialised pre-treatment which can be costly.

Heat Input Technique	Technology Suppliers	Where used
Plasma Arc	“PACT” – Retech	Zwilag, Switzerland 2000 Tsuruga, Japan 2006
Plasma Arc	Tetronics	UK PCM Research
Joule Heating	GeoMelt – AMEC	Marlinga, Hanford
Joule Heating	Duramelt – Energy Solutions	LLW Systems
Plasma Arc/ Joule Heating	PEM2 – Integrated Environmental Technologies	LLW prototype Hazardous chemicals
Plasma	Phoenix Solutions	JAERI, Japan
Steam Reformation	THOR – Studsvick	USA commercial plant
Synroc - Ansto	ANSTO	Idaho, Hanford Australia

Radioactive ion exchange bead, powdered filter media and activated carbon resin is processed by Studsvik using the Thermal Organic Reduction (THOR^{TM}) process at Erwin, Tennessee. The process utilises pyrolysis/steam reforming technology and treats liquid and solid LLW with high water and/or organic content.

4.1.4 Melting

Melting can be used to decontaminate items if the contamination is volatile or collects in the slag but even if the contamination is held within the ingot produced by the process, melting usually results in a significant volume reduction. Also as the contamination is distributed homogeneously in the product some may be re-used within the nuclear industry. Melting is particularly effective at decontaminating waste containing ^{137}Cs as it accumulates in dust collected by ventilation filters.

Industrial scale plants for melting contaminated metal steels include the following:

Plant	Site	Country	Start year
STUDSVIK	Studsvik	Sweden	1987
CARLA	Siempelkamp	Germany	1989
INFANTE	Marcoule	France	1992
Oak Ridge	Oak Ridge	USA	1992
Oak Ridge	Oak Ridge	USA	1996

In France the treatment for low level metal wastes is melting, for example in Socodel's Centraco plant at Marcoule. Incinerable LLW is sent to an incinerator on the same site. Non combustible wastes are compacted in drums. The scrap metal is recycled as shielding in disposal packages or used to construct waste drums.

4.1.5 Encapsulation

After treatment the waste is immobilised using either cementation, bituminisation, incorporation into polymers, glass matrixes, ceramics etc. [24]. The most common approach for waste encapsulation across the world is now encapsulation in cement

Vitrification was developed for high level wastes but has been suggested as being suitable also for lower activity wastes. Whilst vitrification produces a low leachability waste form and a high volume reduction some wastes (organics) require separate destruction and blending processes. Also the gas cleaning will generate a secondary waste that needs to be considered.

4.2 Best Practice for the Minimisation of Sludge and Liquid Radioactive Wastes

International sites follow the same techniques for the minimisation of liquid and sludge wastes as applied on UK nuclear sites.

The most common method of dealing with sludges is to mix them with a material that sets to form a solid mass. The use of hydraulic cements to immobilise particulates or sludges is widespread although the development of a suitable formulation can present problems. Potentially difficult residues include metastable intermediaries with a high demand for water, hydrophobic materials, or extremes in pH [25].

Sludge from water treatment is generally amenable to immobilisation in common agents such as Portland cement.

Typical liquid effluent treatments are ion exchange, precipitation and evaporation [22].

Treatments of liquid wastes are based on conventional waste water treatment processes. The primary processes are the removal of suspended solids and neutralisation, if required. The removed solids are treated as sludge. Evaporation may be used to concentrate the liquid before immobilisation. High salt liquid wastes, unsuitable for stabilisation using common immobilisation agents such as Portland cement, may be dried and stabilised using polymers or other salt tolerant media such as glass or ceramic [24].

Ion exchange is one of the most common and effective treatment methods for liquid radioactive wastes. It is a well developed technique that has been employed for many years in both the nuclear industry and in other industries. Inorganic ion exchangers often have greater selectivity than organic resins for caesium and strontium and may have advantages with respect to stability and immobilisation, but organic resins have been around for much longer and there is more experience of their use. The IAEA noted that ion exchange is often the most appropriate way of treating a variety of low and intermediate level liquid waste streams. From the standpoints of economy and efficiency, ion exchange lies between the two other major liquid waste treatment processes of evaporation and chemical precipitation. Evaporation may give higher decontamination factors (although the performance of ion exchange resins is improving) but is more costly. Chemical precipitation is cheaper but is not always as effective at removing radionuclides from solution [26].

Widely used treatment methods for aqueous wastes are summarised below:

Method	**Features**	**Limitations [27]**
Chemical precipitation (coagulation / flocculation / separation)	Suitable for large volumes Industrial operation Inexpensive	Low DF
Organic ion exchange	DF good if low salt content	Limited radiation stability Difficult immobilisation
Inorganic ion exchange	Good DF Easy immobilisation	Affected by high salt content Possible high cost
Evaporation	Good DF Well established Suitable for large number of radionuclides	May be process limitations (scaling, foaming etc.) High capital and operations cost
Solvent extraction	Selective removal of some radionuclides	Generates aqueous and organic secondary wastes

Other processes such as reverse osmosis, ultrafiltration, microfiltration and electrochemical are less frequently used, but can offer benefits for some wastes.

Evaporation is widely used by the US Department of Energy to reduce the volume of liquid wastes or to evaporate to dryness. Forced recirculation evaporators and agitated thin film evaporators are examples of specific technologies that have been used. Water removal rates are in excess of several m^3/day [23].

Widely used processes for organic liquids are shown below.

Method	Features	Limitations [27]
Incineration	High volume reduction Deals with all organics	Secondary waste must be treated Off gas filtration needed High temperatures needed to get full decomposition
Emulsification	Allows liquid organics to be incorporated into cement	Low incorporation rates
Absorption	Solidifies and immobilises organics	Only suitable for small quantities
Phase separation (solvent extraction)	Produces clean solvent	Relatively expensive
Wet oxidation	Low temperature Simpler than incineration Suitable for biological wastes	Residues require immobilisation

4.3 Best Practice for the Minimisation of Gaseous and Airborne Wastes

International sites follow the same techniques for the minimisation of gaseous and airborne wastes as applied on UK nuclear sites.

Depending on the nature of the off gas it may require treatment prior to discharge. Treatment may involve scrubbing to remove acid gases or other noxious substances, filtration to remove particulates, absorption (charcoal bed) to remove volatiles, or further heating to destroy toxic or hazardous substances such as dioxin. Each of these stages could produce secondary wastes. If the gas contains tritium or carbon-14, other treatments may be needed, but due to the high costs involved, it is not always the BPM to adopt them.

Frequently, a filtration system is used to remove radionuclides from exhaust air flows. HEPA filters are used to remove aerosols and sorption filters (usually charcoal based) are used to remove noble gases and iodine. In order to extend the life of the HEPA filters, prefilters are used to remove heavy dust concentrations and extraneous materials [27].

5 DOUNREAY APPROACH TO WASTE MANAGEMENT

The approach used by DSRL to waste management can be summarised by the following principles:

- Protection of the public, workforce and environment
- Keeping radiological doses and environmental impact ALARA
- Converting wastes into a passively safe state as soon as practicable
- Minimising discharges through the use of BPM
- Strategic planning
- Application of the waste hierarchy
- Consideration of BPEO/BPM in the selection of waste management options
- Proximity principle
- Sustainable development
- Use of good practice guidance such as the industry code of practice on clearance and exemption
- Application of SEPA Waste Strategy for non-radioactive wastes.

One of the key requirements of the waste management policy is to ensure the production and accumulation of new wastes (both radioactive and non-radioactive) is minimised. This is achieved through the application of the waste hierarchy to ensure:

- The amount of waste requiring disposal is minimised
- The planning of projects addresses opportunities to
    - Avoid waste production
    - Minimise waste volumes
    - Maximise reuse and recycle of materials

In addition to the above, the management of wastes at Dounreay also takes into account the requirements of local and regional waste plans [28]. The main objectives of these are:

- Effective waste minimisation measures will be adopted and management will be aimed at the highest achievable level within the waste hierarchy
- The waste will be managed as near as possible to where it is produced
- Environmental impacts will be kept to a minimum
- Increased community and stakeholder involvement and ownership

A number of sources of guidance for all the aspects of waste management outlined previously in this section are used by DSRL. These include:

- Nuclear Industry Code of Practice for Clearance and Exemption [29]
- SAFEGROUNDS – Good practice guidance for the management of contaminated land [30]
- SD:SPUR – Site decommissioning sustainable practices in the use of resources [31]

- HSE, EA and SEPA – Joint Guidance on Radioactive Waste Management [32]
- EA and SEPA – Guidance for the Environment Agency Assessment of BPEO studies at nuclear sites [33]
- EA – Pollution Prevention Guidance Notes [34]
- EA Requirements Working Group (EARWG) – Best Practice in Waste Minimisation [35]

The following sections describe the high level management strategies for the waste streams outlined in Table **1**.

5.1 Management of ILW

Waste materials included within this section are defined as being:

> 'Wastes exceeding the upper boundaries for LLW, but which do not need heat to be taken into account in the design of storage or disposal facilities. Operations such as storage, transport and processing require the waste to be shielded during the operation'.

Wastes which fall within the above definition of ILW are sub-divided into Remote Handleable ILW (RHILW) and Contact Handleable ILW (CHILW). The difference between the two categories being the shielding requirements for handling, storage and transport where RHILW requires more shielding than CHILW. Each of these categories are then further sub divided into waste streams based on physical form such as solids, liquids and sludges.

5.1.1 RHILW Solids

The high level objective for the management of solid RHILW on the Dounreay site is the treatment of wastes to produce a conditioned, passively safe form using a cement matrix. This is underpinned by gaining NDA RWMD Letters of Compliance for the waste which support the early conditioning of wastes pending the availability of a geological disposal facility.

The overall approach to minimisation of RHILW is to segregate it from lower activity materials (if appropriate), size reduce as necessary to meet packaging needs, condition as early as possible to produce a passively safe wasteform and store until a disposal route becomes available. In order to limit the need for new waste management facilities the processes are designed to be flexible enough to meet the specific requirements for several waste types.

Wastes within this section are managed in line with the requirements of the waste hierarchy. To minimise the amount of waste disposed of as ILW, segregation/sorting and decontamination methods are applied as appropriate. Waste which is to be disposed of as ILW will undergo a variety of volume reduction techniques to ensure the overall waste volumes are minimised. Due to the activity of wastes in this category there is generally little scope for the safe re-use and recycle of materials.

In addition to the waste minimisation hierarchy, a major driver for the management of RHILW solids is the conversion of the waste to a passively safe form suitable for disposal in the ILW repository. For these wastes this generally takes the form of encapsulation in cementitious grout.

Wastes included in this section are divided into three groups:

- Operational and decommissioning wastes (e.g. stored historical wastes and wastes generated from reactor decommissioning activities)
- Special Nuclear Materials which have been declared as wastes
- Ion Exchange columns such as those used to decontaminate storage pond water and remove caesium ions from wastes generated by alkali metal treatment operations.

The current and planned waste management methods used for solid wastes are as follows:

- Stored drummed operational wastes – the drums will be transferred to D3900 where the waste will be sorted, assayed and repackaged before encapsulation in 500 litre drums.
- Stored non-drummed historical wastes – the waste will be retrieved from the Shaft and Silo and separated from sludges and liquids. The solids will be size reduced by shredding and packaged in 200 litre drums. The drums will be supercompacted and the pucks grouted into 500 litre drums.
- Decommissioning wastes from small waste consigners in the FCA are assayed and ILW items are placed in 200 litre drums for interim storage, and then the waste will follow the management route for stored operational wastes.
- Bulk decommissioning wastes will be size reduced at the decommissioning facility and packaged and grouted into an approved container. Where necessary the items will be cleaned of NaK/Na before packaging.
- RHILW sources will be packaged alongside other RHILW materials.
- Nuclear materials considered as waste will be packaged in compliance with NDA RWMD guidance for disposal to an ILW or a HLW/spent fuel repository. Some will be packaged in 500 litre drums and encapsulated with a cement grout. Others may be encapsulated with polymer into cans which are themselves grouted into 500 litre drums.
- Ion exchange columns will be stored within 200 litre drums until processing, either by opening the columns and intimately mixing the contents with a cementitious grout in a 500 litre drum, or by injecting polymer into the column to immobilise the resin and then encapsulating the column in a 500 litre drum.

5.1.2 RHILW Liquids and Sludges

The management of liquors and sludges provides a different set of challenges than the management of solids. Because of their physical nature segregation to maximise disposals at a lower radiological category is not a viable management method. Also techniques such as dilution go against many of the underlying management principles applied by DSRL. The application of decontamination techniques (such as ion exchange) can significantly increase the amount of secondary wastes generated so careful consideration needs to be given to the actual management processes used to ensure the amount of material and waste volumes are minimised. There is also little scope for reuse or recycling of these wastes although in some cases water separated from sludges can be reused.

As with RHILW solids the conversion of the waste to a passively safe form suitable for disposal in the ILW repository is encapsulation in cementitious grout.

Wastes included in this section are:

Liquids

- Raffinates from the reprocessing of MTR, PFR and DFR fuels
- Liquid metal fast reactor coolant (NaK and Na)
- Special Nuclear Materials which have been declared as wastes

Sludges

- ADU floc
- Shaft and silo sludges

The current waste management methods used for liquid wastes are as follows:

- Raffinates are transferred to treatment facilities where they are immobilised in a cement matrix in 500 litre drums. The concentration of some liquors may need to be adjusted to meet process parameter restrictions and some liquids may need to be filtered to remove particulates, also to meet process constraints. The process constraints are set by the requirements of the Letter of Compliance to produce a waste product acceptable for long term storage and disposal.
- ILW contaminated solvent from PFR fuel reprocessing will be decontaminated to remove as much activity as possible and the “cleaned” solvent will then be incinerated.
- Radioactive Na and NaK will be reacted to produce a sodium hydroxide (or mixed sodium hydroxide/ potassium hydroxide solution) which after neutralisation will be passed through an ion exchange column to remove Cs-137. The ion exchange columns have been discussed under RHILW solids

The current and planned waste management methods used for sludge wastes are as follows:

- Sludges separated from wastes retrieved from the Shaft and Silo will be treated to precipitate solids and concentrated before immobilisation in a cement matrix in 500 litre drums using a lost paddle process.
- The ADU floc will be dissolved and processed by immobilisation in a cement matrix in 500 litre drums.

5.1.3 CHILW Solids

The high level objective for solid CHILW management on the Dounreay site is to segregate from lower activity materials (if appropriate), size reduce as necessary to meet packaging needs, condition as early as possible to produce a passively safe wasteform and store until a disposal route becomes available. This is underpinned by gaining NDA RWMD Letters of Compliance for the waste which support the early conditioning of wastes pending the availability of a deep geological disposal facility. Wastes included in this section are divided into three groups:

- Plutonium, Uranium and Thorium contaminated materials
- Special Nuclear Materials which have been declared as wastes
- Graphite

The majority of the wastes within this section have the same application of the waste hierarchy as described in Section 5.1.1.

The current and planned waste management methods used for solid wastes are as follows:

- Pu, U and Th contaminated materials and Special Nuclear Materials which have been declared as wastes – The waste is loaded into 200 litre drums and transferred to D3200. The waste is assayed and any LLW will be transferred to the LLW treatment facility. The remaining waste is compacted and the pucks grouted into 500 litre drums
- Graphite – DFR Neutron shield graphite will be packaged into 4m boxes and stored un-encapsulated and THTR graphite will be immobilised within a 200 litre drum then packaged in a 500 litre drum.

Graphite is recognised as a problem area because of the large volume of graphite waste to be disposed of to the repository. The current strategy does align with part of the waste management hierarchy as waste volume reduction is being considered as part of the management method. Additionally there is scope for other types of management processes (such as thermal treatment) to be applied.

5.1.4 CHILW Liquids

Wastes included in this section are divided into two groups:

- Special Nuclear Materials which have been declared as wastes (including thorium nitrate)
- Solvents and oils from fuel reprocessing operations

The current and planned waste management methods used for liquid wastes are as follows:

- Special Nuclear Materials declared as wastes - These materials will be managed by the same method as RHILW liquid wastes, except they will be immobilised in a mobile cementation facility rather than the facilities used for RHILW liquids
- Contaminated Solvents and oils - The proposed management method is to decontaminate the solvents and oils using a wet abatement system followed by incineration

The Special Nuclear Materials declared as wastes will be immobilised in cement.

Solvents and oils have a different proposed waste management method but still comply with the requirements of the waste management hierarchy. The direct conditioning of solvents and oils into a passively safe form suitable for disposal is challenging so instead incineration is proposed to reduce the volume of the waste (gaseous products would be discharged in accordance with the relevant site discharge authorisation) and to convert the waste to ash which can be encapsulated in a passively safe form for disposal. To minimise discharges to the environment the activity of the oils and solvents is reduced by wet abatement, the product of this process can then be managed in the same way as solids or sludges.

5.2 Management of LLW

Waste materials included within this section are defined as being:

> ‘‘Wastes other than those suitable for disposal with ordinary refuse, but not exceeding 4 GBq per tonne of alpha, or 12 GBq per tonne of beta/gamma activity”.

For the purposes of the BPEO, the wastes in this category are further broken down into waste streams labelled solids, liquids and sludges. The high level objective for LLW management on the Dounreay site is the treatment of wastes into a conditioned, passively safe form which is acceptable for disposal at the proposed on-site LLW repository.

5.2.1 LLW Solids

Wastes included in this section are divided into three categories:

- Compactable wastes
- Bulk (non-compactable) wastes
- Spoil

The current and planned waste management methods used for LLW solid wastes on the Dounreay site are as follows:

- Wastes undergo size reduction, decontamination and grit blasting as appropriate
- Wastes are assayed and sorted to minimise the amount of materials disposed of as LLW. Where possible wastes are to be managed as clean, exempt or HVLA wastes
- Items identified as still being LLW are further segregated into compactable wastes and non-compactable wastes (bulk and spoil) for further processing as required
- Compactable wastes are loaded into 200 litre drums and supercompacted to form pucks which are cemented in HHISOs prior to disposal at an appropriate LLW repository
- Non-compactable (bulk) wastes are loaded into 200 litre drums or (if large items) wrapped in plastic and cemented in HHISOs prior to disposal at an appropriate LLW repository
- Spoil wastes are loaded into 1 te bags and stored in HHISOs prior to disposal at an appropriate LLW repository

Wastes within this category have a much greater scope for the application of the waste hierarchy principles. Segregation based on radiological classification, decontamination and assay all play an important role in ensuring waste is managed as HVLA/ clean/ exempt wherever possible. Waste which is to be disposed of as LLW undergoes further segregation/sorting based on the volume reduction techniques which are to be applied to the waste (i.e. soft materials compacted, hard materials cut) to ensure the overall waste volumes are minimised as far as possible. Finally, where possible items are re-used or recycled on site.

5.2.2 LLW Liquids and Sludges

Wastes included in this section are:

- Liquids
  - Effluents produced by active facilities
  - Solvents and oils
- Sludges
  - Sludge and granular material
  - Putrescible material
  - LSA Scale

The current and planned waste management methods used for liquid wastes are as follows:

- Effluents produced by active facilities – all major sources of liquid waste are filtered at source and, where Cs-137 levels are expected to be significant, ion exchange plants are operated in accordance with BPM considerations [36]. The effluents are then transferred to the LLLETP where they undergo pH adjustment, settling and final filtration prior to discharge. In addition liquid wastes from small scale operations are evaporated
- Contaminated Solvents and Oils - the proposed management method is to decontaminate the solvents and oils using a wet abatement system followed by incineration

The current and planned waste management methods used for sludge wastes are as follows:

- Sludge and granular material – the materials will be de-watered as required and cemented in 200 litre drums
- Putrescible material – materials will be dried and stored until a management solution can be found
- LSA Scale – materials have been immobilised and will be stored until a management solution can be found

There are three sub-categories within this section, effluents, solvents/oils and sludges, each with their own management methods and thus different applications of the waste hierarchy.

Effluents are to be discharged in accordance with the site discharge authorisations and to minimise the amount of active material released to the environment the effluents are decontaminated by ion exchange, filtered and conditioned prior to discharge. Although this management method generates secondary wastes, these can be converted to passively safe forms for disposal.

The LLW solvents / oils will undergo the same process as the ILW sludges and oils. They will be incinerated to reduce the volume of the waste (gaseous products would be discharged in accordance with the relevant site discharge authorisation) and to convert the waste to ash which can be encapsulated in a passively safe form for disposal. To minimise discharges to the environment the activity of the oils and solvents is reduced by wet abatement, the product of this process can then be managed in the same way as solids or sludges.

The sludges can be divided into three waste streams with different management methods. The sludges (granular material) will be separated and concentrated and immobilised in cement in such a way that is will be accepted for disposal in the proposed on-site LLW repository. The management methods used for the millscreen putrescible wastes and the LSA scale are still under consideration. The former waste is currently dried and stored and the latter has been drummed, immobilised stored and is currently awaiting a disposal strategy.

For all wastes in this category the application of segregation, reuse and recycle principles have little real application because of the physical nature of the wastes.

5.3 HVLA Solids

Although HVLA is not a legally recognised waste category it does allow the application of different management methods to improve the results of applying principles such as the waste hierarchy.

High Volume Low Activity Materials are defined as:

> 'Waste at the lower end of the LLW range, sometimes also called VLRM. The waste is still legally LLW. The activity levels for this waste are <0.04GBq/te beta-gamma and 0.001–0.002GBq/te alpha activity'.

For the purposes of the BPEO, the wastes in this category are only broken down into solid waste streams.

Wastes included in this section are:

- Construction and demolition materials;
- Soil.

HVLA solids typically comprise of construction / demolition materials and contaminated soil. The current and planned waste management strategy for these wastes is that the materials which fall into this category will be packaged in 1 te bags and placed in interim storage in HHISOs. This material will later be used as backfill for the DSRL LLW repository and for voids on-site.

In keeping with the waste hierarchy, materials which fall into this radiological category will have undergone sorting, decontamination and assaying to maximise the amount of material which is correctly disposed of as Clean or Exempt wastes. The HVLA wastes are to be re-used on site as backfill, particularly for the proposed on-site LLW repository satisfying this aspect of the waste hierarchy. The wastes will also be volume reduced (crushed) to minimise voidage before it is re-used.

5.4 Clean and Exempt Waste Management

Waste materials included within this section are defined as:

> 'EXEMPT: The SoLA exemption order specifies that waste is exempt from the regulatory requirements under the Radioactive Substances Act 1993 (RSA 93) provided that it is substantially insoluble in water and has an activity that does not exceed 0.4 Bq/g. Material is also classed as exempt even though it may be clean due to lack of historical evidence of its providence'.

> 'CLEAN: An article or substance which has had no reasonable potential to have become contaminated or activated, or upon or within which no radioactivity other than normal background is detectable when suitable comprehensive measurement (monitoring and sampling) is practicable and has been undertaken'.

For each of the categories Exempt and Clean, the wastes are further divided into solid and liquid waste categories. These in turn are sub-divided into the following categories as appropriate:

- Solids
    - Construction and demolition materials
    - Soil
    - Recyclable other materials
    - Non-recyclable other materials
    - Sludges.
- Liquids
    - Recyclable
    - Non-recyclable

The Exempt liquids categories refer only to organic liquid waste containing C-14 or H-3 but with an activity less than 4Bq/ml.

5.4.1 RSA Exempt and Clean Non Hazardous Waste

In addition to the definition of Exempt and Clean waste given above, non-hazardous waste materials also include the following definition:

> 'NON HAZARDOUS: Controlled waste not covered by the definition of hazardous waste'.

Wastes in these categories will have undergone segregation (by radiological classification), decontamination (where appropriate) and assay to maximise the amount of material managed in these categories. In line with the waste hierarchy principles the volume of waste for disposal will be minimised by using volume reduction techniques and by maximising the reuse and recycle of materials for use on-site. Wastes which can not be re-used or recycled will be consigned to landfill for disposal.

5.4.2 RSA Exempt and Clean Inert Waste

In addition to the definition of Exempt and Clean waste given above, inert waste materials also include the following definition:

> 'INERT: Controlled waste defined in the landfill directive as waste that does not undergo any significant physical, chemical or biological transformations'.

The management of wastes in these categories is the same as the management of exempt and clean non hazardous waste.

5.4.3 RSA Exempt and Clean Hazardous Waste

In addition to the definition of exempt waste given above, hazardous waste materials also include the following definition:

> 'HAZARDOUS: Any waste which is classified in the European Waste Catalogue'.

For Solid Exempt Hazardous Wastes segregation will be carried out to ensure that only wastes which are covered by the definition of hazardous materials are managed as such. Additionally, materials will be treated for on-site reuse where possible and those which cannot be reused will be consigned to an appropriate specialist waste contractor.

Solid Clean Hazardous Wastes will be managed in a similar manner to Solid Exempt Hazardous Wastes. The major differences being a greater scope for recycle or down categorising of wastes (as dictated by current legislation) and the opportunity to treat chemically contaminated materials. The actual mode of treatment will be determined using cost benefit principles.

The management strategy for the Clean and Exempt Hazardous sludges is under development. As an interim measure the sludges will be collected (millscreens), dried, bagged and placed in interim storage. As such proper consideration has not yet been given to the application of the waste hierarchy to these materials.

5.4.4 Clean and Exempt Liquids

All liquids which fall within this category will either be recycled or transferred to a specialist contractor for disposal. Liquids generated as part of routine non-radiological site operations (such as waste water) will be discharged to the site drain.

5.4.5 Gaseous and Aerial Discharges

Where appropriate, discharges via stacks from active areas are HEPA filtered to remove particulates. These discharges can also contain radioactive gases which include (amongst others) tritium, Carbon 14 and Krypton 85. The gaseous discharges are made in compliance with the appropriate site discharge authorisations, and abatement techniques such as condensers and scrubbers are not generally used.

6 COMPARISON OF DOUNREAY STRATEGY AGAINST THE REVIEW OF BEST PRACTICE

To facilitate the comparison of DSRL strategy against the review of best practice for waste minimisation, a series of detailed tables (Table 3 to Table 6) have been prepared. For each waste stream grouping a comment is made relating to the application (or otherwise) of that particular high level waste minimisation technique. The techniques are not looked at in more detail as it is beyond the remit of this study to investigate how a management technique is applied as that aspect will be dealt with as part of a facility BPM.

For a given waste stream, minimisation techniques which are applied or are deemed not applicable are not coloured. Minimisation techniques which could be applied but are not are coded red, however, it must be noted that in some cases NOT applying the technique may be Best Practice as applying the technique may not confer an improvement to the overall waste management process. Additionally, if there is some doubt about the application of the high level technique or if there is insufficient detail then these entries are marked in amber.

The discussion in subsequent sections is focussed on areas which are coded 'red' or 'amber'.

6.1 ILW

Typical examples of waste management / minimisation practices are given in Section 3 and the current waste management process used by DSRL for RHILW and CHILW is generally in agreement with these principles. The exception identified is CHILW graphite.

6.1.1 RHILW Solids

The current waste management strategy demonstrates the application of Best Practice waste minimisation principles for these waste streams.

6.1.2 RHILW Liquids

The current waste management strategy demonstrates the application of Best Practice waste minimisation principles for these waste streams.

6.1.3 RHILW Sludges

The current waste management strategy demonstrates the application of Best Practice waste minimisation principles for these waste streams.

6.1.4 CHILW Solids

6.1.4.1 Pu, U, Th contaminated materials and Special Nuclear Materials declared as wastes

The current waste management strategy demonstrates the application of Best Practice waste minimisation principles for these waste streams.

6.1.4.2 Graphite

For this waste streams, the current waste management strategy has not been fully developed against the application of best practice waste minimisation principles.

6.1.5 CHILW Liquids

6.1.5.1 Special Nuclear Materials declared as wastes

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.1.5.2 Solvents and oils

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.2 LLW

Typical examples of waste management / minimisation practices are given in Section 3 and the current waste management process used by DSRL for LLW is generally in agreement with these principles as summarised below. The exceptions to this are the LLW sludge (granular material), LLW sludge (putrescible) and LLW sludge (LSA scale).

6.2.1 LLW Solids

This category offers the most opportunity for the application of waste minimisation techniques to make a significant difference to the volumes of waste to be disposed of to the Dounreay LLW facility. Owing to this it was felt that this strategy should undergo some further assessment, however as this relates only to some aspects of the waste minimisation hierarchy, this is deemed appropriate for further consideration via the BPM process.

6.2.2 LLW Liquids

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.2.3 LLW Sludges

6.2.3.1 Granular material

For this waste stream, the current waste management strategy does not fully demonstrate the application of best practice waste minimisation principles. The strategy for this particular waste stream has not been fully developed and until it has been developed further compliance with Best Practice can not be confirmed.

6.2.3.2 Putrescible material

For this waste stream, the current waste management strategy does not fully demonstrate the application of best practice waste minimisation principles. The strategy for this particular waste stream has not been fully developed and until it has been developed further compliance with best practice can not be confirmed.

6.2.3.3 LSA scale

For this waste stream, the current waste management strategy does not fully demonstrate the application of best practice waste minimisation principles. The strategy for this particular waste stream has not been fully developed and until it has been developed further compliance with best practice can not be confirmed. This particularly applies to the current requirement for the disposal of this material in the ILW repository as opposed to disposal as LLW.

6.2.4 HVLA Solids

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.3 Clean and Exempt waste

Typical examples of waste management / minimisation practices are given in Section 3 and the current waste management process used by DSRL for clean and exempt wastes is generally in agreement with these principles as summarised below. The exceptions to this are the Clean and Exempt Hazardous Sludges.

6.3.1 RSA Exempt and Clean Non Hazardous Waste

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.3.2 RSA Exempt and Clean Inert Waste

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.3.3 RSA Exempt and Clean Hazardous Waste

6.3.3.1 Solids and liquids

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.3.3.2 Hazardous sludge

For this waste stream, the current waste management strategy does not fully demonstrate the application of best practice waste minimisation principles. The strategy for this particular waste stream has not been fully developed and until it has been developed further compliance with Best Practice can not be confirmed.

6.3.4 Clean and Exempt Liquid Discharges

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

6.4 Gaseous and Airborne discharges

The current waste management strategy demonstrates the application of best practice waste minimisation principles for these waste streams.

Table 3: Summary of DSRL ILW high level strategy

Waste group / category	Waste stream	Summary of contents	Current IWS high level strategy
RHILW solid	Other	Operational and decommissioning wastes, mainly metals and some plastics	The following will be applied where appropriate: • Assay • Size reduction (dismantling / cutting / shredding) • Volume reduction (supercompaction) • Sorting by radiological classification • Sorting by material type • Immobilisation / encapsulation The conditioned wastes will then be stored in a passively safe form and packaged in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
RHILW solid	Special Nuclear Materials	Special Nuclear Materials declared as wastes	Store then when appropriate immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
RHILW solid	Ion exchange columns	Caesium contaminated columns from storage pond operations and NaK disposal operations	Store then when appropriate immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
RHILW Liquids	Reprocessing liquors	Raffinates from the reprocessing of MTR, PFR, DFR fuels and ADU floc supernatant	Store then when appropriate immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
	Special Nuclear Materials	Special Nuclear Materials declared as wastes	Store then when appropriate immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
	Liquid metal fast reactor coolant	NaK and Na	Chemical treatment (to make passively safe), decontaminate by ion exchange, condition to comply with discharge authorisations and discharge
RHILW Sludges	Sludge	Sludge recovered from the shaft and silo and ADU floc	Materials will be de-watered prior to immobilisation The conditioned wastes will then be stored in a passively safe form and packaged in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage. The water will be filtered, decontaminated by ion exchange, conditioned and discharged
Solid CHILW	P, U and Th contaminated materials	Material from glovebox / fume cupboard operations and decommissioning wastes	The following will be applied where appropriate: • Assay • Sorting by radiological classification • Volume reduction (supercompaction) • Immobilisation / encapsulation The conditioned wastes will then be stored in a passively safe form and packaged in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
Solid CHILW	Special Nuclear Materials	Special Nuclear Materials declared as wastes	Store then when appropriate immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage

Waste group / category	Waste stream	Summary of contents	Current IWS high level strategy
Solid CHILW	Graphite	Graphite powder and reactor decommissioning graphite	THTR graphite in 200 litre drums will be immobilised into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage. Activated graphite will be stored un-encapsulated in 4m boxes
Liquid CHILW	Special Nuclear Materials	Special Nuclear Materials declared as wastes	Store then when appropriate immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
Liquid CHILW	Solvents and oils	Solvents and oils from fuel reprocessing operations	Decontaminate by wet abatement (oxidation?) followed by incineration. The residual ash is to be immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage

Table 4: Summary of DSRL LLW high level strategy

Waste group / category	Waste stream	Summary of contents	Current IWS high level strategy
Solid LLW	Compactable	General operational and decommissioning LLW, includes already compacted material	The following will be applied where appropriate: • Assay • Sorting by radiological classification to maximise disposals through HVLA / clean / exempt routes • Volume reduction (supercompaction) • Decontamination (chemical and grit blasting) • Sorting into compactable / bulk • Immobilisation / encapsulation The waste will then be stored in a passively safe form until consignment to the proposed on-site LLW repository is possible
Solid LLW	Bulk	General operational / decommissioning LLW, granular ion exchange resins, treated sludges and spoil	The following will be applied where appropriate: • Assay • Sorting by radiological classification to maximise disposals through HVLA / clean / exempt routes • Size reduction where possible (cutting techniques) • Decontamination (chemical and grit blasting) • Sorting into compactable / bulk • Immobilisation / encapsulation The waste will then be stored in a passively safe form until consignment to the proposed on-site repository is possible
Solid LLW	Spoil	Contaminated soil etc	The following will be applied where appropriate: • Assay • Sorting by radiological classification to maximise disposals through HVLA / clean / exempt routes • Packaging in 1 te bags The waste will then be stored in HHISOs until consignment to the proposed on-site LLW repository is possible
Liquid LLW	Effluents	Effluents for discharge via LLLETP	Effluents will be decontaminated at the source facility (typically by ion exchange), conditioned at the LLLETP (pH adjustment), and particulates removed (settling and filtration) prior to discharge in accordance with site discharge authorisations
Liquid LLW	Solvents and oils	Solvents and oils from fuel reprocessing operations	Decontaminate by wet abatement (oxidation?) followed by incineration. The residual ash is to be immobilise into a passively safe form and package in accordance with RWMD guidance for transfer to the ILW repository after a period of interim storage
Sludge LLW	Sludge / granular material	Sludge from settling process in LLLETP	Retrieve and immobilise into a passively safe form and package for consignment to the proposed on-site LLW repository
Sludge LLW	Putrescible	Millscreen material	Currently under consideration – dried and stored
Sludge LLW	LSA scale	Scale recovered from pipes used in North Sea oil operation	Currently under consideration – dried, immobilised and stored
Solid HVLA	Construction and demolition material	Building rubble and contaminated land	The waste will be packaged in 1 te bags and stored in HHISOs until used for backfill for the proposed LLW on-site repository

Table 5: Summary of DSRL Clean and Exempt waste high level strategy

Waste group / category	Waste stream	Summary of contents	Current IWS high level strategy
Solid Exempt non hazardous	Construction and demolition materials	General items such as plasterboard, insulation etc	Where possible LLW will be treated to render it as exempt waste Waste minimisation will be carried out (techniques selected from grinding and cutting) Materials will be recycled / reused on site where practicable All other materials not suitable for on-site re-use will be disposed of by transfer to a specialist contractor (for scrap metals) or to landfill
	Soil	Soil	
	Recyclable other materials	Scrap metals, surplus machinery	
	Non-recyclable other materials	All other materials	
Liquid Exempt non hazardous	Recyclable	Organic liquid waste containing C-14 or H-3 but with activity <4Bq/ml	Recycle or transfer to specialist contractor
	Non-recyclable		Transfer to specialist contractor
Solid Exempt Inert	Construction and demolition materials	Building rubble	Where possible LLW will be treated to render it as exempt waste Waste minimisation will be carried out (techniques selected from grinding and cutting) Materials will be recycled / reused on site where practicable All other materials not suitable for on-site re-use will be disposed of by transfer to a specialist contractor (for scrap metals) or to landfill
	Soil	Excavated material	
	Recyclable other materials	General	
	Non-recyclable other materials	General	
Liquid Exempt inert	Recyclable	Organic liquid waste containing C-14 or H-3 but with activity <4Bq/ml General	Recycle or transfer to specialist contractor
	Non-recyclable		Transfer to specialist contractor
Solid Clean Hazardous	Recyclable	WEEE, batteries, chemically contaminated material	Waste hierarchy principles will be applied All clean hazardous materials will be managed in accordance with legislative requirements and opportunities to either recycle or down categorise hazardous wastes will be utilised as appropriate Cost benefit principles will be applied to the choice of treatment applied to chemically contaminated materials
	Non-recyclable	Asbestos, MMMF	
Liquid Exempt Hazardous	Recyclable	Organic liquid waste containing C-14 or H-3 but with activity <4Bq/ml	Recycle or transfer to specialist contractor
	Non-recyclable		Transfer to specialist contractor
Sludge Exempt Hazardous	Millscreen sludge	Putrescible	Dry and store pending finalisation of the management strategy
Solid clean non-hazardous	Construction and demolition materials	General items such as plasterboard, insulation etc	Waste minimisation will be carried out (techniques selected from grinding and cutting) Materials will be recycled / reused on site where practicable All other materials not suitable for on-site re-use will be disposed of by transfer to a specialist contractor (for scrap metals) or to landfill
	Soil	Excavated material	
	Recyclable other materials	Paper, metal, tyres	

Waste group / category	Waste stream	Summary of contents	Current IWS high level strategy
	Non-recyclable other materials	Clinical waste, operational waste	
Liquid clean non-hazardous	Recyclable	General	Recycle or transfer to specialist contractor
	Non-recyclable	Solvents / oils	Transfer to specialist contractor
Solid Clean Inert	Construction and demolition materials	Building rubble	Waste minimisation will be carried out (techniques selected from grinding and cutting) Materials will be recycled / reused on site where practicable All other materials not suitable for on-site re-use will be disposed of by transfer to a specialist contractor (for scrap metals) or to landfill The level of separation carried out will be determined by project specific safety requirements, industry good practice and economic factors
	Soil	Excavated material	
	Recyclable other materials	General	
	Non-recyclable other materials	General	
Liquid Clean inert	Recyclable	General	Recycle or transfer to specialist contractor
	Non-recyclable	General	Transfer to specialist contractor
Solid Clean Hazardous	Recyclable	WEEE, batteries, chemically contaminated material	Waste minimisation will be carried out Materials will be treated on-site for reuse where practicable All other exempt hazardous materials not suitable for on-site re-use will be consigned to an appropriate specialist waste contractor
	Non-recyclable	Asbestos. MMMF	
Liquid Clean Hazardous	Recyclable	General	Recycle or transfer to specialist contractor
	Non-recyclable	PCL decommissioning waste	Transfer to specialist contractor
Sludge Clean Hazardous	Millscreen sludge	Putrescible	Dry and store pending finalisation of the management strategy

Table 6: Summary of DSRL Gaseous and airborne waste high level strategy

Waste group / category	Waste stream	Summary of contents	Current IWS high level strategy
Gaseous and Airborne wastes	Gas	Radioactive and non-radioactive gases and particulates	HEPA filter particulates and discharge in accordance with site discharge authorisations

7 WAY FORWARD

The results of this review have been compared with the current and planned waste management strategies at Dounreay to identify any areas for potential improvement. The Dounreay site waste management strategies are largely compliant with best practice, however, a number of waste streams have been identified where there is scope for further assessment or consideration of the waste strategy.

These waste streams are:

- Solid CHILW – Graphite
- Sludge LLW –Granular material
- Sludge LLW – Putrescible
- Sludge LLW – LSA scale
- Sludge Clean Hazardous – Putrescible
- Sludge Exempt Hazardous – Putrescible

These waste streams will be taken forward for further review by the BPEO assessment process. The Clean/Exempt Putrescible waste streams will be combined into one assessment as they are both part of the same stream.

8 REFERENCES

1. The National Waste Strategy for Scotland, SEPA 1999.
2. The National Waste Plan, SEPA 2003.
3. Management of radioactive materials and radioactive waste on Nuclear Licensed Sites, T/AST/024, R P Pape, March 2001, Appendix 5 – Radioactive Waste Minimisation.
4. Dounreay "Interim" Integrated Waste Strategy WSU/Strategy/P033(08) Issue 4 February 2008.
5. Magnox South 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary.
6. Bradwell 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary.
7. Hunterston A Integrated Waste Strategy 2007/2008 HNA/3800/TC/SR/949 – Issue 2.
8. Magnox South 2008/09 Lifetime Plan Supporting Volume Technical Baseline and Underpinning Research & Development.
9. Harwell Integrated Waste Strategy NDA/LCBL(2005)P12/IWS Submitted with LTP08 Issue 4 February 2008.
10. Technical Baseline and Research & Development Document for Bradwell Decommissioning Site, Lifetime Plan 2008/2009.
11. Hinkley Point A 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary.
12. Magnox Electric Ltd. Waste and Decommissioning Research & Development Programme, Lifetime Plan 2008/09.
13. Thermal Treatment Symposium 29th November 2007, The Centre Birchwood Park.
14. Sellafield Integrated Waste Strategy Version 2 June 2007.
15. Winfrith Integrated Waste Strategy NDA/LCBL(2005)P16/IWS Submitted with LTP08 Issue 4 February 2008.
16. Sizewell A 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary.
17. Capenhurst Integrated Waste Strategy Issue 1 August 2007.
18. Draft of LLW Strategy, August 2008.
19. Technical Baseline and Research & Development Document for Berkeley Nuclear Licensed Site Lifetime Plan 2008/2009.
20. Good practice guidance on the application of sustainable practices to the management of decommissioning wastes from nuclear licensed sites, W Miller and J Tooley, 2005.
21. www.nuclearmarket.com/proc/hkq.cfm?ID=25869
22. Recycle and reuse of materials and components from waste streams of nuclear fuel cycle facilities, IAEA-TECDOC-1130, January 2000.
23. Review of US waste volume reduction technologies, 0185412-EG-RPT-005, Rev1, October 2002.
24. Management of low and intermediate level radioactive wastes with regard to their chemical toxicity, IAEA-TECDOC-1325, December 2002.
25. Predisposal management of organic radioactive waste, IAEA Technical Reports Series no. 427, July 2004.
26. Application of Ion Exchange Processes for the treatment of radioactive waste and management of spent Ion Exchangers, IAEA Technical Reports Series no. 408, June 2002.
27. Selection of efficient options for processing and storage of radioactive wastes in countries with small amounts of waste generation, IAEA-TECDOC-1371, September 2003.

28. The National Waste Strategy: Scotland Highland Area Waste Plan, SEPA March 2003.
29. Clearance and Exemption Principles, Processes, and Practices for Use by the Nuclear Industry - A Nuclear Industry Code of Practice, published on behalf of the Nuclear Industry Directors Safety Forum, July 2005.
30. SAFEGROUNDS – Good practice guidance for the management of contaminated land on nuclear and defence sites, CIRA W13, London 2002.
31. Site decommissioning sustainable practices in the use of resources – SD: SPUR (RP705).
32. www.hse.gov.uk/nuclear/wastemanage.htm
33. Guidance for the Environment Agency Assessment of BPEO studies at nuclear sites, Environment Agency, February 2004.
34. www.netregs.gov.uk/netregs/resources/278006/277807
35. www.rwbestpractice.co.uk
36. The Application of BAT in UK Nuclear Facilities Report, OSPAR Commission 2005.

APPENDIX 1 - REVIEW OF PROCESS TECHNOLOGIES AVAILABLE FOR WASTE PROCESSING AND STORAGE

Table 7: Dismantling

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Thermal Cutting [Ref 1: Section 6.3.2, Ref 2]	Size reduction of components	Widely used	Uses heat to melt a small section of component, which can then be separated. Flame cutting is used on mild steel and plasma arc cutting on steel and other non-oxidising metals.	The cutting speed is high compared to mechanical cutting. The equipment is relatively lightweight compared to mechanical cutting equipment, as the reaction forces during cutting are low due to no physical contact between the component and cutter. Remote operation is more practicable than mechanical cutting.	The technique produces dust, aerosols and dross. Potential fire hazard. Contamination may be incorporated into the solidified slag. When being used underwater, e.g. for shielding, visibility can be problematic. Flame cutting is not suitable for stainless steel.	Large quantities of particulate aerosols and molten metal slag, dusts, pre-filters and HEPA filters.
Mechanical Demolition [Ref 1: Section 6.3.4, Ref 3, 4]	Large-scale removal of concrete and other civil engineering.	Very wide in the nuclear and non-nuclear sectors. Robots have been used at Windscale and AWE.		Very simple and straightforward, hence cheap. Various techniques which can be applied depending on the type of concrete and the level of contamination. Demolition robots can be used to perform a variety of demolition functions in order to reduce risks to personnel.	The method is limited to concrete, brick and similar materials, and is not well suited to very thick concrete. Cast iron components can sometimes be demolished. Possible missile generation, due to internal stresses in the components. Significant quantities of dust are produced therefore HEPA filters and respirators are necessary.	HEPA filters
Mechanical Cutting [Ref 1: Section 6.3.1, Refs 5, 6]	Disassembly of facilities and size reduction, using equipment such as saws, shears, abrasive cutting wheels, nibblers, orbital and wire cutters, and core borers.	Generally widespread. Orbital cutters: limited.		These simple and generally well established methods generally produce an easily handled secondary waste stream and fewer airborne emissions than thermal cutting. Can be manually or remotely operated. There is a large range of sizes available. Shears have been developed for small pipes, which crimp the cut ends, sealing the pipe and preventing escape of loose contamination. Metal cutting portable circular saws are not available for cutting thick steel components. Nibblers can be operated underwater and the technique is not influenced by the internal stresses of the component. For large vessels, such as heat exchangers, ice sawing can be used, which minimises aerosol generation and reduces the area dose-rate. A long range sequential core boring system is being developed in Japan which enables the removal of large blocks of concrete.	Cutting speeds are low compared to thermal cutting. The equipment is heavy so difficult to handle and laborious if being used manually e.g. for orbital cutters the equipment must be positioned manually on the component to be cut, and this component must be (nearly) circular. With hand held equipment there is a risk of wounding to the operator. Abrasive cutting wheels and wire saw cutting produce large amounts of dust during dry cutting, but secondary waste arisings increase when used wet. Sparks generated are a fire hazard. Shears are large compared to the cutting capacity. With shears, the action crushes the component being cut.	
Electrical Cutting [Ref 1: Section 6.3.5]	Size reduction of metal components. Based on principle of thermomechanical erosion in metals through the accurate control of fine electrical discharges (sparks) whilst immersed in a dielectric fluid.	Fairly limited, mainly testing or small 'surgical' cutting		The technique is very accurate. No melt produced as there is in thermal cutting techniques. Can be used underwater.	Only applicable to electrically conductive materials. Large amounts of aerosols, or hydrosols under water, are produced when compared to thermal cutting. Large amounts of electricity required.	Aerosols or hydrosols, which require filtration. Dielectric fluid requires treatment prior to disposal.
Laser cutting [Ref 1: Section 6.3.6.2, Refs 7, 2, 8]	Size reduction, cutting through almost any material.	Limited R&D work. Used at Dounreay in D1206 to cut PFR wrappers but high cost and size mean unlikely to be used for decommissioning operations.		Very thin kerf is produced – the cut is clean and precise. There is a low aerosol (particularly if used in water) and slag production compared with thermal/electrical cutting. Significantly reduces personnel exposure. Can be used for large applications and can be used to cut concrete and steel. Laser is superior in cutting deformed or dirty metal and is much faster than plasma cutting.	High capital costs of the laser cutting equipment and the lower maintenance costs than other thermal cutting techniques do not achieve payback for this. Risk associated with high temperature and electrical current. Eye protection required. Equipment is bulky.	Use of water not required, and minimal kerf is produced therefore secondary waste and dust are minimal. Some HEPA filtration necessary.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Abrasive Water Jet [Ref 1: Section 6.3.3]	Size reduction of components during decommissioning	Relatively novel technique when applied to cutting.		This technique is effective for cutting reinforced concrete, and capable of cutting virtually all materials.	Large amounts of sludge and other secondary wastes are produced. The cutting depth is difficult to control.	
Liquefied Gas Cutting [Ref 1: Section 6.3.6.1]	Size reduction of components	Limited to research at present.		There is no secondary waste stream. The technique is cheaper than water cutting. There is no fire, explosion or oxidation hazard.	Depth control can be difficult, and aerosol generation can be a problem.	
Shape Memory Alloys [Ref 1: Section 6.3.6.3]	Fracturing (of concrete)	Research only	Holes are drilled and alloys inserted into holes. When heated, and the metals 'try' to return to their original shape, creating stresses in the concrete.	Very large forces are generated.	Very expensive compared with expandable grout, which does the same job almost as well.	
Electrical Resistance Fracturing [Ref 1: Section 6.3.6.4]	Dismantling of reinforced concrete	Limited to R&D	Large currents are passed through the reinforcing bars of concrete, causing heating and expansion of the bars. This splits the concrete.	The technique is simple.	Other techniques are required to finish the job. The technique uses a lot of energy for what is achieved. Risk of electrocution.	

Table 8: Decontamination

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Use of Strong Mineral Acids [Ref 1: Section 6.2.1.1; Refs 9, 10, 11]	Removing contamination from metal and some other surfaces and to lower the pH of solutions, increasing the solubility or ion exchange potential of metal ions.	Widespread	The surface to be decontaminated is soaked in acid, which removes metal oxide films and increases the solubility of metal ions. The acid may be applied in solution or as a paste, gel or foam, by various methods such as swabbing, immersion and flushing. Acids used vary between applications, usually nitric, sulphuric, phosphoric, flouroboric or flouronitric acids depending on the surface to be cleaned. E.g. use of nitric acid to remove uranium from stainless steel, use of sulphuric acid to decontaminate 'hot spots' on concrete. The acid may be mixed with abrasives or complexing agents to enhance performance. The addition of hydrofluoric acid greatly increases the decontamination factor.	The technique is well established. High DF of more than 100 can be achieved. There are many agents available for a wide range of applications: • Flouroboric acid has been specifically developed for decontamination for decommissioning. This can remove thin layers of contaminated waste, hence reducing secondary waste volumes. The properties are easily changed for different applications. • Flouronitric provides a method for rapid decontamination of stainless steel.	Usually involves application of large quantities of aqueous reagent and rinse water, which results in large volumes of acidic radioactive waste requiring treatment and disposal. The secondary wastes generated when using phosphoric acid are difficult to treat. Some acids may be incompatible with downstream effluent treatment plants. Chemical hazards e.g. toxicity, corrosivity, generation of by-products such as airborne contamination. Common hazard arises from inadvertent feeds of the wrong metal to the decontamination plant e.g. if copper and brass inadvertently fed to nitric acid bath, toxic nitrous fumes are produced. Sulphuric acid cannot be used if deposits on the equipment could contain calcium compounds. Fluorinated acids are extremely corrosive and their use should generally be avoided.	Contaminated acid and rinse water. Chemical reagent may be recyclable. Relatively little airborne contamination is produced at ambient temperatures.
Use of Bases and Alkaline Salts [Ref 1: Section 6.2.1.4, 12, 13, 14]	Degreasing, acid neutralisation, paint/coating removal, rust removal from mild steel, solvent, providing correct chemical environment for other agents (e.g. oxidisers). Common application is as part of a two-stage process to soften paint which is then later removed by mechanical means rather than dissolving the paint – this prevents re-contamination of the underlying surface.	Widespread		NaOH baths have proved adequate to reach levels of contamination sufficiently low to be below regulatory concern, for items that had low initial levels of contamination.	May involve application of large quantities of water, which results in large volumes of hazardous and radioactive waste. Use of high pH with aluminium and magnesium components is not recommended. Bases are highly corrosive and there is potential to generate significant heat when mixed with water or acid.	Contaminated alkali and rinse water. Chemical reagent may be recyclable. Relatively little airborne contamination is produced at ambient temperatures.
Use of Complexing Agents [Ref 1: Section 6.2.1.5; Ref 9, 15]	Forming soluble complexes with metal ions and preventing redeposition from solution. Sometimes used alone but mainly as part of formulations to increase the solubility of metal ions/radionuclides and extend the range of pH over which they remain in solution. The most common complexing agents used for decontamination include EDTA, organic acids and sodium or ammonium salts.	Relatively widespread, largely for maintenance purposes.		Prevents redeposition of solid species, and increases the DF of most other decontaminating agents. There is a wide variety of available complexing agents. Relatively safe to use and are not aggressive to the metal surface being cleaned. Oxalates, carbonates and citrates are easily stored and carbonates and citrates are non-toxic and non-corrosive.	Is best on smooth surfaces unaffected by rust or calcerous deposits. Complexing agents are hard to dispose of. There can problems with secondary waste conditioning, for example reduced stability of resins or solidification of the concrete can be hindered. Because of such secondary waste problems, chelating agents are not recommended for use at Dounreay.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Bleaching [Ref 1: Section 6.2.1.6, Ref 12]	Removal of chemical agents from surfaces (metal and concrete) by breaking down organic and inorganic matter. Peroxide is preferred over hypochlorite as it is less environmentally damaging.	Widespread		Bleach is cheap and widely available. Peroxide solutions are stable at room temperature, easy to prepare, inexpensive, and the decontamination reactions can be easily controlled.	Relatively large volumes of aqueous waste arise, containing hazardous and radioactive contaminants that may require treatment. Bleach is toxic, there is a risk of fire or explosion and chlorine is very toxic to aquatic organisms. Work is needed to improve the technique for application to porous surfaces and lessen the corrosive impact on equipment and buildings.	
Use of Detergents and Surfactants [Ref 1: Section 6.2.1.7, Refs 16, 15, 17, 18]	General purpose cleaning, wetting agent and emulsifier of variety of surfaces. Surfactants are organic compounds which make it easier for water to dissolve dirt and grease. Detergents also contain ingredients to help the surfactants work better.	Widespread		These are cheap and widely available. Effective and mild. Non-corrosive and relatively low hazard. Contamination may be reduced by 90 % and contaminated films and oils are dissolved.	Metal corrosion, long-standing contamination, porous surfaces and crevices cannot be cleaned. Relatively large volumes of hazardous and radioactive waste are produced. May be a labour intensive technique with high personnel exposure. Disposal of detergent-bearing effluent is a concern as it complicates waste treatment, and is toxic to aquatic life; even biodegradable detergents cause problems of eutrophication in water bodies.	
Use of Organic Solvents [Ref 1: Section 6.2.1.8, Refs 12, 18, 19]	Removal of organic material (grease, wax oil etc) from surfaces and clothes by dissolving the contaminants.	Widespread		Solvents are relatively cheap. Can be used in situations where water cannot be used.	There can be disposal problems. Solvents release VOCs, and must therefore be handled properly. Their use is limited to certain materials e.g. plastics must be avoided. Requirement for good ventilation and fire precautions and use should be limited to small areas or closed systems.	Sludge and a small amount of solvent. Solvent off-gas requires treatment. Most radioactive waste systems can't handle organic solvents.
Foam Decontamination [Ref 1: Section 6.2.1.10; Ref 9]	Decontamination of surfaces, especially large components with complex shapes. Generally used as a pre-treatment to remove loose contaminants and grease.	Widespread	Chemical foam consists of a micro-dispersion of air and gas, which contains chemicals such as acids and surfactants. Foam is sprayed onto the equipment to be decontaminated, and then washed off after a time. Water consumption is 3-18 litres per sq metre.	Foam can be used by itself or as a carrier for chemical decontaminants. It can be applied to surfaces in any orientation, and the residence time for the reagent is increased. Low volumes of secondary waste are produced compared to aqueous chemical solutions. Foam is cheap, simple and suitable for manual or remote deployment. The residual contamination levels are low. Foam can be removed using vacuum equipment.	A secondary waste stream is generated. Foam has limited penetrating power. Keeping foam on vertical surfaces can be a problem as it may 'collapse'. Presence of organic constituents such as surfactants could complicate waste management.	
Use of Chemical Gels and Pastes [Ref 1: Section 6.2.1.6 and 6.2.1.12, Refs 9, 20, 21]	Decontamination of surfaces when long reagent contact times are required.	Fairly widespread	Gel or paste is 'painted' onto surfaces, then removed. Self peeling gels are available.	Can be applied to inclined, overhead or vertical surfaces where liquid reagents run off. Can have abrasives included to assist breakdown of surface films, increasing the effectiveness. Gels are well suited to beta/gamma contamination. Pastes have demonstrated DF of 10-50 on stainless steel and other similar surfaces. Secondary waste arisings are very low as can allow to dry then remove physically without use of liquids. Pastes trap and remove particulates, reducing the risk or spread of contamination.	**O**nly suitable for components with simple geometry, as they are applied and removed by hand. Is not appropriate for cracked surfaces or deep crevices, and have limited substrate presentation. The application and removal procedure requires the operators to be properly protected and trained. Gels can not be removed by vacuuming. Presence of phosphates, detergents or surfactants in the formulation can complicate waste management.	Small volume of contaminated residual gel/paste, possibly rinse water. Contaminated application and removal tools and PPE.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Chemical Fog Decontamination/Gas Phase Decontamination [Ref 1: Section 6.2.1.13, 6.2.1.14, Refs 20, 22]	Fixing airborne contamination in place on larger equipment and uranium-contaminated cells.	Experimental, apart from the Russian Federation, where it is used for decontaminating liquid metal-cooled reactors. Being considered at AWE. Some positive experience at Sellafield.	A fog is generated, which adheres to the surfaces and results in a tacky coating. It encapsulates the contamination and prevents its resuspension by slowly and evenly coating all surfaces within the fog area.	Components with complex geometry can be effectively decontaminated.	Once the fog settles, the surface requires application of tie-down coating over the top – requires man-entries. So does not actually decontaminate plant, it all becomes radioactive waste for disposal unless accompanying decontamination technique is employed	Secondary waste arisings are low. Condensate is produced and requires management. There is potential for gaseous emissions, both of radionuclides and toxic materials (can be abated with HEPA filters).
Exothermic Metallised Powders (Thermite) [Ref 1: Section 6.2.4.6, Refs 19, 23, 24, 25]	Removal of surface coatings from concrete, such as metal by thermosorption decontamination.	Semi-industrial scale tests in the Russian Federation.	The reactants for the thermite reaction (aluminium, magnesium, sodium nitrate and oil) are mixed together as powders and applied to the surface to be treated. The reaction is started by applying heat. The reaction then proceeds exothermically, generating heat, which degrades the surface coating, allowing removal along with absorbed radionuclides.	Decontamination factor is maximal due to removal of radioactivity from metal surfaces, irrespective of type of metal and contaminants. During decontamination of metals, the radioactivity lost as aerosol is low. The method has proved effective for the removal of asphalt.	Large amounts of secondary wastes are produced during removal of asphalt. The reaction products need collecting and treating. Hazards associated with chemicals.	Cooling water, airborne particulates and reaction products. Small volume of secondary waste during decontamination of metal, large volumes during decontamination of asphalt.
Supercritical Fluids [Refs 26, 27, 28, 29]	Decontamination of materials by dissolving contaminating radionuclides.	Technology still under development.	A supercritical fluid (SCF) is a substance which is above its critical temperature and pressure, so is neither a liquid or gas but exhibits some of the properties of both. A favoured SCF is carbon dioxide. It flows into a chamber containing the item to be cleaned, dissolves the contaminant, then is allowed to change back into a gas and 'releases' the contaminant in liquid or solid form.	Cleaning cycle is self contained and all of the CO_2 is reused. Cleaning of radioactive, organic and many other contaminants is possible. Variety of materials can be cleaned. SCF CO_2 can dissolve 95-99 % of radionuclides.	CO_2 can react with material being decontaminated. Pressure vessel is required. Effectiveness depends on contaminant and is less effective for sorbed contamination.	Contaminant only.
Low Oxidation Metal Ion (LOMI) Reagent [Refs 30, 31, 32]	Decontamination of in situ equipment such as reactor primary cooling circuits.	Has been used in reactors in the UK and USA.	A REDOX chemical technique in which the decontamination liquor is circulated and a strong reducing agent attacks the ferric ion in a metal matrix.	Extensive programme of testing has demonstrated that the reagent is compatible with materials used in PWRs. Process faster than acid dissolution, typically takes 6 hours.	DF variable (between 1.6 and 65). Equipment being contaminated must be of suitable integrity to prevent leaks. Unstable in carbon steel systems. Reagent sensitive to oxygen and has a short shelf life.	Can generate large volume of contaminated spent reagent although can clean and recycle. At termination of the process the spent reagents are passed through ion exchange columns, producing waste ion exchange resin.
Use of Water Flushing [Ref 1: Section 6.2.2.1, Refs 33, 34	Removal of surface contaminants (water soluble, loose debris).	Widespread		Large surfaces can be cleaned. The cleaning agent is relatively inexpensive. Can be performed at close range or at a distance.	A large volume of secondary waste is produced, which should be treated. There is potential for contamination of surrounding ground, due to surface run off. Dissolved metals less easily separated from the waste stream. Will not remove contaminants that are chemically bound to the surface. Potential for criticality issues.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Washing of Soil, Rock and Rubble [Refs 35, 36]	Removal of contaminants sorbed onto fine soil particles. Contaminants are separated from the bulk soil in a water-based system on the basis of particle size.	Mostly pilot scale, by UKAEA and BNG.		Contaminants are concentrated into a smaller volume of soil that can be further treated or disposed of.	Success can be limited. Complex waste mixtures (e.g. metals with organics) make formulating washing fluid difficult. Aqueous stream requires treatment. May be difficult to remove organics adsorbed onto clay-sized particles. Air pollution control equipment may be required.	
Use of Vacuuming/Dusting/Wiping/Scrubbing [Ref 1: Section 6.2.2.2; Ref 37 (LaGuardia); Refs 9, 38, 39, 40, 41, 42, 43]	Initial removal of surface contaminants.	Wide. Standard practice for cleaning areas where loose contamination is present. Vacuuming can also be used for sludge removal in certain limited applications. Has been used to remove particulate material under water, where dose limitations required remote operation.		A simple process and no expensive equipment required. Low energy requirements. High DFs can be achieved. Suction cleaning is the most useful pre-treatment when large quantities of loose contaminants exist. A variety of systems are available in the market, ranging from mobile to fixed units. Can be used remotely.	Limited to loose debris and contaminated dust. Extra equipment is required to clean the dust-laden air produced. Filter units (local or remote) usually required. Scrubbing not appropriate for porous surfaces. Vacuum cleaner itself becomes contaminated and respiratory protection zone must be set up surrounding vacuuming operations. Hazards associated with any cleaning chemicals used. Wiping is carried out manually so not suitable for high dose environments. Labour intensive.	Large volumes of radioactive solid waste may be produced from dry or wet surface wiping, contaminated with particulates. Cleaning chemicals used may influence disposal route. When vacuuming is used, wastes are contained in the vacuum cleaner bag or filter.
Use of Strippable Coatings [Ref 1: Section 6.2.2.3; Refs 9, 44, 45, 46]	Removal of (loose) surface contamination from smooth and semi-porous surfaces. Also used as a fixative for contamination control. Particularly useful in plutonium contaminated facilities, where the levels of contamination are low, but with high radiotoxicity.	Fairly widespread	A synthetic polymer is sprayed onto a surface, where it sets to a tacky solid. This can then be peeled off by hand. This is often used as a coating prior to operation, enabling easier decontamination later. As an alternative to strippable coatings, Hydrogel foil can be used for non-porous and noncomplex surfaces.	The contaminant is immobilised without generating secondary gaseous or liquid wastes. When used to seal in contamination, other operations can proceed in the vicinity while the potential for disturbing contamination is reduced. If applied using an airless pressure spray, the atmosphere of the enclosure can be scrubbed thus reducing air-count.	Strippable coatings are only really effective on large, accessible surfaces. If technique carried out manually there is a radiological risk to operators. Removal times can be long. Effectiveness reduced if surface peeled, cracked or rusty.	Removed contaminated layer which requires no additional treatment. If strong adhesion between coating and surface material, this may amount to a large volume.
Use of Steam Cleaning [Ref 1: Section 6.2.2.4, Refs 47, 48, 49]	Removal of loose plate contamination from surfaces in-situ. Contaminated soil removal from earth moving equipment.	Wide		It is the IAEA recommended method for decontamination of complex shapes and large surfaces. Steam cleaning is also useful for cleaning grease-covered equipment. The production of secondary waste is reduced, especially if the steam can be condensed and re-used. Can be carried out remotely. High DF for surface, water soluble contaminants.	There is potential for aerosol generation and atmospheric emission and hence spread of contamination, so suited mainly to decontaminating internal surfaces or HEPA vacuum required. Can't remove chemically bound species. Risk of surface thermal degradation. Minimum of 2 operators required. Criticality controls necessary for fissile contaminants.	Contaminated filters containing particulates. Wastewater requiring treatment. Steam may be condensed and reused although will still require treatment.
Low Pressure Water Jets [Ref 1: Section 6.2.2.11, Refs 44, 50]	Removal of contamination from surfaces.	Wide and varied, sometimes used with abrasives.		Mains or gravity pressure employed hence requirements for pumping may be avoided. Secondary waste arisings can be reduced by recirculating the water. The pressure and/or flow can be set to be very delicate if required. The technology is well suited to inaccessible areas, such as pipe interiors. The underlying surface is not damaged by the cleaning.	Without recirculation, high volumes of secondary aqueous wastes can be created (20 litres per sq metre hosed). Secondary containment is required, and the technique is not suitable for areas where there are permeable floors or the potential for soakaway. Tritiated water vapour may need to be removed from ventilation air.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
(Ultra) High Pressure Water Jets [Ref 1: Section 6.2.2.11; Refs 51, 52, 53]	Removal of contamination from surfaces and for cutting.	Used in the nuclear industry for a number of different applications.		Secondary waste arisings can be reduced by recirculating the water. The technology is well suited to inaccessible areas, such as pipe interiors or structural steel. The underlying surface is generally not damaged by the cleaning. There is no dust generation.	Without water recirculation, high volumes of secondary aqueous wastes can be created. Secondary containment is required, and the technique is not suitable for areas where there are permeable floors or the potential for soakaway. High power use. Typical water requirement 25-50 litres per sq metre treated. High maintenance possible if abrasives used and hazardous to use. Aerosol produced which may need to be abated. Considered to be relatively expensive. Pressure of water jet could cause damage to operators.	
Grinding/Shaving [Ref 1: Section 6.2.2.12; Ref 9]	Mechanically removing (thin) surface layer of contamination from floors and walls.	Fairly wide in non-nuclear applications. There are some nuclear applications e.g. decontamination of lead shielding bricks, where the extent (depth) of contamination is known to be low. Useful for soft metals (e.g. lead). Used for coating removals from steel and concrete.		This is the IAEA recommended technology for removal of thin layers of surface contamination. Good DF achieved since target surface is eroded. Secondary waste arisings are low (30-35 % less than standard scabbling). Grinders not as prone to jamming as some blades, and can produce a deep cut and can cope with welds and brackets. Can be operated remotely.	The technique produces dust. However shrouded systems are available that extract the dust through integral HEPA filters to reduce dust levels. Water cooling can also reduce the amount of dust produced. If the contamination is deep, the grind wheel or discs are quickly worn down.	Treatment of one sq metre results in approx. 100 g of removed shavings. Any lubrication system will require a system for liquid recovery.
Scarifying/Scabbling /Planing [Ref 1: Section 6.2.2.13, Refs 20, 54, 55]	Abrading concrete and steel surfaces to remove contamination.	Becoming more widely used as the technology improves. The most common process to remove concrete surfaces.		Decontamination efficiency 95 % or higher. Secondary waste arisings are low. The method is proving reliable. This can be used to provide a good key for applying new coatings. Hand-held, remotely operated and robotic machines available.	This method can generate significant quantities of dust and contaminated aerosols. The technique is limited to larger surfaces. The underlying surface is damaged. Noise and vibration protection necessary for workers.	Detached ‘scabblings’ (small chips) are collected. Airborne dust requires filtration.
Metal Milling [Ref 1: Section 6.2.2.14, Refs 20, 56]	Decontamination of metal and concrete components by shaving.	Large number of similarly shaped components or large areas.		Effective for removing the surface, especially corrosion products.	The underlying surface is damaged. Small metal shards can be produced, as can sparks which are a fire hazard. Leaves some residual contamination. Milling tool may require lubrication, which requires a system for liquid recovery. Very difficult to use remotely due to weight of machine although large capacity machines are often automatic.	The removed shavings will contain the majority of the activity. Minimal dust production. Lubricating liquid.
Drilling and Spalling/Expansive Grout [Ref 1: Section 6.2.2.15/16, Refs 20, 57]	Decontamination of concrete by removal of surface contamination that penetrates 2.5 – 5 cm into the surface. Effective for large scale, obstruction free applications.	Used in decommissioning projects by a small number of nuclear operators.	Holes are made in the component. The holes are filled with grout or tapered metal. The component in the hole either expands or is driven in harder, causing the concrete surface to crack.	Contamination to a depth of several centimetres below the surface can be removed. Concrete spallers can be automated.	The method is labour intensive. Not suitable for concrete blocks. Expansive grout is better suited to decommissioning. Surface is left in a rough condition. Potential for generation of large amounts of dust and contaminated aerosols therefore appropriate safety and mitigation arrangements must be in place. Operational safety issues associated with drilling.	Contaminated concrete pieces, contaminated dusts, HEPA filters, possibly aerosols, contaminated water if a wet process is applied.
Jackhammer [Ref 1: Section 6.2.2.17, Ref 20]	Removal of surface contamination from concrete, generally of floors and walls.	Limited for decontamination (more widespread for decommissioning).	A hydraulically operated chisel is used to break up the concrete.	Jackhammers are a fairly quick method for breaking up a large area. Allows contaminated material to be removed at great depths. Can be used on floors to remove areas inaccessible to heavy equipment.	A very rough surface is left, and the method can easily remove too much, creating more ‘contaminated’ waste than necessary. Large amounts of airborne dust may be produced therefore water spray and containment is recommended. If water is used then it will require treatment and disposal. Health and safety concerns due to noise and vibration, and respiratory protection may need to be worn.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Vacuum Desorption [Refs 58, 59]	Decontamination of process residues, inorganic sludges, soil and debris which may be volatile.	Is a 'special case' technology applicable to a limited set of waste types.	Organic contaminants are separated from a waste matrix, leaving the solid processed material amenable to further treatment or disposal. It is a thermal desorption process which takes place in a vacuum. The volatile contaminants are collected and passed through a demister, carbon filter and HEPA filter prior to discharge of the off-gas.	Releases to the environment are minimised. No limit on the number of treatment cycles that can be performed.	Limited to certain waste types. Off-gas requires treatment.	Condensate is a waste. Spent filters and carbon adsorption media.
Ultrasonic cleaning [Ref 1: Section 6.2.3.2, Refs 20, 60, 61, 62]	Decontamination of small objects particularly with complex surfaces and inaccessible crevices.	Generally used for enhancing effectiveness of chemical methods. Relatively limited use, for specific applications.	Wet ultrasonic vibratory cleaning is the most common and involves components being vibrated at ultrasonic frequencies in a decontamination bath to enhance removal of contaminants. Ultrasonic waves form bubbles which cause small voids to open and collapse on the material, which loosens and dislodges the contamination. Dry ultrasonic vacuum techniques are also available.	The effectiveness of the method is often better than expected due to interactions between ultrasound and the cleaning chemicals.	The technique is not applicable to large components, concrete or other sound absorbing materials. Require close control by experienced operators to achieve high DFs. Extremely hazardous if operators' hands are immersed in the bath.	Produces low waste volumes which are easy to collect and handle. Regeneration of spent chemical solution can be employed to minimise waste.
Melting [Ref 1: Section 6.2.3.3; Refs 9, 63, 64]	Primarily waste minimisation to allow recycling of small metallic components, occasionally for decontamination.	Not that widely used specifically for decontamination. A facility at Studsvik will accept metals from outside Sweden.	Melting homogenises any residual activity on metal items therefore sampling of the melt can demonstrate that it has levels below regulatory concern. When used as a decontamination technique, components are heated to above the melting point, and isotopes with higher melting points are retained in the resulting slag, or volatile contaminant escape.	The volume of components is reduced. Isotopes with higher melting points than the base metal are immobilised in slag. The base metal can be recycled.	The process uses quite a lot of energy. There can be slag disposal problems. Pollutants may be transferred to the gas phase. Not generally suited to metals containing induced radioactivity, except for volume to mass considerations.	
Light/Laser Ablation [Ref 1: Section 6.2.4.1, Ref 65]	Selective removal of surface coatings and/or contaminants from concrete and metals.	Experimental. Considered to be a 'special application' technology and not suited for a wide range of applications.	This technique uses low power lasers focused specifically at the surface, heating the coating and removing by vaporising it. The ablated material is then passed through HEPA filters to remove the contaminants.	There is commercially available equipment, for example Lasers and Xenon flashlights, for producing the light. The laser beam can be transmitted through optical fibres, so the process can be operated remotely. Removal is very precise which minimises waste arisings. Up to 6mm depth of concrete can be removed if required.	The technology is undeveloped and unproven in the nuclear sector, and is potentially expensive due to the cost of the laser system and the long time needed for decontamination. Equipment tends to be large and bulky.	Ablated particulates, gases and vapours, spent HEPA filters.
Microwave Scabbling [Ref 1: Section 6.2.4.2]	Removal of surface contamination from concrete.	Under development. It was used experimentally on the LIDO reactor.	Microwave energy is used to heat the water contained in the top few mm of concrete. This causes expansion and the concrete falls apart. Concrete debris and dust collected by a vacuum device and filtered by a HEPA filter.	Research shows the method to be reliable. No damage to underlying substrate. Hotspots can be removed and segregated so minimising radioactive waste.	The effectiveness of the method depends on the moisture content of the concrete. The flexibility and ease of operation need to be improved before this technique is widely adopted. The process is energy intensive. Modular containment needed.	Contaminated concrete fragments and dust, spent HEPA filters.
Thermal Degradation [Ref 1: Section 6.2.4.3, Refs 33, 66, 67, 68]	Removal of organic surface coatings from non-combustible surfaces.	The technique has been used in one or two applications, such as at the Frankford Arsenal in the USA and at a Magnox Electric solvent treatment plant.	Components are heated to thermally degrade organic layers from the surface, using gas flaming (oxyacetylene) equipment or gas plasma (electric arc) equipment.	This can be used to scarify concrete. Only the coating is removed, so secondary waste arisings are low. High DF are achievable when the contaminant is organic.	The process is likely to use a lot of energy. The contamination is volatilised therefore containment is essential. Some substances may produce toxic gases. Forced ventilation required in confined areas.	Very small quantities of ash waste. Smoke particles which may be difficult to filter.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Use of Abrasive Cleaning [Ref 1: Section 6.2.2.5, Refs 13, 69]	Removes smeared or fixed contamination from surfaces using abrasive media (sand, grit, bead, metal shot, ice crystals, dry ice etc.) suspended in a medium of water and/or compressed air, which is propelled onto the surface being treated.	Widespread		Well developed, easy to implement, fast, cheap and can effectively remove contamination from flat surfaces, corners and undulating surfaces. Can be used on hard to reach surfaces, e.g. ceilings or behind equipment.	Generates large quantities of secondary waste (except for dry ice) and significant amounts of base material can be removed. Used abrasive needs to be collected unless using vacuum suction. Dust needs to be suppressed in dry abrasive methods. Generally limited to easy to access surface contaminants and not used for deep, or neutron induced radioactivity.	
Sponge blasting [Ref 1: Section 6.2.2.6; Ref 66]	Abrasive cleaning.	Limited. Has been used in the nuclear industry for the removal of contamination from concrete floors. Different sponge media are available for different applications.		Sponge blasting is less aggressive than abrasive cleaners, otherwise the methods are similar. Other soft abrasive media available include plastic pellets and coconut shells, which are easily recycled if they are not radioactive. Lower operating pressures are required than for traditional blasting technologies. There is low dust generation as 95% of the particulates removed are contained within the sponge. There is no aqueous effluent to dispose of. The sponge can be re-used several times thereby reducing waste volumes. Generally simple to use.	Problems occur if the sponge comes in contact with water.	
CO2 blasting (Dry Ice Crystal Blasting) [Ref 1: Section 6.2.2.7; Refs 70, 71, 72, 73]	Abrasive cleaning.	Limited and experimental within the nuclear industry. Used for paint stripping, slag removal, parts de-flashing, surface preparation and flux removal in the electronics industry. Has been used at BNFL to decontaminate a pond and cell. Trials completed at AWE and future use expected for decontamination of metal surfaces. Has been used to decontaminate the JET Torus.	CO_2 (dry ice) pellets are entrained in a pressurised air stream to strip surface contamination. Decontamination occurs in three different ways – abrasive effect, thermal shock and sonic shocks. Different sized pellets are available depending on the force required to remove the decontamination. About 85% of the contamination goes into the solid waste stream. The decontaminated material quickly returns to ambient temperature after blasting.	The abrasive content (dry ice) and abrasive carrier (air) mean that there are no aqueous waste streams. By adjusting the air pressure, it is possible to use the technique for heavy duty applications (e.g. paint stripping) or more delicate operations (e.g. flux removal from circuit boards). Generally easy to use. Can be used on metals, plastics, concrete, glass and electronics. Will remove oil, paint, dirt, adhesives and most surface films. Less aggressive than sand blasting so won't damage metal surfaces therefore decontaminated equipment can be reused.	Soft materials can be damaged. There are gaseous emissions of radionuclides and carbon dioxide (a greenhouse gas). Relatively expensive (£23,000 for equipment and £230 per 10 hour batch for pellets) and pellets have limited shelf life (about 5 days). Storage of large quantities of dry ice has safety implications. Deeply engrained contamination will not be removed. Not all coating materials can be removed.	
Wet Ice Blasting [Ref 1: Section 6.2.2.10, Refs 13, 33]	Abrasive cleaning.	Used for various applications including over 20 full scale decontamination projects.		The cleaning agent is cheap and less harsh than other grit blasting techniques. The surface is not degraded. Does not generate dust.	Ice blasting will not remove contaminants that are beneath the immediate surface. Criticality considerations.	Contaminated waste water generated by melting ice particles. Airborne contamination much lower than comparable techniques e.g. dry ice blasting.
High Pressure Liquid Nitrogen Blasting [Ref 1: Section 6.2.2.8]	Abrasive cleaning.	Still under evaluation.		The combination of nitrogen-induced embrittlement and abrasive action gives an effective clean.	The technology is not fully developed, and is therefore relatively expensive. The applications of this technique are probably limited.	
Freon Jetting [Ref 1: Section 6.2.2.9]	Abrasive cleaning.	Very limited		Effective at removing specific contaminants.	Freon availability is limited, due to regulatory limits on the use as a result of their effects on the ozone layer.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Electropolishing/ Electrodeplating [Ref 1: Section 6.2.3.1; Refs 74, 3, 10]	Decontamination of electrically conductive material.	Widely used in the Russian Federation. Used in a few plants in the UK. Used in D2900 at Dounreay. Considered the decontamination method of choice for recovery of plutonium and other transuranics.	An electrochemical cell is used to remove surface contaminants. A low voltage is passed from the anode (the contaminated item) to cathode through an electrolyte, causing the oxidation and dissolution of the contaminants. In D2900, the process employs a stainless steel tank (cathode) and a titanium basket (anode), with the electrolyte being dilute nitric acid. Typical process runs take 2 – 4 hours.	High removal efficiencies can be obtained if the operating parameters (current, total load in the basket, process time) are carefully set up. Can remove practically all radionuclides and heavy metals. The waste volumes produced are low, but not negligible.	Likely to be relatively expensive. The method is limited in that: • Coated or painted metals can not be decontaminated. • The efficiency is poor if the metals are greased or dirty, or if there are holes and crevices. • It requires that only one type of metal is used in any one batch, to avoid selective de-plating. • Problems of effluent treatment can arise if certain metals are decontaminated (e.g. stainless steels containing chromium, lead, and brass (copper and zinc). Concentrations need to be controlled such that conditions in any IPC/IPPC authorisation are not breached. Lead can be removed from the electrolyte by precipitation with potassium carbonate. • Nitrogen oxide fumes are emitted during the process which may need to be abated.	5-15 litres liquid waste produces per sq metre treated, which is likely to be acidic due to the electrolyte.
Electokinetics/ Electromigration [Refs 16, 75, 76]	Decontamination of soil and concrete, via the migration of contaminants in an imposed electric field. Often used in conjunction with electro-osmosis.	Technology under development in terms of applications in the nuclear industry. Has been used in the removal of mostly heavy metal and radionuclide contaminants from soils. Increasingly becoming an effective option for decontamination of concrete, with high potential for extensive use in waste management.	Involves the movement of charged species under the influence of an applied electric field, resulting in the migration of contaminants. For decontaminating concrete, the contaminants are fixed in the concrete matrix and need to be made soluble before the process is applied. The soluble contaminants are then transported through the concrete pores and collected.	High removal efficiency, high cost-effectiveness, adaptable. Treats waste in a truly in situ manner. Is frequently considered the BAT for the decontamination of concrete, because: no airborne particulates are produced, minimises secondary waste, removes contaminants that are deeply diffused in the concrete matrix, and does not damage the internal structure.	Problematic for waste streams that contain contaminants with low aqueous solubility such as hydrophobic organic compounds.	The waste arisings are the contaminants.
Microbial Degradation (Biodecontamination) [Ref 1: Section 6.2.4.4, Refs 33, 77, 78]	Removal of contaminant from porous surfaces.	Research (E.g. at AWE, BNG)	A biological system (enzymes, bacteria etc) is used to digest contamination from surfaces.	Only the contaminant is removed, hence the component is (theoretically) undamaged. Removes all contaminants within the layer of concrete. Microbial solutions or gels are easy to apply. No dust generated. Low labour requirement and low worker exposure; few materials handling issues. Hazardous contaminants are degraded rapidly to environmentally safe levels. Tests have shown a wide variety of potential applications. May also be able to be adapted to degrade metal surfaces (biocorrosion).	Noxious by-products may result. Time-consuming process, requiring months. Non-promoted biocorrosion of concrete has been observed.	Includes the microbial solution and detergent wash in addition to contaminant.

Table 9: Encapsulation of Waste

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Polymer Macroencapsulation [Refs 63, 79, 80]	Mainly the encapsulation of large pieces of solid LLW with metal components.	Used at some sites in the USA, some limited use in the UK.	Involves encapsulating a mass of waste in a polymer coating. Various polymeric matrices are available.	This technique is considered "Best Demonstrated Available Technology" by the US EPA for mixed waste debris. Matrix has good chemical and biological resistance, is flexible and has high mechanical strength. Suitable for certain soluble and toxic materials that other technologies cannot treat. Commercially available technology.	Generally, the waste is not compacted, and therefore the waste volume is high and the density is low. The technique is only applicable to solid wastes. More complex and costly than cementation for certain waste streams. NDA RWMD (Nuclear Decommissioning Authority Radioactive Waste Management Directorate) (formerly Nirex) are evaluating the use of polymers in the UK for ILW through the LoC process, for some wastes.	Gas and particulates from off-gas treatment system.
Bitumenisation [Refs 81, 20, 82, 83, 84, 85]	Immobilisation of LLW and ILW, mainly chemical sludges, ion exchange material, regenerants and concentrate salt solutions, organic solutions, incinerator ash, plastic and other solid waste.	Full scale for ~25 yr in Europe (not UK).	Waste is mixed with liquid bitumen and allowed to solidify.	Wastes with a wide range of water content can be immobilised. The process also dries out the waste stream to some extent. Product is compatible with most environmental conditions and has high heat stability. Enables higher waste loadings than cementation.	Operating and capital costs of the equipment are high. High energy input. The quality of waste varies with waste composition, bitumen grade and solids loading. The waste volume is increased by the encapsulation. Not suitable for wastes with significant alpha contamination or large metal pieces. Only suitable for very low heat generating wastes. Bitumen is biodegradable therefore there are uncertainties over its long term stability – it is not currently acceptable to the NDA RWMD.	Generates a large amount of secondary waste consisting of off-gas containing water vapour and degradation products of the waste and bitumen.
Cementation [Refs 81, 86, 79, 83, 87]	Immobilising liquid/solid LLW/ILW	Wide	Waste is mixed with cement and allowed to cure.	Currently the cheapest encapsulant. It has desirable mechanical properties for immobilisation of waste - radiation stability, thermal stability, non-combustible, easy to process and handle, tolerant of a wide range of waste types, provides some shielding and is compatible with various environmental conditions. Process can be operated remotely. Is compatible with the NDA RWMD phased disposal concept. Cement can be combined with fly ash (potentially using a waste stream from boilers and incinerators) to increase density, decrease permeability and partially compensate for the set-retarding effects of heavy metals. It also increases workability, lowers the heat generated during setting and lowers the redox potential of the cement.	Some wastes can react with cement so require calcining before encapsulation. Problems occur from the presence of oil and grease, and if the waste has a high alpha content. Radiolytic reactions can occur, generating explosive gas mixtures. The volume of the waste is increased by the immobilisation. The hydrogenous content of wastes must be carefully assessed, to reduce the likelihood of radiolytic reactions generating gases. It is foreseen that there may be a shortage of suitable cements in the future. Portland cement is the most suitable at present. It has been found that other currently known or common cements do not set adequately in the presence of organics.	
Synthetic Polymer Encapsulation [Refs 81, 80, 88]	Immobilisation of LLW and ILW.	Successfully used on a commercial scale. Used on a small scale by UKAEA.	Melted synthetic molten polymer resin is mixed with the waste and then allowed to cool and harden. This differs from polymer macroencapsulation in that the polymer matrix coats the individual waste particles. Polymers that have been used in encapsulation include polyethylene, sulphur polymer cement, polyester and epoxy resins.	Good pressure, temperature, radiation and chemical resistance. The polymer matrix is resistant to corrosion. The resin has very low permeability, which reduces leaching.	Generally, the waste is not compacted, and therefore the waste volume is high and the density is low. A waste container is required to provide physical strength; waste product is less likely to maintain physical stability than cemented waste. Process can lead to release of hydrocarbon gas. Pre-treatment of waste may be necessary to meet specifications e.g. particle size. The resins are expensive, approximately 25 times the price of cement. Most resins can only be used to encapsulate dry waste, although Dow has a polymer available that can handle liquids.	Waste from off-gas treatment and any waste pre-treatment processes.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Vitrification (Borosilicate Glass) [Refs 89, 90, 60, 3]	Immobilising liquid or finely divided solid wastes.	Fairly widespread, particularly for HLW.	Waste is mixed with constituents for glass making. This is then heated to high temperature and compressed to seal the waste within the glass matrix.	Reduces the volume of aqueous waste as the water is evaporated. Can be used for a wide range of waste compositions. The waste form is relatively stable. An effective barrier is formed, which is expected to last for the order of 100 years. The range of applications and widespread use means there is a lot of information available on performance characteristics. The corrosion mechanisms of the glass are well understood. There is potential for production of lower temperature sintered glass.	The operation is energy intensive and the facility is high cost. Glass has a low stability at higher temperatures, such as those experienced at depths of approximately 4 km, and will corrode rapidly if subjected to the wrong kind of situation. Glass has a questionable mechanical resistance to mishandling as it is brittle. Not suitable for waste with high salt content (except nitrates). As with cement, the overall waste volume is increased if used for solid waste.	Combustion gas and solid or liquid waste from the off-scrubbing system. May be waste water from cleaning of waste container surface.
In-situ Vitrification [Refs 50, 91, 92]	Encapsulation of waste.	Has been used at a number of sites overseas, particularly in the US, e.g. at the Oak Ridge Y-12 plant and Los Alamos National Laboratory.	Small waste stores are heated up to very high temperature, which melts the minerals and surrounding soil. The waste is incorporated into the resulting glass.	As with general vitrification, but the waste release pathways are reduced due to the waste not being moved. The surrounding soil is also vitrified, reducing the need for land remediation. Workers are exposed to a lower risk, due to no requirement to move wastes.	Gases are generated by the waste during vitrification. The technique is more energy intensive, due to vitrifying extra material. The waste is required to be properly segregated in the first instance. Subsequent land use is affected as the contamination is not removed, simply immobilised. The topography of the land may be affected. The soil is essentially converted to glass with contamination, therefore this technique is not environmentally sustainable on a large scale.	
Mineral Matrix (Synroc) [Refs 89, 93, 94, 95]	Immobilising solid/liquid wastes.	Developed and used in Australia. Has been used to immobilise military wastes containing plutonium.	Waste is mixed with Synroc precursor, then heated, compressed and allowed to solidify.	The characteristics of Synroc are well documented. Research has shown that Synroc is more stable at higher temps than borosilicate glass, which allows deeper disposal. The mechanical integrity of Synroc is greater than glass. Leach rates have been shown to be independent of the groundwater flow. The main matrix material is less soluble than glass. It is possible to investigate the long-term stability by using natural analogues.	Not yet been used commercially with radioactive wastes. As with cement and glass encapsulation, the overall volume of waste is increased.	Gases and particulates from the gas scrubber.
Ceramic Encapsulation (Titanium Dioxide) [Refs 89, 96, 97]	Immobilisation of HLW	Under development	Waste is mixed with TiO_2, heated and solidified.	Simple to implement as no novel mixing or pouring equipment is required. TiO_2 has a higher chemical durability than BS glass therefore a wide range of wastes can be encapsulated. During processing, lower temperatures than used for glass making mean a lower evaporative loss of radionuclides. The waste and precursor do not need to be as well mixed for the process. The effects of radiation on the matrix are expected to be lower than for current alternatives.	This technique has not been developed fully, and is currently not available for large-scale use. Waste containing liquids needs to be pre-treated. Unsuitable for large debris, organic wastes and reactive or explosive wastes.	No secondary wastes or hazardous off-gases are generated.

Table 10: Volume Reduction

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Compaction [Ref 49: Sec 4, Refs 98, 82, 99]	Reduction of volume of solid waste to allow packaging for transport to other treatment or to an interim storage facility.	Widespread – nearly all nuclear facilities have some form of compaction unit for waste volume reduction. Waste generators generally use low pressure compaction. Super-compactors, which employ high pressures, are also routinely used with great success, in particular for final treatment of waste prior to disposal to the LLWR.		Compaction is a simple, reliable and effective process. The equipment can be adapted for small scale or large scale and a variety of compactor types are available. Automation of methods is increasing and hence reducing worker exposure and waste release pathways.	There is some concern over the use of compaction for AGR fuel hulls, as fragmented zirconium poses a pyrophoricity hazard. Not suitable for waste with high free moisture content, for items such as rubber that are capable of storing compressive energy, or for robust metal objects. High force compaction equipment is expensive, requires a lot of space, and if it is remotely operated it requires highly skilled personnel.	Leachate if waste contains free moisture. Dust can be generated. Waste is generated if the drum ruptures during compaction.
Incineration [Ref 49: Sec 5, Refs 21, 100]	Volume reduction of combustible waste.	The most common thermal waste treatment. The use of incinerators for LLW is becoming more widespread. There are several types of incinerator, excess-air being the most common. Alternatives are controlled air, fluidised bed and slagging incinerators.		Incineration results in a substantial reduction in the volume and mass of wastes and the residues are often more compatible with downsteam management processes. Incinerators can treat a wide variety of wastes including dry solids, liquid organics, wet solids, and to some extent liquid aqueous wastes. ILW can be incinerated, but this requires extra shielding and remote handling, which increases the capital cost and complexity of the equipment. Fluidised bed incinerators can use pelletised $NaCO_3$ as the bed media, which reduces the amount of acidic off-gases. This results in a less expensive off-gas treatment process. Slagging incinerators give a highly insoluble basaltic slag which is immobile and easy to handle.	Incinerators for radioactive waste are expensive due to the advanced off-gas treatment necessary. There are several problems with older designs, namely incomplete combustion (leading to emissions of carbon monoxide, particulate material and, under some conditions, dioxins), excessive corrosion and frequent clogging of the off-gas treatment system. Incineration will volume-reduce combustible materials only. There are some combustibles that may not be allowed to be incinerated, due to local legislation. Incineration produces a gaseous waste stream, which must be processed. The possibility of tritium emissions, either to the atmosphere or to an aqueous phase should always be considered unless the incinerator system has been specifically designed for burning tritium-hydrogen. There can be problems with the product ash, as this is highly mobile and therefore easily dispersed. It is possible that some of the combustion products may be more toxic than the original waste, e.g. N_2 combustion leads to NOx, and this would need to be investigated and the risks assessed.	Contaminated off-gas, which itself generates secondary waste when treated. The product gas can usually be easily cemented.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Wet Oxidation (Acid Digestion) [Ref 49: Sec 5.4.1 Ref 101]	Volume reduction of organically contaminated mixed waste.	Relatively new technology. Chemical, electrochemical and hydrothermal processes are available. Electrochemical process has now been proven at full scale and demonstrated on ion exchange resins contaminated with complexing agents, cellulosic tissues and polymeric materials.	Waste is fed into a vessel with strong oxidising agents such as oxidising silver species in nitric acid. Organics in the waste are oxidised to carbon dioxide, water and constituent materials. In the case of hydrothermal wet oxidation, oxygen under high pressure is used.	Radioactive products of oxidation are retained in the aqueous solution and are readily immobilised by ceramification. The process operates at low temperatures and atmospheric pressure, so the equipment is cheaper and no compressor is required. This would reduce capital and operating costs. Process generates minimal off-gas.	The process uses concentrated sulphuric and nitric acid, and sometimes phosphoric acid, which are all hazardous. The technique is not fully developed on an industrial scale.	Radioactive products of oxidation are retained in the aqueous solution. The process generates NOx gases which can be reclaimed as nitric acid. Oxidising agent and process water can be recycled to minimise environmental discharges. Hydrothermal process results in mineralised concentrated sludge, liquid effluent with a high organic content and gases.
Molten Salt Oxidation [Refs 82, 102, 103]	Destruction of organic constituents of waste.	Has been considered for use in the US.	Waste and air are continuously introduced into a bed of molten sodium carbonate for incineration.	The molten salt reaction medium permits lower combustion temperatures and the bed acts like a scrub medium for acid gases and other undesirable by-products so less off-gases produced compared to standard incineration. Can treat a wide variety of solid, liquid and gaseous wastes. Is able to tolerate fluctuations in wastes and can be used for explosives. Less off-gases produced compared to incineration, and no NOx emissions.	Technique not developed on an industrial scale. Process intake limited to low ash, low water feeds. Material separation stages associated with salt recycling are troublesome. Potential for superheated explosions when liquid wastes are introduced. Gaseous emissions may require filtering due to entrainment of fine salt particles.	Organic materials are converted into carbon dioxide, nitrogen and water vapour. Radionuclides, metals and other inorganic materials are captured and held in the salt.
Biodegradation [Refs 82, 104, 105]	Decomposition of solid organic wastes.	Ex-situ biodegradation is a commercially available technique. It was originally developed in Finland, use thought to be limited so far within UK nuclear industry. In-situ biodegradation is also commercially available but is in the early stages of development.	Ex-situ: Solid waste is added to a bioreactor, and microbes are used to decompose the organic material. In-situ: Live cells or enzymes are used to clean and reduce the volume of in situ waste. Bioventing uses indigenous micro-organisms to do this. Phytoremediation involves the use of plants for in-situ soil and water clean-up.	Results in a volume reduction factor of between 10 and 20 for organic wastes. Does not require the use of highly toxic or flammable materials. In-situ techniques can also immobilise a variety of heavy metal contaminants.	In-situ biodegradation is still largely in the experimental stage therefore is costly and the long-term effects on the environment are not fully understood. Phytoremediation is also still in the R&D stage. Ex-situ: Bioreactors produce a large volume of biogas. Certain organic substances are not easily biodegradable. Growth of micro-organisms in the bioreactor can be inhibited by the presence of heavy metals.	Bioreactor waste consists of biogas and sludge. The treatment of the sludge could lead to large volumes of waste.
Cracking/Pyrolysis [Refs 82, 106, 107]	Separation of organics from wastes, including radioactive and hazardous wastes.	Unknown	Involves the chemical decomposition of organic materials in the waste by heating it under low oxygen conditions. It transforms organic materials into gaseous components, small quantities of liquid and a solid residue containing fixed carbon and ash.	Can be used for a variety of mixed wastes. The scrubbed gas may be able to be used to generate electricity or CHP. If a plasma torch pyrolysis is used rather than incineration pyrolysis, secondary waste arisings are reduced.	Not effective in destroying or separating inorganics from the contaminated medium. Volatile metals may be removed as a result of the high temperatures but they are not destroyed. Concerns over emissions of toxic pollutants including dioxins. Is unable to sufficiently reduce levels of tritium in waste.	Gases require further treatment. Solid residue and small amount of liquid.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Metal Melting [Refs 108, 109, 110]	Volume-reducing metal waste (as well as for decontaminating as discussed earlier).	Not currently used in the UK as a radioactive waste management technique but its technical feasibility has been proven in other countries. Has been carried out on exported UK waste.	Works by resolving complex geometries into much simpler ones. Most of the contamination can be separated off as radioactive slag and the remaining metal recycled.	Redistributes any radioactive materials which are not removed in the slag throughout the volume of the metal, thereby removing any high concentrations of radioactivity. It also permanently fixes the radionuclides, reducing the risk associated with storage. Technology is readily available, economical and has low environmental discharges and can represent the short-term BPEO.	Safety issues when melting waste contaminated with fissile material. Exposure limits are associated with the use of electric arcs and induction heaters.	Radioactive slag, and metal ingots which may be radioactive. Radioactive gases which require removal in an aqueous scrubber, generating an aqueous effluent. Dust from ventilation filters.
Shredding [Refs 79, 111]	Processing dry solids before further treatment e.g. incineration, compaction.	Low speed shredders routinely used at some UK nuclear sites in recent years.		Can be used on many types of dry solids including some light metal. Components of shredders are easily available. Generally, shredding prior to compaction results in greater waste volume reduction, means that mixing of the waste during shredding prevents the generation of radioactive 'hot spots' during compaction, and that non-compactable waste such as wood can be compacted. It reduces springback after compaction and reduces the required compaction pressure. Is a cost-saving and relatively easy to use method.	Shredders have high maintenance requirements. Liners of high speed shredders require periodic replacement, which would need to be carried out remotely in high radiation areas.	Can create fugitive dust emissions. Replacement parts for shredders become a waste stream.
Thermochemical Conversion [Refs 112, 113]	Breaking down waste materials using a combination of heat and chemical treatment.	Can be applied to treat a wide array of waste materials from the nuclear industry e.g. PPE, radioactive metals, spent ion exchange resins. Process has not yet been tested on a large scale for UK nuclear waste clean-up although studies are currently underway by the NDA.		Has been identified as a BAT in waste minimisation, particularly for treatment of asbestos containing material from UK nuclear decommissioning (by a Value Engineering study). Extensive scope for adapting the process parameters to suit the waste stream. Has achieved waste volume reductions of 50 – 90 %. Has advantages over incineration in that: it produces 'useful' gases such as hydrogen; volume of gas produced per ton of waste is less therefore pollution control is made easier; and it involves less aggressive environments and higher throughputs of waste.	Specialised plant and equipment are required. Flammable/explosive gases produced are a disadvantage in a radwaste plant even though they have commercial value and may hinder the safety case. Solid waste produced would need to be demonstrated to be compatible with UK disposal routes.	Much of the waste products can be treated and put to further use or used directly in other applications. Some undesirable waste products such as sintered heavy metals and radioactive contaminated products will require disposal.

Table 11: Storage of Waste

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Waste Containers [Ref 39: Sec 4]	Containment of solid waste for storage, transport or disposal	Wide				PPE, and HEPA filters from the storage area ventilation system.

APPENDIX 2 - TECHNOLOGIES FOR ABATEMENT OF AQUEOUS RELEASES

Table 12: Filtration Technologies

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Simple Filtration [114] [115] [116] [117] [118]	To remove active particulates directly or those formed by pre-treatment, such as flocculation.	Widespread use	Liquid is pumped or gravity fed through a filter medium, which traps particles above a predetermined size. Backwashing is often used to clean the medium.	Well understood and often cheap and simple to use. There is a large range of filter medium available depending on particle size. Generate less secondary waste than pre-coat filters.	Smallest particle size that can be filtered is ~0.001 microns, and particles below 5 microns are not removed as well as they are by reusable filters that use precoat materials. Once the filter becomes plugged by a 'filter cake', the rate of flow decreases and the there is a build up of excessive differential pressure. Therefore filter life is limited. However in some systems, by design, development of a thin cake assists filtration efficiency. Most filters need to be replaced manually so unsuitable where remote handling would be required, and dose uptake to operators needs to be considered.	Sludge arises from backwash cleaning of filter medium. Regular replacement of filters creates solid waste.
Pre-coat filters [115] [118] [119] [120] [121] [122]	As simple filters	Not clear, but unlikely to be widely used. Used at Sellafield THORP feed pond.	As with 'simple' filters, but the filter medium has a coating of particles applied before use. The filter cake is effectively used as the filter medium. Pre-coat filters can be used to remove particles as small as 1µm. They require a solid content of over 0.01 % in the input waste stream. Pre-coat filters operate under flow rates of between 5 to 15 m^3. m-2.h-2.	The efficiency of the filter process is increased – can be used on liquids with a higher solid content than disposable filters with no pre-coating. The filter medium can be cleaned easily by backflushing. Suitable for highly radioactive waste as enables the process to be operated automatically and remotely.	There is an increase in secondary waste volumes. More complicated than simple filters and incur more cost in installation and maintenance. High cost and time required to backwash and apply new filter medium if filter medium becomes plugged.	Removed filter medium sludge from backwashing needs to be treated.
Funda Filters [123] [124] [125] [126] [127]	A pressure leaf filter or centrifugal pre-coat filter used to remove solids from liquid.	Used in various industries. In nuclear industry use not widespread but used in Sellafield THORP pond feed plant, at Rolls Royce's Derby plant and in some nuclear power stations.	Filter assembly consists of horizontal filter plates mounted on a vertical hollow motor-connected shaft. The solid particles are separated from the liquid with the help of porous layers that allow the liquid to pass through but retain the solid matter. It takes place in a totally enclosed vessel without any risk for people or the environment. Rotation of the filter assembly discharges the cake in dry or slurry form.	Enclosed and self-cleaning system so no risk of contamination. Results in uniform cake formation, and no build-up inside the filter. Amount of washing liquid required is very small. High crud holding capacity and low maintenance requirements.	As filter operates under pressure, there is a risk of leakage of the filter cake, although cake build-up is on upper side of the filter leafs in the MAVAG Funda filter so cake doesn't fall off during pressure fluctuations. May require relatively high head-room.	Cake discharge (with waste and pre-coat solids) and small amount of washing liquid.
Cross-flow filtration [118] [128]	Direct filtration or removal of solids formed by flocculation treatments.	Becoming more widespread	The liquor to be filtered is passed through a series of parallel tubes within a larger vessel, similar in appearance to a shell and tube heat exchanger. However, in this case, the tubes are porous, allowing some flow from tube side to shell side. Clarified liquid collects in the shell side and amore concentrated waste liquor comes from the tube side outlet. The tubes are usually constructed of a spirally wound carbon fibre material impregnated with resin.	The filter can operate on a 'bleed and feed' basis in a continuous loop. Can be operated using remote handling. Limited cake build-up. A mobile waste stream is produced, which is easy to handle with conventional equipment. A very high quality treated liquor is produced. The equipment appears to have a long operating life compared to other filtering systems.	The process is complex, requiring pumps for the feed and permeate streams. High energy cost. The technology is relatively new, so may be expensive.	Concentrated sludge waste stream is created. Replacement of filter medium creates solid waste.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Microfiltration and Ultrafiltration [129] [130] [131] [115] [132]	Removal of sub-micronspecies (gases, vapours, liquids and suspended solids) from aqueous effluent streams.	Membrane systems are in widespread use in radioactive waste management and other applications. Microfiltration is used for suspended solids removal (particles 0.1 – 5 microns). Ultrafiltration is used for removal of particles and large dissolved molecule (particles in the range of 0.005 to 0.1 microns). Nanofiltration is used for removal of dissolved medium sized molecules.	The process involves the passing of the water requiring treatment through a semi-permeable membrane that acts as a barrier to the suspended solid and some dissolved species. The process is usually run in batches with the solids concentration increasing in the feed water stream whose volume decreases as the batch is run. In the case of nuclear site waste waters, flocculants are usually added to the wastewaters to precipitate out the radionuclides before feeding them to the membrane filter.	High quality permeates are produced due to high efficiency in removal of particles, allowing recycling of the waste waters in some instances, which are often suitable for disposing to drain. Ability to use different membrane sizes to remove a variety of particles.	Most suitable for liquids where particles make up less than 10 % of the total weight of the feed. High pressures are needed to force the permeate through the membrane. Some membranes are damaged by halogens and other chemicals. The process is relatively complex and can be expensive. Membrane damage or blinding can occur if the wrong membrane material is chosen or if there is a high concentration of particles. Very poor rate of removal of dissolved ionised solids.	Concentrated secondary waste stream, usually less than 5 % of original volume of liquid waste. Waste liquid from regular cleaning of membrane. Replacement of membranes creates solid waste.

Table 13: Precipitation and Flocculation Technologies

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Co-Precipitation [118] [133] [134] [135]	Precipitation of radioactive contaminants from an aqueous waste stream when the contaminant cannot be precipitated in isolation (e.g. if too fine to settle).	Used to treat reprocessing aqueous wastes where the high nitrate content limits scope of evaporation to treat the waste. Used at various nuclear facilities including NFPP at Rolls Royce, and at UKAEA Harwell in various forms.	Consists of several steps – pH adjustment, addition of a soluble carrier species (generally iron salts such as ferrous sulphate), addition of alkali to precipitate the carrier as an insoluble flocculent mass with high surface area. Active species are either entrained within the floc, or incorporated into the crystal structure of the iron complexes formed.	Relatively low cost, relatively simple technology. High volume reduction. Several precipitants have been developed for specific applications.	Removal usually requires one or more filtration stages to make a waste stream suitable for cementation. Not efficient at treating wastes containing complexes, detergent or oils, or highly salt laden solutions. Optimisation for removal of one metal may prevent removal of another. Can involve addition of a complex series of reagents for a mixture of active species. Addition of extra chemicals (usually ferrous sulphate) increases the waste volume and may generate hazardous substances such as hydrogen sulphide under certain conditions. Addition of chemicals may raise the level of toxic material in the treated effluent to above the discharge authorisation level. Chemical and environmental hazards associated with reagents.	Relatively small volume of insoluble floc containing most of radioactivity. Large volume of decontaminated low activity supernate which may require further treatment.
Barium Nitrate Addition [136]	A type of co-precipitation used in the treatment of the off-gas from reprocessing fuel dissolvers, to remove C-14, and on a small scale to precipitate C-14 from analytical samples.	Limited use as the process has very specific applications. Used at the THORP C-14 plant.	Dissolver off-gas is passed through a scrubber system where radionuclides are absorbed into a sodium hydroxide liquor. The addition of barium nitrate to the spent liquor co-precipitates barium carbonate (which contains C-14) with barium hydroxide, thus separates C-14 from the scrubber liquor in a solid form suitable for encapsulation.	Specialist application.	Barium nitrate hazardous as it is toxic and highly soluble, and is a strong oxidising agent. It is therefore important that all added barium is precipitated.	Encapsulated barium carbonate containing radioactive C-14, low active alkaline supernatant liquor containing traces of barium carbonate and radioactive C-14, barium hydroxide and barium nitrate.
Precipitation [118] [134]	Treatment of a liquid waste stream to remove dissolved radioactive substances.	Widely used in the nuclear industry, well established method for removing radioactivity from low and intermediate level liquid wastes.	A physical process by which dissolved substances are converted to insoluble particles by chemical reaction. The precipitate is then separated from the treated water by settling or filtration. Generally a four stage process involving addition of reagents, flocculation, sedimentation and solid/liquid separation. Decontamination factor 10-100 for beta-gamma, 1000 for alpha. Volume reduction factor 10-100 if wet sludge produced; 200-10000 if dried solids produced.	Suitable for treating large volumes of liquid effluents containing relatively low concentrations of radioactive species. Uses readily available chemicals so low cost compared to evaporation which can be 20-50 times more expensive. Filtration effectiveness is increased. Some soluble species are removed. There is no requirement for the addition of carriers as in co-precipitation. Process can be tailored to a wide variety of species as easy to adjust the additives during the process and a wide range of precipitants are in use. Can be combined with evaporation and ultrafiltration.	As for co-precipitation. Relies on the existence of species that can be converted to insoluble complexes. Tends not to form dense, rapidly settling mass so removal usually requires one or more filtration stages to make a waste stream suitable for cementation.	As for co-precipitation.
Polyelectrolyte Bases Precipitation [118] [120] [133]	Agglomerating small particles. Generally used for fine precipitates formed during co-precipitation.	Limited use, e.g. previously used at AWE, used at Magnox SIXEP plant.	Polyelectrolyte bases are added to a waste stream containing suspended solids, to promote the formation of insoluble flocs. The polyelectrolyte causes agglomeration of fine particles, allowing the use of coarser filters. They are added during the flocculation stage of the precipitation process.	Cheaper, coarse filters can be used.	Involves the addition of extra chemical reagents. Otherwise as for co-precipitation.	As for co-precipitation.

Table 14: Evaporation Technologies

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Evaporation Technologies (generally) [118]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	Evaporation is used mainly for reducing volumes of HLW and in some cases ILW liquids.	The waste stream is heated, driving off water. The steam is condensed, giving a relatively clean water stream. The concentrated sludge is then passed for immobilisation.	High DFs are possible. There is a wide variety of commercially available equipment. It is suggested by [Ref 8] that wiped film evaporators are the best available.	There is potential to carry-over some active components in the distillate, both as aerosols and from volatile active species. This requires a second stage treatment, generally solvent extraction. Capital and running costs are high. The process is not well suited to high throughput streams. There can be problems with corrosion and fouling, which leads to an increased maintenance requirement. There is limited abatement of volatile compounds (e.g. carbon dioxide, sulphur oxides, tritium gas). The technique is not selective if just the removal of a specific radionuclide, or radionuclides is required, hence the waste volumes can be high, at relatively low activity. Higher energy costs than non-thermal separation technologies.	Produces a vapour phase and a liquid residue separated from the feed. Radioactivity usually concentrated in the residue and suitable for immobilisation. A small non-condensable gas stream may be produced comprising feed volatiles and feed decomposition chemicals. An off-gas scrubber system may be required to remove these and would generate an aqueous effluent stream.
Coil / Pot/Drum Evaporators [115] [137] [138] [139]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	Used on various sites, suitable for use as a volume reduction technique when the waste stream is mostly water.	The process uses a small vessel with an internal heating element, which acts as an engineered kettle. Vapour is passed from the evaporator into a condenser and off-gas system to ensure low activity level before release to atmosphere. In the case of a drum evaporator the waste is loaded into a unit within a drum, then the drum is electrically heated from the outside.	The process is simple, with simple construction methods and low maintenance requirements. This gives a cheap system in comparison to other methods. Operation is effective up to solid concentrations of 25 wt%. Decontamination factors (DF) between feed and distillate are high and evaporators can be strung together to achieve a higher DF. Can be designed to be readily transportable. Drum evaporator minimises contamination spread by keeping the waste within the drum at all times, and the waste can be evaporated to complete dryness without damage to the permanently installed equipment.	The equipment has a small heating surface per unit area, leading to a high space requirement. Inefficient compared to other types of evaporator due to poor heat transfer coefficient and poor circulation of liquor. Pot evaporators are unsuitable for heavily foaming or scaling liquids. There is a large hold-up in the process vessel. Capacity is limited due to material constraints. The process operates on a batch basis.	
Horizontal Natural Circulation Evaporator [126] [137] [139] [140]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	These are rarely used in radwaste evaporation. Does not make good advantage of the thermal currents induced by heating so most of these types of evaporator have been replaced.	A basic, shell and tube boiler, with the tubes running horizontally and the process flow across the tubes. The only type of evaporator employing steam in tubes. Circulation of the liquor is brought about by convection currents arising from the tubes. Available in bent or straight tube types.	The equipment has a low headroom requirement. Entrainment of liquid aerosols is limited. Straight tube units are relatively inexpensive. Bent tube type or large tubes are suitable for scaling, foaming and corrosive liquids. These evaporators can operate on a continuous basis. Allows for in-situ settling of solids.	The straight tube type is unsuitable for salting or scaling liquids. This type of evaporator cannot be used for foaming liquids. These have a limited capacity. The bent tube type of evaporator is expensive. Scale removal from the tubes can be difficult, and concentration of radionuclides in the scale will increase dose rates. Suitable for solid loadings of up to 30 wt%.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Vertical Natural Circulation Evaporator [118] [128] [137] [139]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	Relatively widespread use.	This process is similar to horizontal, but the tubes are vertical, so heating fluid and process fluid flow in the same plane. Basket and calandria types are available.	These have a high heat transfer coefficient, so the required area for evaporation is lower, leading to smaller, cheaper units. A wide variety of waste can be handled. Operation is on a continuous basis. The plant headroom requirement is low.	Unsuitable for highly scaling liquids. At low differential temperatures or low differential pressures, the heat transfer to the fluid is generally poor, requiring a larger surface area. The liquid hold-up is relatively high. The units are heavy. When handling viscous fluids, the heat transfer is not very good. The units are not suitable for foaming liquids. Concentration of radionuclides in the scale will increase dose rates. Suitable for solids loadings up to 30 wt%.	
Vertical Thermosyphon Evaporator [137] [139] [141]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	Relatively widespread use, most common natural circulation evaporator, have been used on wastes from LWRs, experimental fast breeder reactors and on highly active waste.	A vertical shell and tube unit with an attached vessel (flash chamber), where the vapour and liquid are separated. The thickened liquor is removed from the bottom of the flash chamber, and cleaned vapour from the top. A variant is the rising film evaporator where the upward motion of the evaporated vapour drives a film of liquid up narrow tubes to the disengagement chamber.	The design is relatively cheap. A wide variety of waste can be handled. Operation can be continuous. Heat transfer coefficients are higher than a vertical natural circulation evaporator. Maintenance is relatively simple due to the heat exchanger being separate. Space requirements are generally low.	As with most units, these are unsuitable for foaming liquids. The units cannot handle liquors with solids content above 30 wt%.	
Forced Circulation Evaporators [137] [139]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	Relatively widespread in the USA. Some use in UK e.g. DML, AWE Plc.	As with thermosyphon evaporators, but the circulation flow is boosted by a pump.	These have high heat transfer coefficients. A positive circulation system is well suited to nuclear applications. Salting, scaling and fouling are less problematic than other types. Crystalline product can be handled. Due to the construction with an external reboiler, maintenance of the heating tubes is generally easier. Viscous fluids (up to 100 mPaS) can be handled. Boiling in the tubes is prevented by the hydrostatic head. Smaller than the equivalent natural convection type. They can operate continuously.	The capital and running costs are high, due to the additional energy requirement of the circulation pump. Residence times are generally high. Salt deposits can cause blockages. Head losses in the pipework can give rise to poor circulation. If boiling does occur in the tubes, due to mal-operation, the resulting salt formation can be difficult to remove. Maintenance of the circulation pump can be difficult for high dose rate liquids. Circulation units are unsuitable for corrosive or erosive liquids, which would lead to premature wear of pumps and lines. If the unit is inadequately designed, foaming and entrainment of aerosols will occur.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Falling Film Evaporator [128] [139] [142]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	Not widely used in the nuclear industry. Useful for situations where the feed is heat sensitive therefore a high degree of evaporation is required without excessive heating.	Liquid is fed in at the top of the heater and runs down the surface of a bundle of vertical heated tubes as a film. The concentrated liquid and vapour exit the bottom of the tube bundle into a disengagement vessel where the vapour and liquid separate.	The capital cost for the equipment is relatively low. There is a large heating surface in one body, hence a small plant footprint. The hold-up within the equipment is small, hence short residence times. Large evaporation loads can be handled by the equipment. The equipment is suited to continuous operation. These evaporators are suitable for clear, foaming or corrosive liquids. Heat transfer is not adversely affected by low differential pressures. Due to the large heating surface area, relatively low temperatures can be used, and therefore temperature-sensitive wastes can be handled. Droplet entrainment in the off-gas is low due to the disengagement vessel.	The vessels are tall. The equipment is unsuitable for salting or severely scaling liquids. Recirculation of the liquor is usually required, which increases liquid loading. Feed distribution within the evaporator can be poor, which leads to fouling. With high viscosity liquids, gravity is not enough to cause a downward motion of a thin film. If feed composition is variable, it is difficult to maintain a stable evaporation film, and the efficiency is compromised.	
Wiped Film Evaporator [137] [139]	Evaporating aqueous waste streams to either: • Aid in the precipitation of soluble contaminants present; or • Concentrate up solid and soluble contaminants into a more concentrated waste stream, producing a clean condensate for disposal to the site drains.	Not widely used in the nuclear industry. Have been used for concentrating aqueous effluents from reactors, and dewatering ion exchange resins. Horizontal designs have proved more reliable in the nuclear industry than the vertical designs.	A vertical or horizontal cylindrical vessel with a rotating shaft to enhance heat transfer. The feed is distributed over the vessel walls by blades or wipers that rotate around the central shaft. A highly turbulent area is created between the rotor and the wall, enhancing heat transfer. An external jacket supplies heat, usually from steam through the vessel wall.	The equipment is suitable for high solids loading (50-95 WT%), foaming and scaling liquids and highly viscous fluids. The residence time and liquid hold up are small. The system is well suited to continuous operation. The equipment can operate at very low pressures (e.g. 1 kPa abs). Reduced liquid loads do not cause significant operability problems. One pass is usually adequate for a high concentration factor. High degree of evaporation achieved without excessive temperatures.	Vertical evaporators are tall. The capital cost of the equipment is high, and the in-service costs are potentially high. Wear on rotor, bearings and seals of the rotating shaft can increase maintenance requirements. These are not very economical when handling solutions with very low solids content. Not suitable for high activity liquids due to need to carry out maintenance on bearings and seals.	

Table 15: Other Technologies- Physical

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Delay, Hold-up and Out-gassing [118] [143] [144]	Abatement of liquid releases of short half-life nuclides.	Commonly used in the nuclear industry and are likely to be integrated into all RA effluent systems. E.g. S-35 (Wylfa), Ru-106 (Sellafield), P-32 and P-33 (GE Healthcare).	The liquid is delay stored in tanks until the short-lived radionuclides have decayed sufficiently to enable subsequent treatment or disposal. Tanks are usually constructed in sets of two or more, are double contained in a secondary enclosure, and are constructed from corrosion-resistant material.	Tanks are simple. They can be used to mix treated liquid wastes, carry out neutralisation or flocculation. Any subsequent treatment will be easier and safer.	Only suitable for nuclides with short half-lives, and not suitable for HLW. Potential for tank corrosion and accumulation of toxic and radioactive gases above the tank (controlled venting may be required).	May require systems for the cleaning of off-gases from the tanks. Liquid waste may require further treatment.
Centrifuge / Hydrocyclone [118] [130] [134] [145] [146]	Removal of solid particles from aqueous waste, to separate fluids with different densities (e.g. dewatering sludge), and solids from gases.	Wide use in other industries (especially oil/water separators), some use in nuclear industry e.g. Sellafield, Springfields, Magnox.	A spin is imposed on the fluid, causing separation by centrifugal force. A centrifuge is a rotating drum, and a hydrocyclone is a non-rotating inverted cone, with the spiral movement down the cone creating a spinning effect.	Hydrocyclones have no moving parts and are more compact than centrifuges of the same capacity. The throughput is higher than the equivalent filter. The maintenance requirement is low, hence operating costs are low. Can be more economical than gravity operated settling devices.	The smallest particle size that can be removed is limited by the centrifugal forces generated and by the residence time. Small particle removal is not as efficient as filters. Energy consumption is higher than filters. Not well suited to highly stable emulsions. Hydrocyclone not normally suitable when solids of less than 5 mm are to be removed, or the liquid is of high viscosity. Centrifuges cannot handle thoxitropic fluids.	Separated solids and liquids both require treatment before disposal.
Reverse Osmosis [115] [118] [128] [133] [134] [147]	Removal of small solute molecules from aqueous effluent streams where the solute molecules are of the same order of size as the solvent molecules.	Widely used for desalination of water. Some limited use in nuclear industry e.g. AWE for secondary treatment of aqueous waste. Often used as a pre-concentration stage for evaporators.	Reverse osmosis utilises membrane pore sizes <0.001 microns. It separates a solute from a solution by forcing the solvent to flow through a selective membrane by applying a pressure greater than the normal osmotic pressure. The ionic species and large molecules that cannot pass through the membrane are therefore concentrated.	Can remove colloids and organic polymers. Can operate at ambient temperatures. Less energy input, cheaper and more compact than evaporation or distillation.	Decontamination factors of 10-100 are achievable – less than evaporation and distillation. Membrane prone to blocking or fouling. Only suitable for waste streams with very low level of solids content to avoid blocking pores. Membrane can be sensitive to high chloride levels or extreme pH. Process requires high pressure for flow through membrane, hence high pumping costs. System throughput relatively low.	Concentrated secondary waste stream, between 10 and 70 % of original volume of liquid waste. Waste liquid from regular cleaning of membrane. Replacement of membranes creates solid waste.
Freeze Crystallisation [132]	Removing contaminants from aqueous waste streams as frozen crystals.	Technique not yet fully developed.	A refrigerant is injected into the liquid waste, which boils up through the solution and slowly freezes it. Ice crystals form on the surface, which due to the solubility differences between the solid and liquid phases, do not contain contaminants. When a certain quantity of ice is formed the liquid containing the waste is drained off, leaving behind pure ice crystals. This is repeated until all of the contamination has been separated.	More efficient than distillation. Has been successfully demonstrated for volume reduction of radioactive high-sodium surrogate liquid waste with simultaneous removal of sodium. Removal of >80 % of the sodium was achieved.	Limited to aqueous waste streams. Presence of oil contaminants may interfere with the process. Feed stream must be dilute enough to achieve significant volume reduction before a eutectic mixture forms.	Contaminants concentrated into a solution which requires further treatment e.g. stabilisation.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Calcination and Steam Reforming [148] [149] [150] [151] [152]	A thermal treatment process used to treat a variety of waste streams.	Calcination and steam reforming are widely used in the nuclear industry.	The calcination process involves thermal treatment of the liquid waste to elicit a phase transition, thermal decomposition or removal of a volatile fraction. It is conducted at temperatures at or above thermal decomposition, but below the melting point. The two main types of calciner used in the treatment of nuclear waste are the fluidised bed calciner (for liquid wastes) and the rotary ball kiln calciner (for higher density wastes). Liquid waste is fed into the calciner, which dries and calcines the waste prior to feeding into a melter to produce a final vitrified waste. Steam reforming is a type of calcination in which the calciner is operated under controlled stochiometric conditions. It is performed in a steam-laden, oxygen deficient environment to convert hazardous organic and biochemical compounds to off-gases such as CO, H_2, CO_2 and H_2O.	Is able to be used to treat almost any inorganic liquid waste and the process parameters and instrumentation can be adjusted to treat many waste types. When treating liquid wastes there is a large volume reduction due to the high temperatures driving off the majority of the waste fraction. Waste streams may be blended with other waste types prior to calcination. The reducing environment present in steam reforming destroys some undesirable gases such as dioxins therefore emissions are reduced. Off-gases such as H_2 from steam reforming can be put to further use. Waste solids in the calciner are not exposed to excessive temperatures therefore hazardous metals and radionuclides are not volatilised. Not classed as an incineration method, which can be an advantage in terms of regulation/licensing.	Operating temperatures must be high enough for calcination to take place but not so high as to cause agglomerations of melted material. The typically high radioactivity and corrosivity of the feeds means that strict fugitive emissions control is required. Waste volume reductions are comparatively small when used for solid waste streams.	Off-gases which may require treatment to destroy NOx and residual hydrocarbons, and calcined (powdered) waste which requires further treatment as its easy dispersal means it is unsafe for transport.
Immobilised Moss [153] [154]	Potentially an environmentally friendly, low technology and cost effective way to clean up liquid LLW, removing radionuclides and heavy metals.	A relatively new process which has so far had limited use due to time taken to transfer technology from laboratory to industrial scale. Has been identified by a recent study as a potential BAT for the removal of Cs-137 and Sr-90 from liquid LLW.	Moss is immobilised in a granular or polymeric matrix. The immobilised moss (IM) is dead material with the organic ligand molecules still intact. The process involves using the IM to remove radionuclides and heavy metals from wastewaters by using it in conventional hydrometallurgical processing equipment such as packed and fluidised-bed columns. The adsorbed radionuclides, once adsorbed by the moss, can be leached out using acid and the IM regenerated.	Cs and Sr radionuclides can be effectively removed under constant flow conditions. IM media doesn't lose performance capacity even after multiple cycles of reuse. Media is hard-wearing. Can be operated under gravity.	Interactive effects in waste with mixed contaminants can be detrimental to the process. Not a mature technology so higher engineering and performance risk. Liquid-solid separation of metal-laden biomass from treated water is problematic although recently developed BIO-FIX beads are effective. Performance hindered for waste containing finely ground ore particles.	IM media loaded with contaminant requires treatment with acid. The resulting eluate is then filtrated, and the resulting precipitate dried. This concentrated waste then needs to be dealt with using established methods.

Table 16: Other Technologies- Chemical

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Ion exchange beds [118]	Removal of soluble (active) ionic species from liquid waste stream	Widely used. In the nuclear industry, the most common use is after filtration.	The liquid phase is passed through a solid stationary phase (the ion exchange medium). Soluble ionic species are removed by replacement with non-active species from the ion exchange resin. Generally, 'mixed' beds are used to remove both positive (cation exchange) and negative (anion exchange) active species. Usually, two beds are used, one on standby/being regenerated whilst the other is operating. Ion exchange media are either naturally occurring inorganic zeolites or synthetically produced organic resins. The latter are the predominant type used today because their characteristics can be tailored to specific applications.	There is a well-developed range of resins for specific contaminants such as cobalt, strontium, caesium, plutonium and uranium, and activated fission product nuclides. A mixed bed can be used to remove a variety of ions. Non-active species can also be removed. Decontamination factors range from 10-10,000 and waste volume reduction factor of 500-10,000 can be achieved. Suitable for feeds with low concentrations of the target ion in a large volume. Process can be fully automated.	Neutral complexes and particulates cannot be removed. Only effective with low solids and low salt content feeds. There are only a small number of functional groups that can attach to organic polymers. Organic resins have disposal problems. There is a requirement for an operating/standby system. The beds can become exhausted due to uptake of non-active species, and become less effective with each cycle. Inorganic media are more expensive than organic media. The beds are prone to channelling, where the liquid can pass without effective treatment. The beds are also prone to media breakage, usually caused by sudden changes in feedstock. Organic resins are susceptible to oxidation and carbonation. Limited radiation stability and heat resistance.	Ion exchange media when it is spent. Regeneration of media creates difficult effluents so is not normally used in the nuclear industry.
Solvent Extraction [118] [155]	Decontamination of aqueous solutions – a selective separation procedure for isolating and concentrating substances, mostly dissolved in acidic solution.	Routine in fuel reprocessing.	This is a multi-stage process. Conditioning is carried out to achieve optimum pH and oxidation states. An organic compound is added to form nuclide-organic compounds. A second organic liquid (the solvent), which is immiscible in the aqueous phase, is mixed in. This preferentially dissolves the organic complexes from the aqueous phase. The aqueous and organic phases are then separated and the complexed contaminants recovered into a more concentrated form by 'stripping' the solvent with acid or water.	Is well understood and well developed.	Not an established technique for effluent treatment. The effectiveness of treatment for low-level wastes and those with high solids content is not very good. There is no 'off the shelf' design available, and each system must be specifically designed therefore increasing costs. It is very sensitive to changes in the condition of the feedstock. Very selective therefore not as effective if there is more than one contaminant to be removed.	Solvents may be recycled directly or recovered by distillation. Contaminant complex may require further treatment.
UV Ozonolysis [142]	Oxidation of organic waste.	Unknown	Combinations of UV radiation, ozone, hydrogen peroxide, catalyst and high pH are used to generate free radicals within an aqueous solution, which then oxidise the organic contaminants to carbon dioxide, water and other non-organic products.	The process is effective.	Process occurs in a corrosive environment so plant must be constructed from specialist materials. Process can be slow. Ozone in exhaust gas must be decomposed before release. Ozone generators require high voltage electricity. UV radiation is ineffective/problematic if waste is particularly opaque or where there are suspended solids in the waste stream. UV radiation protection required.	Off-gas requires treatment. Processed effluent will require further treatment.

Table 17: Other Technologies- Electrochemical

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Electrochemical Ion exchange (electrochemical) [118] [131] [156] [157] [158]	As for ion exchange	Two full-scale plants are in operation (in USA and UK – at Paragon, GE Cardiff).	This is a development of ion exchange (see 4.5.1). Is essentially an ion exchange process, which is assisted by application of an electrode potential between the electrode and a counter electrode to promote separation.	Regenerating the media electrochemically rather than chemically means there is a reduction in secondary waste arisings. Compared to traditional ion exchange, there is less dependence on pH of waste. There is increased migration of ionic components in a shorter amount of time; hence a smaller plant is required. Wastes with higher salt loading can be treated. The electric field breaks down complexes, so nuclides trapped in the complexes can be removed. Decontamination factors exceeding 1000 and concentration factors of greater than 100 can be achieved.	Only a small number of plants are in operation as the process is relatively new. The energy usage is higher than traditional ion exchange (although it is less than 5 % that required for evaporation). Neutral complexes and suspended solids cannot be removed. Facility required is complex and expensive. Pre-filtering of the feed stream may be necessary.	A waste treatment route may be required for potentially highly radioactive spent ion exchange electrodes. Elution of the ion exchange media transfers most of the radioactivity into a small volume of liquid which will require treatment.
Electroflotation/ Electroflocculation [118] [159] [160] [161]	Enhancing separation of charged species from aqueous waste.	In nuclear industry, pilot-scale plants only.	Electroflotation: Bubbles of gas (hydrogen and oxygen) are generated in the waste stream by electrolysis. The bubbles formed carry particulates to the surface, where they can be skimmed off. Electroflocculation: A sacrificial anode (iron or aluminium) is placed in the waste stream, creating ions that work as a co-precipitant.	Electrically enhanced separation is effective at scavenging active species, and is quick and efficient. Low maintenance and can be used at remote locations. Can operate continuous or bathwise. It works without the addition of chemicals to the process. Commercial electroflotation cells are widely available, being well developed for use in other industries.	Energy consumption is relatively high. Hazardous levels of H_2 and O_2 may be produced, therefore extra ventilation may be required. pH value must be between 5 and 9.	Result of process is purified waste water and filter cake, which can be suitable for immobilisation.
Electrodialysis [118] [162] [163] [164] [165]	Final clean up of LLW	In nuclear industry, pilot plant only	A sequence of semi-permeable membranes are used, across which an electric field is applied. Ionic species are removed from one set of membrane compartments to another, thus a given feed solution is converted into two products, one with decreased ion content and one with increased. In practice, ionic species such as Sr-90, Cs-137, Co-60 and Ru-106 are usually transferred from one liquid stream to another. A new development for processing liquid radioactive waste uses a three-cell chamber assemble, which eliminates the problem of reverse diffusion of cations, therefore the extraction of isotopes becomes possible at a very high level and efficiency. This is being developed into a mobile liquid radioactive waste processing system which can process high volumes of liquid.	Process has a very high efficiency and can be run until essentially all of the ions have been stripped from the feed solution. Can be applied to low and high activity waters and can attain a decontamination factor of 100-10,000. The capacity if five times larger than a comparable electrochemical ion exchange unit.	Capital costs are moderately high. Non-ionic contaminants will not be removed. This technique is limited to well characterised wastes with low levels of dissolved solids. Can only treat solutions with a lower concentration limit of 200-300 ppm and is economically unfavourable above 700 ppm salinity level. Membrane seals are prone to leaks. The membrane is easily fouled and can be polarised by the electric field, reducing the effectiveness.	Membrane will be LLW or ILW. Sludge will require treatment.
Electrodeposition [118] [166] [167]	Removal of active metal cations	Experimental at present	An electric current is applied to the waste, causing deposition of active metal cations on a suitable cathode.	Complexes are broken down, releasing 'trapped' cations.	Trial results have so far been inconsistent. The high capital costs mean that smallscale facilities are the only sensible application. Energy use is relatively high. A well-characterised waste feed is required, so this techniques is not useful for streams that may have fluctuating composition. This technique cannot be used for metal ions less electronegative than zinc, i.e. alkali or alkali earth metals. Potential for generation of flammable and toxic gases, depending on feed characteristics.	Metal and radioactivity laden cathodes. Effluent may require further treatment e.g. chelating ion exchange.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Plasma Mass Filter [168] [169]	Separation of nuclear waste mixture into mass groups, to reduce volumes of HLW in sludge.	A full scale demonstration unit has been operating in the US since 2003, developed by Archimides Technology Group.	The process involves pre-processing to adjust the carbonates in the slurry, then two stages of vaporisation using a plasma torch, then ionisation using radio frequency power to create a plasma, then separation using electric and magnetic fields to create a specific 'cut-off mass' at which point heavy ions are spun out and collected while light ions are confined to the plasma.	Can reduce the fraction of HLW in sludge requiring vitrification, and can also reduce the amount of LLW. Is economically efficient if there is a high mass balance of light non-radioactive elements in the sludge.	If amount of light non-radioactive elements in the waste is too small then the filter process will be unproductive. High energy requirement (however less than vitrification of HLW). Large free area needed adjacent to the hot cell for overhead cranes to have access for periodic replacement of filter unit. Elements near cut-off mass (e.g. Sr-90) not so easily separated.	Off-gases formed during initial vaporisation stage. Light elements are collected as a caustic melt mixture and will be LLW. Heavy elements (the remaining HLW) will be collected as aqueous slurry.

APPENDIX 3 - TECHNOLOGIES FOR ABATEMENT OF AIR RELEASES

Table 18: Particulate Removal

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Standard HEPA Filters [170]	Abatement of particulate emissions from ventilation systems to control discharges to internal and external environment.	HEPA filters are in widespread use, especially in ambient ventilation systems and for air conditioning.	HEPA filters are High Efficiency Particulate Air filters, and are available for low (Type I) and higher temperature (Type II) applications. They act to capture particles by several processes e.g. interception and particle inertia for capturing large particles, and diffusion and electrostatic forces for smaller particles. Filters are standardised, and consist of a metal or wooden case housing fibrous material (selected according to the application) woven into a pad. The outer faces of the filter are usually protected by a mesh and the surface open to the 'dirty' stream is normally sealed with a gasket. The filter material itself is 'pleated', giving a large surface area in a small space. Multiple filters can be attached to a frame, but this is not considered good practice, as the large surface area makes sealing problematic. Normal practice is to use canisters, where each filter is in an individual housing.	These filters have a 99.95–99.99% particle removal efficiency (DF ~ 2000 – 10,000), and the higher end is normally reached in nuclear applications. Flowrates of up to 1700 m3/hr per filter insert can be handled effectively – for higher flows, more filter inserts are used in parallel. Wooden cases (as used for Type I) can be incinerated, reducing waste volume. Type I filters can be completely incinerated; (Type II cannot, as they contain metallic and ceramic parts to handle higher temperatures). Can be maintained during operation if fitted with an integrated flap which allows the inside of the filter chamber to be emptied. Type II can operate at high temperatures (tested to 500°C).	The standard HEPA filter has largely been replaced by the circular HEPA filter in terms of good practice (see next section). The wooden framed filters provide less efficient sealing than the cartridge used in circular filters. Type I filters limited to a max temperature of 70°C (although tested to 120°C for 2 hours). Filters are low density and large cartridge volumes are expensive to store and dispose of. If the air stream is wet, HEPA filters can become saturated, with consequent pressure drop problems. For some applications, it is necessary to fit in-line heaters before the filter units. Pre-filters are required for gas streams with high solids loading e.g. process off-gas streams. Extract fans must be sized to accommodate the dirty filter differential pressure drop.	Wooden cases can be incinerated to reduce waste volume.
Circular HEPA Filters [170] [171] [172] [173]	Abatement of particulate emissions from ventilation systems.	Widespread use at a number of nuclear sites.	The basic operation of circular filters is as for standard HEPA filters. These filters are approximately 500 mm diameter by 620 mm length, and have the appearance of a cartridge. Higher capacity filters have been developed.	Offer significant advantages over standard HEPA filters, which they have superseded. Being circular, the filters are easier to mount in circular ductwork. Filter replacement is improved by using a 'push-through' replacement system, which makes handling as safe as is practicable, and gives less scope for release of dust during changes. They collect the contaminants on the inside which allows the filter to be plugged after use to limit the loss of collected material. Simplified gasketing. Spent filters are more easily disposed of, by compression and drum containment.	More expensive than standard filters. Due to the construction involving metals, the whole filter cannot be incinerated. Moisture on the face of the filter will have a negative effect on its performance. Have been found to have manufacturing difficulties and increased susceptibility to leakage.	The filter and any PPE used during filter changes. Can be easily size reduced.
Large Area Roll Filters [170]	Particle removal from reactor shield cooling air.	Were used in early MAGNOX Stations. Not considered good practice.	Filter consists of a roll of synthetic fibre filter medium, which passes over a frame installed in the extract duct. When the filter gets dirty, it is automatically rolled on, and a section of new filter medium is used. The roll-on mechanism is activated by differential pressure (DP) across the filter.	These filters are suitable for high throughput applications, being designed to handle large flows (~30,000 cfm). Automatic renewal of filter medium ensuring lower DP.	They are unlikely to be considered at Dounreay, and were generally limited to early MAGNOX plants. Operating experience suggests low reliability. The filter medium is easily torn, requiring maintenance in a potentially active area. This method has a low filtration efficiency of 90% – 95% (DF ~ 10 – 20). The roll-on actuators are prone to failure, and many are now rolled manually, which is operator intensive. During reactor operations there is significant radiation dose in the vicinity of the filter.	Filter roll requires disposal.

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Cyclone Separators [174] [175] [176] [177]	Removal of suspended particles from a gas stream.	Wide in the general process industries. Particularly useful in the nuclear industry for cleaning gas streams with high density particles e.g. uranium compounds.	The entire process is driven by the vapour and contaminants themselves, coupled with an applied force to pressurise the vapours. A cyclone consists of a vertical cylindrical body, with a dust outlet at the conical bottom. As the gas spirals downward, the particles are driven to the wall by centrifugal force, and are collected in the dust hopper. In some systems, the walls of the cyclone are wetted to reduce levels of re-entrainment.	Can be configured to meet a variety of operating conditions. The equipment is simple, with no moving parts. Construction costs are low and operating costs are also low because of low maintenance requirements. Differential pressures across cyclones are relatively low. Operating temperature and pressure is limited only by the materials of construction. The generated waste stream is dry. Cyclones are compact, and do not require much space. They can be used in series or parallel, and are often installed as arrays of cyclone units.	Particle removal efficiencies are low, especially < 10um. Sticky materials cannot be handled. Simpler designs (e.g. gravity settlers) are better for larger particles (>200 µm). Cyclones are not suitable for highly flocculated dusts or high dust content (>230 g/m³). Separation efficiency is low, and can be as little as 50 %, therefore cyclones are mainly used as a preliminary dust separation technique to remove bulk contamination from an air stream.	Dust collected may require further treatment. Potential dose hazard to operators when removing the dust. Exhausted air requires sampling before release.
Mechanical Centrifugal Separators [174] [178]	Removal of solid particles from gas stream.	Not widely used for this application although effective in separation of heavy isotopes such as uranium. Used in a plant at Springfields.	A motor (generally electric) spins a vessel at high speed, and particles are separated by centrifugal force, and collected.	As for cyclones, except centrifuges have moving parts. Dust removal and fans can be combined in one unit. Clearances are smaller and centrifugal fields higher than in a cyclone.	The equipment contains many moving parts. For very dusty gases, bearing wear could be considerable. Energy consumption and maintenance requirements are greater; hence operating costs are higher than cyclones. Noise attenuation required. Inherent re-entrainment tendency.	As for cyclones.

Table 19: Removal of Other Gaseous Contaminants

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Delay Beds [170]	Delaying the release of radioactive noble gases and short-lived iodine radioisotopes.	PWR reactors, pharmaceutical industry and some radon applications.	Delay beds are tanks that contain an absorption media, which depends on the type of radionuclide contaminants present. The radionuclides in a stream of gas pass through the medium, and are held up due to adsorption/desorption. The delay time depends to a large extent on the adsorption/desorption equilibria. When the bed is fully loaded it can be sealed to allow further decay of the contaminant. The main bed is normally preceded by a guard bed, which is much smaller and designed to remove moisture and other materials which could damage the main bed.	Reduces activity by factor of ~50.	The delay bed can deteriorate due to ageing and poisoning processes reducing the availability of active sites. Only useful for a limited number of relatively short half life noble gases. Other non-active contaminants in the gas stream may interfere with the absorption process. Shielding may be required as the concentration of radionuclides on the delay bed will increase local dose rates.	Spent adsorption material loaded with the radioactive contaminant is generated due to periodic replacement of the bed. After time is given for the target radionuclide to decay sufficiently, the bed can be vented.
Decay Tanks [170]	Reduction of noble gas isotopes in gaseous emissions.	Many nuclear plants, particularly PWRs in the US. Used at Vulcan for decay of Ar-41.	A decay tank is a large pressure vessel, holding gas under pressure for a time to allow decay of short-lived radioisotopes.	Tanks are simple in construction.	Decay tanks are more expensive to install than delay beds as due to their non-selectivity they must be higher capacity, and they must be constructed to withstand the pressurised inventory. Only useful for a limited number of relatively short half life noble gases. Tanks are pressurised therefore will release radioactive material should they leak.	Process does not produce any waste except for a lower activity discharge.
Charcoal Filters/Iodine Adsorbers [170] [179] [180] [181] [182] [183]	Adsorbing organic solvent fumes particularly the removal of radioactive iodine fission products from areas where significant potential exists for the release of fission products into ventilation systems.	Charcoal filters are a widely used form of adsorbant. Used to adsorb iodine in MAGNOX and AGR Stations, some fuel cycle (reprocessing) applications.	Iodine (or organic solvent gas) is adsorbed onto a granulated carbon bed held between wire mesh. The specific surface area is very high (~1,000 m²/g). Iodine trapping performance is related to the pore size distribution, the nature of the carbon surface and impurities in the carbon. The activated carbon can be impregnated to improve its capacity for iodine compounds, with potassium iodide (KI) for high temperature applications or tri-ethylene diamine (TEDA) for lower temperature, moist environments. Adsorbers are usually preceded by filters to prevent blockage. This filter is often incorporated into the body of the adsorber. For routine continuous discharges, regeneration is necessary, so the adsorbers operate in pairs. Coconut based carbon and copper impregnated coconut based carbons (for sulphur and other low molecular weight gases) are also available; these have improved adsorption capacities.	Often the best option for removing contaminants from gas streams. The adsorbents have a large effective surface area. They are good for most organic solvent fumes. They are stable and do not incur high cost. Adsorbents are available for various conditions. There are modular and rechargeable designs available. When the carbon bed is new, very high decontamination factors are obtained. Catalysts can be added to the charcoal filters to enable them to attract non-carbon based chemicals. It is possible to decontaminate the charcoal media by desorbing it using stream.	Standard carbon is not effective at adsorbing low molecular weight gases. TEDA is unsuitable for use if significant quantities CO_2 are present. Ageing can be caused by O_2 and H_2O when treating vent air, which reduces the availability of adsorption sites. Poisoning (hydrocarbons and trace impurities) also reduces the availability of active sites, and hence lowers the DF. Carbon dust can be generated during operation. The maximum operating temperature is 200 °C; so the pipework from the reactor must allow off-gas to be cooled below this temperature. Process is more efficient at lower temperatures as iodine becomes less adsorbable as temperatures increase. The beds age with time and must be periodically replaced. Not suitable for use at high humidity.	

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Gaseous Tritium Abatement [184] [185] [186] [187]	1. Small scale tritium processes, particularly where tritium is recovered for re-use, e.g. manufacture of gaseous tritium lighting devices and manufacture of radiopharmaceuticals. 2. Processes using tritium in the manufacture or maintenance of nuclear weapons. 3. Abatement of accidental release of tritium from experimental fusion facilities. 4. Dryer units in British Energy's AGRs to divert tritium to liquid effluent 5. As part of a dehumidifier in the Thorp vent system.	Tritium abatement on major nuclear plant (e.g. nuclear power reactor vessels) is not common. The low radiotoxicity of tritium and the domination of the dose by other volatile radioactive materials means that there are usually other priorities for abatement on such plants.	A review of abatement technologies for gaseous tritium has been carried out by Amersham plc (now GE Healthcare) at their Cardiff laboratories (Ref 36) in support of an application (2001) for a variation to their Authorisation under the Radioactive Substances Act. Tritium can be captured following oxidation to tritiated water. The tritiated water is then condensed or adsorbed onto an adsorber medium. Tritium gas can also be adsorbed directly using molecular sieves. Finally, the captured water can be disposed of or enriched for recovery (note that the decision as to whether to convert the gaseous tritium to tritiated water for disposal should take into account that the tritiated water has greater toxicity than the gaseous tritium). Details on these process stages are given at the foot of this table.*	Oxidation techniques can be designed to deal with a range of tritium compounds in the gas stream. Close to 100 % recovery can be achieved. Molecular sieves are one of the most efficient and safest ways to capture tritiated water.	Systems have been designed for small-scale operations only. Purchase and operation of equipment for large-scale recovery (e.g. oxidation units, cryogenic distillation plant) is likely to be prohibitively expensive. Tritium has a low radiotoxicity, and therefore the costs in terms of expenditure/dose saved is high. The pressure inside a sealed molecular sieve bed can increase due to processes such as self radiolysis of water, therefore a pressure vessel is required, and any failure in the pressure vessel will result in a gradual desorption of tritium and migration out of the vessel.	Spent molecular sieves or other medium loaded with tritium. The tritium can be removed from the medium and the sieves recycled, as carried out at GE Healthcare. If tritium is exchanged into water, a tritiated water waste stream is created; however this is easier to contain than tritiated gas.

* Further information on Gaseous Tritium Abatement:

Oxidation

- The methods available for oxidation are: Flameless thermal oxidation (mainly used for volatile organic compounds).
- Molten salt oxidation (mainly used for volatile organic compounds).
- Two-stage oxidation (the Johnson Process): combustion in excess oxygen followed by catalytic oxidation on Pt/Al.

The above methods are expensive if complete oxidation is required. Simple combustion would be acceptable for large airflows if 100 % conversion was not required.

Capture

The methods available for the capture of tritiated water or tritium gas are:

- Condensation, using liquid nitrogen traps
- Water scrubbers
- Hydrogen getters, which can be used to remove tritium from the gas stream onto a metallic material such as uranium. Mainly used for process line temporary storage.
- Molecular sieves

Condensation and water scrubbers are the preferred options for bulk and routine duty. Molecular sieves have been employed for small scale (e.g. glove box duty) or for accidental releases (as at the Joint European Torus facility). The sieves are regenerated by driving off the tritiated water (by heating) which then needs to be recovered by, for instance, condensation.

Recovery

Recovery for re-use of tritium usually involves enrichment of the tritium isotope.
The tritium is first regenerated from tritiated water using electrolysis. It is then enriched by either gas chromatography or cryogenic distillation. The tritium is then captured by adsorption onto uranium beds, which can be regenerated to supply tritium to a process. The enrichment methods are expensive and, due to the relatively low market value of this isotope, there is little economic incentive to enrichment but there are obvious environmental advantages.

Disposal

If the tritium is to be disposed of, the tritiated water it can be converted into a solid waste form, typically by cementation. The solid waste form will still require containment as it is likely to release tritium gas. The decision on the disposal method must involve Best Practicable Environmental Option (BPEO) considerations, since it can be disposed of as a solid waste or as tritiated water.

Table 20: Gas Scrubbing

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Gas Scrubbing [170] [174] [188]	Removal of particulate and gaseous contaminants from process gas streams and ventilation systems. Can also be used for removal of aerosol and water-soluble contaminants from process off-gases, and to neutralise acidic gases.	Relatively widespread, in various applications.	Scrubbers are items of process equipment where a gas stream is contacted with a liquid stream. Contaminants that are soluble in the scrubber liquor are dissolved and are thus removed from the gas stream. Various designs (e.g. plate scrubbers, packed column scrubbers, Venturi scrubbers, bioscrubbers, tank scrubbers, rotary scrubbers), but generally the process consists of a column with several plates or packing. Scrubbing liquors are fed in towards the top, whilst dust-laden gas is fed in towards the bottom. Moving counter-current, the soluble gases are dissolved and particles washed out.	Scrubber liquor chemical composition can be tailored to the waste stream being treated. Handles heavily laden gases that would quickly blind filters. High temperature off-gases can be handled. The scrubbing liquid can be chosen to neutralise acidic or basic off-gases if required. Particulates and water-soluble gaseous contaminants are removed effectively. The wet system reduces the generation of dust from waste handling. A scrubber has a relatively small space requirement compared to other systems. Venturi scrubbers have no moving parts and are self-cleaning.	Scrubbing creates a secondary liquid effluent stream for disposal. The system is relatively complex. Fine particulates are not removed very effectively so may require an extra filtration stage downstream on large installations, before which the humidity may need to be reduced to prevent damage to the filters. In some cases (depending on the scrubbing liquor and gas properties) corrosion can be a problem. Solids can build up at the wet-dry interface. Operating costs are relatively high.	Process needs to be optimised to remove as much gaseous contamination as possible whilst minimising the amount of liquid waste produced.

Table 21: Gas Condensors

Technology	Used for	Extent of use	Process Description	Advantages	Disadvantages/ Limitations	Secondary Waste Arisings
Gas Condensors [189] [190]	Principally the recovery (rather than abatement) of large volumes of volatile components from a gas stream, especially organic compounds. However, it is also used for the abatement of low levels of volatile organics.	Extensively used for recovery and abatement throughout the organic chemicals, petrochemicals and oil industries in distillation and evaporation systems. Used in the nuclear industry, particularly in processes for the dissolving and concentration of uranium and plutonium in nitric acid.	Condensers operate by cooling the incoming gas to cause vapour contaminants to condense to a liquid. Condensers are often used in conjunction with evaporators, with the condenser being placed downstream of the vapour extract from the evaporator. In many situations, an abatement condenser is placed downstream of a recovery condenser, usually in the atmospheric vent line. The method of cooling the gas depends on the type of condenser. The primary recovery condenser will often use conventional cooling water as the coolant, whereas the downstream abatement condenser may use chilled water or a refrigerant. Other methods include cryogenic condensing, pressure condensing, and use of air cooling.	The solvent can be recovered for re-use, hence reducing secondary waste arisings.	Only of use when the contaminant is in the vapour phase. Other vapours in the contaminated gas stream may also condense. Not suitable for gas streams containing particulates. Can be energy intensive where a large amount of chilling is needed. If water is present in the process vapours, freezing problems can limit the final temperature obtainable hence the extent of recovery. Low dew point organics are difficult to recover economically.	Dependent on condenser employed. Usually produces a cleaned gas stream and the recovered solvent. Cryogenic condenser requires a method to separate the condensed solvent from the coolant.

APPENDIX 4 – NATIONAL BEST PRACTICE FOR WASTE MINIMISATION

Table 22: Summary of National Application of Best Practice

Waste Cat/ Form	RSRL	Sellafield Ltd Sites				Magnox North					Magnox South					AWE
	Harwell/ Winfrith	Windscale	Sellafield	Capenhurst	Springfields	Chapelcross	Hunterston A	Oldbury	Trawsfynydd	Wylfa	Berkeley	Bradwell	Dungeness	Hinkley Point A	Sizewell A	
RHILW Solid- Solids	Sorting and segregation Decontamination where appropriate Encapsulation in cement	Sorting and segregation Decontamination where appropriate Encapsulation in cement	Sorting and segregation Decontamination where appropriate Encapsulation in cement	N/A	N/A	Sorting and segregation Decontamination where appropriate Encapsulation in cement Entombment of certain wastes such as desiccant and IX resins currently being trialled. This work will support all Magnox sites	Sorting and segregation Decontamination where appropriate [191] Encapsulation in cement of Magnox and graphite wastes Decontamination of pond skips to LLW	Sorting and segregation Decontamination where appropriate Encapsulation in cement	Sorting and segregation Encapsulation in cement	Sorting and segregation Decontamination where appropriate Encapsulation in cement	Sorting and segregation Decontamination where appropriate Encapsulation in cement	Sorting and segregation Dissolution of FED being considered Decontamination where appropriate Encapsulation in cement was the preferred strategy but dissolution of Fuel Element Debris now being considered	Dissolution of FED. Encapsulation in cement of other misc contaminated items	High temperature processing being trialled. Concept LoC received. Will cover all waste types both solid incl graphite, liquid and sludges [194] [192] [193] Decontamination of pond skips to LLW [194]	Dissolution of FED being considered Encapsulation in cement of other misc contaminated items	Encap in cement Polymer encap for salts
RHILW Solid- SNM	Encapsulation in polymer	Encapsulation in polymer	Encapsulation in cement	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
RHILW Solid- IX Columns as opposed to loose waste	Encapsulation in cement	Encapsulation in cement	Encapsulation in cement	N/A	N/A	N/A	Trials have been done on polymer but cement entombment also considered	Trials have been done on polymer but cement entombment also considered	N/A	N/A	N/A	Trials have been done on polymer but cement entombment also considered	Trials have been done on polymer but cement entombment also considered	Trials have been done on polymer but cement entombment also considered	Trials have been done on polymer but cement entombment also considered	N/A
RHILW Liquids and Sludges- Raffinates	Encapsulated in cement	N/A	Evaporation followed by vitrification	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
RHILW Liquids and Sludges- SNM	N/A	N/A	None declared as wastes	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
RHILW Liquids and Sludges- Liquids	N/A	N/A	Encapsulated in cement			N/A	Modular Active Effluent Treatment Plant using IONSIV cartridges	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	N/A	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	N/A
RHILW Liquids and Sludges- Sludges	N/A	N/A	Encapsulated in cement			Encapsulated in cement	Encapsulated in cement	Encapsulated in cement	Polymer encapsulation of loose ion exchange resin in sea disposal drums	N/A	Encapsulated in cement	Co-packaging and blending of sludges and IX resins to maximise waste loading prior to encapsulation Encapsulated in cement	Encapsulated in cement	Co-packaging and blending of sludges and IX resins to maximise waste loading prior to encapsulation Encapsulated in cement	Encapsulated in cement	Encapsulated in cement

Waste Cat/ Form	RSRL	Sellafield Ltd Sites				Magnox North					Magnox South					AWE
	Harwell/ Winfrith	Windscale	Sellafield	Capenhurst	Springfields	Chapelcross	Hunterston A	Oldbury	Trawsfynydd	Wylfa	Berkeley	Bradwell	Dungeness	Hinkley Point A	Sizewell A	
CHILW- Solids	Sorting and segregation Decontamination where appropriate Shredding of waste Encapsulated in cement Polymer encapsulation of sea disposal drums	N/A	Sorting and segregation Decontamination where appropriate Supercompaction Many alternative techniques are being considered including high temperature processing [195].	Sorting and segregation Decontamination where appropriate Encapsulation in cement	Sorting and segregation Decontamination where appropriate Encapsulation in cement	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Polymer encapsulation of desiccants currently under investigation. Also grout entombment being considered	Segregation Decontamination where appropriate Supercompaction
CHILW- Liquids/ sludges	Solvents and oils sent for incineration Sludges encapsulated in cement	N/A	Solvents destroyed and discharged to sea Oils and greases are collected and incineration is being considered	N/A	N/A	N/A	N/A	N/A	Trials on grout encapsulation of oily sludges has been undertaken This experience shared with all sites	N/A	N/A	N/A	N/A	High temperature processing being trialled. Concept LoC received. Will cover all waste types both solid incl graphite, liquid and sludges [195]	N/A	A route for alpha contaminated oils is being sought. Grout encapsulation has been considered.
LLW- Solid	Segregation of LLW and potentially clean waste [196] Decontamination to exempt levels [197] Supercompaction	Segregation of LLW and potentially clean waste Decontamination to exempt levels [196] Supercompaction [196]	Segregation of LLW and potentially clean waste Decontamination to exempt levels [196] Supercompaction [196]	Segregation of HVLA for direct disposal [198]		Segregation of LLW and potentially clean waste Decontamination to exempt levels Supercompaction	Segregation of LLW and potentially clean waste Decontamination to exempt levels Supercompaction	Segregation of LLW and potentially clean waste Decontamination to exempt levels Supercompaction	Segregation of LLW and potentially clean waste Decontamination to exempt levels Supercompaction	Segregation of LLW and potentially clean waste Decontamination to exempt levels Supercompaction	Decontamination to exempt levels Incineration o combustible wastes [199] Supercompaction	Segregation of LLW and potentially clean waste Decontamination to exempt levels [200] Incineration of combustible wastes [199] Size reduction [200]	Decontamination to exempt levels Incineration of combustible wastes [199]	Decontamination to exempt levels Incineration of combustible wastes [199] Segregation of metal followed by melting [194]	Decontamination to exempt levels [201] Incineration of combustible wastes [199]	
LLW- Liquid	Flocculation and settling of the liquid prior to discharge	N/A	Flocculation and settling of the liquid prior to discharge Filtration and Ion exchange of liquids in the SIXEP plant			N/A	Modular Active Effluent Treatment Plant using IONSIV cartridges	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	N/A	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	Installed Active Effluent Treatment Plant using IONSIV	
LLW- Sludge	Encapsulation in cement	N/A	Encapsulation in cement						Dewatering of LLW sludges	N/A	Dewatering of LLW sludges [202]					
HVLA waste- Solid	On site HVLA disposal facility													On site HVLA disposal facility		

Waste Cat/ Form	RSRL	Sellafield Ltd Sites				Magnox North					Magnox South					AWE
	Harwell/ Winfrith	Windscale	Sellafield	Capenhurst	Springfields	Chapelcross	Hunterston A	Oldbury	Trawsfynydd	Wylfa	Berkeley	Bradwell	Dungeness	Hinkley Point A	Sizewell A	
RSA Exempt and Clean Non Hazardous Waste- Solid	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196]	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196]	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196]	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196] [203] Incineration with energy recovery for combustible non-recyclable wastes		Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196]	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196]	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196]	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling	Segregation from inert wastes followed by segregation by material type to enable maximum reuse/recycling	
RSA Exempt and Clean Inert Waste- Solid	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]			Retain on site to be recycled as backfill for voids generated during decommissioning	Retain on site to be recycled as backfill for voids generated during decommissioning	Retain on site to be recycled as backfill for voids generated during decommissioning	Retain on site to be recycled as backfill for voids generated during decommissioning	Retain on site to be recycled as backfill for voids generated during decommissioning	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]	Retain on site to be recycled as backfill for voids generated during decommissioning [194] 196]	
RSA Exempt and Clean Hazardous Waste- Solid	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] 196] Incineration of combustible non-recyclable wastes [194] [196] Clearance of asbestos by a specialist contractor	Clearance of asbestos by a specialist contractor Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] 196] Incineration of combustible non-recyclable wastes [194] [196]	Clearance of asbestos by a specialist contractor Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] 196] Incineration of combustible non-recyclable wastes [194] [196]	Clearance of asbestos by a specialist contractor	Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling Incineration of combustible non-recyclable wastes Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling Incineration of combustible non-recyclable wastes Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling Incineration of combustible non-recyclable wastes Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling Incineration of combustible non-recyclable wastes Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling Incineration of combustible non-recyclable wastes Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] 196] Incineration of combustible non-recyclable wastes [194] [196] Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196] Incineration of combustible non-recyclable wastes [194] 196] Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196] Incineration of combustible non-recyclable wastes [194] [196] Optimisation of waste retrieval process Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196] Incineration of combustible non-recyclable wastes [194] [196] Clearance of asbestos by a specialist contractor	Segregation from non-hazardous wastes followed by segregation by material type to enable maximum reuse/recycling [194] [196] Incineration of combustible non-recyclable wastes [194] 196] Clearance of asbestos by a specialist contractor	Clearance of asbestos by a specialist contractor

Waste Cat/ Form	RSRL	Sellafield Ltd Sites				Magnox North					Magnox South					AWE
	Harwell/ Winfrith	Windscale	Sellafield	Capenhurst	Springfields	Chapelcross	Hunterston A	Oldbury	Trawsfynydd	Wylfa	Berkeley	Bradwell	Dungeness	Hinkley Point A	Sizewell A	
Liquid Discharges	Treatment prior to discharge e.g. separation, flocculation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance [194][196]		Treatment prior to discharge e.g. separation, flocculation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance [194][196]			Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance [194] 196]	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance [194] 196]	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance [194] 196]	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance [194] 196]	Treatment prior to discharge e.g. separation, filtration to minimise the activity discharged and to exclude all entrained solids. Thorough maintenance of treatment plant Sampling and analysis of liquids prior to discharge to ensure compliance [194] 196]	
Gaseous Discharges	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]	Periodic cleaning of equipment to reduce levels of 'loose' surface activity which might become airborne. [196] Use of containment e.g. tenting to minimise the spread of airborne contamination. Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids, wet scrubbers to remove significant volatile activity, electrostatic precipitators, packed beds, condensers and pre-heaters (to prevent condensation in the filters).	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196] Authorisations for the discharge of Ar-41, S-35, C-14 and H-3	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196] Authorisations for the discharge of Ar-41, S-35, C-14 and H-3	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196] Authorisations for the discharge of Ar-41, S-35, C-14 and H-3	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196] Authorisations for the discharge of Ar-41, S-35, C-14 and H-3	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196] Authorisations for the discharge of Ar-41, S-35, C-14 and H-3	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196] Authorisations for the discharge of Ar-41, S-35, C-14 and H-3	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196] Authorisations for the discharge of Ar-41, S-35, C-14 and H-3	Treatment prior to discharge e.g. filtration - High Efficiency Particulate in Air (HEPA) filter to remove solids [196]

APPENDIX 5 – DETAIL OF COMPARISON OF DOUNREAY STRATEGY AGAINST THE REVIEW OF BEST PRACTICE

Table 23: Gap analysis for ILW solid wastes

Management Technique	Application of Best Practice (or Application of Management Techniques)					
	RHILW Solid other	**RHILW Solid SNM**	**RHILW Solid Ion exchange resins**	**CHILW Solid SNM**	**CHILW Pu, U, Th contaminated materials**	**CHILW graphite**
Sorting	Yes – sorting to maximise management as LLW and sorting to facilitate volume reduction	Yes – sorting to separate from other wastes that could be treated through alternative processes	No – Grouting whole item as one is Best Practice	Yes – sorting to separate from other wastes that could be treated through alternative processes	Yes – sorting to maximise management as LLW and sorting to facilitate volume reduction	No – No advantage gained from sorting
Dismantling	Yes – applied as appropriate	Not applicable	Not applicable	Not applicable	Yes – applied as appropriate	Not applicable
Volume reduction	Yes – Compaction, shredding, cutting applied as appropriate	Yes –cutting applied as appropriate	No – Volume reduction is not used	Yes –cutting applied as appropriate	Yes - supercompaction	Uncertain – wastes may be shredded but strategy not finalised.
Physical Decontamination	Yes - Partial applicability	Not applicable	Partial applicability	Not applicable	Yes - Partial applicability	Not applicable
Chemical Decontamination	Yes - Only if applicable at initial dismantling stage	Not applicable	No - Some resins can be re-genearated however significant secondary wastes would be generated if applied	Not applicable	Yes - Only if applicable at initial dismantling stage	Yes – only applicable for the THTR
Electrochemical Decontamination	Partial applicability	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Encapsulation / immobilisation	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository
Storage	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers
Direct disposal	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository

Table 24: Gap analysis for LLW solid wastes

Management Technique	Application of Best Practice (or Application of Management Techniques)	
	LLW Solids	**HVLA Solids**
Sorting	Yes – sorting to maximise management as Clean / Exempt and sorting to facilitate volume reduction	Yes – sorting to maximise management as Clean / Exempt
Dismantling	Yes – Applied as appropriate	Yes – Applied as appropriate
Volume reduction	Uncertain – many waste minimisation techniques are utilised for LLW solids but it is unclear whether there has been a full consideration of all options including incineration, compaction, shredding, cutting applied as appropriate	Yes – Crushing
Physical Decontamination	Yes – Grit blasting where appropriate	Not applicable
Chemical Decontamination	Yes – Where appropriate	Yes – Where appropriate
Electrochemical Decontamination	Not applicable	Not applicable
Encapsulation / immobilisation	Yes – Requirement for consignment to the proposed on-site LLW repository	Not applicable
Storage	Yes – Storage of passively safe wastes in approved containers	Yes – Stored in bags in purpose built store
Direct disposal	Yes – To the proposed on-site LLW repository	Yes – To the proposed on-site LLW repository

Table 25: Gap analysis for ILW liquid and sludge wastes

Management technique	**Application of Best Practice (or Application of Management Techniques)**				
	RHILW liquors (PFR, DFR, MTR, ADU floc supernatant)	**RHILW Liquid SNM**	**RHILW Sludge**	**CHILW Liquid SNM**	**CHILW Solvents and oils**
Filtration	Not applicable	Yes – Filtration only required to remove residual particulates	Not applicable	Yes – Filtration only required to remove residual particulates	Yes to remove products of wet abatement
Precipitation / flocculation	Not applicable	Yes – precipitation to produce a solid could be used	No - Ion exchange is used in preference	Yes – precipitation to produce a solid could be used	No - Wet abatement used in preference
Treatment of non-aqueous liquids	Not applicable	Not applicable	Not applicable	Not applicable	Yes – Volume reduction by incineration
Chemical Separation	No - However significant secondary wastes would be generated if applied	Not applicable	Yes – Effluent water conditioned by ion exchange prior to discharge	Not applicable	Yes – Wet abatement to reduce activity to allow incineration
Electrochemical Separation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Physical Separation	Only for one dilute component of the waste stream	Not applicable	Not applicable	Not applicable	Not applicable
Encapsulation / immobilisation	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository	Yes – Requirement for consignment to the ILW repository
Storage	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers	Yes – Storage of passively safe wastes in RWMD approved containers
Direct disposal	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository	Yes – To the proposed ILW repository

Table 26: Gap analysis for LLW liquid and sludge wastes

Management technique	Application of Best Practice (or Application of Management Techniques)				
	LLW Liquids (Effluents produced by facilities)	**LLW Liquids (Oils and solvents)**	**LLW Sludges (Sludge)**	**LLW Sludges (Putrescible)**	**LLW Sludges (LSA scale)**
Filtration	Yes – but only to remove residual particulates	Yes – As part of the wet abatement process to remove residual activity	Uncertain, method for retrieval of sludge not yet determined	Yes – As part of the initial recovery of the sludge	No – Already recovered and dried
Precipitation / flocculation	Yes – As a by product of the pH adjustment prior to discharge	Yes – As part of the wet abatement process to remove residual activity	Not applicable	Not applicable	Not applicable
Treatment of non-aqueous liquids	Not applicable	Yes – Incineration to reduce disposal volumes	Not applicable	Not applicable	Not applicable
Chemical Separation	Yes – Ion exchange as appropriate at the facility where the effluent originates	Yes – Activity removal by wet abatement prior to incineration	No – Sludge is to be retrieved and conditioned for packaging	No – Strategy still under development	Not applicable
Electrochemical Separation	Not applicable	Not applicable	Not applicable	Not applicable	Not applicable
Physical Separation	Not applicable	Not applicable	Uncertain, method for retrieval of sludge not yet determined	Yes – Material is dried prior to storage	Yes - Prior to immobilisation
Encapsulation / immobilisation	No – Discharged in accordance with site discharge authorisations	Not directly, the residual solid ash will be immobilised	Yes – Requirement for consignment to the proposed on-site LLW repository	No – Strategy still under development	Yes – However current condition unknown
Storage	Stored as required. Discharged in accordance with site discharge authorisations	Yes – Storage of passively safe wastes in approved containers	Yes – Storage of passively safe wastes in approved containers	Yes but strategy still under development	Yes – However current condition unknown
Direct disposal	Yes – In accordance with site discharge authorisations	Not directly, the decontamination products and residual solid ash will be sent for disposal. The remainder will be discharged to air after particulate removal	Yes – To the proposed on-site LLW repository	No – No disposal route identified	Although LLW, inventory currently requires disposal as ILW

Table 27: Gap analysis for clean and exempt solid wastes

Management technique	Application of Best Practice (or Application of Management Techniques)		
	Clean and Exempt Non-hazardous solid	**Clean and Exempt Inert solid**	**Clean and Exempt hazardous solid**
Sorting	Yes – To ensure maximum disposals at these categories and to ensure recycling and reuse opportunities are maximised	Yes – To ensure maximum disposals at these categories and to ensure recycling and reuse opportunities are maximised	Yes – To ensure maximum possible disposals as inert or Non-hazardous materials as determined by legislative requirements. Also to ensure recycling and reuse opportunities are maximised
Dismantling	Yes – Dismantling applied to aid sorting	Yes – Dismantling applied to aid sorting	Yes – Dismantling applied to aid sorting
Volume reduction	Yes – A variety of size reduction techniques are used	Yes – A variety of size reduction techniques are used	Yes – A variety of size reduction techniques are used
Physical Decontamination	Not applicable – Decontamination not used at this stage	Not applicable – Decontamination not used at this stage	Not applicable – Decontamination not used at this stage
Chemical Decontamination	Not applicable – Decontamination not used at this stage	Not applicable – Decontamination not used at this stage	Yes – Chemical treatments will be applied based on cost – benefit principles
Electrochemical Decontamination	Not applicable	Not applicable	Not applicable
Encapsulation / immobilisation	Not Applicable	Not Applicable	Not Applicable
Storage	Yes – Items stored prior to reuse / recycle or consignment to landfill	Yes – Items stored prior to reuse / recycle or consignment to landfill	Yes – Items stored prior to reuse / recycle, disposal or treatment
Direct disposal	Yes – To specialist contractor for off-site reuse or recycle or to landfill as a last resort	Yes – To specialist contractor for off-site reuse or recycle or to landfill as a last resort	Yes – Transfer to specialist contractor

Table 28: Gap analysis for clean hazardous sludge and clean / exempt liquid wastes

Management technique	Application of Best Practice (or Application of Management Techniques)	
	Clean and Exempt Hazardous Sludge	**Clean and Exempt liquids**
Filtration	Yes – As part of the initial recovery of the sludge	Not Applicable
Precipitation / flocculation	Not Applicable	Not Applicable
Treatment of non-aqueous liquids	Not applicable	Not Applicable
Chemical Separation	No – Strategy still under development	No – No treatment required
Electrochemical Separation	Not Applicable	Not applicable
Physical Separation	Yes – As part of the initial recovery of the sludge	No – No treatment required
Encapsulation / immobilisation	No – Strategy still under development	Not Applicable
Storage	Yes – Until strategy determined	Yes – Items stored prior to reuse / recycle or disposal
Direct disposal	No – No disposal route identified	Yes – Transfer to specialist contractor

Table 29: Gap analysis for gaseous and aerial discharges

Management technique	Application of Best Practice (or Application of Management Techniques)
	Gaseous and Aerial Discharges
Condensers	No
Particulate removal	Yes – HEPA filtration of discharges as required
Separation of components	No
Decay tanks	No
Gas Scrubbers / absorbers	No

APPENDIX 6 – REFERENCES FOR APPENDICES 1-4

1. ‘State of the Art Technology for Decontamination and Dismantling of Nuclear Facilities’, IAEA Technical report 395, 1999.
2. Nuclear Decommissioning, Waste Management and Environmental Site Remediation, Bayliss C.R & K.F Langley, Elsevier, 2003.
3. Handbook of Radioactive Contamination and Decontamination. Studies in Environmental Science 47. Severa, J. and Bar, J. Elsevier. Amsterdam, 1991.
4. Brokk AB. Retrieved: 20th July 2004. www.brokk.com
5. http://id.inel.gov/lsddp
6. Large-range Sequential Core Boring (LSCB) System for Dismantling of Contaminated Concrete Structure. Komatsu, Y. et. al. Decommissioning, Decontamination & Reutilization. Denver, USA, 7 – 11 August 2005.
7. Decontamination and Demolition of Concrete and Metal Structures During the Demolition of Nuclear Facilities. IAEA, Technical Reports Series No. 286, Vienna, 1988.
8. Laser Cutting and Size Reduction, Deactivation and Decommissioning Focus Area, Innovative Technology Summary Report, DOE/EM-0612, September 2001. (http://apps.em.doe.gov/OST/itsrddfa.asp)
9. Langley K F and Williams J: Decontamination and Waste Minimiation Techniques in Nuclear Decommisioning (UKAEA undated).
10. Preferred Alternatives Matrices Decommissioning, US Department of Energy Office of Environmental Restoration, Rev. 2, 1997
11. Decontamination Techniques Used in Decommissioning Activities, NEA Task Group, 1999
12. Decommissioning Handbook. DOE. DOE/EM-0142P. Washington, 1994.
13. Decommissioning Benchmarking Study, US Department of Energy Office of Environmental Restoration, 1997.
14. Preferred Alternatives Matrices Decommissioning, US Department of Energy Office of Environmental Restoration, Rev. 2, 1997.
15. Hospitality Net tm. www.hospitalitynet.org, 12th January 2004
16. Washington State University Safety Policies and Procedures Manual, www.wsu.edu, 29th January, 2004
17. Methods for the Minimisation of Radioactive Waste from Decontamination and Decommissioning of Nuclear Facilities, IAEA Technical Report Series No. 401, 2001
18. Enviro Solutions. http://www.enviro-solution.com/envirosound/ 17th June 2004.
19. Decommissioning of Nuclear Facilities: Decontamination, Disassembly and Waste Management, IAEA, Technical Report Series No. 230, 1983
20. Nuclear Science and Technology: Handbook on decommissioning of nuclear installations, EUR 16211, 1995
21. Status of technology for volume reduction and treatment of low and intermediate level solid radioactive waste, IAEA Technical Report No. 360, IAEA, ISBN 92-0-100494-X, 1994
22. Encapsulation Technologies LLC. www.fogging.com, 12th January 2004
23. High Temperature Decontamination of Metal Scrap, Mamaev, L., Khrabov, L., and Tikhomirov, V. WM'99 Conference, Moscow. February 28 – March 4, 1999
24. Decommissioning Preferred Alternatives Matrices. Rev. 2, US DOE, 1997
25. eMedicine.com Inc. www.emedicine.com, 5th January 2004
26. What are Supercritical Fluids’; Chemistry Department, University of Leeds: http://www.chem.leeds.ac.uk/People/CMR/whatarescf.html Retrieved 21 November 2005.
27. ‘Development of Radioactive Waste Treatment System using Supercritical Water’; Y. Akai et al. Toshiba Corporation. WM’05 conference; 27 February – 3 March, 2005.
28. C-ACT, Los Alamos national Laboratory: http://scrub.lanl.gov/2002/scf/index.htm Retrieved 21 November 2005.
29. Supercritical Fluid Cleaning, Edited by John McHardy and Samual Sawan, Noyes Publications, New Jersey, copyright 1998, ISBN: 0-8155-1416-6.
30. The American Society of Mechanical Engineers, Nuclear Facilities Decommissioning Handbook, Chapter 17: Decontamination, http://www.asme.org/pro_dev/D&D/Ch17.pdf. Retrieved: 20 July 2004
31. Decontamination Techniques Used in Decommissioning Activities, F. Motte et al, Nuclear Energy Task Group on Decontamination, June 1998
32. Recycling System of Decontamination Liquid Waste, S Saishu et al., Nuclear Power Engineering Corporation, Tokyo, Retrieved 20/07/04
33. Contaminated Concrete: Occurrence and Emerging Technologies for DOE Decontamination, Oak Ridge National Laboratory, DOE/ORO/2
34. Testing and Comparison of Seventeen Decontamination Chemicals, Demmer, R.L., Idaho National Engineering Laboratory, INEL-96/0361, September 1996
35. United States Environmental Protection Agency, Technology Innovation Programme, Technology Focus, Soil Washing. Retrieved: 24 September 2004 http://clu-in.org/techfocus/default.focus/sec/Soil_Washing/cat/Overview/
36. North Atlantic Treaty Organisation, Committee on the Challenges of Modern Society, NATO/CCMS Pilot Study, Evaluation of Demonstrated and Emerging Technologies for the Treatment and Clean up of Contaminated Land and Groundwater, Phase 2, Final Report, Number 219, June 1998. Retrieved: 21 October 2004 http://www.clu-in.org/download/partner/phase-2.pdf
37. ‘Decommissioning of Nuclear Facilities’ IBC 7th International Conference and Exhibition, IBC October 2000
38. Nederman - promotional literature
39. ‘Containers for Packaging of Solid Low and Intermediate Level Radioactive Wastes’, IAEA Technical Report 355, 1993
40. Preferred Alternatives Matrices Decommissioning, US Department of Energy Office of Environmental Restoration, Rev. 2, 1997
41. Environmental Restoration, DOE/EM-142P, 1994
42. Decontamination of Nuclear Facilities to Permit Operation, Inspection, Maintenance, Modification or Plant Decommissioning, IAEA, Technical Report Series No. 249, Vienna, 1985.
43. AECP 1072, ‘Sampling and Monitoring of airborne radioactive discharges’, UKAEA Code of Practice, 1998
44. Guidelines for Planning Interventions Against External Exposure in Industrial Areas After A Nuclear Accident, Part I, Eged K. et al., Institut fur Strahlenschutz, 2003.
45. ‘Safe Handling of Tritium – Review of Data and Experience’, IAEA Technical Report 324, 1991
46. Decontamination Technique with Hydrogel Foils as Alternative Method of Strippable Coating. Dragusin, M. Decommissioning, Decontamination & Reutilization. Denver, USA, 7 – 11 August 2005

47. Technical Guidance A2, 'Pollution Abatement Technology for the Reduction of Solvent Vapour Emissions', HMIP 1994
48. 'Spotlight on the Tanks Focus Area', Initiatives online, http://www.wpi.org/initiatives/init/spring00/spotlite.htm
49. 'Treatment of Low and Intermediate-level Solid radioactive wastes', IAEA Technical Report 223, 1983
50. http://nuclearweaponarchive.org/Smyth/Smyth9.html
51. Aquablast promotional literature
52. W ter Kuile & Dr. R. Doig. Circular HEPA Filters for use in Nuclear Containment and Ventilation Systems, Proceedings of the 25th DOE/NRC Nuclear Air Cleaning and Treatment Conference, Minneapolis, Minnesota, August 3 - 6, 1998
53. Kranzle. www.kranzle.co.uk, 12th January 2004
54. Nuclear Science and Technology: Handbook on decommissioning of nuclear installations, EUR 16211, 1995
55. Robertshaw Industrial Products Division, www.robertshawindustrial.com, 2nd February 2004.
56. Radiation Safety, University of Cincinnati, www.uc.edu/radsafety/auapp9.htm, 2003
57. Espitech Air Products. http://members.fortunecity.com/espitech/carbonpower.html, 21st July 2004.
58. WM'05 Conference; 'RCRA Permitting of a Vacuum Thermal Desorption System'; T.L. Orton; February 27 – March 3, 2005
59. Thermal Desorption Pre-Demonstration Plan for Volatile and Semi-volatile Organic Compounds. December 5, 2003. http://www.hazardouswaste.utah. gov/ADOBE/envirocare/attachmentII-1-12-2.pdf
60. Waste Vitrification: A Historical Perspective. McElroy, J.L., Bjorklund, W.J. and Bonner, W.F. in The Treatment and Handling of Radioactive Wastes. Blasewitz, A. G, Davis, J. M. and Smith, M. R. (eds.) Battelle Press, Richland, 1983
61. Technical Guidance M11, 'Monitoring or Radioactive Releases to Atmosphere from Nuclear Facilities', Environment Agency, 1999
62. Ultrasonic Cleaning Systems. Clean Tech tm. Witter Publishing. 2003, http://www.cleantechcentral.com/KnowledgeBase/TechnologySpotlight/ultrasonic.asp
63. 'Spotlight on the mixed waste focus area', Initiatives Online, http://www.wpi.org/initiatives/init/aug97/4.htm
64. Chemical Precipitation Processes for the Treatment of Aqueous Radioactive Waste. Technical Report Series 337. IAEA. Vienna, 1992
65. 'Laser Surface Cleaning'; E.C. Crivella, J. Freiwald, D.A. Freiwald
66. OIS promotional literature
67. Brookhaven Graphite Research Reactor Decommissioning Project Removal Action Alternatives Study
68. Brookhaven National Laboratory, US DOE BGRR-015, Rev. 0, 2000
69. 'Quality Assurance for Radioactive Waste Packages', IAEA Technical Report 376, 1995
70. Radioactive Waste: Advanced Management Methods for Medium Active Liquid Waste, Harwood Academic Publishers, 1981
71. Dry Ice Blasting Technical Papers, Coldjet LLC, http://www.coldjet.com/, 2003
72. Clean Surfaces Ltd., http://www.dryiceblasting.co.uk/
73. Research and Development Results for Dismantling and Decontamination Application. Versemann, R. et.al. WM'05 Conference. Tucson, USA, 27 February – 3 March 2004
74. 'DNE Electrochemical Decontamination Immersion Tank – Operation with Aluminium, Brass, Lead and Mild Steel', AEA-TPD-0200, Harwell 1994
75. Sustainable waste management: recovery of fuels from petroleum sludge, M. Elektorowicz and S. Habibi, Can. J. Civ. Eng., 32, 2005
76. Electrokinetic Decontamination of Concrete, H.L. Lomasney et al., Industry Partnerships to Deploy Environmental Technology, DOE/MC/30162-97/C0804, October 19
77. Microbial Janitors Tackle Nuclear Clean-Up Problems 18/08/1999
78. The Physical and Theoretical Chemistry Laboratory Oxford University Chemical and Other Safety Information, Oxford University, http://physchem.ox.ac.uk, 2003
79. Commercially Available Low-level Radioactive and Mixed Waste Treatment Technologies. Garcia, R.S. DOE/LLW-240. Idaho National Engineering Laboratory, Idaho Falls, 1996. www.state.sc.us/energy/PDFs/Commercially_Available_LLRW_Treatment_Technologies.pdf
80. Advances in Encapsulation Technologies for the Management of Mercury-Contaminated Hazardous Wastes, U.S. Environmental Protection Agency, National Risk Management Research Laboratory, S Chattopadhyay & WE Condit, August 2002, http://www.epa.gov/ORD/NRMRL/Pubs/600R02081/600R02081.pdf
81. AERA R 10835, 'The concentration of medium level radioactive wastes by evaporation', UKAEA, 1985
82. Handling And Processing Of Radioactive Waste From Nuclear Applications, IAEA Technical Report No. 402, IAEA 2001
83. Interim Storage of Radioactive Waste Packages. IAEA. Technical Report Series No. 390. Vienna, 1998
84. Conditioning Technology for Radioactive Waste Resulted from the Treatment of Liquid Waste From the Romanian Nuclear Power Plant. Arsene, C., Andrei, V., and Negoiu, D. WM'03 Conference, Tucson, February 23-27, 2003, http://www.wmsym.org
85. Fusion Programme Annual Report 2002. Decreton, M. BL6-927, www.sckcen.be/scjcen_en/activities/research/reactorsafety/fusion/annualreport2002
86. 'Radioactive Wastes Dispersed in Stabilized Ash Cements', Los Alamos National Laboratory, Supercritical Fluids Facility, 1997. http://www.scrub.lanl.gov/pubs/1009.htm
87. Cementitious Systems for Encapsulation of Intermediate Level Waste. Sharp, J.A. et al. ICEM'03. Oxford, September 21-25, 2003.
88. Silicon-polymer encapsulation of High-level Calcine Waste for Transportation or Disposal. Loomis, G.G., WM'00 Conference, Tucson, February 27-March 2, 2000
89. 'Radioactive Waste Forms for the Future' Werner Lutze, Rodney Ewing, North Holland Physics Publishing, 1988
90. Vitrification of Mixed Wastes, the Good, the Bad, and the Ugly, Gombert, D. WM'99 Conference, Tucson, 28 February – 4 March, 1999, http://www.wmsym.org
91. Los Alamos National Lab website http://www.lanl.gov
92. http://www.sciencedaily.com/releases/2002/06/020611071658.htm

93. Synroc. World Nuclear Association. 2003. www.world-nuclear.org/info/inf58.htm
94. Immobilization of High-level Defence Waste in Synroc-D: Recent Research and Development Results on Process Scale-Up. Campbell, J.H., Rozsa, R.B. and Hoenig, C.L. in The Treatment and Handling of Radioactive Waste. Blasewitz, A.G., Davis, J.M. and Smith, M.R. Battelle Press. Richland, 1982
95. www.sea-us.org.au
96. Spray Calcination of SRP Waste Compositions for Ceramic Waste Forms. Grantham, L.F. and Flintoff, J.F. in The Treatment and Handling of Radioactive Waste. Blasewitz, A.G., Davis, J.M. and Smith, M. R. Battelle Press, Richland, 1983
97. Stabilization Using Phosphate Bonded Ceramics. U.S. Department of Energy. DOE/EM-0486. 1999, http://apps.em.doe.gov/ost/pubs/itsrs/itsr117.pdf
98. Engineering and Design - Guidance For Low-Level Radioactive Waste (LLRW) and Mixed Waste (MW) Treatment and Handling. U. S. Army Corps of Engineers. EM 1110-1-4002. 1997
99. Predisposal Management of Organic Radioactive Waste. IAEA. Technical Report Series No. 427. Vienna, 20
100. Combustion Improvement of Boilers and Incinerators using Ecotube System – First US Installation. Hagstrom, U., International Conference on Incineration and Thermal Treatment Technologies. Texas, USA, 9-13 May 2005
101. Direct Chemical Oxidation, Innovative Technology Summary Report, OST Ref. #109, US DOE, December 1998
102. Molten Salt Oxidation Process, P. Hsu, Lawrence Livermore National Laboratory, 2001. Retrieved: 27 February 2004. http://www-cms.llnl.gov/s-t/molten.html
103. Regional Facilities for dealing with hazardous waste, DTI Environment Directorate, November 2000
104. Review and Evaluation of the Army Non-Stockpile Chemical Material Disposal Program: Disposal of Neutralent Wastes. Board on Army Science and Technology. National Academy Press. Washington, D.C., 2001. Retrieved 24 September 2004. http://books.nap.edu/books/0309072875/html/30.html#pagetop
105. Biodegradation of Used Machine Tool Cutting Fluids. Taylor, G.T. et al. WM'99 Conference. Tucson, 1999.
106. Centre for Phytoremediation Research and Development. Environmental Security Technology Certification Programme.http://www.estcp.org/projects/cleanup/199519v.cfm
107. Purdue researchers prod plants to clean up pollution, Purdue News April 1997. http://www.purdue.edu/UNS/html4ever/9704.Goldsbrough.phyto.html
108. 'Summary of the Workshop on the Potential Application of Metal Melting in the UK Nuclear Sector'; 6th October 2004; Z.K. Hillis and M. Buckley, NNC Ltd. http://www.hse.gov.uk/research/nuclear/meltmetalworkshop.pdf
109. 'Literature Review of the Potential Application of Metal Melting in the UK Nuclear Sector'; M. Buckley, B. Handy, Z.K. Hillis (NNC/HSE); November 2004
110. Waste Treatment: Metal Melting. Studsvik UK Limited. http://www.erslimited.co.uk/files/STUDSVIK_UK-Flyer-Metal-Melt-December-2006.pdf Retrieved 23 February 2007
111. Solid Waste Management, Departments of the Army (Corps of Engineers), Army TM 5-634, May 1990, http://www.usace.army.mil/publications/armytm/TM5-634/chap4.pdf
112. Thermochemical technologies for conversion of biomass to fuels and chemicals, R.L. Bain, National Renewable Energy Laboratory, Texas, U.S.A. September 2006, http://www.rice.edu/energy/publications/eventpres/Biofuels_Bain_092606.pdf
113. Study into the applicability of thermochemical conversion technology to legacy asbestos wastes in the UK, A. Downey and D.M. Timmons, WM'05 Conference, Tucson, AZ. March 2005
114. Guidance for Operators and Inspectors of IPC Processes, 'Effluent Treatment Techniques', Environment Agency 1999
115. Commercially Available Low-level Radioactive and Mixed Waste Treatment Technologies. Garcia, R.S. DOE/LLW-240. Idaho National Engineering Laboratory, Idaho Falls, 1996. www.state.sc.us/energy/PDFs/Commercially_Available_LLRW_Treatment_Technologies.pdf
116. Mercury Work Group, Phase II Reports: Pre-treatment Manual. MASCO, Boston. 2000. http://www.masco.org/mercury/pretreatment/pretreatment.html
117. Technical Guidance A5, 'Abatement of Atmospheric Radioactive Releases From Nuclear Facilities', Environment Agency, 1998
118. Technical Guidance A6, 'Abatement of Radioactive Releases to Water from Nuclear Facilities', Environment Agency, 1999
119. Mechanical Science Vol. 2.DOE. DOE-HDBK-101812-93. www.tpub.com/content/doe/h1018v2/css/h1018v2_124.htm, 16th January 2004.
120. Chemical Precipitation Processes for the Treatment of Aqueous Radioactive Waste. Technical Report Series 337. IAEA. Vienna, 1992.
121. Precoat Filters. Hoffmann Maschinen. http://www. hoffmann-filter.de/english/anschwemmfilter.htm#operation, 26th January 2004.
122. Engineering and Design: Filtration Treatment Systems. US Army Corps of Engineers. ETL 1110-1-159. 1994. http://www.usace.army.mil/publications/eng-tech-ltrs/etl1110-1-159/a-iv.pdf
123. Funda. MAVAG AG, http://www.mavag.com/Start_e.htm. Retrieved Oct 2005.
124. Funda Filters by Steri. Steri Technologies. http://www.steri.com/funda.html#easy retrieved 28th November 2005.
125. MAVAG - FUNDA®-Filter Systems for Pharmaceutical Applications. SPD Media Ltd. http://www.pharmaceuticaltechnology.com/contractors/purification/stawag Retrieved 28th November 2005
126. Engineering and Design - Guidance For Low-Level Radioactive Waste (LLRW) and Mixed Waste (MW) Treatment and Handling. U. S. Army Corps of Engineers. EM 1110-1-4002. 1997.
127. Funda Filters by Steri: Filtration Made Easy. Brochure. Steri Technologies. 2005.
128. 'Perry's Chemical Engineer's handbook', 6th Ed, McGraw-Hill, 1984
129. Guidance for Operators and Inspectors of IPC Processes, 'Effluent Treatment Techniques', Environment Agency 1999
130. The Environmental Guide, Environment Technology Centre, University of Nottingham, http://www.nottingham.ac.uk/~enzetc/guide
131. Decommissioning Handbook. DOE. DOE/EM-0142P. Washington, 1994.
132. Remediation Technologies Screening Matrix and Reference Guide, Version 4.0. FRTR. www.frtr.gov/matrix2/section4/4-51.html, 16th January 2004.
133. Radioactive Waste: Advanced Management Methods for Medium Active Liquid Waste, Harwood Academic Publishers, 1981
134. Handling And Processing Of Radioactive Waste From Nuclear Applications, IAEA Technical Report No. 402, IAEA 2001
135. Precipitation / Coagulation / Flocculation, Remediation Technologies Screening Matrix and Reference guide, Version 4.0, The Federal Remediation Technology Roundtable (FRTR), 2004
136. Verifications Under the Terms of Article 35 of the Euratom Treaty, V. Tanner, S. Van der Stricht, E. Henrich, T. Ryan, European Commission, UK-04/1, 8 March 2005.

137. The Concentration of Medium Level Radioactive Wastes by Evaporation, AERE R 10835, July 1985.
138. Drum Evaporator / Heater - Encon Wastewater Evaporator System, PSI Water systems Inc., http://www.evaporator.com/drum_evaporator.html, 2004
139. AERA R 10835, 'The concentration of medium level radioactive wastes by evaporation', UKAEA, 1985
140. Process Heat Transfer, D Q Kern, McGraw-Hill Kogakusha Ltd
141. Rising Film Evaporators, Niro Inc., 2003. Retrieved: 30th January 2004. http://niroinc.com/html/evaporator/rising_film_evaporators.html, 2003
142. The Detoxification of Chlorinated Organics in Dilute Solution (ppm / ppb), DW McHugh, PhD Thesis, UMIST, 1998
143. Radiation Health Series No. 5, Code of Practice for the Handling, Storage, Packaging, Transport and Disposal of Radioactive Wastes, Radiation Health Unit, Department of Health, The Government of Hong Kong Special Administrative Region, 1997.
144. Management of Abnormal Radioactive Wastes at Nuclear Power Plants, IAEA Technical Report Series No. 307, 1989.
145. http://www.quantum-dynamics.com/Centrifugal.html
146. http://www.psl.bc.ca/equipment/hydrocyclone/
147. Reverse Osmosis Process, Capsule Report, US EPA/625/R96/009, 1996.
148. Development of radioactive waste management technology, JAEA R&D Review, 2006. http://jolisfukyu.tokai-sc.jaea.go.jp/fukyu/mirai-en/9_1f9_2.html
149. Steam Reforming Process, C. Barnes et al., INEEL/EXT-04-01692, Appendix A, Idaho National Laboratory, U.S.A., February 2004.
150. Steam Reforming: Alternative Process for Organic Waste, Energy Solutions Datasheet, 2006. www.energysolutions.com/infosheets/steam_reforming_es_061206.pdf
151. Improving the characterisation and treatment of radioactive wastes for the department of energy's accelerated site clean-up program, Department of Energy Nuclear Weapons sites, National Research Council, 2005. www.nap.edu/catalog/11200.html
152. The steam reforming process, Katalco Performance technical note, Johnson Matthey Catalysts, 2007. www.jmcatalysts.com/pct/marketshome
153. Biosorption of metal contaminants using immobilized biomass-field studies, T.H. Jeffers, United States Department of the Interior, Bureau of Mines, 1993. www.p2pays.org/ref/15/14420.pdf. Retrieved: 21st February 2007
154. Performance of immobilised moss in the removal of 137Cs and 90Sr from actual low-level radioactive waste solutions, K. Balarama et al., J. Radioanal. Nucl. Chem., 261 (3), September 2004.
155. What is Solvent Extraction? www.nc.chalmers.se/general/VX.HTM 15th January, 2004
156. Electrochemical Wastewater Treatment Final Report, Blithgoe, B, Heng, T., Wilson, B., Parekh, S., Electrochemical Ion Exchange Group, 20 March, 2003, University of California, San Diego, chemelab.ucsd.edu, 19th January, 2004.
157. www.aeat.com Our EIX [Electrochemical Ion Exchange] Systems, 19th January, 2004
158. Guidelines for Planning Interventions Against External Exposure in Industrial Areas After A Nuclear Accident, Part I, Eged K. et al., Institut fur Strahlenschutz, 2003
159. Electrochemistry dictionary, Zoltan Nagy, Chemical Engineering Department, Case Western Reserve University , Cleveland, Ohio, http://electrochem.cwru.edu/ed/dict.htm#e126, 2004
160. Electroflocculation in the Treatment of Polluted Water. Robinson, V. Australian Water & Watewater Association Joint NSW and Victoria State Conference, Wodonga 22 - 24 November 1999. http://www.electropure.com.au/techinfo/AWA1999Paper.html
161. The Hydroclean Redbox System, http://www.hydroclean.co.uk/redbox.htm, Morgan Newmark Ltd, 2003
162. Electrodialysis Reduces Waste in the Treatment of Pyrochemical Salt Residues, www.lanl.gov/orgs/nmt/nmtdo/AQarchive/96fall/electrodialysis.html, retrieved 26 April 2004.
163. The Extraction of Heavy Metals by means of A New Electrolytic Method, Guiragossian, Z.G., et al, WM'03 Conference, Tuscon AZ. 23 - 27 February, 2003
164. Innovative Mobile High-volume Liquid Radioactive Waste Processing System. Guiragossian, Z. G. et. al. WM'04 Conference, Tuscon AZ. 29 February – 4 March, 2004
165. www.atserve.co.uk/ats.htm, retrieved 26 April 2004
166. Technical Guidance Note for Operators and Inspectors of IPC Processes (Abatement) A4, Effluent Treatment Techniques: Environment Agency, 1999
167. Physical and Theoretical Chemistry Laboratory at Oxford http://physchem.ox.ac.uk/MSDS/NI/nitrogen_dioxide.html, 11th June 2004 Physical and Theoretical Chemistry Laboratory at Oxford http://physchem.ox.ac.uk/MSDS/NI/nitrogen_dioxide.html, 11th June 2004
168. Commercial Application Of The Plasma Mass Separation In The Archimedes Filter Plant, C.E. Ahlfeld, J.G. Gilleland and J.D. Wagoner, WM'03 Conference, Tucson, AZ, 23rd – 27th February
169. The Archimedes Filter Plant: A New concept For Reducing The Amount Of HLW At Hanford, J. Gilleland, C. Ahlfeld, C. Little, H. Pluche, K. Umstadter and J. Wagoner, WM'05 Conference, Tucson, AZ, 27th February - 3rd March
170. Technical Guidance A5, 'Abatement of Atmospheric Radioactive Releases From Nuclear Facilities', Environment Agency, 1998
171. Nuclear Science and Technology: Handbook on decommissioning of nuclear installations, EUR 16211, 1995
172. Nuclear Air Cleaning Handbook, DOE-HDBK-XXXX-2002, June 2002
173. W ter Kuile & Dr. R. Doig. Circular HEPA Filters for use in Nuclear Containment and Ventilation Systems, Proceedings of the 25th DOE/NRC Nuclear Air Cleaning and Treatment Conference, Minneapolis, Minnesota, August 3 - 6, 1998
174. 'Perry's Chemical Engineer's handbook', 6th Ed, McGraw-Hill, 1984
175. Technical Guidance A3, Pollution Abatement Technology for Particulate and Trace Gas Removal', HMIP 1994
176. http://www.wsu.edu:8080/~gmhyde/433_web_pages/cyclones/CycloneOverview.html
177. Chapter 11: Cyclone Separator, ME431 Emission and Pollution Control, Hong Kong Polytechnic University. Mechanical Engineering
178. http://nuclearweaponarchive.org/Smyth/Smyth9.html
179. Residential Air Cleaning Devices. American Lung Association. http://www.lungusa.org/site/pp.asp?c=dvLUK9O0E&b=39289, 21st July 2004

180. Espitech Air Products. http://members.fortunecity.com/espitech/carbonpower.html, 21st July 2004
181. Waste gas treatment. Hochschule der Medien. http://www.hdm-stuttgart.de/projekte/printing-inks/e_waste0.htm, 30th July 2004
182. Activated Carbon: SULFUSORB 8. Calgon Carbon Corporation. www.calgoncarbon.com/products/activated/vp_sulfsorb8.html retrieved 1st November 2005
183. Soelberg, N. R., "Advanced Off-Gas Control System Design for Radioactive and Mixed Waste Treatment," proceedings of the 10th International Conference on Environmental Remediation and Radioactive Waste Management, Glasgow, Scotland, September 4-8, 2005
184. 'Safe Handling of Tritium – Review of Data and Experience', IAEA Technical Report 324, 1991
185. 'A Review of the Use and Disposal of Gaseous Tritium Lighting Devices', NRPB. Environment Agency, 1998
186. 'Application by Nycomed Amersham Cardiff Site for a Variation to the Authorisation for Disposal of Radioactive Wastes', 2001. Environment Agency of England and Wales Public Registers and Website
187. 'Consultation Document on Application by AWE for Authorisation to Dispose of Radioactive Wastes from the Atomic Weapons Establishments at Aldermaston and Burghfield', 1999. Environment Agency of England and Wales Public Registers.
188. The Environmental Guide, Environment Technology Centre, University of Nottingham, http://www.nottingham.ac.uk/~enzetc/guide
189. Technical Guidance A2, 'Pollution Abatement Technology for the Reduction of Solvent Vapour Emissions', HMIP 1994.
190. The Environmental Guide, Environment Technology Centre, University of Nottingham, http://www.nottingham.ac.uk/~enzetc/guide
191. Hunterston A Integrated Waste Strategy 2007/2008 HNA/3800/TC/SR/949 – Issue 2
192. Hinkley Point A 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary
193. Magnox Electric Ltd. Waste and Decommissioning Research & Development Programme Lifetime Plan 2008/09
194. Magnox South 2008/09 Lifetime Plan Supporting Volume Technical Baseline and Underpinning Research & Development
195. Thermal Treatment Symposium 29th November 2007, The Centre Birchwood Park
196. Sellafield Integrated Waste Strategy Version 2 June 2007
197. Winfrith Integrated Waste Strategy NDA/LCBL(2005)P16/IWS Submitted with LTP08 Issue 4 February 2008
198. Capenhurst Integrated Waste Strategy Issue 1 August 2007
199. South 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary
200. Bradwell 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary
201. Sizewell A 2007/08 Integrated Waste Strategy Magnox South Ltd. Summary
202. Technical Baseline and Research & Development Document for Berkeley Nuclear Licensed Site Lifetime Plan 2008/2009
203. Capenhurst Integrated Waste Strategy Issue 1 August 2007