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Innovative waste treatment and conditioning technologies at nuclear power plants

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FOREWORD

The objective of this publication is to provide Member States with information on the most innovative technologies and strategies used in waste treatment and conditioning. At present, some of those technologies and strategies might not be widely implemented at nuclear power plants (NPP), but they have an important potential for their use as part of the long range NPP, utility, or national strategy. Thus, the target audience is those decision makers at the national and organizational level responsible for selecting waste processing technologies and strategies over a period of three to ten years.

Countries and individual nuclear plants have limited financial resources which can be applied toward radioactive waste processing (treatment and conditioning). They are challenged to determine which of the many available technologies and strategies are best suited to meet national or local needs. This publication reduces the selection of processes for wastes generated by nuclear power plants to those technologies and strategies which are considered innovative. The report further identifies the key benefits which may derive from the adoption of those technologies, the different waste streams to which each technology is relevant, and the limitations of the technologies.

The technologies and strategies identified have been evaluated to differentiate between (1) predominant technologies (those that are widely practiced in multiple countries or a large number of nuclear plants), and (2) innovative technologies (those which are not so widely used but are considered to offer benefits which make them suitable for broader application across the industry). Those which fall into the second category are the primary focus of this report.

Many IAEA publications address the technical aspects of treatment and conditioning for radioactive wastes, covering research, technological advances, and safety issues. These studies and reports primarily target the research and technical staff of a nuclear power plant, other waste generators, or regulatory bodies. What is absent from the available literature is a publication written for managers, plant designers, and other decision makers which will assist them to synthesize the growing list of available technologies in a way which best meets their local needs. Thus, a need existed to develop a document which provides an overview of the innovative technologies currently employed at or in support of NPP, including the applicable waste streams, benefits and impacts of each technology, current applications within the nuclear community (who is using the technology), and any non-technical innovative approaches. This publication provides that information for key decision makers.

The report was prepared by series of consultants and technical meetings during 2004–2006. A list of contributors to review of the material collected and to drafting and revision of the report is provided at the end of this report. The IAEA is grateful to those who participated in preparation of the report. Special thanks are extended to H. Masui (Japan), J. Schunk (Hungary), and J. Kelly (US) who were involved in preparation of the report from the initial draft through its final version.

The IAEA officers responsible for this publication were J. Gonzalez and J. Kelly of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

The International Atomic Energy Agency (IAEA) has made extensive progress assisting Member States in all aspects of safe management of radioactive wastes, including treatment and conditioning technologies. Many IAEA publications address the technical aspects of treatment and conditioning for radioactive wastes, covering research, technological advances, and safety issues [1–5]. These studies and reports primarily target the research and technical staff of a nuclear power plant (NPP), other waste generators, or regulatory body. What is absent from the available literature is a publication written for managers, plant designers, and other decision makers which will assist them to synthesize the growing list of available technologies in a way which best meets their local needs.

Thus, a need existed to develop a publication which provides an overview of the innovative technologies currently employed at or in support of NPP, including the applicable waste streams, benefits and impacts of each technology, current applications within the nuclear community (who is using the technology), and any non-technical innovative approaches. This publication provides that information for key decision makers.

1.2. OBJECTIVES

The objective is to provide information on innovative technologies and strategies used in waste treatment and conditioning. At the present time, some of those technologies and strategies might not be widely implemented at nuclear power plants (NPP), but they have an important potential for their use as part of the long range NPP, utility, or national strategy.

1.3. SCOPE

The specific target audience is those decision makers responsible for low and intermediate level wastes (LILW) strategy over the next 3 to 10 years and who are responsible for developing LILW management strategies and associated technologies. This publication is not directed toward the working level technical/scientific personnel, and it is not directed toward utility executives. The purpose of the publication is to provide reactor designers and decision makers at nuclear power plants (NPP) and other involved bodies with technologically oriented information on recent achievements in innovative processing of liquid, semi-liquid and solid wastes, and of their potential use. The focus is on LILW for water cooled reactors. This includes existing plants which are operational or in decommissioning. It also includes advanced nuclear plants which are under construction or being considered for construction. It is noted that many of the technologies and approaches described are also applicable to other reactor types (e.g. gas cooled reactors).

1.4. STRUCTURE

Section 2 provides a brief Summary of the report, followed by a section on legislative considerations related to evaluating and encouraging the use of innovative technologies. Section 4 provides an important discussion and review of the key drivers which typically control the decision making process for any given LILW treatment and conditioning technology.

Section 5 examines and compares proven, currently available, and already implemented waste treatment and conditioning technologies, along with the countries where the technologies are being used. Section 5 takes maximum advantage of tables to provide the reader with fast identification of the available and competing technologies for any significant waste stream, including both predominant and innovative technologies. These technology tables are linked to specific sections in the Appendix for further detailed discussion the benefits, impacts, limitations and applications of the included technologies.

Section 6 examines the technologies used at off site treatment and conditioning facilities, such as regional, central waste processing facilities. It also explores the use of mobile systems which deliver advanced technologies on a short term lease or rental basis. This is followed by a section which discusses non-technology, alternative "approaches" to managing waste which are sufficiently innovative and important to the waste management equation that they should be included in the decision making process. Section 8 summarizes the conclusions of the study.

Some technologies listed in the various tables or mentioned in various passages may be new to some readers at the management level. Therefore, each innovative technology is briefly discussed in the Appendix, along with a brief listing of the applicable waste streams, benefits and impacts of each technology, etc. Appropriate references are included at the end of the report.

1.5. KEY DEFINITIONS

The technical experts who participated in the development of this report identified three terms which may not be recognized by many readers as used within the context of this publication. As used herein, the terms have the following meanings. Reference [6] provides additional information on these and other terms.

Waste segregation – An activity where waste or materials (radioactive and exempt) are separated or are kept separate according to radiological, chemical and/or physical properties which will facilitate waste handling and/or processing. For example, it may be possible to segregate radioactive from exempt material and thus reduce the waste volume.

Sludge – The unabsorbed and unfiltered sediment and other solids remaining after removal of the liquid phase in aqueous solutions.

Clearance – Removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body [7]. It is included as a "key definition" because it is discussed in this report as an innovative strategy worthy of expansion across the Member States. (Exemption is not included as a "key definition," because it is not addressed herein as an innovative strategy; defined in Reference [7].)

2. SUMMARY OF KEY CONSIDERATIONS

The experts who participated in the development of this publication reviewed all of the waste treatment and conditioning technologies and strategies known to be deployed at nuclear power plants around the world. In so doing, the authors were not constrained by differentiating between operational and decommissioning power plants. Although some technologies clearly are more relevant to one particular phase of the life cycle of nuclear power plants, emphasis was placed on technologies which can benefit operational plants. The listing was then narrowed to those innovative technologies and approaches which might be more widely exploited to the benefit of the worldwide nuclear power industry.

2.1. INNOVATIVE STRATEGIES

As used in this publication, the term “innovative technology” has been broadly interpreted to include innovative strategies or approaches which are also deserving of broader implementation. Such strategies might require some specific technology to make them possible, but it is not the technology which makes the concept innovative. For example, various laundry technologies can be employed to allow the reuse of protective clothing; it is not the laundry equipment which is considered innovative for the purposes of this publication; it is the strategy for re-using protective clothing which is innovative to some Member States and which is deserving of broader implementation. The innovative strategies addressed in this publication are categorized as:

- waste minimisation
- recycle and reuse
- use of centralised processing facilities
- use of mobile treatment plants

These technological strategies are not common to all countries or organisations, and it is important to understand what makes a strategy more attractive or beneficial to any given situation. Therefore, the publication includes a discussion of the key drivers which influence the selection of technological strategies to be adopted, including the available financial and labour resources, public acceptability, and legislation. Of particular note is legislation: this can be a driver for the selection of specific strategies; but sometimes there is a need for legislation to be driven by the available technologies.

2.2. TECHNOLOGY SELECTION, APPLICATION AND DEPLOYMENT

The technologies identified have been reviewed and assessed to differentiate between those that are widely practiced (i.e. predominant) and those which are not as widely used but are considered to offer benefits which make them suitable for broader application. Where possible, reference has been made to examples of where the innovative technology is being deployed or developed, and to specific organisations which hold some expertise in the technology. The publication identifies the key benefits which may be derived from the adoption of the technologies, the different waste types to which the technologies are relevant, and the limitations of the technologies. The publication does not attempt to provide a comprehensive description of the technologies, preferring to provide references where further detail can be found. Many of these can be found in other IAEA publications.

2.3. CENTRALISED PROCESSING TECHNOLOGIES

Many of the innovative technologies are “high temperature” processes. These thermal technologies include cold crucible vitrification, pyrolysis, hot isostatic pressing, metal melting, and incineration. These are generally considered to be technologically advanced, require significant expertise for plant operation and management, and potentially represent high capital investments. The high capital cost of such facilities, together with the level of technical expertise required to operate them, are key reasons for suggesting centralised (national or regional) processing facilities as an alternative management strategy to a site specific application.

2.4. MOBILE TECHNOLOGIES

Many waste treatment technologies are available in the form of mobile plants which can be delivered to a site, operated on a campaign basis, and then moved for use at another site. This strategy is an alternative approach to addressing these issues, and it has the added advantage of flexibility, allowing power plants to adapt to changing circumstances and to adopt new technologies as they emerge. The publication has identified each technology where these options are available.

2.5. CONCLUSION

This publication is not a source of new, previously unheard of technologies. It is a review of what is already available, and it is an attempt to highlight those technologies deserving of further consideration and more widespread application. Accordingly, the layout of this publication is intended to assist all decision makers, regulators, and those charged with developing long range LILW technology strategies to identify and compare innovative technologies and approaches which merit further, careful consideration for inclusion in the mix of available, country specific or organisation specific waste management technologies.

3. EVOLUTION OF REGULATIONS AND LEGISLATION

3.1. TECHNOLOGY DRIVERS AND INHIBITORS

Regulations and their associated legislation have a strong influence on the types of low and intermediate level radioactive waste (LILW) technologies and strategies which can be implemented in any country. They can serve as the driver for introducing innovative technologies and approaches, yet they can also inhibit the introduction of technologies which may be considered as high risk, immature (insufficient demonstration of the successful application of technology), or unusually expensive. It must also be recognized that regulations and related legislation do not evolve at the same pace as technology, especially when those technologies include an elevated level of risk to the public over an extended period of time.

The implementation of new and innovative LILW technologies may impact significantly on the site of waste generation, the site of technology operation (if different), and local labour resources. Conversely the development of innovative technologies can be significantly influenced, driven by, or constrained by such issues as waste transport, strategies for interim storage, and disposal.

Technology developers may be less concerned with such issues, but regulators and legislators must, appropriately, take all these factors and more into consideration. It is critical that regulations and legislation evolve to ensure the adoption and introduction of highly beneficial innovative technologies. It is equally important that the potential benefits and impacts be carefully considered at the government level.

3.2. NATIONAL POLICIES

Today, an increasing number of nuclear safety authorities encourage the use of the “Best Available Technology” for any given waste stream, and some regulations require that waste producers engage in waste studies with the following intent:

- limit waste production at the source;
- know and control waste streams and their characteristics;
- ensure recycle for reuse if possible;
- ensure volume reduction if not recyclable; and
- optimise waste disposal.

These national policies serve as drivers to encourage and develop more efficient waste management through iterative and progressive approaches. They also support the need for decision makers to implement enhanced environmental management programs in accordance with international standard ISO 14001. At the same time, these waste studies recognize that some existing regulations tend to inhibit the introduction of technologies which are more efficient, both in terms of waste management and in terms of meeting the legislative and national objectives. One obvious example might be a prohibition against—or the absence of support for—central processing facilities. Centralised (national or regional) facilities which are accessible by multiple nuclear facilities can deploy highly advanced and innovative technologies which are prohibitively expensive for individual plants to implement.

3.3. CONCLUSIONS

Perhaps the best conclusions to be drawn from the preceding discussion are:

- The development and implementation of innovative technologies and regulation are inextricably linked. New innovative technologies may require changes in regulation in order to be implemented, while changes in regulations can often prohibit the use of some technologies and force the development of new technologies.
- It is incumbent upon technology developers, utility waste management strategists, and regulators to work together so as to ensure that innovation is focused in areas where it is most beneficial, and ensure that national goals and regulatory concerns do not unnecessarily restrict innovation.
- Some of the issues faced by regulators and legislators reach beyond the basic technical considerations. The use of mobile or central processing facilities are particular examples of innovative approaches, the adoption of which may be influenced (accelerated or delayed) by non-technical considerations.

4. DRIVERS OF LILW MANAGEMENT STRATEGIES

The selection of technologies will be influenced by local utility or country circumstances, including national waste management strategies and waste generation rates. Perhaps the most important factor is whether disposal facilities are available. If they are, then treatment technologies will be driven by the constraints that the disposal facilities impose, including performance requirements for the waste form and packaging. If there are no disposal facilities available, then waste producers will require the adoption of a storage strategy, either on the site of origin or at a central, off site facility. The selection of treatment and conditioning technologies for storage will be driven by different factors, such as storage capacity, retrievability, the potential need for post-storage conditioning, etc. These factors are discussed below in some detail.

4.1. AVAILABILITY OF DISPOSAL REPOSITORIES AND ACCEPTANCE CRITERIA

This is fundamental to the selection of strategy. The availability or absence of a disposal repository, as well as the waste acceptance criteria which waste producers must comply with for waste to be disposed, will determine the effort applied to pre-treatment, treatment, conditioning, and packaging. It also determines the need for and type of storage facilities and the probable duration of interim storage.

The waste acceptance criteria for disposal will vary depending on the location and type of facility: near surface disposal, deep geological disposal, above ground engineered structure, etc. Typically included in the acceptance criteria will be requirements on the quantity of free liquids permissible, whether stabilization is required, type of containers to be used, the type of radionuclides accepted, and related technical restrictions. For example, near surface disposal facilities are only suitable for relatively short lived radionuclides, whereas long lived nuclides typically require subsurface disposal.

Disposal facility capacity also will influence the choice of treatment and conditioning technologies, and this is usually reflected in the repository waste acceptance criteria. For example, a small disposal capacity will usually force large waste producers to implement technologies which have a higher volume reduction efficiency.

A country that does not yet have an operating disposal facility may still have disposal acceptance criteria in place. These could be based on either a planned facility or on generic criteria. If generic criteria are used, they are often based on very conservative assumptions and may be very restrictive.

4.2. DISPOSAL FEE STRUCTURE

The disposal fee structure can influence, deliberately or otherwise, the selection of treatment and conditioning technologies. For example, an annual lump sum disposal access fee which is independent of the volume of waste disposed will discourage volume reduction. In contrast, a volume-based or weight-based disposal fee schedule with a high cost for each cubic meter or kilogram of waste disposed will encourage waste producers to implement both source reduction and volume reduction technologies.

There is a clear link between the disposal fee structure and disposal capacity, since a small capacity will almost always result in a higher, volume-based disposal fee schedule. It is also worth noting that there usually are significant fixed costs associated with the licensing and construction of disposal facilities, which are amortized over the planned disposal capacity. Attempts to reduce volumes below the planned capacity so as to achieve disposal cost savings may be met by increased disposal fees in order to recover the fixed costs.

4.3. FINANCIAL RESOURCES

The capital costs of constructing waste pre-treatment, treatment and conditioning plants can vary by several orders of magnitude. For example, a simple cementation plant might cost ~500,000 Euros, compared with a cold-crucible vitrification plant which might cost 30 million Euros. The cost of introducing a new technology can be significant, including development and licencing costs. The schedule to implement a new technology will also be significant, partially due to performing the necessary development and proving trials, and also to completing all the necessary safety and regulatory documentation.

Generally the more complex the technology, the greater the capital cost, the greater the operation and maintenance costs, and the longer time needed for implementation. For high temperature processes, fuel costs also need to be considered, particularly where the wastes have little or no calorific value. Finally, the production of secondary wastes must be taken into account, both in terms of cost and their suitability for processing and disposal.

4.4. LABOR RESOURCES

Labor resources could be important considering the many steps in the waste management process. These include collection, sorting, characterization, treatment, conditioning, packaging, contamination control, onsite storage, transportation control, shipment operation, regulatory agency inspections, and other control documentation.

The quality and training of personnel participating in each of the above steps also may be an issue for the more complex technologies. Establishing an adequate training program may require a long time and may be required as part of the administrative procedure to obtain operation approval. In some cases, the designer or constructor of a facility may provide training as part of the facility contract. As an alternative, qualified contract staff might be used until trained local staff are available.

4.5. AVAILABILITY OF CAPACITIES OF STORAGE ONSITE OR OFF SITE

If a disposal option is not available, onsite interim storage is best provided for as part of the original power plant design where allowed by law or national policy. For example, several countries (Russia, Lithuania, Japan) allow onsite interim storage pending construction of a disposal repository; and the province of Ontario, Canada, licenses regional storage for NPP wastes. Member States either discourage or prohibit interim storage of LILW wastes when a disposal option is available, and many countries (e.g. France, Japan, Lithuania, Finland) discourage interim storage of “raw” bulk wastes (untreated, unprocessed wastes).

In some cases, limitations on the available land space at the NPP, or compliance with national regulations or policy, may restrict the construction of additional storage capacity. In the UK and France, for example, the regulators actively discourage extensions to storage facilities, preferring that waste producers process the wastes rather than continue to store. Still others are willing to continue interim storage for existing wastes or storage facilities, yet they discourage the construction of new storage facilities (e.g. France, UK). In these situations, the age of the waste storage facilities and the age and condition of the stored waste containers are relevant factors, prompting regulators to seek justification or analysis from waste producers as to the acceptability of their waste storage facilities for continued operation.

4.6. AVAILABILITY OF CLEARANCE LEVELS OR OF DISCHARGE FOR VERY LOW LEVEL RADIOACTIVE WASTE

Where clearance levels and protocols exist to enable unrestricted release of very low level waste, waste treatment (decontamination) processes which reduce waste activities below the clearance levels are worth pursuing. But if clearance levels do not exist, then decontamination for the sake of it is usually not justified. Exceptions would apply when reducing the waste from a higher category to a lower category (e.g. from ILW to LLW)—thus permitting disposal via a different disposal route—and for improving the safety of waste storage.

Many waste treatment processes will generate secondary wastes, such as liquid or gaseous effluents which may require discharge into the environment. Such discharges will be the subject of authorisations, and the treatment will not be possible without such authorisations. The process of obtaining authorisations is time consuming and may involve public consultation, so it should not be undertaken lightly.

Further discussion on clearance issues as they relate to the topic of this report can be found in Section 6.1. General guidance on clearance and authorized discharges can be found in other publications, such as References [7, 8].

4.7. OPERATIONAL IMPACTS ON PLANT

Waste treatment operations will introduce their own safety risks and radiological impacts which must be taken into account in the overall acceptability of the operation of the nuclear power plant [1]. Power plant operators will generally have procedures for allocation of acceptable risk and radiation exposure across different operations on the same site. The introduction of new waste treatment processes must be considered against these risk and dose levels, and this may have an impact on the selection of technology. Maintenance of the technology may be a significant contributor to the overall worker dose impact. This is especially true for higher activity wastes, which may impose requirements on the design for additional shielding, remote maintenance, etc.

4.8. PUBLIC ACCEPTANCE

Public acceptability of operations at nuclear power plants is very important, and most nuclear plant operators have well-developed consultative procedures and public education programs to explain the introduction of new processes or facilities to the public, if not to involve them in the decision making process itself. In some instances, legislation may require formal public consultation. For example, the introduction of a new technology may involve significant onsite construction.

4.9. AVAILABILITY OF TRANSPORTATION

Disposal of waste from the power plant to an off site disposal facility, or adoption of strategies involving transportation of waste off the site to a central processing facility, will inevitably involve transport through public areas. Minimisation of the volumes of waste for transport may be an important consideration, thus favouring treatment processes deployed on the power plant sites and which maximise volume reduction. Many countries have expanding programmes of decommissioning work which require increased shipments of radioactive and other hazardous wastes from the site. The acceptability of transport of such wastes must be considered as part of the entire work scope, and it may meet resistance from the local population.

Transportation of waste off the power plant site will require the availability of suitable licensed transport containers and authorisations to transport the waste. Both of these are likely to be more demanding for the transport of untreated waste, particularly if the wastes are “dispersable” (e.g. wet). The cost of transportation is an important consideration in the overall cost profile for managing wastes. In most countries, the regulations for transport of radioactive materials are based on the IAEA Regulations for the Safe Transport of Radioactive Material [9].

4.10. AVAILABILITY OF SUPPORT SYSTEMS, SERVICES AND UTILITIES

Waste processing will almost certainly require supporting systems, such as active drains to collect any liquid radioactive effluents or spillages, and active ventilation systems to contain and process gaseous effluents and control aerial emissions from the process. Most processing technologies require one or more support utilities, such as significant electrical power loads, instrument or service air, and demineralised water. Other services required include radiation protection and waste assaying capabilities and services. (See Section 6.2.1 for other support needs.) These are generally readily available at nuclear power plants, but they may need to be added if waste processing is to be conducted off the power plant site.

4.11. AVAILABILITY OF MOBILE TREATMENT AND PROCESSING SYSTEMS

Owner/operators of a fleet of nuclear power plants of similar type will almost certainly wish to adopt a common waste management strategy across the fleet of plants and deploy similar technologies at all their sites. This will deliver benefits in terms of ease of licensing and cost savings. Where wastes cannot be transported easily from one site to another for treatment, there is an incentive to develop and deploy mobile systems across the fleet of power plants, thus reducing capital costs. This strategy also provides the opportunity to deploy specialist teams of operators with the waste treatment plants rather than having to train operators at each power plant. As a result, mobile systems are being incorporated as options or as part of the integrated design of some new NPPs, and they certainly have their applications at existing facilities.

Not all waste treatment processes can be made mobile or transportable, and some equipment designs may have to be compromised in order to make them mobile. However there is considerable experience throughout Europe and the USA in both design and operation of mobile plants. Commonly available mobile technologies are described in Section 6.

5. WORLDWIDE APPLICATION OF PREDOMINANT AND INNOVATIVE TREATMENT AND CONDITIONING TECHNOLOGIES

This publication distinguishes between "predominant technologies" and "innovative technologies," which are defined as follows:

- *Predominant Technologies* — These are the major treatment and conditioning technologies which are commonly used at the present time in multiple countries or in a large number of nuclear power plants.
- *Innovative Technologies* — These are treatment and conditioning technologies which are already proven but which are either fairly new, relatively advanced, or not widely used. These are technologies which typically are high efficiency in terms of volume reduction and which are deserving of further evaluation and consideration for wider application.

Table I identifies the ***innovative*** technologies which are deserving of further evaluation and consideration. It provides a cross-reference of various treatment and conditioning technologies applicable to different waste types. The table includes only practical applications which have been implemented at one or more facilities on a production basis. Other possible applications of a given technology to different waste streams may be possible, as well as entirely new technologies, but have not yet progressed beyond the investigative or experimental stage.

Note that the waste streams listed in this table are not comprehensive, and the list does not include those waste streams which represent a fairly limited volume of waste. It also should be noted that many of the predominant technologies offer a high degree of versatility and can by applied to a number of waste streams. When searching for a solution to a problem related to a given waste stream, it is often economically beneficial to examine the technologies already existing within a given waste management system to see if they can be extended to that particular waste stream. This minimizes the number of technologies that has to be supported and, in doing so, will often minimize the cost of waste management. The Appendix provides additional discussion on these innovative technologies and strategies.

Note that some waste streams in Table I include the same technology as both predominant and innovative. This indicates that these technologies have already been implemented in support of a large number of NPP either as a locally installed (plant specific) technology, a central processing facility technology, or a mobile technology. Yet they are also innovative technologies which should be encouraged for wider distribution among other countries. Table III summarizes the implementation options for treatment and conditioning technologies.

The remainder of the report will focus on the applications marked as being "innovative." The conventional or "predominant" applications have been previously described in numerous standard texts on radioactive waste management, such as references [2-5, 10-15]. Some technologies result in an end product (the output of the technology) which will require further treatment or conditioning for final disposition, depending primarily on local legislation and disposal site criteria. Table II describes the end product for each technology. For reference purposes, Table II also identifies which countries are known to be using the technology.

TABLE I. SUMMARY OF TREATMENT AND CONDITIONING TECHNOLOGY APPLICABILITY

		Waste Stream																					
Technology	***Location in Appendix***	Air filters	Aqueous liquids	Asbestos	Bio-waste	Cartridge filters	Charcoal	Combustible solids	Compactible solids	Concrete	Dross/swarf	Evap. concentrates	Filter media	Incinerator ash	IX resins	Lead	Metal	Oils	Plastics	Sludge	Soil, sand, grit	Solvents	Thermal insulation
Cold crucible vitrification	A. *1*		P			I	I	I	I			I	I	I	I								
Crystallization	A. *2*											I											
Drum drying	A. *3*											I			I					I			
Geopolymerization	A. *4*													I	I			I		I			
High temperature incineration	A. *5*	I						I		I			I		I		I						
Hot isostatic pressing	A. *6*											I			I					I			
Incineration	A. *7*	I			P	I	I	P					P,I		P			P	P			P	
Ion exchange membrane	A. *8*		I																				
Ion-specific filtration	A. *9*		I																				
Liquid concentrates VR system	A. *10*											I											
Liquid filter shearing and shredding	A. *11*					I			P								I						
Melt densification of plastic	A. *12*																		I				
Membrane filtration	A. *13*		I																				
Metal melting	A. *14*															I	P,I						
Molten metal	A. *15*	I					I	I	I	I			I	I	I		I		I			I	I
Oil filtration	A. *16*																	I					
Oil solidification	A. *17*																	I		I			
Pelletization	A. *18*											I			I								
Phytoremediation	A. *19*																				I		
Plasma arc melting	A. *20*	I					I	I	I	I	I		I	I	I		I		I			I	I
PVA dissolution	A. *21*					I		I															
Pyrolysis	A. *22*				P	I	P						P		P				I				
Reverse osmosis	A. *23*		I																				

P = Predominant technology; I = Innovative technology; P,I = Innovative technology with potential for wider application

TABLE II. TECHNOLOGY END PRODUCT AND COUNTRY WHERE TECHNOLOGY IS USED

Technologies	**Location in Appendix**	**End product**	**Where technology known to be used**
Cold Crucible Vitrification	A. *1*	Glass-like solid	South Korea
Crystallization	A. *2*	Slurry or crystals	France
Drum drying	A. *3*	Drum containing dried residue	USA
Geopolymerization	A. *4*	Solid material	Slovakia
High temp incineration	A. *5*	Solid granules	Japan
Hot isostatic pressing	A. *6*	Solid pucks suitable for overpacking	Sweden, Germany
Incineration	A. *7*	Ash Secondary wastes include filters, liquid from wet scrubbers	Canada, France, India, Japan, Russia, Slovakia, UK., USA
Ion exchange membrane	A. *8*	Liquid effluent Spent membrane	Canada, Finland, Hungary, USA
Ion-specific filtration	A. *9*	Liquid effluent Spent IX resin	Canada, Finland, France, Hungary, UK,USA
Liquid concentrates VR system	A. *10*	Crystalline boric acid Concentrates from ultrafilitration The treated liquid phase for free release Low volume of secondary waste (IX cartridges, sludge from ultrafiltration and plasma technology)	Finland, Hungary
Liquid filter shearing and shredding	A. *11*	Solid dry or wet shreds	UK, USA
Melt densification	A. *12*	Solid plastic monolith of varying size	India
Membrane filtration	A. *13*	Concentrated solids	Finland, Hungary, Japan, UK, USA
Metal melting	A. *14*	Slag Ingots or steel products for reuse, eg drums, bricks etc	Belgium, France, Germany, Russia, UK, Ukraine
Molten metal	A. *15*	Stabilised ingot in ceramic cannister	Japan, USA

TABLE II. (CONTINUED)

Technologies	**Location in Appendix**	**End product**	**Where technology known to be used**
Oil filtration	A. *16*	Filter cartridges and other filter materials Clean oil	Canada, UK, USA
Oil solidification	A. *17*	Solid monolith	Canada, Hungary, UK, USA
Pelletization	A. *18*	Small pellets of dry solid waste	Japan
Phytoremediation	A. *19*	Biomass	UK
Plasma arc melting	A. *20*	Ingots Slag	Japan, Russia, Switzerland, USA
PVA dissolution	A. *21*	Dissolved liquid (may contain radionuclides) Secondary waste (tape, zippers, other foreign materials)	USA
Pyrolysis	A. *22*	Dry solid granules, similar to coarse sand	Sweden, USA
Reverse osmosis	A. *23*	Liquid effluent Spent membrane	Canada, India, USA
Superabsorbant polymer	A. *24*	Gel	Canada, UK, USA
Supercompaction	A. *25*	“Pucks” which require overpacking Small volumes of liquids	Canada, Czech, Finland, France, Japan, Republic of China, Russia, Slovakia, UK, Ukraine, USA
Thermo-chemical conversion	A. *26*	Dry granules	USA
Wet oxidation	A. *27*	Liquid concentrate	Belgium, Canada, UK

TABLE III. SUMMARY OF IMPLEMENTATION OPTIONS FOR TREATMENT AND CONDITIONING TECHNOLOGIES

Technology	**Location in Appendix**	**Locate at Plant Site**	**Locate at Central Processing Facility**	**Potential as Mobile System**
Cold crucible vitrification	A. *1*	X	X	
Crystallization	A. *2*	X		
Drum drying	A. *3*	X	X	X
Geopolymerization	A. *4*	X	X	
High temperature incineration	A. *5*	X *	X	
Hot isostatic pressing	A. *6*		X	
Incineration	A. *7*		X	
Ion exchange membrane	A. *8*	X	X	X
Ion-specific filtration	A. *9*	X	X	X
Liquid concentrates VR system	A. *10*	X		
Liquid filter shearing and shredding	A. *11*	X	X	X
Melt densification of plastic	A. *12*	X		
Membrane filtration	A. *13*	X		
Metal melting	A. *14*		X	X **
Molten metal	A. *15*	X	X	
Oil filtration	A. *16*	X	X	X
Oil solidification	A. *17*	X	X	X
Pelletization	A. *18*	X	X	
Phytoremediation	A. *19*	X		
Plasma arc melting	A. *20*		X	
PVA dissolution	A. *21*	X	X	
Pyrolysis	A. *22*		X	
Reverse osmosis	A. *23*	X	X	X
Superabsorbant polymers	A. *24*	X	X	X
Supercompaction	A. *25*	X	X	X
Thermo-chemical conversion	A. *26*		X	X
Wet oxidation	A. *27*		X	X

* Some Japanese plants have high temperature incinerators for the larger, multi-reactor sites.

** Metal melting is possible as a mobile process specifically for lead melting.

6. OFF SITE AND MOBILE TREATMENT AND CONDITIONING TECHNOLOGIES

Most utilities and many countries have only one or a few nuclear plants. A small number of plants typically will not produce sufficient volumes of waste to justify the large expenditures required for some high efficiency technologies. For example, a metal melt system may cost in excess of ten million US dollars to build and another half-million dollars or more per year to operate and maintain. If the volume of metal waste is on the order of only 50 metric tons per year, the cost of constructing and operating a metal melt system is difficult to justify.

There are two solutions to this technology challenge. The most common is the use of regional, centralized, off site processing facilities which accept waste from many nuclear plants. These may be used for any individual country, or they may support a consortium of countries.

The second solution is the use of mobile systems which can be transported among multiple nuclear sites for processing campaigns. Typically such a system might be at an individual site for one to three months, but in some situations the mobile system may remain at an individual site for several years (e.g. the use of a supercompactor to recover some of the storage capacity of a ten-year accumulation of drummed and stored waste).

This section discusses treatment and conditioning technologies currently in use at various off site processing facilities around the world. It also identifies the mobile treatment and conditioning technologies which are currently in use by one or more countries. Consistent with the rest of this report, a technology must actually be in use to make the list.

6.1. OFF SITE TECHNOLOGIES

Off site technologies are in common use in many countries. Due to the difficulty in transporting untreated wastes, these technologies are usually for the treatment and conditioning of wet or dry solid waste rather than for pre-treatment of liquid waste. The advantages of off site technologies are:

- Implementation cost can be reduced by sharing it with several waste producers or NPPs.
- Cost efficient operation can be possible because a large input volume is available even if there is a small waste generation locally.
- Technologies unavailable locally (onsite) can be made available off site.
- Cost for treatment of mixed waste can be reduced, because special treatment systems for chemical hazards can be shared.

6.1.1. Limitations and adverse impacts of off site technologies

a) Transportation cost may be high because volumes of wastes are not minimized prior to shipment, leading to more frequent shipments.

b) Transportation may be difficult for certain types of wet wastes (e.g. ion exchange resin, evaporator concentrates, and large components), especially for high activity wastes.

c) Very high activity waste cannot be processed using most of the common off site technologies for dry solid wastes, such as incineration, supercompaction, and metal melt.

This is more of a design limitation rather than a technology limitation, as most off site facilities have limited shielding incorporated into the design for these specific technologies.

Table IV identifies the most important treatment and conditioning technologies currently available at one or more off site processing facilities. Some technologies included in Table IV are not identified in this report as being "innovative." In addition, some technologies lend themselves well to off site facilities. These "potential" off site technologies are identified with an asterisk (*).

TABLE IV: SUMMARY OF OFF SITE TECHNOLOGIES

Technology	**Applicable Waste Streams**	**Where technology known to be used at a centralised off site facility**	**Location in Appendix**
Cold crucible vitrification*	solids, wet solids, liquids		A.1
Liquid filter shearing and shredding*	cartridge filters from liquid purification systems		A.11
High temperature incineration*	combustible solids, IX resins, filter media, non-metal filters, concrete		A.5
Hot isostatic pressing*	IX resins, filter media, non-metal filters		A.6
Incineration	combustible solids, IX resins	Canada, France, Russia, Slovakia, USA	A.7
Metal melting	metals	France, Sweden, USA	A.14
Molten metal*	filter media, IX resins, concrete, asbestos		A.15
Oil & solvent incineration and burning for heat recovery	oils, solvents	France, USA	A.7
Oil filtration*	oils		A.16
Oil solidification*	oils		A.17
Plasma arc melting*	asbestos, combustible solids, compactable solids, concrete, incinerator ash, solvents, oils		A.20
PVA dissolution	PVA materials	USA	A.21
Pyrolysis (including tank conversion reforming)	Bio waste, cartridge filters, charcoal, cartridge filters, filter media, IX resins, plastics	USA	A.22
Supercompaction	air filters, asbestos, cartridge filters, combustible solids, compactable solids, incinerator ash, metals, plastics, thermal insulation	Canada, France, USA	A.25
Thermo-chemical conversion*	solvents		A.26
Wet oxidation*	IX resins, evaporator concentrates		A.27

* potential future off site technologies (technology available, but not yet implemented at off site facilities)

6.2. MOBILE TECHNOLOGIES

For new nuclear power plants, the use of mobile pre-treatment, treatment and conditioning technologies may be incorporated as part of the plant design [16]. The application of mobile technologies offers more flexibility in choosing the optimum technology and waste management approach according to the actual needs of the local plant or country, and without the high implementation cost.

6.2.1. Limitations and adverse impacts of mobile technologies

a) Transportation cost can be high depending on the size of the equipment.
Decontamination cost of the transport equipment must also be taken into consideration.

b) For some countries, mobile technologies are not feasible, because current regulations require that the respective equipment must belong only to a specific nuclear site (i.e. sharing is prohibited by regulation or legislation).

c) Existing NPPs may have difficulty adopting mobile technologies due to plant design restrictions. Efforts to accommodate a number of existing plants may result in costly modifications. The following are examples of some NPP support requirements and considerations which impact the application of mobile systems:

— *System interfaces* — These include high power demand, remote power demand, water requirements, instrument air requirements, drains, gaseous effluent controls and support, vehicle exhaust, communications.

— *Adjacency factors* — These include the impact of elevated dose rates on nearby work or other mobile systems, space required for input and output of waste, crane requirements, crane overhead clearance.

— *Other general access factors* — These include vehicle movement interference (e.g. nearby fences, buildings, power lines), available land space, radiation monitoring, security, floor loading (how much weight can be placed on the floor per square foot or square meter).

Table V lists the mobile treatment and conditioning technologies currently available in one or more countries. Some technologies included in Table V are not identified in this report as being “innovative.” What is innovative is the *mobile application* of the technology, thereby resulting in a more extensive listing.

Table V. SUMMARY OF MOBILE TECHNOLOGIES

Technology	**Applicable Waste Streams**	**Where mobile technology known to be available/used**(1)	**Location in Section 7 and Appendix (7/A.x)**
Baling or low force compaction	incinerable solids, compactable solids, wet solids	USA	N/A
Chemical neutralization/precipitation	aqueous liquids	(2)	N/A
Decontamination	metals, lead, concrete	USA	N/A
Dewatering and drying	concentrates, filters, filter media, IX resins	Germany, UK, USA	A.3
Encapsulation (cementation, polymer binders)	filters, metallic wastes	Japan, UK	N/A
Oil Filtration	oils	Canada, USA	A.16
Incineration	solids, organic liquids	(2)	A.7
Ion exchange	aqueous liquids	Finland, USA	N/A
Laundry cleaning	reuse of protective clothing, mops, etc	USA	N/A
Lead melting	lead	(2)	N/A
PVA dissolution	Polyvinyl alcohol (PVA) plastics	(2)	A.21
Sludge dewatering	sludges	USA, UK	N/A
Solidification (cementation, polymer binders)	concentrates, filters, filter media, IX resins, sludges	France, Germany, Slovakia, UK, USA	N/A
Supercompaction	drummed waste (incinerable solids, compactable solids, wet solids)	Brazil(3), Canada, Czech Republic, Germany, UK, USA	A.25
Ultrafiltration, membrane filtration, reverse osmosis	aqueous liquids	UK, USA	A.13
Wet oxidation	IX resins	UK	A.27

(1) Not necessarily a complete list of where technology is currently being used.

(2) Potential future mobile technologies (technology available, but not yet known to be implemented as mobile).

(3) As of February 2006, Brazil was in the process of leasing a mobile supercompactor for campaign processing of stored wastes.

7. INNOVATIVE, COST EFFECTIVE STRATEGIES

The hazards associated with radioactive wastes vary with the nuclides, concentrations, resultant dose rates, etc. It is appropriate that the strategies (approaches) selected for waste disposition vary relative to the hazard. No single strategy or technology will meet every need. Often, the most cost effective disposition path is a proven safe strategy rather than a specific technology. This is particularly true for wastes which are very low in activity. The application and acceptability of such strategies also varies from one country to another. This section identifies such innovative strategies.

7.1. CLEARANCE

7.1.1. Brief description of strategy

In many establishments all materials entering radiologically controlled areas are treated as radioactive waste, with no attempt being made to segregate clean from contaminated or activated materials. Here "clearance" is used to describe the strategy which may be used to segregate and remove clean materials from the radioactive waste stream. Such a strategy generally requires a combination of management processes and technologies to measure the radioactivity.

The management processes will usually involve measures to prevent clean materials from entering controlled areas, to promote the waste segregation arising from each area, and isolate equipment within controlled areas to prevent them from becoming contaminated, among other measures. An important element of any programme to enable clearance of waste materials will be the establishment of a monitoring protocol which reflects both the volume and physical characteristics of the waste, and which is agreed upon with the appropriate regulatory bodies in advance. Some nuclear instrumentation companies now offer monitoring equipment designed specifically for the monitoring of bulk materials destined for clearance.

7.1.2. Significant benefits of strategy

- Minimise storage and disposal costs.
- Preserve capacity in the radioactive waste storage and disposal facilities.
- Volume reduction efficiencies typically in the range of 2:1 to 3:1.

7.1.3. Significant limitations, inhibitors, or adverse impacts of strategy

- Potential consequence and liability arising from programme failure (i.e. release of radioactive materials into environment leading to a loss of public confidence).
- Regulator reluctance to establish criteria and measurement protocols.
- Public perception of potential impact.

7.1.4. Applicable waste streams

Dry solid wastes: All solid wastes, but particularly building materials (e.g. concrete, metals, and packaging (e.g. paper, cardboard etc.).

Wet wastes: As used herein, clearance is generally applied to solid wastes; however, it could also be applied to any liquid waste which meets the regulated clearance levels.

7.1.5. Implementation options

Implement locally (plant specific), or at an off site central processing facility.

7.2. VERY LOW LEVEL WASTE

7.2.1. Brief description of strategy

Very low level waste (VLLW) typically corresponds <100 Bq/g and/or dose rates of <1 mSv/h for radionuclides with half-lives of ≈30 years or less for artificial nuclides. (For naturally occuring radioactive material (NORM), the activity limit is typically raised to 500 Bq/g.) The segregation of VLLW from LLW produces a category of waste which is very low in terms of radioactive hazard, thereby allowing the country to examine alternative disposal options for this discrete waste category. A VLLW strategy extends the useful life of existing LLW repositories, as well as reducing dispositioning costs. It is an especially useful strategy during dismantling and decommissioning—which generate large volumes of metal, concrete and soil VLLW—as it may allow for some VLLW to be disposed on the site of generation with no long term hazard carried forward to future generations.

7.2.2. Significant benefits of strategy

- High waste throughput.
- No volume reduction requirement: wastes are disposed of in their original volume, except metallic compounds that are generally cut or/and compacted before being disposed. (Some limited volume reduction can be optional and frequently offers cost or other benefits. An example is the French “big bag” concept which allows for easy, safe transport and handling.)
- Inexpensive disposal due to a near surface disposal concept (e.g. engineered trenches in a clay environment) similar to those implemented for industrial nonradioactive wastes.

7.2.3. Significant limitations, inhibitors, or adverse impacts of strategy

- Low activity limit for acceptance in repository (in France where a specific VLLW repositoryis in operation, average massic activity for short lived nuclides, such as Co-60, is limited to 10 Bq/g).
- Difficulty of radioactive characterizations; the best way is based on an envelope declaration of activity by using fingerprints and scaling factors.
- Necessity to densify waste (metallic compounds) to reach an average of 1 to ensure a mechanical stability of vaults (i.e. to eliminate void spaces, thereby minimizing the potential of subsidance).
- No liquid waste.

7.2.4. Applicable waste streams

Dry solid wastes: all dry solid wastes.

Wet wastes: generally not applicable, although it could be used for some secondary ion exchange resin, such as very low activity PWR condensate polisher resin.

7.2.5. Implementation options

Implement locally (plant specific) for dismantling or decommissioning where the long range (e.g. 50 to 100 years) land management and ownership remains in the control of the nuclear utility, or in an off site central VLLW disposal facility.

7.3. RECYCLING FOR INTERNAL REUSE

7.3.1. Brief description of strategy

The recycling for internal reuse is for the repeated reuse of different kind of materials (e.g. protective equipment, tools, shieldings, etc.) in order to minimize dry solid waste volumes. By internal reuse, the yearly production of dry solid waste to be processed and disposed can be greatly decreased. This is commonly used at many NPPs, but it is insufficiently applied worldwide.

7.3.2. Significant benefits of strategy

— Volume reduction (VR) is dependent on the number of recycling events. For example, if a protective garment is rewashed 50 times, then the VR ratio is 50:1.

7.3.3. Significant limitations, inhibitors, or adverse impacts of strategy

— Secondary waste produced should also be treated.

— Number of recycling events is limited due to the properties of the materials recycled.

— Some recycling approaches result in higher costs as compared to direct disposal.

7.3.4. Applicable waste streams

Dry solid wastes: protective equipments, tools, shieldings, etc.

Wet wastes: generally not applicable.

7.3.5. Implementation options

Implement locally (plant specific).

7.4. DISPOSAL IN LICENSED HAZARDOUS WASTE REPOSITORIES

7.4.1. Brief description of strategy

This strategy is applied only to LLW with half-lives of ≈30 years or less. It is based on the fact that most LLW has a relatively short period of radiotoxicity (shorter life) than the chemical or toxic wastes typically disposed in hazardous waste repositories. Thus, the long term access controls applied to many hazardous waste repositories will remain in place long after the decayed radioactivity has ceased to be a concern. This allows agencies regulating hazardous waste disposal facilities to amend the license to accept low levels of short lived radionuclides with package dose rates potentially up to 1 mSv/hour. (Note that this should not be confused with clearance levels.) This is a sound strategy which is insufficiently applied worldwide.

7.4.2. Significant benefits of strategy

- Large reduction in the quantity of LLW which must be disposed in LLW disposal facilities, thereby extending the life of those facilities.
- Provides an alternate, safe disposal route for perhaps as much as 80% of the LLW generated at NPP, depending on the dose rate and nuclide restrictions incorporated into the waste acceptance criteria.
- Typically, hazardous waste disposal facility fees are significantly less than LLW disposal facility fees.
- Provides an immediately available safe disposal solution for countries and NPP which do not have access to a dedicated LLW disposal facility.

7.4.3. Significant limitations, inhibitors, or adverse impacts of strategy

- Typically will require a change in disposal facility licensing.
- May require a change in hazardous waste disposal regulations.
- May require a change in legislation.
- Does not apply to liquid wastes.

7.4.4. Applicable waste streams

Dry solid wastes: all dry solid LLW.

Wet wastes: all wet LLW which have been converted into solid form through drying, absorption, etc.

7.4.5. Implementation options

Implement at a hazardous waste disposal facility.

7.5. DECONTAMINATION FOR MONITORING/RELEASE OR RECYCLE/REUSE

7.5.1. Brief description of strategy

There are many decontamination systems available. Some of these have been developed for very specific applications, while others can be applied across a wide variety of waste types. Some decontamination technologies are based on mechanical processes, whereas others rely on the use of chemical reagents.

There will only be a benefit from decontamination if it results in improved safety conditions or if the waste is moved from a higher category to a lower category: (1) conversion of ILW to LLW, (2) decontamination for unrestricted release, or (3) decontamination for reuse within the industry. The first two are considered as innovative, consistent with the intent of this report, as they offer significant benefits, yet are under-utilized throughout the world.

7.5.2. Significant benefits of strategy

- Potential to rereduce the disposal category for some wastes (e.g. from ILW to LLW) or to allow unrestricted release or reuse.

- Potential to reduce worker radiation exposures from subsequent waste management activities.
- Substantial cost savings from minimizing the volume of higher category wastes. This applies both to conversion and to decontamination for unrestricted release.

7.5.3. Significant limitations, inhibitors, or adverse impacts of strategy

- Creation of secondary wastes, particularly chemically treated wastes which pose difficulties in further treatment and disposal.
- Radiation exposures to operators incurred from decontamination operations.

7.5.4. Applicable waste streams

Dry solid wastes: Metallic waste items, concrete.

Wet wastes: Generally not applicable.

7.5.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing system.

8. CONCLUSIONS

The purpose of this publication is to provide information on the most innovative, proven technologies and strategies used for pre-treatment, treatment and conditioning of LILW arising at nuclear power plants (NPP). The following are some important implications of this publication.

— Innovative technologies are not necessarily expensive. Often, there are some simple solutions or innovative strategies which can be applied to solve specific problems and which do not involve significant investment.

— A decision to apply any innovative technology or strategy depends on the country specific and organisation specific conditions. These include waste generation rates, available disposal solutions, financial and labour resources, and legislation constraints. Innovative technologies and strategies must support the achievement of national and organisational goals relative to waste management, promote safe operation with optimised results, and promote public confidence toward regulatory support for the acceptance of any given technology.

— In some countries, regulations may need to evolve before an innovative technology or strategy can be introduced. Concurrent with the adoption of such technologies and strategies, regulations will need to establish adequate controls to ensure public and environmental safety. The challenge is to strike a balance in the regulations which will support national waste management goals, maintain public confidence, and provide for the introduction of highly beneficial and innovative technologies and strategies.

— It is important to consider the target waste during the decision making process for innovative technologies and strategies (e.g. wet, solid, ILW, LLW, VLLW, etc.). The selection of any individual technology or innovative strategy will not meet all the needs of waste management. On the other hand, faced with limited resources, one must consider choosing technologies and strategies which can be applied to a wider range of waste types with acceptable volume reduction results instead of requiring the "Best Available Technology" for every waste stream. In addition, the decision maker should always consider the trade-off between the high-tech 'one-process-fits-all' technology and the combination of simple, inexpensive and innovative technologies and strategies.

— Some innovative technologies and strategies do not necessarily involve new concepts. The accumulated experience with existing technologies can be applied in a different way so as to achieve different objectives. Focusing resources on *adapting* existing technologies to meet new needs—as opposed to investing in new technologies—may result in considerable cost and time savings for all stakeholders.

— If the nuclear power plant has sufficient capacity for interim storage, then waste treatment or conditioning facilities do not have to operate continuously. For cost reduction, the NPP might choose short term storage onsite, followed by a shipping campaign to a central off site processing facility. Alternatively, short term onsite storage could be followed by the application of an onsite, mobile technology to process and disposition the accumulated wastes.

Appendix

INNOVATIVE TREATMENT AND CONDITIONING TECHNOLOGIES

This appendix provides additional discussion on each of the innovative technologies identified in Table 1. Significant benefits, limitations, inhibitors, or adverse impacts of these technologies are also identified, as applicable.

This appendix should be especially useful to decision makers seeking to identify the best mix of technologies for specific waste streams, optimum operational approach (continuous, campaign), and optimum location (plant site, off site central processing facility, or mobile system). Note that identifying an off site central processing facility as the primary implementation option typically indicates that the technology is high cost, requires high input volumes, and is usually beyond the financial and labour resources of a single NPP site.

According to the IAEA Radioactive Waste Management Glossary [6]:

1. *Pre-treatment* is considered as any operations prior to treatment, such as collections, segregation, chemical adjustment or decontamination;
2. *Treatment* is for waste volume reduction, removal of radionuclides from the waste and change of composition; and
3. *Conditioning* covers stabilization/solidification of waste before disposal, and enclosure in containers.

The difference between pre-treatment, treatment and conditioning is, however, country specific. In some countries, treatment covers all of the mentioned processes. For this reason, in this report, these processes are discussed together without differentiating them as pre-treatment, treatment or conditioning.

Table VI lists the innovative technologies addressed in this appendix, along with the subsection where information can be found on any selected technology. Technologies appear in this appendix in alphabetical order, consistent with the main body of the report. The summary table also identifies which countries are using this technology. Although this information appears in the main body of the report, it is replicated here so as to allow the appendix to be used as a stand-alone reference.

Table VI. SUMMARY OF TECHNOLOGIES IN APPENDIX

Technologies	**Section in report**	**Where technology known to be used**
Cold Crucible Vitrification	A. *1*	Republic of Korea
Crystallization	A. *2*	France
Drum drying	A. *3*	USA
Geopolymerization	A. *4*	Slovakia
High temp incineration	A. *5*	Japan
Hot isostatic pressing	A. *6*	Sweden, Germany
Incineration	A. *7*	Canada, France, India, Japan, Russia, Slovakia, UK, USA
Ion exchange membrane	A. *8*	Canada, Finland, Hungary, USA
Ion-specific filtration	A. *9*	Canada, Finland, France, Hungary, UK, USA
Liquid concentrates VR system	A. *10*	Finland, Hungary
Liquid filter shearing and shredding	A. *11*	UK, USA
Melt densification	A. *12*	India
Membrane filtration	A. *13*	Finland, Hungary, Japan, UK, USA
Metal melting	A. *14*	Belgium, France, Germany, Russia, UK, Ukraine
Molten metal	A. *15*	Japan, USA
Oil filtration	A. *16*	Canada, UK, USA
Oil Solidification	A. *17*	Canada, Hungary, UK, USA
Pelletization	A. *18*	Japan
Phytoremediation	A. *19*	UK
Plasma arc melting	A. *20*	Japan, Russia, Switzerland, USA
PVA Dissolution	A. *21*	USA
Pyrolysis	A. *22*	Sweden, USA
Reverse osmosis	A. *23*	Canada, India, USA
Superabsorbant polymer	A. *24*	Canada, UK, USA
Supercompaction	A. *25*	Canada, Czech, Finland, France, Japan, Republic of China, Russia, Slovakia, UK, Ukraine, USA
Thermo-chemical conversion	A. *26*	USA
Wet oxidation	A. *27*	Belgium, Canada, UK

A.1. COLD-CRUCIBLE VITRIFICATION

A.1.1. Brief description of technology

The accumulated experience from HLW vitrification was successfully used in the development of “cold crucible” vitrification technology for LILW [17]. The cold crucible is typically a water cooled melter design in which glass vit (frit) and waste are melted by high frequency induction or plasma arc torch heating. Cooling of the reactor walls protects melter internals against corrosion, and direct transfer of heat into the melter allows high temperatures without a negative impact on the melter reactor and associated components. Mechanical stirring of the melted mass assures uniform composition of the end product.

A.1.2. Significant benefits of technology

Practically an unlimited melter (reactor) life.

Virtually no limits on upper reaction temperatures.

No requirement for continuous operation.

High waste throughput.

High volume reduction efficiencies typically in the range of 50:1 to 100:1.

Low sensitivity to waste composition.

A.1.3. Significant limitations, inhibitors, or adverse impacts of technology

Generally applicable to low dose rate materials, as the vitrification reactor typically is not heavily shielded.

The most effective implementations require full-time (24-hour) operation to maintain operating temperatures and a melted mass, thereby avoiding heat-up and cooldown cycles. To avoid continuous operation when only small waste input volumes are available, campaign processing should be considered.

Generally requires a large input volume to support continuous, cost efficient operation, and therefore is more suited to use in a centralised processing facility.

A.1.4. Applicable waste stream

— Dry solid wastes: combustibles, noncombustible compactables, incinerator ash.

— Wet wastes: ion exchange resin and related media (charcoal, back-flushable filter media), cartridge filters, evaporator concentrates.

A.1.5. Implementation options

Implement locally (plant specific) or at an off site central processing facility.

A.2. CRYSTALIZATION

A.2.1. Brief description of technology

Crystallization is a deep drying process for high salinity solutions. For example, it is commonly used to perform the initial volume reduction of liquid waste containing boric acid prior to the final imobilization. With this technology, the boric acid is crystallized by heating and producing either a slurry stream with high boric acid content (e.g. 60%) or solid form boric acid crystallines ready to solidify.

A.2.2. Significant benefits of technology

Volume reduction is dependent on the starting concentration, but is typically in the range of 4:1.

Can also be used for boric acid recycling to the NPP combining with additional treatment methods.

A.2.3. Significant limitations, inhibitors, or adverse impacts of technology

Heating of pipes throughout the entire crystallization system is required to prevent blockages, which requires substantial thermal energy (i.e. high operating cost).

A.2.4. Applicable waste streams

— Dry solid wastes: N/A.

— Wet wastes: evaporator concentrates.

A.2.5. Implementation options

Implement locally at plant site.

A.3. DRUM DRYING

A.3.1. Brief description of technology

This is a simple technology for wet wastes which produces a dry end product usually with reduced volume and better suited to storage or disposal. There are several proprietary systems available, but the process is essentially the same. Waste is loaded into a standard 200 litre storage drum, and the drum is then heated within a cabinet to drive off the contained water. Heating may be by circulation of warm air or electrical heating jackets fitted around the drum. Vacuum can be applied to increase the rate of drying. Systems are available to process individual drums or multiple drums for faster processing. The removed water is extracted via an air recirculation system, where it is condensed and monitored prior to further treatment or disposal.

A.3.2. Significant benefits of technology

Simple, rugged technology and equipment.

Low cost.

Volume reduction efficiencies typically in the range of 2:1 to 6:1; higher VR ratios achievable for liquid wastes with low solids concentration.

A.3.3. Significant limitations, inhibitors, or adverse impacts of technology

Slow throughput.

Potential fire risk from solvents and other organic components.

A.3.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: Sludges, filter aid materials, IX resins, concentrates.

A.3.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing facility.

A.4. GEOPOLYMERIZATION

A.4.1. Brief description of technology

The technology achieves the waste immobilization objectives through reactions of the activated aluminosilicates (kaolinitic raw materials) dissolved in an alkali aqueous solution. It is a polycondensation reaction of aluminosilicates under the formation of a siloxo-sialate network consisting of aluminum and silica tetrahedrons. The basic factors affecting the reaction process are the dehydroxylation of the starting materials, their particle size distribution, the pH of the alkaline aqueous solution, and the intensity of agitation.

A.4.2. Significants benefits of technology

In comparison to common Portland cements, it has a higher capacity to immobilize soluble salts in a dense network of aluminium and silica tetrahedrons.

This technology can be carried out at room temperatures and does not require complicated off-gas technology like vitrification.

There are no secondary wastes.

A.4.3. Significant limitations, inhibitors, or adverse impacts of technology

There have been a number of research activities of this technology, but so far only one application for radioactive sludge was put in operation in Slovakia. Further research activities are needed for other waste streams.

A.4.4. Applicable waste streams

- Dry waste: Incinerator ash.

— Wet wastes: sludges, ion-exchange resins.

A.4.5. Implementation options

Implement locally (plant specific) or at an off site central processing facility.

A.5. HIGH TEMPERATURE INCINERATION

A.5.1. Brief description of technology

High temperature incineration (HTI) is an improved incineration technology [18]. The conventional incineration is a self-sustaining process, because only combustible wastes are treated. Since HTI has a powerful burner and runs at 1500°C (whereas a conventional incinerator runs at 700 to 1000°C), a small percentage of metal, air filters, and insulation can be incinerated along with other combustible waste. The waste is melted in a rotating furnace, then discharged at a controlled rate with water jet cooling to produce a granular product.

A.5.2. Significant benefits of technology

Stabilized waste form.

Volume reduction efficiencies typically in the range of 3:1 to 5:1 for light metal, air filters and insulation. The VR ratio rises as high as 100:1 for some other combustibles.

Applicable to wide range of waste, though the mix proportion requires careful control.

A.5.3. Significant limitations, inhibitors, or adverse impacts of technology

Very sensitive to waste composition; deviation may shut down the system.

Pre-sorting of waste required.

High installation cost.

Massive off gas treatment system required.

Not generally suitable for high dose rate wastes.

A.5.4. Applicable waste streams

— Dry solid wastes: combustible, non-combustible compactable, metal, air filters, and insulation.

— Wet waste: not generally applicable, although it could be used for both spent resin and filter cartridges.

A.5.5. Implementation options

Implement at an off site central processing facility. (Some large, multi-reactor Japanese sites have installed high temperature incinerators locally (plant specific application).)

A.6. HOT ISOSTATIC PRESSING

A.6.1. Brief description of technology

In this process, spent resins are first dewatered or dried to a residual water content (water of hydration) of between 12% and 50% in a drying vessel. Different resin types can be mixed in this vessel with other wastes, such as sludges and evaporator bottoms with higher water content may also be added. Following the drying step, the waste is loaded into special metal cartridges which are capped (lid attached) and then immediately transferred into a high force compactor. The resulting pellets are then measured for dose rate, height and weight, and then packed for storage and/or disposal. The resulting products must be packed into watertight containers to avoid resin swelling from contact with water. (See reference [4].)

A.6.2. Significant benefits of technology

Treats multiple waste streams.

Will potentially produce a solid monolithic waste form, depending on waste types.

Good volume reduction efficiencies typically on the order of 6:1.

A.6.3. Significant limitations, inhibitors, or adverse impacts of technology

Potential problems with disposability of product due to possibility of resin rehydration.

Potential off-gas treatment requirements.

Potential adverse chemical reaction between waste types.

A.6.4. Applicable waste streams

- Dry solid wastes: None.
- Wet wastes: Ion exchange resins, sludges, evaporator bottoms.

A.6.5. Implementation options

Off site central processing facility. Probably not suited to mobile application due to the requirement for heating and off gas treatment.

A.7. INCINERATION

A.7.1. Brief description of technology

The majority of dry solid wastes generated at NPP are combustible. This explains why many countries have adopted this technology as a predominant treatment technology (e.g. USA, Belgium, Sweden, Japan, Germany, UK). Incinerator designs are very comparable to classical incinerators used for household and industrial trash, but they can differ in size and need to be installed in a containment building due to radioactive contaminants. (See reference [16].)

A.7.2. Significant benefits of technology

High waste throughput (solids, liquids). More than 50% of all dry solid wastes can be incinerated.

The use of a combustible container is recommended to allow the waste to be directly introduced into the incinerator.

High volume reduction efficiencies typically in the range of 7:1 to 100:1, depending on waste composition. (Secondary wastes are taken into account, such as off-gas HEPA filters, which reduces the net VR efficiency).

Toxicity reduction, prevents putrefication.

A.7.3. Significant limitations, inhibitors, or adverse impacts of technology

Activity within LLW is generally limited to an average of <1000 Bq/g. This restriction is due to the need to maintain activity concentrations in the resulting incinerator ash low enough to be disposed either as LLW or ILW.

Off-gas treatment generally does not accept high content of chlorine due to the potential for Cl gas release. Thus, PVC plastic concentration in the combusted waste typically is strictly limited. (Note: The CENTRACO central processing facility in France adds sodium to the in-line ventilation system to capture Cl gas, thereby allowing for higher than normal chlorine content in the waste.)

Limited by volatility of radionuclides, and other gaseous effluents released by the stack (alpha emitters, tritium, CO_2, SO_2, NOx, etc.).

A.7.4. Applicable waste streams

- Dry solid wastes: paper and other cellulosic compounds (clothes), plastic (PVC limited), rubber, paper, watering filters.
- Wet wastes: ion exchange resin and related media (charcoal and backwash filter media), cartridge filters, oils.

A.7.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing facility (one has been developed to incinerate steam generator chemical cleaning solutions).

A.8. ION EXCHANGE MEMBRANE

A.8.1. Brief description of technology

Ion exchange membranes are used in a number of treatment systems [19, 35]. The ion exchange membranes themselves are thin sheets of polymeric materials. There are two principal types of ion exchange membranes: heterogeneous and homogeneous. Heterogeneous membranes can be prepared using almost any ion exchanger. They are prepared by dispersing colloidal or finely ground ion exchange materials throughout an inert thermoplastics binder. Homogeneous membranes are condensation products of sulphonated phenol and formaldehyde, or of nitrogen-containing compounds and formaldehyde. These strong acid or strong base condensates are laid out in thin sheets to form the membranes.

A.8.2. Significant benefits of technology

High ion exchange efficiency.

Can be incinerated or compacted when expired.

A.8.3. Significant limitations, inhibitors, or adverse impacts of technology

Relatively high cost.

Limited mechanical stability.

Chemical precipitation on and in the membrane will affect its useful life.

A.8.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: most liquid wastes.

A.8.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing facility.

A.9. ION-SPECIFIC FILTRATION

A.9.1. Brief description of technology

In the past decade, families of materials have been developed that are highly selective in removing specific ions from liquid effluent streams. These materials are generally molecular sieves or filters rather than ion exchangers. In particular, materials have been developed for the removal of Cs and Co from effluent streams.

They are used, for example, in the form of cartridges, contained within a submersible unit comprising pump, prefilter, ion exchange cartridge, and post filter. Water is circulated through the submersible unit, and the activity of the selected radionuclide is concentrated on the ion exchange cartridge. A single ion exchange cartridge can replace a large volume of ion-exchange material.

A.9.2. Significant benefits of technology

Very high specific radionuclide capacity, up to 10^6 times that of traditional ion exchange materials.

High volume reduction factors, but in reality limited by the practical difficulties in handling the materials after use.

Inorganic by nature, hence generally advantageous from a disposal perspective.

Packaging is simpler compared to bulk ion exchange resin; requires encapsulation of the cartridge in a container rather than in-drum mixing.

A.9.3. Significant lmitations, inhibitors, or adverse impacts of technology

The potential capacity of these materials cannot generally be exploited to the full extent because of problems in handling very high-specific activity materials.

Release of even small amounts of these materials into existing plant effluent systems can lead to serious operational problems if they become lodged in pipework, valves, pumps, etc. If this occurs, they will continue to remove activity and give rise to hot spots around the plant causing potentially unacceptable levels of radiation exposure to operators and maintenance staff.

A.9.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: liquid waste containing specific radionuclides in ionic form.

A.9.5. Implementation options

These materials may be used in any plant, fixed or mobile.

A.10. LIQUID CONCENTRATES VOLUME REDUCTION SYSTEM

A.10.1. Brief description of technology

This is a new technology developed by the PAKS nuclear station in Hungary, which offers the potential for a significant improvement in volume reduction of boric acid concentrates [20–22]. In this process, liquid radioactive concentrates with a boric acid content in the range of 200–250 g/kg are treated using a multi-step technology to separate boric acid from other radioactive constituents in order to minimize the final volume of LLW to be solidified. A large percentage (minimum 70%) of the original volume of concentrates will be separated as pure boric acid, which can be recovered and reused again in the NPP. The technology consists of the following elements:

Cobalt-complex removal system: complexing and chelating agents are destroyed by an underwater plasma technolgy, which assures the effective removal of Co-58 and Co-60 isotopes.

Boron recovery system: boron content is separated by adjusting the pH value of the concentrates to precipitate and filtrate it in alkaline-borate form, that can be transformed into boric acid to recycle or store as a non-radioactive salt. Activity is typically low enough to accept for alternative industrial use where allowed by law.

Ultrafiltration system: used to remove particle-bound radioactivities from the liquid phase with a decontamination factor higher than 100 in preparation for releasing the effluent to the environment.

Cesium-removal system: inorganic sorbents are used for removal of Cs-134 and Cs-137 isotopes from the liquid phase with a decontamination factor of better than 1000 in preparation for releasing the effluent to the environment.

A.10.2. Significant benefits of technology

Low secondary waste generation (filter cartridges, sludge from ultrafiltration, and plasma arc technology) that can easily be conditioned with the predominant technologies.

Boric acid recovery for reuse.

The treated liquid phase (as an end-product without boric acid and below the release limit values for different radionuclides) usually can be freely released via the existing, monitored routes.

High volume reduction efficiency, typically in the range of 40:1 to 100:1; results in considerable reduction of solidified waste volume and disposal costs.

A.10.3. Significant limitations, inhibitors, or adverse impacts of technology

The as-generated concentrates should contain boric acid in high concentration (higher than 200 g/kg).

System operation has a high energy consumption (only the cobalt-complex removal system itself requires 8–10 kWh/l).

Low capacity (250–500 l/h), semi-continuous operation, high maintenance reqirements.

A.10.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: evaporator concentrates.

A.10.5. Implementation options

Implement locally (plant specific).

A.11. LIQUID CARTRIDGE FILTER SHEARING AND SHREDDING

A.11.1. Brief description of technology

Shredding is a widely applied technology for volume reduction of many types of LLW. Shearing can be applied to cartridge filters and involves cutting or sectioning of the cartridge filters to minimize the void spaces internal to the filters. This promotes greater packaging efficiencies. In general, filter shearing is a lower risk technology from a radiological perspective than filter shredding, in terms of a reduced potential for airborne contamination and an improved ability to control the spread of contaminants. Both approaches offer similar

VR efficiencies for filter cartridges. (Note: if considering these similar but different technologies, evalute both rather than just one.)

A.11.2. Significant benefits of technology

Inexpensive VR technology to construct and operate.

Low labor resource requirement.

Shearing offers improved contamination control benefits over shredding.

Significant reduction in stored and disposed waste volumes.

Good volume reduction efficiencies, typically in the range of 3:1 to 4:1.

A.11.3. Significant limitations, inhibitors, or adverse impacts of technology

Both shearing and shredding have the potential for airborne contamination and spreading of loose surface contaminates, with shredding generally having a higher potential than shearing.

A.11.4. Applicable waste streams

- Dry solid wastes: non-combustible compactables, HEPA filters.
- Wet wastes: filter cartridges.

A.11.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing facility.

A.12. MELT DENSIFICATION OF PLASTIC WASTE

A.12.1. Brief description of technology

Polyethylene with up to 15% of PVC & rubber waste packed in polyethylene bags are fed into an insulated oven in a standard 200 l metal drum. Temperature controllers maintain the temperature within the operating values of 170 – 180 °C for 3–4 hours for complete melting and densification. The exhaust gases are passed through a scrubber and a HEPA filter for removing organic vapours and any possible particulate activity.

A.12.2. Significant benefits of technology

Simple process.

Practically no airborne activity.

Low temperature process

High volume reduction factor, typically in the range of 20:1.

A.12.3. Significant limitations, inhibitors, or adverse impacts of technology

Low throughput.

HCl production expected if PVC is in the feedstock.

A.12.4. Applicable waste streams

- Dry solid wastes: Polyethylene, polyurethane, polyvinyl-alcohol, and other plastic wastes; small content (percentage) of polyvinyl-chloride (PVC) allowed due to the release of chlorine gas.

- Wet wastes: N/A.

A.12.5. Implementation options

Can be implemented locally (plant specific).

A.13. MEMBRANE FILTRATION

A.13.1. Brief description of technology

Innovative membrane technologies employed in the nuclear industry are Hollow Fiber Filtration (HFF), cross flow filtration, and ultrafiltration [23]. Ultrafiltration and cross flow filtration are used to remove suspended fine particles from liquid streams. HFF is used in condensate systems, as well as in liquid waste treatment systems. Filter cartridges consist of hundreds of fine, hollow fibers, or they contain numerous micro-pores on the surface. The differential pressure must be monitored for backwash. The life of filters is determined by the pressure drop after backwash and is usually 3 to 10 years.

A.13.2. Significant benefits of technology

High removal effiiency for crud or other suspended fine particles (initial efficiency is nearly 100%).

Long life (3 to 10 years).

Combustibility leading to waste minimization.

A.13.3. Significant limitations, inhibitors, or adverse impacts of technology

Cannot use as an ion trap.

If installing in an existing plant as an addition to an existing system, the filter capacity may be limited due to pressure restrictions in the existing system design.

A.13.4. Applicable waste streams

- Dry solid wastes: N/A.

- Wet wastes: most liquid wastes.

A.13.5. Implementation options

Implement locally (plant specific).

A.14. METAL MELTING

A.14.1. Brief description of technology

Metal melting eliminates the void spaces in metal pipes and components, creating a homogeneous metal monolith [16]. Metal melting is also used to convert bulk metal into moulded waste containers, which are subsequently used for LILW storage or disposal. Typically, the types of metals are restricted to individual melting operations, such as an aluminum melter, ferrous metal melter, or lead melter, requiring advance (upfront) segregation of metal wastes. Metal melting is typically accomplished in smelting furnaces or through the use of plasma arc technologies. Capacities of the furnace are generally in the range of 1 to 5 metric tons/cycle.

A.14.2. Significant benefits of technology

High waste throughput.

High volume reduction efficiencies typically in the range of 5:1 to 20:1 (if end product is recycled, the effective VR is 100%, exclusive of secondary slag waste).

A.14.3. Significant limitations, inhibitors, or adverse impacts of technology

Non ferrogeneous metals can be added in very small quantities.

Heavy preparatory requirements: cutting (depends on the furnace size), grinding, blasting, sorting of prohibited species, such as liquids (explosion risk), plastics and paint (fire risk by accumulation of organics in cold parts of off-gas treatment), lead (refractory lining destruction).

High maintenance, and frequent replacement of refractory lining.

Off-gas treatment system required.

A.14.4. Applicable waste streams

— Dry solid wastes: most metals, although specific to type of furnace (either ferrous metals, aluminum, lead, but not a combination of these).

— Wet wastes: N/A.

A.14.5. Implementation options

Implement at off site central processing facility. Possible mobile technology specifically for lead melting.

A.15. MOLTEN METAL

A.15.1. Brief description of technology

Molten metal is a relatively new technology. It is widely used throughout Japan, but has not yet made significant inroads into other countries [24]. The origin of this technology is in the steel industry; dry active wastes (metal, concrete, etc.) are combined in a ceramic canister and melted by high frequency induction. The melting temperature is about 1500°C. The eventual waste form is a stabilized ingot. (Note this differs from metal melt in that it combines multiple waste forms with at least 10% metal composition, and not just metallic waste.).

A.15.2. Significant benefits of technology

Volume reduction efficiencies typically in the range of 3:1 to 5:1, without the addition of a non-waste binder (e.g. without requiring the addition of cement, bitumen, etc., which would increase the final disposal volume).

Stabilized waste form, leading to better performance in the safety assessment of the disposal facility.

Applicable to hazardous waste (e.g. asbestos).

Minimization of contamination, because the molten mass is discharged directly into a disposal canister.

Relatively low maintenance cost (compared to plasma arc melting).

Practically unlimited meltor life

A.15.3. Significant limitations, inhibitors, or adverse impacts of technology

High installation cost and high energy requirement cost for melting; does not generally apply to a small lead melter.

Relatively low throughput.

Expensive ceramic canister.

Massive off gas teratment system.

Slow startup (more than 1 hour is required for elevation of temperature).

A.15.4. Applicable waste streams

- Wet wastes: ion exchange resins, low activity filter cartridges.
- Dry solid wastes: combustible, non-combustible compactable, metal, concrete, ash, air filter, solvents, asbestos.

A.15.5. Implementation options

Implement at an off site central processing facility. Small lead melters can be implemented locally (plant site) or potentially as a lead-specific mobile system.

A.16. OIL FILTRATION

A.16.1. Brief description of technology

Particle-bound radioactive species can be removed from contaminated oils by using different separation processes (e.g. pressure filters, cartridge filters, centrifugation).

A.16.2. Significant benefits of technology

Volume reduction is dependent on the starting contamination.

Oils and lubricants can be reused after filtration.

A.16.3. Significant limitations, inhibitors, or adverse impacts of technology

Only particle-bound radioactivity can be removed effectively.

Secondary wastes require treatment.

Could be economical only in case of large volume of oils to be filtered.

A.16.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: oils and lubricants.

A.16.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing facility.

A.17. OIL SOLIDIFICATION

A.17.1. Brief description of technology

Solidification of oil is possible in several different matrices [25]. Some make use of absorbing the oil onto a solid substrate prior to solidification; others use emulsifiers to create a suspension of oil in water prior to solidification in cementitious materials.

A.17.2. Significant benefits of technology

Converts a liquid waste into a solid waste for increased safety during storage.

A.17.3. Significant limitations, inhibitors, or adverse impacts of technology

Net *increase* in disposal volume, typically by a factor of 2.

Product may release oil under compressive loading.

A.17.4. Applicable waste streams

- Dry solid wastes: N/A.

— Wet wastes: Oil and oil bearing sludges.

A.17.5. Implementation options

Implement locally (plant specific) using typical cement solidification equipment, at an off site central processing facility, or using mobile solidification equipment.

A.18. PELLETIZATION

A.18.1. Brief description of technology

Pelletization technology is suitable for conversion of wet waste into a dry solid waste. For this process the raw waste is dried into a powder form, compacted in a mold into a solid form, and cut into small pieces. The name of pelletization is derived from the eventual form of the waste, which appears as small pellets. The treatment of ion exchange resins requires a chemical binder, whereas other waste types may not.

A.18.2. Significant benefits of technology

High waste throughput.

Volume reduction efficiencies typically in the range of 4:1 to 8:1.

Suitable technology for storage because of conversion of wet form into dry form.

No requirement for continuous operation.

A.18.3. Significant limitations, inhibitors, or adverse impacts of technology

Difficulty of post-pelletization solidification with cement due to absorbency of moisture. (Grinding of pellets is an efficient solution if solidification is to be performed with cement. Alternatively, a cement-glass solidification approach is adequate for the solidification of whole pellets.)

Potential of explosion due to treatment of powdered waste.

Carsinogenicity of binder if DOP (dioptalthalate) is used. Alternative, noncarcinogenic binders are available.

A.18.4. Applicable waste streams

— Dry solid wastes: N/A.

— Wet wastes: evaporate concentrates, spent resin.

A.18.5. Implementation options

Implement locally (plant specific), or at an off site central processing facility (although off site processing may not be feasible for evaporate concentrates due to difficulty in transport).

A.19. PHYTOREMEDIATION (ALSO PHYTOSTABILIZATION)

A.19.1. Brief description of technology

Phytoremediation involves the use of plant life to selectively absorb radioactive species from contaminated land (e.g. soils, sand, clay). The vegetation can then be cropped to remove the activity, and treated by further means, for example incineration [26].

Phytostabilisation similarly makes use of vegetation to stabilise areas of contaminated ground and reduce the risk of activity spread by erosion, thus reducing waterborne and dustborne exposure pathways.

A.19.2. Significant benefits of technology

Simple in application, hence low cost.

A.19.3. Significant limitations, inhibitors, or adverse impacts of technology

Potential slow process, requiring several growing seasons to realise results.

Cropped vegetation requires further processing.

Applicable to low levels of contamination or large areas of land.

A.19.4. Applicable waste streams

- Dry solid wastes: contaminated land.
- Wet wastes: N/A.

A.19.5. Implementation options

Implement locally (plant specific).

A.20. PLASMA ARC MELTING

A.20.1. Brief description of technology

A plasma arc torch is formidable method for volume reduction. This technology was developed as a metal cutting method in the steel industry. Wastes emplaced in the melting furnace are exposed to the plasma arc torch at temperatures above 5000°C. Melted waste is discharged into the disposal container and cooled into ingots. To prevent the melted waste from sticking inside of the furnace, the furnace is always rotating.

A.20.2. Significant benefits of technology

High waste throughput.

Stabilized waste form.

Volume reduction efficiencies typically in the range of 3:1 to 6:1.

Applicable to wide range of waste (metal, resin, plastic, concretes etc.).

A.20.3. Significant limitations, inhibitors, or adverse impacts of technology

High installation cost.

Relatively high maintenace cost.

Massive off gas treatment system.

Slow startup (more than 1 hour is required for the elevation of temperature).

Generally requires a large input volume to support cost efficient operation.

A.20.4. Applicable waste streams

- Dry solid wastes: combustible, non-combustible compactable, metal, concrete, ash, air filter, solvents, asbestos, soil.
- Wet wastes: ion exchange resins.

A.20.5. Implementation options

Implement at an off site central processing facility.

A.21. PVA DISSOLUTION

A.21.1. Brief description of technology

This process requires plant operators to first adopt the use of protective clothing manufactured from polyvinyl alcohol (PVA) plastic. The technology has been perfected to dissolve PVA materials at high temperature in a tank (reactor) containing the PVA waste and a dilute hydrogen peroxide solution. The end product is a completely dissolved liquid which can be discharged or directed to a bioreactor for further treatment of any organics [27]. (Organics are derived from human perspiration, oily rags and mop heads, and other cleanup activities.) Secondary waste arises from tape, zippers, or other foreign materials attached to the PVA product.

PVA filter cartridges are being developed as a potential replacement for commonly used metal filter cartridges in low pressure, low temperature applications. These non-metal, PVA filters can be dissolved in the same manner described above or sent to an incinerator.

A.21.2. Significant benefits of technology

High waste throughput.

Eliminates need for conventional laundry.

Relatively inexpensive to construct and operate.

Operated in batch mode at user-selected frequency (daily, weekly, monthly).

Low labor resource requirement.

High volume reduction efficiencies typically in the range of 20:1 to 40:1 for cartridge filter applications, depending on crud-loading of the filters. For dry solid waste, the vr approaches 100%.

A.21.3. Significant limitations, inhibitors, or adverse impacts of technology

Relies on single-use (non-recyclable) protective clothing and other materials.

A.21.4. Applicable waste streams

— Dry solid wastes: combustibles made from PVA.

— Wet wastes: cartridge filters made from PVA.

A.21.5. Implementation options

Implement at a large, multi-reactor plant site or at an off site central processing facility.

A.22. PYROLYSIS (INCLUDES TANK CONVERSION REFORMING)

A.22.1. Brief description of technology

Pyrolysis is a relatively low temperature thermal process that operates over a temperature range of 500 to 800°C. During pyrolysis the wastes are degraded in an inert atmosphere and any long chain polymer materials are dissociated into a solid residue and a gas-vapour fraction. At the upper range of operating temperatures, the organics are destroyed, and the resulting synthesis gas exits the pyrolyser. The solid residues are transferred to a fluidized bed reformer, heated again, and subsequently transferred to a disposal or storage container [26, 28–32].

This technology can also be apllied to non-metal cartridge filters and high density plastics, when it is referred to as “tank conversion reforming”. The name is given to the process because it is accomplished in a separate “tank” (reactor) connected to the main pyrolysis reactor, in which individual filter cartridges or wastes are manually fed, whereas the main pyrolysis reactor is designed for automatic feed of large quantities. An important consideration of this process is that the end product is a reformed residue which is identical to the end product of the pyrolyzed resin. This allows the reformed residue from both waste streams to be combined into a homogenous mixture without the need for concentration averaging for disposal characterization.

A.22.2. Significant benefits of technology

Provides a biologically and chemically stable end product (a solid reformed residue).

The reformed residue can be stored for many years and subsequently encapsulated if required by disposal site waste acceptance criteria.

An almost total retention of non-volatile radioactivity in the reformed residue.

High volume reduction efficiencies typically in the range of 5:1 to 20:1.

A.22.3. Significant limitations, inhibitors, or adverse impacts of technology

Very expensive to construct, operate and maintain.

Requires a large input volume to be cost effective.

Not suitable for wastes containing significant levels of volatile radionuclides.

A.22.4. Applicable waste streams

- Dry solid wastes: cartridge filters, high density plastics.
- Wet wastes: ion exchange resin and backwash filter media.

A.22.5. Implementation options

Implement at an off site central processing facility.

A.23. REVERSE OSMOSIS

A.23.1. Brief description of technology

This technology involves movement of a solvent out of solution under pressure through a semipermeable membrane into pure solvent or a less concentrated solution at lower pressure. This process can be used to increase the radionuclide concentration in solution. The permeate is free of ionic species and can be released to the environment. This is often used as the final polishing stage in low level liquid waste treatment.

A.23.2. Significant benefits of technology

Established for large scale operation.

Concentrates dissolved salts.

High waste throughput.

High decontamination factor in the range of 100:1 to 1000:1.

A.23.3. Significant limitations, inhibitors, or adverse impacts of technology

High pressure system.

Limited by osmotic pressure.

Not backwashable.

Highly susceptible to fouling.

A.23.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: most liquid wastes.

A.23.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing facility.

A.24. SUPER ABSORBENT POLYMERS

A.24.1. Brief description of technology

Super absorbent polymers refers to a class of compounds based on sodium polyacrylate and similar molecules [33–34]. The technology has two primary uses: (1) to absorb liquid in otherwise "dry wastes;" (2) and to convert a liquid to a solid for the purpose of simplifying transportation or further processing (e.g. to feed the liquid into an incinerator as a solid waste). When mixed with liquids, they have the ability to absorb several hundred times their weight in liquid. The original liquid is locked in the molecular structure along with any disolved or suspended solids. Formulations are available for aqueous and organic liquids.

A.24.2. Significant benefits of technology

- High absorption capacity (typically several 100:1 weight ratio of liquid to polymer), often without mixing.
- Waste form can be incinerated later, as solid waste.
- Wide range of formulations commercially available, with very common usage in non-nuclear industries.
- Only very small increase in volume compared to original liquid volume.
- Requires only simple equipment.
- Formulations produce a stable product over wide range of incorporation ratios.

A.24.3. Significant limitations, inhibitors, or adverse impacts of technology

- High concentrations of certain ions (especially sodium) will limit absorption efficiency.
- waste form has low compressive strength and may not meet disposal/storage stability requirements for some facilities.
- Requires testing with real waste stream to determine optimum formulation.
- High radiation fields may cause damage to polymer.

A.24.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: Usually low activity aqueous liquids over wide range of compositions, oils and solvents. Some special formulations are available for higher activity liquids.

A.24.5. Implementation options

Normally implemented locally (at generating plant site), but can be used at a central location. Can be implemented as a mobile process with very simple equipment.

A.25. SUPERCOMPACTION

A.25.1. Brief description of technology

Supercompaction (above 500 metric tons compaction force) involves compressing directly metallic drums then placing the compressed drums into a larger overpack to reduce the volume disposed [16]. Supercompaction is used extensively in many countries, yet expansion of this technology to other countries is encouraged.

A.25.2. Significant benefits of technology

High waste throughput : all technological waste, filters, insulatiors.

volume reduction efficiencies typically in the range of 4:1 to 10:1 (VR as low as 2:1 if wastes are pre-compacted in drums using a low force of 5 to 10 metric tons).

Increased mechanical strength of package in the repository structures (inhibits trench collapse or subsidance).

Increased confinement, commonly cement or mortar is added to the final overpack to eliminate void spaces and enhance overall structural strength.

A.25.3. Significant limitations, inhibitors, or adverse impacts of technology

Generally limited to LLW and to dry solid wastes.

No free or absorbed liquid.

No large metallic pieces (risk of blocking the compaction ram).

Plastic limited or need of pre-cutting or shredding (risk of blocking the compaction ram with a drum explosion due to trapped air content).

Heavy maintenance particularly for large centralized automatic supercompaction facility.

It has been noted that a non-automatic processing facility (such as is generally the case with mobile facilities) allows optimization in filling the final disposal package with compressed drums.

A.25.4. Applicable waste streams

— Dry solid wastes: incinerator ash, all technological waste even concrete

— Wet wastes: non-combustible, non-metal cartridge filters.

A.25.5. Implementation options

Implement locally (plant specific), at an off site central processing facility, or as a mobile processing facility.

A.26. THERMO-CHEMICAL CONVERSION PROCESS (TCCP)

A.26.1. Brief description of technology

Thermo-chemical conversion is a patented process that utilizes chemical reagents and heat to promote accelerated solid solution reactions in silicate media, in particular asbestos bearing wastes. The waste must first be shredded and then mixed with the chemical reagents in a furnace at temperatures typically in excess of 2000°C. The process results in the remineralisation of the asbestos fibres, and conversion into non-asbestos minerals such as diopside, olivine and glass. The product is removed from the furnace by mechanical means and dropped into a water bath. Finally the material can be removed and dried to produce a dry granular product suitable for infilling of other waste or mixed with cement. Other wastes suitable for incineration can be treated in the rotary hearth furnace after first mixing with the asbestos materials.

A.26.2. Significant benefits of technology

High waste throughput, typically 37 metric tons/day throughput, scale up to >100 metric tons/day are claimed.

Elimination of chemical toxicity of waste.

A.26.3. Significant limitations, inhibitors, or adverse impacts of technology

Plant must comply with all requirements for handling of asbestos.

Aerial discharges requiring authorisation.

Subject to regulations governing incineration.

Off-gas treatment system required.

A.26.4. Applicable waste streams

Asbestos, usually from wet stripping operations. PCBs, organic liquids, oil, ion exchange resins.

- Dry solid wastes: All solid waste suitable for incineration.

- Wet wastes: N/A.

A.26.5. Implementation options

Off site central processing facility, or as a mobile processing facility.

A.27. WET OXIDATION (WETOX)

A.27.1. Brief description of technology

The WETOX process is intended for the volume reduction of organic waste streams, such as decontamination reagents [11]. In this process the organic waste is reacted with hydrogen peroxide in the presence of a catalyst at modest temperatures and atmospheric pressure with excess water and distilled or evaporated to leave a concentrated inorganic waste which contains the radioactivity. The concentrated residue may then be sent for continued storage in liquid form or solidificied for storage and potentially disposal.

A.27.2. Significant benefits of technology

Destruction of the organic component of a waste with potential benefits for downstream treatment in terms of long term stability and disposability.

Volume reduction efficiencies typically in the range of 5:1 to 100:1.

Reduced salinity of solution.

A.27.3. Significant limitations, inhibitors, or adverse impacts of technology

Gaseous emissions.

Concentration of activity and hence increase in potential doses to operators.

Potential to raise the categorisation of the waste (e.g. from LLW to ILW).

A.27.4. Applicable waste streams

- Dry solid wastes: N/A.
- Wet wastes: Organic ion exchange resins, spent decontamination solutions (e.g. decontamination reagents and other organic liquid streams.

A.27.5. Implementation options

Off site central processing facility, or as a mobile processing facility. The process has not as yet found widespread application, although a mobile unit is in service.

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