IAEA TECDOC SERIES

IAEA-TECDOC-1817

IAEA-TECDOC-1817

Selection of Technical Solutions for the Management of Radioactive Waste

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International Atomic Energy Agency

SELECTION OF TECHNICAL SOLUTIONS FOR THE MANAGEMENT OF RADIOACTIVE WASTE

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The Agency's Statute was approved on 23 October 1956 by the Conference on the Statute of the IAEA held at United Nations Headquarters, New York; it entered into force on 29 July 1957. The Headquarters of the Agency are situated in Vienna. Its principal objective is "to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world".

IAEA-TECDOC-1817

SELECTION OF TECHNICAL SOLUTIONS FOR THE MANAGEMENT OF RADIOACTIVE WASTE

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2017

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tel.: +43 1 2600 22417
email: sales.publications@iaea.org
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Printed by the IAEA in Austria
July 2017

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Selection of technical solutions for the management of radioactive waste / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2017. | Series: IAEA TECDOC series, ISSN 1011–4289 ; no. 1817 | Includes bibliographical references.
Identifiers: IAEAL 17-01095 | ISBN 978–92–0–104717–5 (paperback : alk. paper)
Subjects: LCSH: Radioactive waste management. | Radioactive wastes — Characterization. | Radioactive waste disposal. | Radioactive wastes — Management.

FOREWORD

The IAEA has issued many publications on the development and implementation of waste management in Member States. One such example is IAEA Nuclear Energy Series No. NW-G-1.1, Policies and Strategies for Radioactive Waste Management, which serves as guidance on the proper and systematic planning of all waste management activities. There is a need for professionals in waste management to find sound and efficient technical solutions for integrated management of all waste streams.

The best approach when selecting these solutions is to ensure that the underlying safety logic is correctly understood and that there is a demonstrated link between the characteristics and amounts of radioactive waste at generation and the proposed technologies, the associated risks in implementing these technologies, the resultant safety management arrangements and the costs incurred. This publication links the policy and strategy publication to detailed technical publications. It consolidates, organizes and updates information in previous IAEA publications to enhance the value of the technical information for professionals involved in the implementation of radioactive waste management.

The IAEA is grateful to all the experts who contributed to the preparation of this publication. The IAEA officers responsible for this publication were Z. Drace and M. Ojovan of the Division of Nuclear Fuel Cycle and Waste Technology.

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1. INTRODUCTION

1.1. BACKGROUND

A radioactive waste management strategy sets out the means for achieving the goals and requirements set out in the national policy. It is normally established by the relevant waste owner or nuclear facility operator, or by government (institutional waste). The organization responsible for radioactive waste management implements a strategy by selecting one or more technologies available to manage the waste in accordance with national policy stipulations or legal regulations. Ideally the strategy should be determined before the system is put in place, though in practice this may be not the case. Member States can enhance the safety and effectiveness of their overall radioactive waste management system by formalizing the selection and use of radioactive waste technologies.

Waste management has received considerable attention due to the important link between the safe management of radioactive waste and public acceptance of nuclear facilities or applications. This linkage should be maintained by selecting and developing an optimal waste management strategy to prevent accidents, minimize exposure to radionuclides and ensure radiological safety for workers and the public.

Moreover, the optimal application of technologies related to radioactive waste minimization, treatment, conditioning, and storage or disposal has become a necessity due to several factors:

- Radioactive waste can only be disposed of in facilities licensed to accept radioactive waste;
- Direct near surface disposal of radioactive waste into the ground without appropriate treatment, immobilization and packaging is generally unacceptable, except in some specific cases involving very low level wastes with activities close to exemption levels;
- Restrictions on discharges and the acceptable levels below which diluted effluents can be released to the environment are increasingly strict;
- With the steep increases in radioactive waste disposal costs, reducing the waste volume offers great economic advantages;
- The regulatory criteria for waste management steps such as transportation, storage and disposal have recently become more restrictive; with the rise of societal concern for resource scarcity and increased public opposition to the siting of radioactive waste facilities in their vicinity, the development of new facilities is an expensive, prolonged and difficult process;
- Recent advances in various technologies suited to radioactive waste management have made their application cost effective and easier to implement;
- Optimal selection of waste management technology is essential in order to achieve goals for human health, safety and environmental protection.

A wealth of information is available about various waste management technologies [1,2]. Although each may have merit, not all technologies and processes discussed are well developed or well suited to all kinds of waste and situations.

Technologies can be selected according to national policy preferences and optimization procedures. Because of the costs involved, the complexity of technical and environmental considerations, and the necessity to assure adequate performance, the selection methodology should have clear criteria. Some criteria will be fairly general and apply to almost all waste management systems, while others may apply to specific waste categories or to selected management steps.

In the past a multitude of technical publications have been issued by the IAEA on methods and technologies for managing various categories of radioactive waste. Because of the variety of processes, techniques and equipment available for different waste streams and waste management steps, optimized technologies have to be selected for each stream and step. To optimize the overall radioactive waste management approach, technologies selected for different waste management steps should be combined into an integrated system.

1.2. OBJECTIVE

The objectives of this publication are to identify and critically review the criteria to be considered while selecting waste management technologies; summarize, evaluate, rank and compare the different technical solutions; and offer a systematic approach for selecting the best matching solution.

This publication can be used most effectively as an initial selection tool to identify whether any given technology will best serve the local waste management strategy in terms of the waste generated, the technical complexity, the available economic resources, the environmental impact considerations, and the end product (output) of the technology and can be instrumental in comparing the technologies and assisting the user to reach an informed decision based on local needs, economics and priorities.

1.3. SCOPE

This publication covers the management of radioactive waste from all nuclear operations, including waste generated from research reactors, power reactors, and nuclear fuel cycle activities including high level waste (HLW) arising from reprocessing and spent nuclear fuel declared as waste (SFW), as well as low level waste (LLW) and intermediate level waste (ILW) arising from the production and use of radionuclides in industry, agriculture, medicine, education and research. Although waste from decommissioning is not specifically addressed, the management of this waste is not significantly different from other types of waste in the same category.

Waste generated from the technologically enhanced concentration of NORM including uranium mining and milling waste is also included in the scope of this report, although the technologies applied for its management may be quite different due large volumes and low activity of such waste.

1.4. STRUCTURE OF THE REPORT

The report consists of six sections. Section 2 proposes an approach adopted for the selection of waste management technologies and reviews the principal waste management end points widely accepted by the international community. Section 3 introduces the waste inventory as a basis for selecting proper technologies with emphasis on important waste properties. Section 4 summarizes the general options available for different waste management steps. Section 5 addresses the major criteria affecting the selection of waste management technologies. Section 6 briefly describes different methodologies for selecting an optimal waste management technology, and Section 7 contains some concluding remarks.

2. WASTE MANAGEMENT ROUTEING

2.1. DEVELOPMENT PROCESS FOR TECHNOLOGY SELECTION

Member States typically begin by considering the full life cycle costs, including the cost of radioactive waste management when planning to commence the development of a national capability to produce and/or use radionuclides, to operate research reactors and/or to generate electricity by nuclear power plants, and determine in advance that they have adequate legal, institutional, financial and technical resources to manage the full cycle impact of the proposed activity. In this respect, countries involved in nuclear activities have a dedicated form of policy and strategies for managing all potential radioactive waste. Such a policy and strategies are important, not only to articulate a national approach, but to provide visible evidence of the concern and intention of the government and relevant organizations to ensure that radioactive waste and spent fuel are safely and appropriately managed [1]. While a national policy for spent fuel and radioactive waste management is needed as a starting point for the development of national strategy [2, 3], strategies themselves are essential to specify "the ways in which the various types of radioactive waste (including spent fuel if declared waste) in the country or site will be managed during all phases of the radioactive waste life cycle (from cradle to grave)" [1].

Because of the variety of processes, techniques and equipment available for different waste streams and waste management steps, an optimized technology has to be selected for each of them. Subsequently the technologies selected for different waste management steps should be combined in an integrated system to optimize the overall waste management [4]. The selection of waste technologies for each specific waste stream/category is based on an evaluation process followed by authorization. Typical elements for an evaluating process can be as follows:

- Identification and nature of facility/site/region/country specific radioactive waste inventories and associated waste management issues;
- Consideration and review of realistic options for the management of specific radioactive waste streams/categories;
- Evaluation of the merits and disadvantages of each option using multi-attribute utility analysis (MUA) [5] or any other suitable methodology covering cost effectiveness, technological status, operational safety, social and environmental factors;
- Identification of the best available technology not entailing excessive cost and satisfying all regulatory requirements [3, 4];
- Acceptance (e.g. licensing, authorization) of the selected technology by the regulatory authority.

The development process and associated considerations are indicated in Fig. 1.

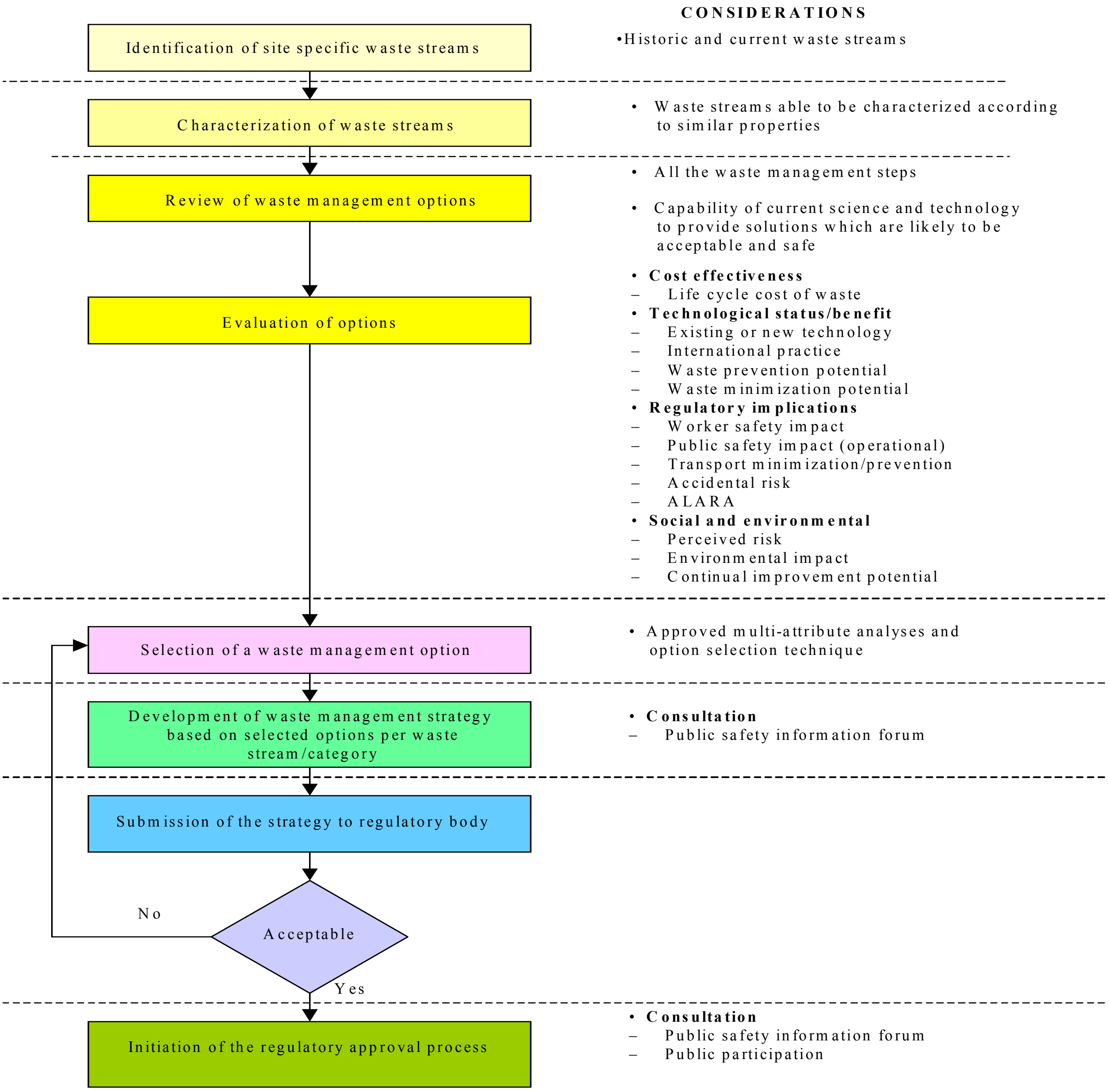


FIG. 1. Development process for selection of a waste management option.

2.2. WASTE ROUTEING

The main radioactive waste routes correspond with the principal waste management options, and may be regarded as the outcome of a specific waste management approach. The principal waste management options are:

— Clearance from regulatory control (unrestricted disposal of waste, reuse of useful materials);

— Authorized release to the environment (disposal via discharge of waste, reuse of useful materials);

— Regulated disposal (for waste) or regulated transfer (for useful materials).

In many cases, radioactive waste is stored in dedicated storage facilities. Such dedicated storage can be utilized over a long period of time (potentially 50 and more years).

2.2.1. Clearance

Radioactive waste arising within a practice that is under regulatory control may be released from control under conditions specified by the Regulatory Body. If it can be shown that any radiological hazards resulting from the release are negligible (specifically that they meet the criteria for clearance), the materials should be cleared from regulatory control. Clearance levels are intended to establish which material under regulatory control can be removed from this control.

The general principles and criteria for exclusion, exemption and clearance have been detailed in the Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (BSS) [6]. In the case of clearance, the BSS defines the concept and the radiological criteria to be used as a basis for determining clearance levels but leaves the establishment of clearance levels to national authorities. The BSS provides radiological criteria to serve as a basis for the derivation of clearance levels but does not provide definitive quantitative guidance on clearance levels. Clearance is defined as the removal of radioactive materials or radioactive objects within authorized practices from any further regulatory control by the regulatory body [7]. The corresponding levels of activity or activity concentration in materials that could be released from regulatory control are called clearance levels.

Many studies undertaken at the national and international levels have derived radionuclide specific levels for the clearance of solid material [8–11]. The IAEA Safety Guide (RS-G-1.7) [7] provides specific values of radionuclide activity concentration for exclusion and exemption of bulk amounts of material, and also elaborates on the possible application of these values to clearance. Clearance can apply both to materials that are being discarded as waste and to radioactive materials intended for further use or recycling. Consequently, cleared waste (or exempt waste) may be treated as normal refuse or effluent, and materials cleared for reuse or recycling may be transferred to any other party and used or processed for any purpose.

Cleared materials should not become subject of regulatory control again so long as activity concentration levels do not exceed exemption levels. Routes commonly used for the disposal of cleared waste are as follows:

(a) For airborne effluents: discharge into the atmosphere either directly or through filtration systems;

(b) For aqueous effluents: discharge directly to sewage systems, septic tanks, collection ponds, various water bodies such as rivers, lakes and the marine environment;

(c) For organic liquids (including scintillation fluids): incineration resulting in off gas which may or may not require cleaning;

(d) For solid waste: non-combustible solids such as construction materials, ceramics, glass are usually disposed of with normal refuse in landfills; combustible waste may be incinerated with normal refuse, resulting in gaseous and particulate effluents that may or may not require off gas cleaning prior to disposal in landfills.

2.2.2. Authorized discharge or use

There are three approaches to the management of radioactive materials which cannot be released from regulatory control by clearance, commonly termed *'delay and decay,' 'concentrate and contain'* and *'dilute and disperse.'* 'Delay and decay' involves holding the waste in storage until the desired reduction in activity has occurred through radioactive decay of the radionuclides contained in the waste. ‘Concentrate and contain’ refers to reduction of volume and confinement of the radionuclide content by means of a conditioning process to prevent or substantially reduce dispersion in the environment. ‘Dilute and disperse’ involves discharging effluent to the environment in such a way that environmental conditions and processes ensure that the concentrations of the radionuclides are reduced to such levels in the environment that the radiological impacts of the released material are acceptable. ‘Dilute and disperse’ is a legitimate practice only when carried out within authorized limitations established by the regulatory body [12].

Waste treatment typically results in concentrating most of the activity in a lower volume material while larger volumes of liquids and gases significantly deplete in contaminants. These slightly contaminated effluents could be released to the environment under the limits authorized by national regulatory authorities through *authorized discharge*. Generic guidance on the authorization procedure is provided the IAEA Safety Guide [12] as well as IAEA-TECDOC-1638 [13], which summarizes international experience on the optimization of discharges and the regulation of authorized limits on discharges for nuclear installations and non-nuclear facilities.

Regulatory control of materials which do not meet the criteria for clearance but are intended for reuse or recycling may be relinquished when such use is authorized by a regulatory authority and when *authorized use* has been verified. Authorized use of valuable materials and equipment is an important element of waste minimization which has been widely implemented in several nuclear fuel cycle processes since the early days of the commercial nuclear power [14].

Economic considerations are a major driving force when considering the practice of recycle and reuse over alternative disposal options for radioactive and non-radioactive materials arising from operation, maintenance, upgrade and decommissioning of nuclear facilities. However, it should be clear that recycle and reuse practices are typical examples of industrial activities that are governed by multiple factors, some of which may be mutually exclusive. Consequently, some level of optimization is an inherent part of determining whether recycle and reuse practices could be applied on a larger scale in particular case or at particular facility in the nuclear industry. The economic advantages, coupled with reduced environmental impact and consideration of full cycle benefits, could provide a sound incentive to recycle and reuse.

2.2.3. Regulated disposal or transfer

Radioactive waste which cannot be cleared from regulation, released for authorized use or discharged under authorized limits should be disposed of in a licensed facility (repository) specifically designed for this purpose. The general aim in the management of radioactive waste is to reduce the associated risks to as low as practicable and justifiable, by appropriate processing, containment and eventual disposal. The generally preferred approach for this is to concentrate waste and contain the radionuclides in it by means of a suitable waste form and waste container, and then dispose of the container in an appropriate repository designed to provide isolation from the biosphere. The effectiveness and safe isolation of radioactive waste depends on the performance of the overall disposal system, which consists of three major components:

- The site (the host rock and surrounding geological media representing natural barriers aiding waste isolation);
- The repository (the facility into which waste packages are emplaced for disposal, including any engineered barriers); and

— The waste package (the waste form in any suitable container).

The design of a waste disposal facility should consider all of the components of the system, including interactions between its parts; it can be optimized only on a site specific and disposal concept specific basis. Therefore the matching of waste types to the disposal system in order to ensure isolation of the waste from the biosphere is based on a number of complex, interrelated issues. The conditioning of the waste and the preparation of the waste package, together with the other components of the disposal system, provide the appropriate degree of protection and isolation. Only waste packages which comply with 'waste acceptance criteria' (WAC) are accepted for disposal [4]. WAC comprise a key component of the assemblage of limits, controls and conditions to be applied by the operator. Consequently, WAC are usually used to ensure that the wastes are compatible with all stages of waste management through the imposition of a series of technical and management controls. WAC are a safety component of the facility design and can therefore change as a result of internal safety reviews and regulatory scrutiny.

Instead of regulated disposal, some radioactive materials may be transferred for reuse or recycling within another regulated practice. An example of such transfer is the regulated transfer of some disused sealed radioactive sources from one organization to another, where the sources are utilized within a separate regulated practice. Such transfer cannot be done without proper assurance of the safety of further use of the materials.

The relationships between materials clearance, authorized discharge or use and regulated disposal or transfer are illustrated in Table 1. The first line of the table represents a region where materials may be cleared from regulatory control because exposures are estimated to be too small to require regulation. The second and third lines line of the Table represents the region where regulatory control of materials should be retained because the risks arising from the lack of control are regarded as unacceptable.

TABLE 1. Options for radioactive materials routeing (e.g. radioactive waste road map)

Useful radioactive materials (materials that can be used and/or recycled)	**Radioactive waste (materials with no further use foreseen)**
Clearance allowing unrestricted use and/or recycling	Clearance allowing to treat materials as normal refuse or effluent
Authorised use	Authorised discharge
Regulated transfer to another practice	Regulated storage and/or disposal

3. WASTE CHARATERISTICS

There is great diversity in the types and amounts of radioactive waste in different countries. Technologies for implementing waste management are also diverse, although the main technological approaches are likely to be similar everywhere. Adequate waste management processes and technologies can be identified based on detailed information available or expected about waste classification, categorization, properties and inventory.

3.1. WASTE CLASSIFICATION

The IAEA classifies radioactive waste into six categories according to the activity and half-life of radionuclides [15]:

- Exempt waste (EW);
- Very short lived waste (VSLW);
- Very low level waste (VLLW);
- Low level waste (LLW);
- Intermediate level waste (ILW);
- High level waste (HLW).

VSLW refers to radioactive waste which can be stored for decay over a limited period (no longer than a few years) before clearance from regulatory control. Clearance takes place according to existing national arrangements, after which VSLW can be disposed of, discharged or used. VSLW includes waste containing primarily radionuclides with very short half-lives, which are most often used for research and medicine.

VLLW is radioactive waste which does not necessarily meet the criteria of EW but does not need a high level of containment and isolation and therefore is suitable for disposal in near surface landfill type facilities with limited regulatory control. Typical VLLW includes soil and rubble with low levels of activity concentration.

LLW has higher activity contents compared VLLW but contains limited amounts of long lived radionuclides. Such waste requires robust isolation and containment for up to a few hundred years but is suitable for disposal in engineered near surface facilities. LLW covers a broad range of waste, including long lived radionuclides when levels of activity concentration are relatively low. ILW is that radioactive waste that requires a greater degree of containment and isolation than that provided by near surface disposal due to radionuclide content (including long lived radionuclides), but requires little or no provision for heat dissipation during its storage and disposal. ILW may contain long lived radionuclides, including alpha emitting radionuclides which will not decay to a level of activity concentration acceptable for near surface disposal during the time for which institutional controls can be relied upon. Therefore ILW requires disposal at greater depths, of the order of tens of metres to a few hundred metres. A precise boundary between LLW and ILW cannot be universally provided, as limits on the acceptable level of activity concentration will differ between individual radionuclides or groups of radionuclides. WAC for a particular near surface disposal facility depend on the actual design and operation plans for the facility (e.g. engineered barriers, duration of institutional control, site specific factors). Many States have adopted a limit of long lived alpha emitting radionuclides, typically around 400 Bq/g (and up to 4000 Bq/g for individual packages). For long lived beta and/or gamma emitting radionuclides such as ^{14}C, ^{36}Cl, ^{63}Ni, ^{93}Zr, ^{94}Nb, ^{99}Tc and ^{129}I, the allowable average activity concentrations may be considerably higher (up to tens of kBq/g) and may be specific to the site and disposal facility [16].

HLW is radioactive waste with high levels of activity concentration that requires shielding in handling operations and generates significant quantities of heat by the radioactive decay process. HLW can contain large amounts of long lived radionuclides that need to be considered in the design of a disposal facility. Disposal in deep, stable geological formations – usually several hundred metres or more below the surface – is generally recognized as the preferred long term option for HLW.

The IAEA classification is based primarily on long term safety and therefore is oriented to the most appropriate disposal routes (end points) for solid or solidified waste.

3.2. WASTE CATEGORIZATION

Classifying wastes based solely on radioactivity and half-life is plausible, but this approach has to be complemented with additional information on the waste properties relevant for activities performed in various predisposal waste management steps. A more consistent and effective approach to waste processing and storage will take into account information such as origin, physical state, types, properties and process options.

3.2.1. Origin related categories

Radioactive waste is produced from a range of activities resulting in waste streams varying by form, activity, physical state, etc. The sources of radioactive waste are often termed ‘point of origin,’ which may include:

(a) The nuclear fuel cycle, including the refining and conversion of uranium concentrates (yellow cake), enrichment, fuel fabrication, and fuel reprocessing;

(b) Operation of nuclear power reactors;

(c) Support facilities, such as laboratories, research and development facilities, hot cells, maintenance and repair facilities and other specialized facilities;

(d) Production and various applications of radionuclides in commercial research, industry, education and medicine;

(e) Operation of and activities related to research reactors;

(f) NORM (or TENORM) waste generated from industrial applications, such as mineral extraction or oil and gas drilling including uranium milling and mining.

Additional detail related to the above waste generating activities is available in many IAEA and industry oriented publications. Categorization of a waste stream based on its point of origin provides valuable insights related to expected waste stream properties. This can reduce the burden associated with subsequent characterization analyses, processes, classification and disposition.

3.2.2. Physical state related categories

Radioactive waste can be first categorized into three generic groups according to their physical and chemical properties:

- Solid waste (sub categories: wet, dry);

- Liquid waste (subcategories: aqueous, organic);
- Gaseous waste (including airborne effluents).

Each waste category may consist of material contaminated by or containing radionuclides, which are differentiated by activity (α-emitters, β/γ-emitters, fissile materials), half-life, and by their different physical (e.g. wet or dry), chemical (e.g. organic or inorganic) and biological properties. Management step related categories

Waste categories are most often related to the actual management steps, such as the processing, storage and disposal technologies used. Examples of management-related categories of waste include:

Process related waste categories

- Combustible waste – paper, plastic, wood, organics;
- Non-combustible waste such as construction materials and bulk metallic items;
- Compactable waste – compressible materials, including solid combustibles and light metals (e.g. aluminium);
- Non-compactable – metals, concrete, glass.

Storage/disposal related waste categories

- Unstable – biological, non-solidified bulk waste, such as soil, rubble, and combustible and compactable wastes which are not solidified (grouted);
- Stable or stabilized – solidified, encapsulated or waste which has been placed in a container which is inherently stable (e.g. a high integrity container).

3.3. WASTE PROPERTIES

Waste properties influence the choice of process or technology that is required for:

- Pretreatment and treatment;
- Conditioning for storage;
- Interim storage;
- Conditioning for disposal;
- Packaging for transport or disposal;
- Direct disposal;
- Discharge to the environment;
- Clearance.

This section presents a summary of the properties of unconditioned (raw, pretreated and treated) waste and conditioned waste (waste forms and waste packages) that need to be taken into account during the entire waste management process.

3.3.1. Unconditioned waste properties

The three groups of unconditioned waste properties (radiological, physical-chemical and biological) and their roles/significance in the waste management process are illustrated in Table 2 below.

TABLE 2. PRIMARY WASTE PROPERTIES

	Property	**Role/Significance of the property**
Radiological properties	– Total activity and activity concentration – Radionuclide composition (type of radiation, half-life) – Fissile mass – Thermal power – Surface dose rate – Type of contamination (fixed, non-fixed) – Origin of the activity (contamination or activation)	– To segregate the waste with regard to processing and disposal options – Avoid mixing streams with different isotopic content or distribution. – Select processing techniques, technologies and equipment design. – Prevent criticality. – Design storage or disposal facility o Optimizing radiological protection, design of shielding, etc. – Optimize characterization methods – Define handling (transfer) and transport considerations.
Physical and Chemical properties	– Physical state – Volume, mass and dimensions of waste items – Density – Volatility – Chemical composition – Combustibility and thermal resistance – Chemical compatibility – Ignitability, pyrophoricity – Gas generation – Acidity/alkalinity (pH) – Toxicity	– To define a treatment method according to the physical state (solid, liquid, gaseous) A categorization of unconditioned waste based on the physical and chemical properties provides a tool to define: o Waste processing techniques o Operational processing parameters. o Waste handling, transfer and transport packages, containers, shields. ▪ Dimensions, weight, materials, etc. o Handling (transfer) and transport considerations. ▪ Solid to liquid content ratio ▪ Thermal enhancement to maintain solubility ▪ Radiological and occupational safety o Waste stream compatibility considerations o Waste treatment equipment designs ▪ Compatibility between waste and processing equipment construction materials. ▪ Capacity, etc.
Biological properties	– Putrescability – Infectious/pathogenic	– To control and eliminate infectious hazards – To control and prevent degradation of organic material

3.3.2. Properties of waste forms and waste packages

The two groups of conditioned waste properties (radiological and physical-chemical) and their roles/significance in the waste management process are illustrated in the Table 3 below. Since the waste is conditioned biological properties are excluded.

TABLE 3. WASTE FORM AND WASTE PACKAGES PROPERTIES

	Property	**Role/Significance of the property**
Radiological properties	– Total activity – Radionuclide composition – Surface dose rate – Surface contamination – Thermal power – Radiation stability – Fissile content	– To comply with licensing limits of a disposal facility – To meet transport regulations Optimize final waste form activity determination methods. – Dimension, density, shape, etc. should support efficient determination process: o Define handling conditions. o Select appropriate conditioning and packaging technologies. o Minimize waste generation (including secondary waste). o Design the facility for either long term storage or disposal. ▪ Optimizing radiological protection, design of shielding, etc. o To prevent inadvertent criticality
Physical and chemical properties	– Mass and weight – Structural and dimensional stability – Permeability and porosity – Density – Voidage – Mechanical Strength/ Load Resistance – Impact resistance – Homogeneity – Chemical stability (leachability) – Chemical composition – Corrosivity – Explosiveness – Gas generation – Toxicity – Fire resistance	– To maintain the physical integrity of the waste form and/or package, during handling, transportation, storage and disposal – To prevent deformation or cracking of the waste forms and packages A categorization of conditioned waste based on the physical and chemical properties is an adequate tool to define: o Waste conditioning techniques, technologies and equipment design. o Operational processing parameters. o Waste form and package compatibility. o Waste packages. o Dimensions, weight, materials, etc. o Handling and transport conditions. o Compatibility between waste form and WAC. o Chemical, thermal, structural, mechanical and radiation stability. – To prevent the dispersion of long lived radionuclides in the repository – To undertake special measures to preclude ignition during transportation and storage

The properties of unconditioned and conditioned waste together with their role/significance in assessment of technical options for the entire waste management process are provided in more detail in Annex 1.

3.3.3. Properties of NORM

Waste which contains naturally occurring radioactive materials is known as ‘NORM waste.’ It occurs as a by-product, residue or waste from activities such as mining and processing of uranium, extraction of rare earth elements, production and use of thorium and its compounds, mining of ores other than uranium ore, production of oil and gas, and from the phosphate industry.

NORM typically contains radionuclides of the uranium and thorium decay chains and is characterized by very large volumes, especially from uranium milling and mining. NORM often contains other toxic substances such as heavy metals, and for this reason, both radiological and non-radiological aspects have to be taken into account for its management. In some countries, NORM is regulated as a radioactive waste and in others as a chemically toxic waste.

3.3.4. Properties of disused sealed radioactive sources

Sealed radioactive sources (SRS) are widely available and are used extensively in a broad range of applications including medical, industrial and research and education. They are generally small (typically a few centimetres in size) and the radionuclides are typically enclosed in capsules made, with very few exceptions, of stainless steel, titanium, platinum or other inert metals. Source capsules are airtight and durable. The radionuclides may also be closely bonded to a substratum. The recommended useful life of most sealed sources is 5–15 years, but they represent a potential radiation hazard long after the devices containing them have been decommissioned.

In most cases the source capsule will be undamaged at the time it is collected as disused sealed radioactive sources (DSRS) for long term storage or disposal. However, DSRS integrity either before or after collection cannot be taken for granted, nor can the longevity of the source capsule be guaranteed after disposal.

Source activity levels vary over a considerable range from low activity to very highly active, with half-lives varying from some days to thousands of years (see Fig. 2 from [16]).

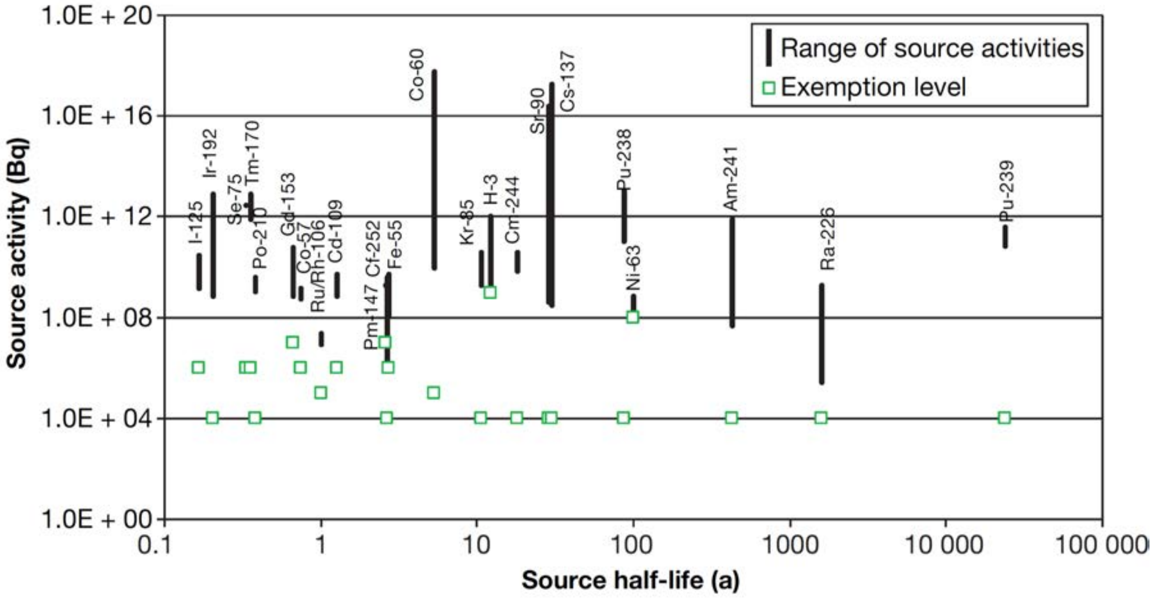


FIG. 2. Radionuclides, half-lives and typical activity levels of SRS (from [16])

3.4. WASTE INVENTORIES

An inventory providing information on current and future quantities and characteristics of the radioactive waste to be managed is required to prepare the waste management policy and strategy(ies). Depending on the needs, several levels of detail on inventory may be required. For example, a waste processor requires a detailed inventory that will suggest management methods for each waste type. National waste management agencies only require sufficient detail to formulate future plans. Policy makers and developers of a national waste management strategy require a more generic inventory.

The waste to be considered in the inventory may include:

- Radioactive waste from all sources identified in the Member State;
- Radioactive materials and other radioactive substances that are not currently classified as waste (but which may become waste in the future);

— Radioactive waste that existed at a given date (i.e. stock date) on the territory (i.e. stock or current inventory);

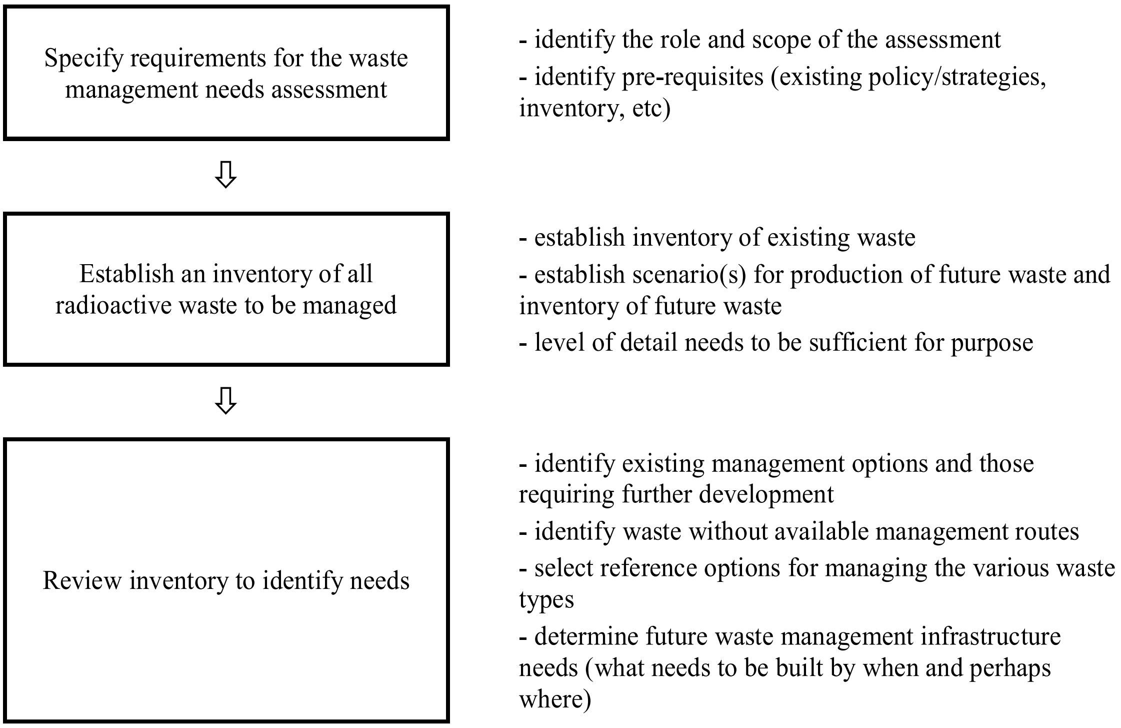
— Radioactive waste that is forecast to arise on the territory beyond the stock date (i.e. future or forecast arising);

— Radioactive waste that has already been disposed of as of the stock date;

— Radioactive substances, which are temporarily managed in another Member State or vice versa.

The waste inventory comprises data on the waste status (stock of future waste, unconditioned or conditioned), waste classes, categories, types and properties. The data on quantities of waste (e.g. volume, mass or number of waste packages and arising schedules) are also required. The level of detail depends on the purpose for which inventory is needed.

The basic steps in preparing an inventory and assessing the resulting waste management needs are summarized in Fig. 3.



- identify the role and scope of the assessment
- identify pre-requisites (existing policy/strategies, inventory, etc)

- establish inventory of existing waste
- establish scenario(s) for production of future waste and inventory of future waste
- level of detail needs to be sufficient for purpose

- identify existing management options and those requiring further development
- identify waste without available management routes
- select reference options for managing the various waste types
- determine future waste management infrastructure needs (what needs to be built by when and perhaps where)

FIG. 3. Basic process for determination of waste management needs.

3.5. NUCLEAR ACTIVITIES AND WASTE GENERATION CLASSIFICATION

Since the use of radioactive materials and technologies varies greatly among all IAEA Member States, Ref. [1] classifies radioactive waste generation into five cases or levels (Table 4):

TABLE 4. GENERATION CASES FOR MEMBER STATES WITH RESPECT TO THEIR RADIOACTIVE WASTE

Waste Generation Case (Level)	Typical nuclear activities in Member States
Case A	Radioactive waste is generated from nuclear power plants, front end and back end fuel cycle facilities, wide use of nuclear R&D facilities, and extensive nuclear applications in industry and medicine.
Case B	Radioactive waste is generated from nuclear power plants, wide use of nuclear R&D facilities, and extensive nuclear applications in industry and medicine. No fuel cycle facilities.
Case C	Radioactive waste is generated from limited use of nuclear R&D facilities, research reactor, limited use of nuclear applications in industry and medicine. No nuclear power plants, no fuel cycle facilities.
Case D	Radioactive waste is generated from limited use of nuclear applications in industry and medicine. No reactors, no fuel cycle facilities, no nuclear R&D.
Case E	Only NORM waste is generated from limited industrial applications, such as mineral extraction or oil and gas drilling.

Case A Member States operate nuclear power plants as well as nuclear fuel cycle facilities, including those that may reprocess spent fuel. The major steps generating radioactive waste in the uranium fuel cycle are:

— *Mining and milling:* Waste results from the production of uranium. It contains low concentrations of uranium and is contaminated principally by its daughter products thorium, radium and radon.

— *Fuel supply*: Waste may result from purification, conversion and enrichment of uranium and the fabrication of fuel elements. It includes contaminated trapping materials from off-gas systems, lightly contaminated trash and residues from recycle or recovery operations. This radioactive waste generally contains uranium, but in the case of mixed oxide fuel, also plutonium.

— Spent fuel reprocessing: Spent fuel from reactor operations contains uranium, fission products and actinides. It generates significant heat when freshly removed from the reactor. Spent fuel is either considered a waste or waste is generated from reprocessing operations. Reprocessing operations generate solid, liquid and gaseous radioactive waste streams. Solid radioactive waste such as fuel element cladding hulls, fuel assembly components, hardware and other insoluble residues are generated during fuel dissolution. They may contain activation products, as well as some undissolved fission products, uranium and plutonium. The principal liquid radioactive waste stream, however, is the nitric acid solution, which contains both high activity fission products and actinides in high concentrations. Liquid waste includes sludges and concentrates from the treatment of liquid effluents, and concentrates from solvent washing and acid recovery, including aqueous and organic liquids. Gaseous fission product waste may be generated in the fuel dissolution process.

- **Case B** Member States have all of the capabilities listed for Case C Member States but also generate waste from nuclear power operations. Liquid waste arises from contaminated coolant water, water cleanup systems, fuel storage pool water, equipment drains, floor drains and laundry waste. Wet solid waste with high water content arises from treatment processes such as filtration, evaporation, chemical precipitation and ion exchange. These processes result in the production of sludges, spent ion exchange resins and evaporator concentrates.
- Contaminated oil and liquids containing organic material may arise from the decontamination, repair and maintenance of facilities and equipment.
- Solid waste generated in routine reactor operations may include contaminated clothing, floor sweepings, plastic, paper and gas trapping devices, filters and discarded components. Both combustible and non-combustible solid waste is generated.
- Gaseous waste sources vary according to reactor type. They may include gases removed from the coolant through degasification and venting systems or air ejectors, and coolant discharges and leakages. In addition, all types of reactor produce activated and contaminated ventilation air and noble gases.
- **Case C** Member States practice all the activities of Case D countries, and in addition have nuclear research reactors or particle accelerators in operation for basic research and/or radionuclide production.
- The size and thermal power of nuclear reactors used for research purposes varies from small critical or sub-critical assemblies to powerful reactors designed for production of radioisotopes and testing of construction materials. The quantity and characteristics of reactor operational waste depend significantly on the reactor power, but the radionuclide inventory and waste composition are generally uniform for a particular facility. The total activity of waste may be high. The main radionuclides in the waste are fission and activation products. Contamination with long lived alpha radionuclides may appear in the case of fuel element leakage. Radioactive waste comprises aqueous effluents (decontamination solutions, laboratory drains, washing water); organic effluents (oils, solvents); ion exchange resins (from cleaning of the reactor coolant and of water from the fuel storage pond); compactable solid waste (paper, plastics, gloves, protective clothing, filters); and non-compactable solid waste (large activated metallic items).
- The use of particle accelerators may lead to the activation of some construction materials or parts by high energy particles. Radioactive waste may be generated during the removal or replacement of activated parts of the accelerator. Some accelerator based neutron generators use large tritium targets, which are the origin of tritium contaminated waste.
- Nuclear research activities of such countries include a broad variety of methods and facilities (hot cells, pilot plant reprocessing facilities, maintenance and repair facilities, post-irradiation examination facilities, etc.), resulting in generation of different categories of radioactive waste, which depend strongly on the problems studied. The radionuclide inventory is also rather variable as research involves different radioisotopes with a variety of activity and concentrations. There is no ‘typical’ waste from these facilities and activities; the waste is diverse and variable. The waste types may include all kinds of liquid, solid, gaseous waste and spent nuclear fuel depending on the particular programme.

- **Case D** Member States use radioactive materials in a number of applications for medical, industrial, agricultural and research purposes, including both short lived and long lived ones radionuclides. Waste in Case D Member States may include: aqueous effluents (decontamination, washing and spent radioisotope solutions); organic liquids (scintillation cocktails, residues from organic synthesis, unused radiopharmaceuticals); compactable solid waste (laboratory dry and wet wastes); gaseous waste (from lung ventilation diagnosis); DSRS; spent radionuclide generators; carcasses; and biological materials.
- **Case E** represents Member States without nuclear activities in which only NORM waste is generated.

3.6. ASSESSING WASTE GENERATION RATES

The quantity and type of waste generated in each Member State will depend on the type of activity and the scope of their commitment to the use of radionuclides and generation of nuclear power. A rough estimation of some typical waste generated by nuclear applications is shown in Table 5 [17, 18]. The amounts of waste generated are not necessarily linked to a number of research reactors in the country, but rather relate to the size of its population (in case of nuclear applications) and to the general level of its development (a number of hospitals, research centres, industrial enterprises, etc.).

TABLE 5. TYPICAL ANNUAL WASTE GENERATION RATES FROM HOSPITALS, INDUSTRIES AND RESEARCH

Waste types	**Case A countries**	**Case B countries**	**Case C countries**	**Case D countries**
Spent sealed sources	>1000	50–1000	20–100	10–50
Scintillation liquids (litres)	50–1000	50–200	20–50	10–20
Solid compactable waste (m^3)	>1000	>1000	50–100	1–3
Solid non-compactable waste (m^3)	100	2–20	1–3	-
Aqueous waste including decontamination waste	>100 m^3	300–1000 m^3	2–200 m^3	1–2 m^3
Organic liquid waste including: oils, lubricants, extraction agents, solvents	10–100 m^3	1–10 m^3	0.1–1 m^3	10–20 L
Biological material (m^3)	1–10	0.1–5	0.1–0.5	-
Spent ion exchange resins (m^3)	1–10	0.5–3.0	0.5–1.0	-
Spent fuel elements (total after 8–10 years)	0.5–10 m^3	0.5–2 m^3	0.5–1 m^3	-

Table 6 shows typical waste generation rates of nuclear fuel cycle facilities applicable for Case A and Case B countries. The table below indicates average annual waste quantities as normalized values, the basis being needs (fuel) and outputs (waste) of a NPP with 1 GW(e) installed capacity.

TABLE 6. TYPICAL ANNUAL WASTE GENERATION RATES FROM THE NUCLEAR FUEL CYCLE

Stage	Waste type	Quantity m^3/GW·a
FRONT END		
– UF_6 conversion	Liquids, solids	50
– UF_6 enrichment	Gaseous, liquids, solids	25
– UO_2 fabrication	Liquids, solids	75
– MOX fabrication		
o Liquids:		
▪ suspect		0.64
▪ contaminated		5
NUCLEAR POWER PLANT OPERATION		
– Evaporator concentrates	Liquids	50
– Filter sludges	Liquids	10
– Ion exchange resins	Solids	2
– Decontamination concentrates	Liquids, solids	10
– Absorber rods, neutron sources, etc.	Solids	0.1
– Others	Solids	260
BACK END		
Reprocessing		
– Hulls/hardware	Solids	15
– Feed sludge	Solids	0.02
– Tritium containing effluents	Liquids	70
– HLW	Liquids	28
– ILW	Liquids	25
– LLW	Liquids	15
	Solids	65
Once through		
– Fuel assemblies (t/U)	Solids	30
Decommissioning of fuel cycle facilities (conditioned waste)		
– UF_6 conversion	Solids	0.5–1
– UF_6 enrichment	Solids	5
– UO_2 fabrication	Solids	1–2
– Power plant	Solids	375
– Reprocessing	Solids	5

While selecting a waste management technology, historic waste, operational waste and future waste generation rates should be assessed, including expected properties. The future usage of equipment and facilities will influence the selection of an appropriate technology. It might, for example, be appropriate to construct temporary facilities or hire services to manage existing waste. This might be complemented at a later date by more permanent facilities to manage future waste streams. Alternatively, a modular waste management facility might be required. Simple modular designs can be readily expanded to accommodate new equipment and processes or simply to increase capacity of an existing process or a waste store.

4. TECHNOLOGICAL OPTIONS

Waste management is typically divided into predisposal and disposal steps. Predisposal comprises all the steps in the management of radioactive waste from its generation up to disposal, including processing (e.g. pretreatment, treatment and conditioning), storage and transport. Disposal envisages emplacement of waste in an appropriate facility without the intention of retrieval. Radioactive waste is prepared for disposal by processing technologies, which may include pretreatment, treatment and conditioning primarily intended to produce a waste form that is compatible with the selected or anticipated disposal option. For evaluation of a particular process or technology it is necessary to review the available options to meet waste processing, storage and disposal requirements.

4.1. TYPICAL WASTE MANAGEMENT STEPS

The life cycle of radioactive waste consists of a number of steps such as pretreatment, treatment, conditioning, storage and transport and disposal. Predisposal management encompasses all of these steps that collectively cover the activities from waste generation up to disposal. Characterization of waste is also an essential predisposal activity that is common to all of the steps above.

Pretreatment includes any operations prior to waste treatment, to allow selection of technologies that will be further used in processing of waste (treatment and conditioning), such as:

- Collection;
- Segregation;
- Decontamination;
- Chemical adjustment.

Treatment of radioactive waste includes those operations intended to improve safety or economy by changing the characteristics of the radioactive waste. The basic objectives of treatment are:

- Volume reduction;
- Radionuclide removal from waste;
- Change of physical and chemical composition.

Conditioning covers those operations that produce a waste package suitable for handling, transportation, storage and/or disposal. It may include:

- Immobilization of the waste;
- Enclosure of the waste in containers;
- Provision of an overpack.

Immobilization refers to the conversion of waste into a waste form by solidification, embedding or encapsulation. Common immobilization matrices include cement, bitumen and glass.

Storage of radioactive waste involves maintaining the radioactive waste such that retrievability is ensured and confinement, isolation, environmental protection and monitoring are provided during storage period.

Radioactive waste may be stored as raw, pretreated, treated or conditioned waste. The purpose and duration of storage depend on policy decisions, which could be to host decaying waste until it is safe for authorized discharge or eventual clearance, or until a future decision on further processing and/or disposal.

Transportation refers to the deliberate physical movement of radioactive waste in specially designed packages from one place to another. For example, raw waste may be transported from its collection point to centralized storage or processing facility. Conditioned waste packages maybe transported from processing or storage facilities to disposal facilities.

The most common modes of transport include the use of trucks, tankers, trains and barges. To protect people, property and the environment, transport is carried out in special packages to and from nuclear facilities in accordance with internationally accepted regulations. Disposal envisages final emplacement of waste in an appropriate facility without the intention of retrieval. Some Member States consider controlled discharge of effluents to the environment to be a regulated disposal option.

Characterization of radioactive waste is an important aspect at every stage of waste management. The physical, chemical and radiological properties of the waste should be characterized in order to establish the need for further adjustment, treatment, conditioning, or its suitability for further handling, processing, storage and disposal.

The main waste management steps are illustrated in Fig. 4. To achieve the overall goal of safe waste management, component steps should be complementary and compatible with each other; no step should preclude or compromise subsequent waste management steps.

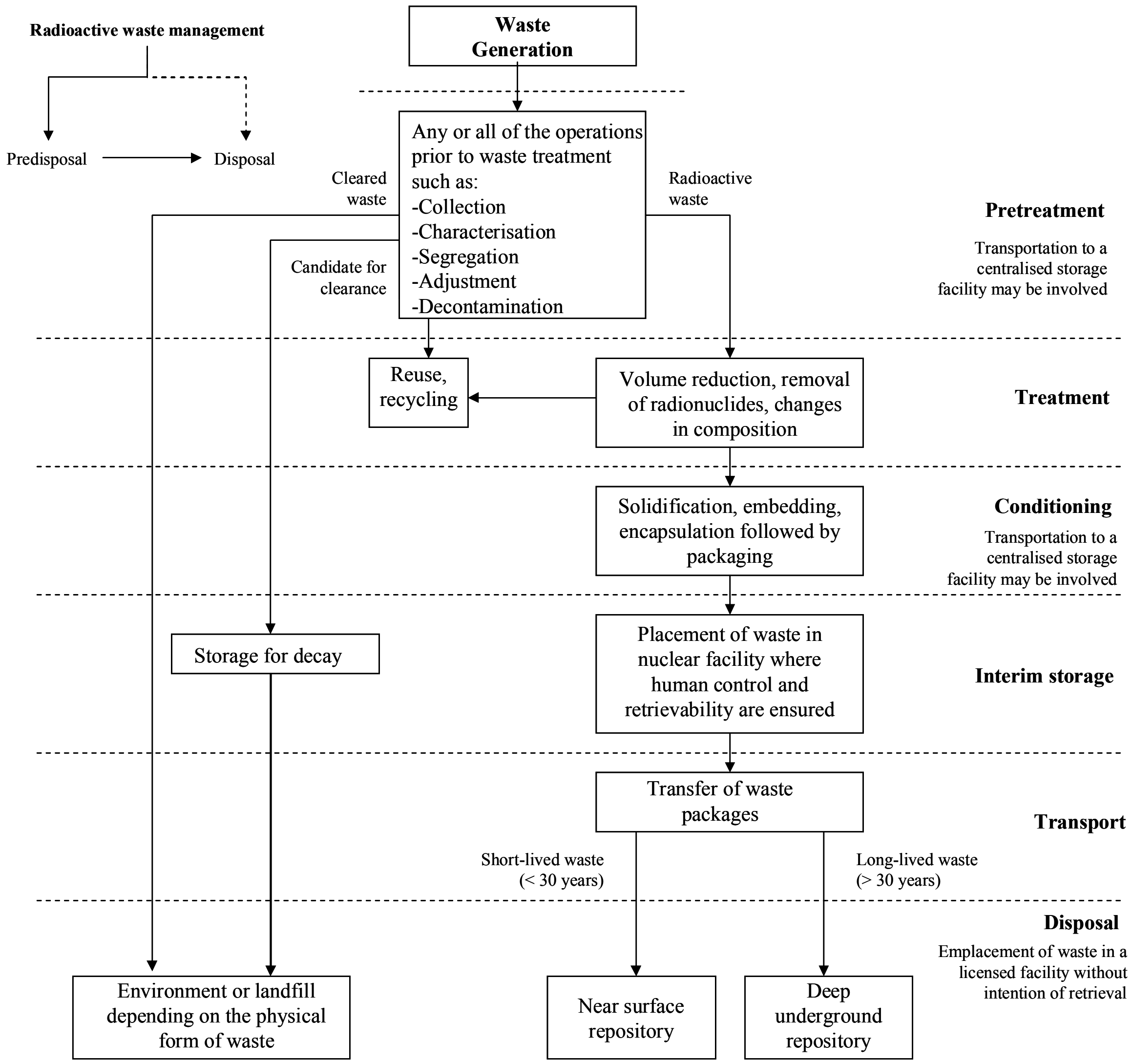


FIG. 4. Typical waste management steps.

4.2. PRETREATMENT

Waste pretreatment is the initial step in waste management that occurs after waste generation. It may consist of collection, segregation, decontamination and chemical adjustment. Pretreatment activities should be carried out so as to minimize the amount of radioactive waste to be further treated, stored and disposed of.

4.2.1. Collection

Collection involves the receipt of the waste from the waste generating processes.

Solid radioactive waste is collected in appropriate containers (boxes, bins, drums, bags and etc.) to comply with transport regulations [19] (if off site transportation is involved), handling requirements, acceptance criteria or waste specifications for further waste processing, and general occupational radiation protection standards.

Combustible low level solid waste is usually collected at the point of origin in transparent plastic bags. Non-combustible small size low and intermediate level waste (LILW) are usually collected as compactable or non-compactable materials in metal, cardboard boxes and metal drums.

Liquid waste is collected in bottles and tanks of different volumes, which are made of different materials depending on their chemical properties. Organic liquid waste should be collected and kept separate from aqueous waste streams.

When collecting biohazardous radioactive waste, it is necessary to consider that the biohazardous waste may arise in a liquid or solid form and also as damp or wet materials [20]. Deep freezing of animal carcasses or similar types of waste is often used to allow convenient collection and storage, although simpler approaches could be pursued (adsorbents, chemical agents). Carcasses are packed in plastic bags before freezing.

Collection of solid waste involves use of variety of very simple technical methods that can significantly improve further waste management steps or minimization of the waste at the point of origin. However, there are no particular technologies that could be identified as preferred technical option for collection of solids. Collection of liquids may involve transferring of waste into collections tanks prior processing by either pumping or tankering from the point of origin. A HLW collection system could be technically complex.

4.2.2. Segregation

Collection of waste is typically followed by segregation, e.g. separation of compactable and non-compactable materials, or separation of long lived and short lived waste, etc. [21]. The main objectives of segregation are to:

— Segregate waste into active and non-active streams in order to reduce the volume of radioactive waste to be processed and ultimately disposed of;

— Separate an active waste stream into groups or types so these groups or types may be easily treated, conditioned, and packaged for storage and/or disposal;

— Recover products for reuse or recycling.

In general the efficiency or applicability of further waste processing should be considered in the selection of proper segregation strategies. Other considerations include whether regulatory control can be removed from the waste (likely clean) and whether it can be recycled or discharged, either directly or after allowing for a decay period or after some other pretreatment/treatment methods.

Mixing liquid waste streams should be limited to those streams that are radiologically and chemically compatible. If the mixing of chemically different waste streams is considered, then all possible consequences need to be taken into account.

Technical options for segregation vary from manual sorting to sophisticated sorting lines that may involve sorting boxes or hot cells with remote handling techniques and tools. In cases of large volumes of solid waste, technical methods involving air classifiers for plastic, use of magnets for separation of magnetic materials, or shredders for defragmentation might be considered, similar to techniques used for municipal solid waste.

4.2.3. Up front waste characterization

As part of the pretreatment stage, up front characterization is essential for the selection of the most efficient treatment process.

To the extent possible, liquid and solid waste should be characterized on the basis of its radiological, physical, chemical and pathogenic properties in order to facilitate collection and segregation. With proper characterization it may be possible to clear the waste or discharge it within authorized limits, provided that the non-radiological characteristics of the waste are appropriate.

It should be noted that up front characterization requires consistency and representative samples. Because there is a risk of significant exposure, there is a need for better and faster non-destructive inspection methods.

Methods of radioactive waste characterization and the methodology of characterization, including sampling procedures, are described in detail in Refs. [22–24].

4.2.4. Decontamination

Decontamination techniques are often applied during pretreatment of solid material to reduce volume of waste [25]. The primary targets are metallic waste and concrete.

The volume of solid radioactive waste requiring storage and disposal in licensed disposal facilities can be reduced by properly arranging decontamination (the removal of contamination from the surfaces). Different decontamination techniques [25] can reduce the volume of solid waste by clearing some of the solid materials, however, the generation of secondary waste and its subsequent treatment needs to be considered. Some decontamination techniques with their advantages and limitations are summarized in Table 7.

TABLE 7. FEATURES OF DECONTAMINATION METHODS

Decontamination methods		**Features**	**Limitations**	**Secondary waste**
Mechanical methods	Swabbing, washing, scrubbing, brushing	Proven methods for Pipeline systems and Concrete surfaces Easy to handle Low cost	Slow process High secondary waste production	Dust and airborne waste Wastewater, abrasive and removed debris
	Vibratory cleaning	Proven technology for Large flat surfaces Low cost	Local ventilation needed Generates relatively large amount of secondary waste	Removed debris
	Vacuum cleaning	Proven method for flat surfaces Low cost Generates small amount of secondary waste	Applicable only for some types of contamination (contamination of glove boxes and cells)	Contaminated dust and filters
	Water and steam jets	Proven methods for Concave surfaces such as pipe and Concrete surfaces Low cost Remotely operation	In case of high pressure jetting, risk of surface quality degradation	Wastewater, removed debris
	Blasting	Common industrial technique High efficiency Quick surface abrasion Possibility of recycling the abrasive materials	Risk of surface recontamination by contaminated abrasive Possibility of a large amount of secondary waste	Wastewater, abrasive and removed debris

Decontamination methods		Features	Limitations	Secondary waste
Chemical methods	By chemical gels	Suitable for large surfaces Small amount of applied chemicals High efficiency of activity removal Suitable for intervention within plants	Significant amounts of secondary waste Corrosive and toxic reagents may need to be handled in order to obtain high DFs Not usually effective on porous surfaces	Organic or mineral components
	By foams (spraying, sprinkling, filling with foam)	Suitable for large surfaces and items of excessive weight Improve the contact between surface and chemicals Short lifespan (15–30 min) Low secondary waste production if reagent is reused When employing strong mineral acids DF greater than 100 can be achieved	Spraying requires direct operator intervention and cannot be used for closed volumes (vessels, cavities) Higher exposure of workers	Toxic or corrosive solutions or gases
Decontamination of surfaces by electrochemical methods (electropolishing)		High decontamination factor for pipes and metallic components Easy process control Adaptability to removing localized contamination Small amount of secondary waste	Difficulties with treatment of secondary waste High cost Need of well trained staff Applicable only for metallic objects Slow process Not applicable to complex or inaccessible surfaces	Hydrogen and contaminated acidic aerosols Iron phosphate sludge
Decontamination of surfaces by ultrasonic cleaning		Ultrasonic agitation makes chemical decontamination more effective for pipes Good for small reusable pieces of equipment and precision components.	Requires careful specification of all variables such as power input, frequency, shape of vessel, size and location of emitters	Removed debris
Thermochemical decontamination		Applied to surface contaminated metals, concrete and asphalt	Requires specially designed powder metal fuels. Can be used on horizontal surfaces only.	Slag containing the bulk of contamination

The optimum decontamination outcome is to reduce contamination of materials below a level of concern, or to levels that allow reuse. Very early in the process of selecting decontamination technologies it is important to perform a cost–benefit analysis to establish whether it is worthwhile decontaminating the components or parts, or to determine whether a mild decontamination at low cost is more advantageous than an aggressive decontamination at a higher cost. This analysis is usually accompanied by extensive experimental work conducted on selected samples from the facility, with a view to characterize before selection of a decontamination technique. The decision on whether to proceed with decontamination and the selection of the final process will depend on the best balance of all factors with respect to established general criteria (in terms of cost, time, safety, etc.).

Efficient techniques for decontamination of metals exist, but some make use of chemicals which may cause new problems in processing of such waste (e.g. chemical complexing agents or an organic solvent). A facility capable of treating secondary waste from decontamination may be required. The concentrated waste, representing a more significant radiation source, should be solidified and shipped for disposal in licensed disposal facilities unless properly treated within the waste reduction/recycling/reclamation processing alternative. The optimal waste reduction configuration should be defined after an economic assessment of treatment versus transportation/disposal costs has been completed. Each of these additional activities could increase occupational exposure rates, the potential for a release, or the uptake of radioactive material.

Such circumstances could conceivably result in higher doses than those received from removing, packaging and shipping the contaminated system without having performed extensive decontamination. Resolution of this question depends on specific facts, such as the exposure rate of the gamma emitting contamination, the level of the contamination, and the effectiveness of the containing component and piping (wall thickness) in reducing work area radiation fields.

In many cases, decontamination is not sufficiently effective as to allow unconditional release of the item without further treatment after dismantling. Therefore savings – both in occupational exposure and in cost – could be realized by simply removing the contaminated system and its components and performing only certain packaging activities (e.g. welding end caps onto pipe sections) with materials removed. However, the additional cost of materials disposal should be weighed in this scenario.

4.2.5. Chemical adjustment and fragmentation

Although in practice pretreatment and treatment processes are not strictly separated, chemical adjustment – for example, changing the pH of water solutions – is considered a pretreatment technique which can assist further treatment or handling of liquids. (Chemical adjustment is discussed in detail under the corresponding chapter on treatment).

Fragmentation (including shredding, granulation, grinding, dismantling and pulping) is usually performed during pretreatment to break down the solid large sized waste, disfiguring the waste and preparing it for treatment. Fragmentation processes typically use cutters with high temperature flames, various sawing methods, hydraulic shearing, abrasive cutting and plasma arc cutting. Means of preventing the spread of particulate contamination should be considered when selecting a method and equipment. The extent to which segmentation is required depends on the capacity of the transport methods and on the size or weight restrictions that exist at the storage/disposal site. Where the cost of disposal is very high, segmentation can be considered as a means of considerably reducing the volume.

4.3. TREATMENT

Treatment includes operations intended to benefit safety and/or economy by changing the characteristics of the waste [26]. Some treatment may result in an appropriate waste form. However in most cases the treated waste requires further conditioning either by solidification, immobilization or encapsulation. The primary objective of treatment processes is volume reduction, as illustrated in a number of IAEA publications [27–36].

Information on treatment processes is presented below in tabular forms for gaseous, aqueous liquid, organic liquid, solid waste, biohazardous waste. In addition, text is provided for spent nuclear fuel (SNF) and NORM wastes.

- Physical and chemical properties of radioactive waste;
- Clearance levels for liquid and gaseous effluents and solid materials;

- Discharge requirements for decontaminated liquids and gases;
- Transfer and concentration of radioactivity from organic to other, more stable, media;
- Requirements for conditioning of treated waste;
- Requirements for processing of secondary waste;
- Requirements for storage, off site transport and disposal of the conditioned waste packages.

For the purpose of this publication and summary of available technical options for treatment the following waste streams have been included:

- Gaseous and airborne waste;
- Aqueous Liquid LILW;
- Organic Liquid LILW;
- Solid waste LILW;
- Biohazardous/infectious waste;
- SNF declared as waste (SFW);
- NORM waste.

4.3.1. Gaseous and airborne waste

Operations involving the handling of radioactive material may generate airborne radioactive contamination. The main difference between airborne effluents and radioactive waste in condensed (i.e. liquid or solid) phase is that airborne material has no definite volume and its dispersion in the environment is very fast.

Gaseous and airborne wastes are discharged to the environment through ventilation and air cleaning systems, which are a vital part of the general design of a nuclear facility or practice [37–40]. The main method of preventing radioactive contamination of the air in working areas and in the surrounding atmosphere is a combination of a well designed ventilation system with thorough cleaning of exhaust air. Ventilation and air cleaning systems should provide efficient treatment of gaseous streams under normal operations, maintenance and accident conditions.

High efficiency particulate air (HEPA) filters are most commonly used for removal of radioactive particulates and aerosols from gaseous streams [40]. Sorption beds charged with activated charcoal are common for removal of volatiles (e.g. Iodine) and as delay beds for noble gases. Wet scrubbers are used for the removal of gaseous chemicals, particulates and aerosols from process off gases. Additional components of the air cleaning system include pre-filters, temperature and humidity control systems, and monitoring equipment such as gauges that show pressure differentials.

The treatment of gaseous streams results in secondary waste, either solid (spent filters or sorption beds) or liquid (scrubbing solutions). The physical and chemical properties of the selected air cleaning media should therefore be compatible with the treatment and conditioning processes for the solid or liquid waste streams in which they will be treated.

The main features and limitations of air cleaning systems are provided in Table 8. Additional details on technical options presented in Refs. [40, 41].

TABLE 8. TREATMENT METHODS FOR GASEOUS AND AIRBORNE WASTE

Treatment method	Features	Limitations	Secondary waste
HEPA filtration	Retention of solid sub-micron particles (0.3 μ) with high efficiency (99.97%) Glass fibre filter media Widespread use	Humidity control is required (e.g. use of moisture separator) Pre-filters are necessary to protect costly HEPA filters	HEPA and pre-filters
Sorption	Used for removal of inorganic and organic iodine in reactors and reprocessing plants Sorption media includes chemically impregnated charcoal or zeolites	Humidity control is required Limited operating temperature-charcoal High cost of impregnated media	Spent sorption media
Cryogenic trapping	Isolates ^{85}Kr from off gases by sorption on solid sorbent (e.g. charcoal) Operates at elevated pressure and reduced temperature Loaded ^{85}Kr can be recovered and sorbent reused multiple times	Further processing and packaging for long term storage is required Commercial experience is limited	Spent (degraded) sorption media
Delay/Decay	Use for decay of short lived noble gases (^{133}Xe, ^{135}Xe, ^{87}Kr, ^{88}Kr, ^{41}Ar)	Large beds are required to provide for long retention times	None
Wet scrubbing	Wet scrubbing works via the contact of target compounds or particulate matter with the scrubbing solution. Commonly used for process off gas treatment. Solutions may simply be water or solutions of reagents that specifically target certain compounds.	Not practical for high volume gaseous stream treatment	Liquid waste streams

4.3.2. Aqueous waste

In most cases treatment of aqueous waste aims at splitting it into two streams: a small fraction of concentrate containing the bulk of radionuclides, and a large portion of concentrate which has a sufficiently low level of contamination to permit discharge to the environment or recycling.

Effective liquid treatment separates as much as of the radioactive components as possible from the waste in a concentrated form. Generally, the radioactive concentrate requires additional conditioning prior to disposal.

Aqueous treatment processes are usually based on conventional physical and chemical treatment principles, adapted to the individual characteristics of the waste. Failure to account for the chemical and biological nature of aqueous waste may result in inadequate treatment and/or conditioning and could damage the waste processing facilities. A flow chart for managing aqueous radioactive waste is given in Fig. 5.

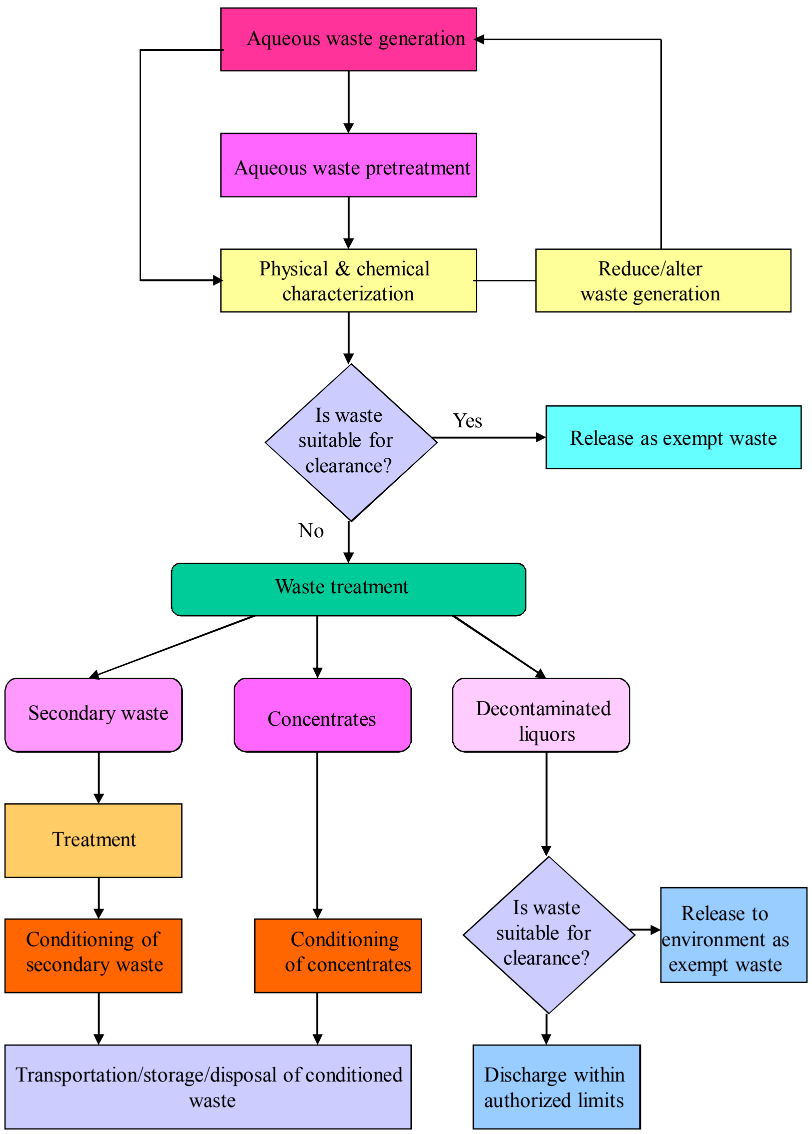


FIG. 5. Management steps for aqueous radioactive waste.

4.3.2.1. Aqueous waste pretreatment

It may be necessary to adjust the chemical composition of liquid waste to ensure its compatibility with subsequent interim storage, treatment or immobilization processes. The most common procedures for this are:

- Acid or alkaline adjustment for interim storage, evaporation, ion exchange or disposal;
- Removal of ammonia by alkaline distillation prior to bituminization;
- Destruction of oxalates in decontamination solutions;
- Use of alkaline earth ions to modify the behaviour of conditioned waste;
- Destruction of nitric acid by the use of organic compounds;
- Electrolytic destruction of organic acids, such as oxalic acid, to reduce corrosion before evaporation.

Although the chemistry of the reactions involved in such procedures is generally well understood and information is likely to be readily available, its translation into facility and equipment which can be routinely operated or performed safely and in conformity with radiation protection standards is likely to require demonstration of the procedure on a significant scale, as well as the application of special project engineering and design skills.

Process effluents may contain entrained organic solvent or other materials such as lubricating oil. Such materials may require removal by physical pretreatment, which could include filtration of any fine particulates by pre-coat or sand bed filtration (which is essential before any effluent treatment by ion exchange).

4.3.2.2. Aqueous waste treatment

A list of available treatment methods for aqueous waste streams together with their main features and limitations is given in Table 9. Additional details on technical options are presented in Ref 1, and more detailed descriptions of the technologies can be found in Refs. [27, 28, 32–35].

TABLE 9. TREATMENT METHODS FOR AQUEOUS WASTE STREAMS

Treatment technologies	**Features**	**Limitations**	**Secondary waste**
Filtration	Removal of suspended solids Use as polishing step after chemical treatment Use upstream of ion exchanger Backwash is possible	Not suitable for colloids Need to replace filter media	Filter media, cartridges and wash liquors
Chemical precipitation (coagulation/flocculation/separation)	Easy industrial operations, not expensive Suitable for large volumes of waste Can be designed to treat different radionuclides at the same time Utilized mostly as batch process	Lower DF than other processes ($10 < DF < 10^2$) Efficient solid–liquid separation step required after treatment Can be affected by presence of complexants, surfactants Adding new chemicals to the existing stream	Sludge Supernatant requiring further treatment
Evaporation	High DF > 10^3 Well established technology – many different designs High volume reduction factor Concentrate can be directly immobilized or dried to produce a salt cake Utilized mostly as batch process Condensate may require polishing depending on the activity	Not suitable for small volumes of aqueous waste generation Process limitations (scaling, foaming, corrosion, volatility of certain radionuclides) High capital and operating cost with high energy consumption	Evaporator concentrate Salt cake if additional drying is applied Condensate requiring further treatment

Treatment technologies		Features	Limitations	Secondary waste
Ion exchange	Organic ion exchange	DF good on low salt content (10^2) Good DF also possible for high salt content by use of specific resins Regeneration of resins possible	Some colloidal particles and resin fines may pass straight through to the treated water Limited radiation, thermal and chemical stability of the resins Resins cost May require some chemical treatment before conditioning	Spent organic ion exchangers Regeneration liquors
	Inorganic ion exchange	$10 < DF < 10^4$ Chemical, thermal and radiation stability better than organic ion exchangers Relatively easy immobilization Mostly used as once through cycle	Some colloidal particles and sorbent fines may pass straight through to the treated water Possible high cost for specific sorbents	Spent inorganic ion exchangers
Membrane technologies	Microfiltration	Removal of fine particulates Pore sizes range from 0.05 and 5 µm Low pressure operation (100–150 kPa) High recovery (99%) Low fouling when air backwash is employed Mostly used as the first step in treatment	Used for suspended fine particles, but not colloidal matter Backwash frequency depends on solids content of waste stream Short lifetime of organic membranes Inorganic membranes exhibit greater mechanical durability than polymeric membranes High cost of inorganic membranes	Used membranes Concentrated streams
	Ultrafiltration	Removal of colloidal materials and large dissolved molecules Pore sizes range from 0.001–0.01 µm Pressure < 1MPa DFs in the region of 1000 for α and 100 for β and γ emitters High volume reduction factor can be achieved Good chemical and radiation stability for inorganic membranes	Fouling – need for chemical cleaning and backflushing Organic membranes subject to radiation damage Short lifetime of organic membranes Inorganic membranes exhibit greater mechanical durability than polymeric membranes High cost of inorganic membranes	Used membranes Concentrated Streams
	Nanofiltration	Separation of salts with charge differences and separation of high molecular weight organics from high concentration monovalent salt solutions Pore sizes between 0.001 and 0.01 µm Pressure from 0.3 to 1.4 MPa. Functions between ultrafiltration and reverse osmosis, and is often termed 'loose reverse osmosis'	Organic membranes subject to radiation damage Short lifetime of organic membranes	Used membranes Concentrate

Treatment technologies	Features	Limitations	Secondary waste
Reverse osmosis	Removes dissolved ions and small molecules that contaminate aqueous solutions $10 < DF < 10^2$ Well established for large scale operations Compete with other separation processes (such as evaporation) Suitable for waste streams with complex radiochemical compositions	High pressure system, limited by osmotic pressure Non-backwashable, subject to fouling	Used membranes Concentrated streams
Biotechnological processes (biodegradation, biosorption, bioaccumulation)	Suitable for large volumes of hazardous waste such as nitrate bearing waste from uranium refining Low cost	Very large chemical reactors to ensure retention time High sludge production	Contaminated biomass – sludge

Historically three technologies are most commonly applied to treat aqueous waste, namely *chemical precipitation*, *ion exchange* and *evaporation*. More recently, membrane processes such as reverse osmosis, nanofiltration, ultrafiltration and microfiltration are also applied, and have demonstrated good performance. In each case, process limitations due to corrosion, scaling, foaming and the risk of fire or explosion in the presence of organic material should be carefully considered, especially with regard to the safety implications of operations and maintenance. If the waste contains fissile material, the potential for criticality should be evaluated and eliminated to the extent practicable by means of design and administrative features.

The objective of a *chemical precipitation* process [33] is to remove radionuclides from liquid waste by the use of an insoluble finely divided solid material. The insoluble material or floc is generally, but not necessarily, formed in situ in the waste stream as a result of a chemical reaction. The use of these processes concentrates the radioactivity present in a liquid waste stream into a small volume of wet solids (sludge) that can be separated by physical methods from the bulk liquid component. Chemical precipitation is suitable for the waste which is low in radioactivity, alkaline in pH and contains a significant salt load. This process is simple and relatively inexpensive in terms of the plant and its operation, but it requires good understanding of the process chemistry and strict consideration of process parameters. The process may be limited by the activity level.

Ion exchange is a standard method of liquid cleanup [35]. Ion exchange materials are insoluble matrices containing displaceable ions which are capable of exchanging with ions in the liquid passing through by reversible reaction. Organic and inorganic, naturally occurring and synthetic ion exchangers have found their specific fields of application in different purification and liquid waste treatment processes. If the waste is relatively free of salts and mildly acidic in pH, and requires a decontamination factor of around 100 or so, ion exchange may be a good choice. This process is more expensive than chemical treatment – especially when special purpose resins are used – but has a wider range of application with regard to radioactivity concentration.

The limitation of conventional filtration and ion exchange is that colloidal particles, some radioactive, pass straight through to the product (treated) water; colloidal particles containing

$^{58/60}Co$, ^{54}Mg, ^{55}Fe and ^{125}Sb are typical examples of these. Ultrafiltration is capable of removing these particles completely and has been adopted at a number of sites to complement the existing conventional filtration/ion exchange systems. At other sites, ultrafiltration has been implemented in combination with reverse osmosis, and ion exchange has been discontinued or is utilized as a polishing step.

In application of ion exchange, the selection of ion exchangers plays a very important role. The current trend in the selection of ion exchange media is towards high capacity, high selectivity media that can remove target ions with a good efficiency in the presence of other ions or under harsh operating conditions. For example, a number of such media are currently available to remove caesium or strontium from liquids with a high concentration of salts. Although currently more costly than natural or conventional materials, the advantages of applying these materials include a reduction in the volume of secondary waste (i.e. the spent ion exchange media produced) and an improvement in the quality of the final conditioned waste product. In many cases this results in overall monetary savings for the waste management programme, especially for those cases for which waste disposal costs are high.

Evaporation is a proven method for the treatment of liquid radioactive waste, providing both good decontamination and good concentration [32]. Water is removed in the vapour phase of the process leaving behind non-volatile components, such as salts and most radionuclides. There could be situations when waste volumes are somewhat high, having a low salt content but a considerably higher activity level; in this event evaporation is used to reduce the waste volume to a concentrate and also to obtain a high decontamination factor (of the order of a few thousand). However, the process is energy intensive and is limited by the presence of radionuclides which are volatile.

Membrane processes [34] are used as one or more of the treatment steps in complex waste treatment schemes that combine conventional and membrane treatment technologies. For example, electrodialysis is a well established membrane technology that has been used widely for the desalination of brackish water, which is also used to separate monovalent ions from multivalent ions. These combined systems offer superior treatment capabilities, particularly in instances where conventional methods alone could not perform a similar task as efficiently or effectively. They are capable of producing high quality treated effluents with an acceptably low level of residual radioactivity for discharge, or for recycle and reuse. The concentrate waste stream containing the removed radioactivity invariably needs further processing by evaporation or other means to facilitate final conditioning to a solid waste form suitable for intermediate storage and disposal.

In application of membrane technologies, the selection of the membrane material, its configuration and the operating parameters are critical. A wide variety of membranes are commercially available with different operational characteristics [34]. The choice of a membrane should take into account performance data (salt rejection, flux), as well as the interaction of the membrane with the feed solution, and whether this will lead to stable operation and minimal fouling. Once these have been achieved the process configuration can be determined and optimized, usually by computer modelling.

4.3.2.3. Secondary waste

The production, treatment and disposal of secondary waste should be considered in the comparison of liquid waste treatment technologies. Any treatment of radioactive waste generates a certain concentrate and decontaminated liquor. Although the decontamination of liquid waste allows for discharging the effluents, one should include in the proper evaluation of the liquid waste treatment that the secondary waste, if not released or discharged, also needs to be managed.

Evaporation gives rise to a small volume of liquid, generally highly salt laden. The application of chemical precipitation produces wet sludge and generally requires a dewatering system capable of concentrating the waste sludge before immobilization. Ion exchange generates a solid which can be subsequently directly immobilized. When regeneration of the ion exchange resins is performed additionally, the resulting highly salt laden solutions have to be treated in a further step either by using a more specific ion exchange process or by evaporation. Elimination of chemicals from the process system reduces the salt content and generally simplifies the treatment process. Another possibility is the elimination of ion exchange regeneration through use of a disposable ion exchange material, such as the powdered ion exchange material. By avoiding chemicals for regeneration, the waste is limited to used resin and the equipment can be reduced for both concentrate and condensate treatment.

Spent ion exchange resins are usually flushed out as slurry and subsequently managed as liquid waste, although some operators retain the resins as a dry solid. When resins are slurried, care should be taken to prevent blockages of the flow as these may cause radiation hot spots and necessitate special maintenance. Special care should also be taken with their prolonged storage while awaiting conditioning, because of the potential for radiolytic or chemical reactions generating combustible gases or causing physical degradation or exothermic reactions.

Membrane processes generate secondary waste streams, as they are, in principle, separation processes. The generation of secondary waste streams needs to be considered in terms of downstream processing. Ideally these streams are considered well before implementation of the new membrane facility, but even then the streams may become problematic and new strategies may need to be devised. The concentrate from a reverse osmosis process will normally undergo further volume reduction, either by another membrane process or by evaporation. For microfiltration and ultrafiltration, the reject stream containing particulate matter needs to be treated or directed to another part of the site processing facility. In each case, the characteristics of the concentrated waste stream and their impact on other (downstream) processes should be considered.

Spent cleaning solutions are another source of secondary waste. These can be voluminous if repeated cleaning is required due to unexpected fouling conditions. The impact of greater than expected volumes of spent cleaning solutions should be considered during the design phase.

Recycling of secondary waste streams to the feed of a membrane treatment plant should be evaluated with extreme caution, as a buildup of unwanted contaminants may severely impact plant operation through reduction in permeate quality, more frequent cleaning cycles, or progressive, irreversible fouling.

When selecting a technology for processing liquid wastes, it should be considered that these liquids could contain some organic impurities, solid particles and corrosion products. Some technologies will permit organic liquids such as oils, solvents, and scintillation liquids to be treated together with the solid waste stream (i.e., the processing system simultaneously accepts both liquid and solids within reasonable limitations). Other technologies may require solid and liquid waste streams to be separated.

Liquids for discharge may be produced as a consequence of the treatment of liquid waste. All discharged liquids should be readily dispersible in water. If the liquid contains suspended materials, it may need to be filtered prior to discharge. Waste that is immiscible with water should be completely excluded from discharge. Acidic or alkaline liquids should be neutralized prior to discharge. If the waste also contains toxic or other chemicals that could adversely affect the environment or the treatment of sewage, the waste should be treated prior to discharge in accordance with the regulations in respect of health and safety and environmental protection.

Waste volumes as well as the amount of effluents discharged into the environment may be reduced by suitable recycle and reuse of some waste streams. For example, reuse of decontamination solutions or recycling of clarified liquors within a process reduces the need for addition of fresh water to the process.

4.3.3. Organic liquid waste

The organic nature of the waste often introduces additional hazards not encountered with inorganic waste, such as susceptibility to radiolysis and biodegradation, flammability, volatility, chemical toxicity and inherent biohazards. This results in special requirements and considerations for storage, treatment, conditioning and disposal of this waste.

The volume of organic liquid waste is small compared with aqueous radioactive waste. Unlike aqueous waste, it may not be possible to discharge treated organic waste to the environment due to its organic chemical content. This organic liquid waste can be treated by:

- Conversion to a solid form either directly or after chemical adjustment to a form compatible with a solidification matrix (e.g. cement);
- Volume reduction;
- Decontamination for reuse.

A flow chart for managing organic liquid waste is given in Fig. 6.

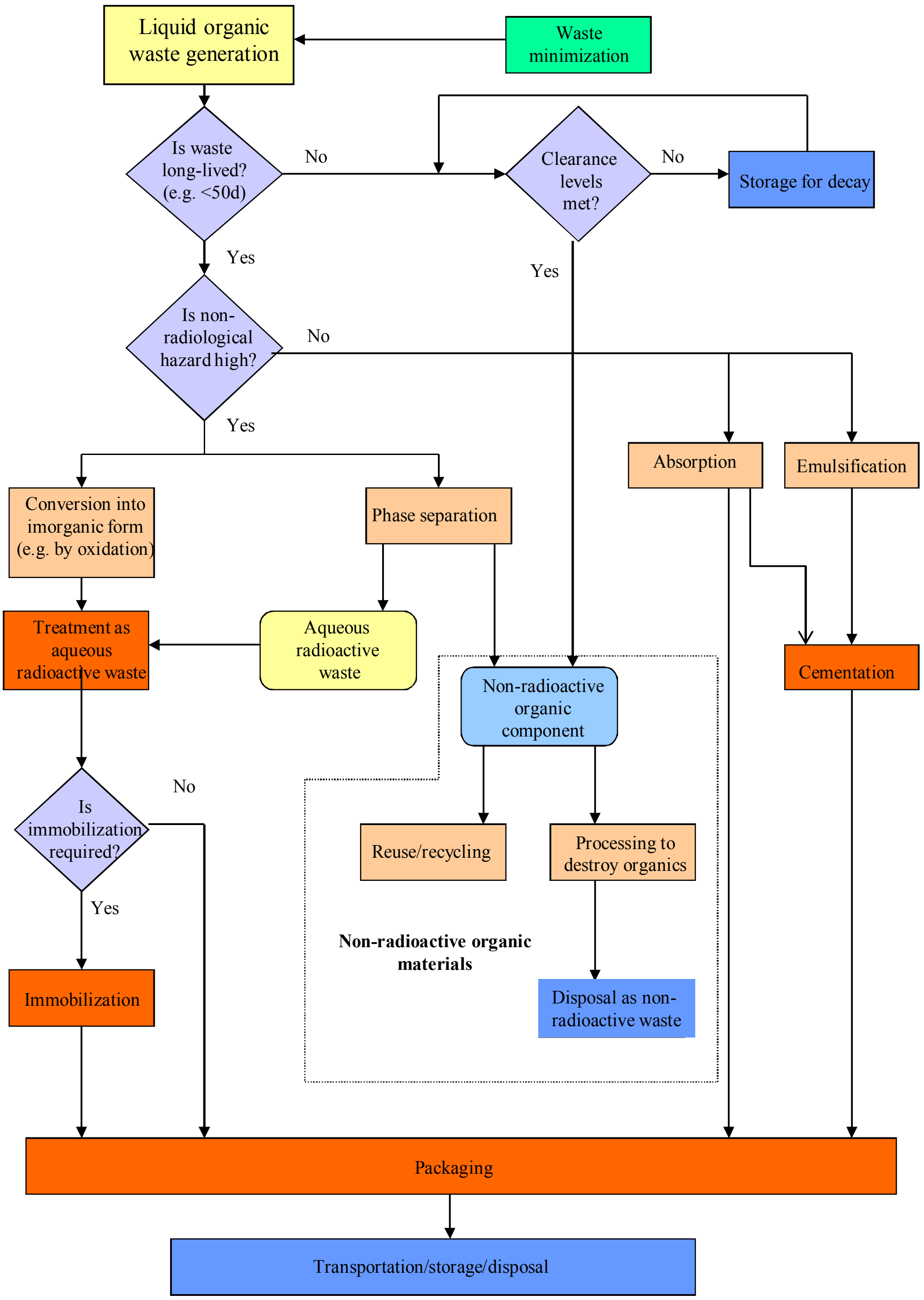


FIG. 6. Management steps for organic liquid radioactive waste.

Various techniques for the treatment of liquid organic waste have been developed and implemented in different countries [29, 30]. In some cases processes and equipment selected for the treatment of aqueous and solid waste had been adapted for processing organic liquid waste, and combined processing was cost effective. For example, small quantities of organic liquid can be readily mixed with solid waste in an incinerator. Advantages and limitations of these processes are given in Table 11.

TABLE 11. TREATMENT TECHNOLOGIES FOR LIQUID ORGANIC WASTE

Treatment methods	Features	Limitations	Secondary waste
Distillation	High efficiency for treatment of solvents Process is simple, well known and cost effective	Process temperature controls are required to eliminate potential explosion hazard	Evaporator bottom concentrate
Liquid–liquid extraction	Reuse of material or possibility of disposal in the non-radioactive area Promising for contaminated lubricants (oil, grease)	No significant process limitation Efficiency is case specific Cost–benefit not fully determined	Aqueous waste
Absorption	Solidify and immobilize organic liquids in absorbents (e.g. vermiculites) Simple and cheap technique	Suitable only for small amounts of waste Absorbed waste is not a stable waste form to meet disposal acceptance criteria	Solid waste absorbents
Incineration (including conventional incinerators – starved air, excess air, rotary kilns and high temperature incinerators with plasma torches)	Decompose and oxidize organic compounds of waste High volume reduction Possible combined use with all other combustible wastes Eliminate infectious (bio) hazard Great reduction in volume and mass	Not suitable for low volumes High capital and operation and maintenance cost Requires specially trained crew Off gas filtration, cleaning and monitoring are required	Ash residue Off gases filters Scrub solutions
Emulsification	Allow embedding of liquid organic waste into cement matrices Possible to implement using simple equipment like in drum mixers	Low limits for content of emulsified liquids in the cement matrix	None
Alkaline hydrolysis	Transfer of the radioactivity to the aqueous phase Has been implement for reprocessing solvent. A well established chemical process Low operating temperature	Produces complex waste products requiring further treatment	Alkaline aqueous waste Separated diluent

Properly controlled *incineration* is an attractive technique for treating organic liquids because they are readily combustible and high volume reduction factors can be achieved. After combustion, radionuclides from the waste will be distributed between the ash, filters and off gas, with a degree which depends on details of the unit's design and operating parameters. Further immobilization, such as grouting of ashes, will be required to stabilize these residues, some of which will have a much higher radionuclide concentrations per unit volume compared original waste.

Wet oxidation is a technique for breaking down organic materials to carbon dioxide and water in a process, which requires significantly lower temperatures compared incineration. The main advantages of this process are the low temperature required and its use of aqueous media, which is easy to treat.

Simple *distillation* may be used for the treatment scintillation fluids and miscellaneous solvent waste. Substantial volume reduction is possible and the recovered organic solvent could be used as a technical grade solvent or as a fuel for an incinerator. Distillation can be practiced with conventional readily available equipment and space requirements for the equipment are small.

There are difficulties with solidification of organic waste by cementation. Only about 12 vol.% of oil can be incorporated directly in cement and still retain a waste form that is dry and monolithic. However, significant increases in waste loadings can be obtained when *emulsification* is applied.

A simple technique for on site treatment of organic liquid radioactive waste is to *convert the liquid to a solid form with absorbents*. As long as there is an excess of absorbent there is no need for mixing; the liquid waste can be added to the absorbent in a suitable container and eventually all liquid will be taken up. This technique is routinely used in the solidification of radioactive turbine and pump oil. The use of absorbents converts the liquid waste into a form, which can vary from loose dry particles to a jelly like solid. The waste forms have no special integrity and are only restrained from dispersing by the container. Another common technique is the embedding of absorbed organics into a cementitious waste form.

In many cases, processes selected for the treatment of aqueous waste can be adapted to the processing of organic liquid waste, and combined processing can be cost effective. Substantial advantages can often be accrued by selecting a combination of two or more processes, rather than a single process.

Some of the processes, such as wet oxidation, acid digestion, electrochemical oxidation and distillation can be carried out for small batches of waste using simple bench top equipment. A dedicated plant may be considered for larger waste arising. Often, substantial advantages can be accrued by selecting a combination of two or more processes, rather than a single process, for treating organic liquid waste. For example, the multiple process approach may allow resource recovery, convert the organic material into an inert form, provide volume reduction or allow processing in equipment designed for solid waste. The final selection of the processes to be used will, of course, be based on the national need and/or availability of resources.

4.3.4. Solid waste

The essential purpose of solid LILW treatment is to reduce the volume. The main features and limitations of solid waste treatment methods are given in Table 12 and additional details on technical options are presented in Ref [1]. The available solid waste treatment options are described in detail in Refs. [31, 36, 41].

TABLE 12. TREATMENT METHODS FOR LOW AND INTERMEDIATE LEVEL SOLID WASTE

Treatment methods		Features	Limitations	Secondary waste
Compaction	Low force compaction	Well proven technology for compactable solid waste Compaction force from 10–50 tonnes Volume reduction factor (3–5) Relatively low cost Easy to operate	Volume reduction factor limited by spring back May require use of embedding of compacted waste	None

Treatment methods		**Features**	**Limitations**	**Secondary waste**
	High force (super) compaction	Used for previously compacted waste as well as for air filters, incinerator ash, small metal pieces, soft plastics, thermal insulation materials High volume reduction factor for un-compacted waste Force 1200–2000 tonnes Mobile compactors are available for campaign mode operation	High equipment cost Frequently requires precompaction Maintenance is costly and frequently required Generally not economical for small amounts of waste	Liquid waste
Thermal treatment methods	Incineration	Well proven technology Very high volume reduction of processed waste (for dry solid waste and small percentage of wet waste) High throughput process Process continuity (i.e. process can operate on a continual basis 24 hours/day) Can be used for both solid and liquid wastes as well as for biohazardous and medical waste.	Very sensitive to waste composition Relatively high capital cost for investment Difficulties with public acceptability and licensing Need to meet the environmental requirements for discharges Generally not economical for small amounts of waste Special regime is required for treatment of alpha bearing waste	Off gases Scrubbing Solutions
	Pyrolysis	Extensive commercial experience in the processing of high organic content waste (e.g. biohazardous waste, cartridge filters, charcoal, IX resins, plastics, waste with high water and organic content) Low process temperatures Retention of volatile species in the ashes Retention of radioactivity in the pyrolyser residue is > 99.99%. Low gas flow rates (compared to incineration) Insignificant NO_x production End product is easily managed The processes can be heated externally, thus minimizing gas flows which would otherwise require radiological control	Limited experience in processing of inorganic waste with a stabilized (monolithic) end product Extensive waste pretreatment is required Sensitive to waste composition and feed Sodium/potassium bearing waste might cause operational problems for fluidized bed pyrolysers	Off gases, Scrubbing Solutions

Treatment methods		Features	Limitations	Secondary waste
Emerging	Plasma	Can usually treat the waste as generated (i.e. no prior segregation is necessary), for solids, liquid and metals The process temperature is up to 1800^0C which allows melting of waste The final waste form is robust, free of organic material and suitable for long term storage and disposal Volume reduction factors can range from 6:1 to 10:1for metallic waste while for other combustibles the volume reduction factor (VRF) can rise as high as 100:1 Less production of certain flue gases	Limited full scale plant experience Process is expensive to construct and operate Comparing to waste incineration demands on an off gas treatment system is more considerable High maintenance frequent to replacement of plasma torches Special regime is required for treatment of alpha bearing waste	Off gases Scrubbing Solutions
	Metal melting	Extensively proven technology for waste metals as ferrous metals (carbon steel and stainless steel), aluminium, lead, copper and brass High volume reduction, typically from 5:1 to 20:1 The end product is typically homogeneous and stable with the remaining activity content bound in the metal End product has the potential to be reused or recycled within the nuclear industry or after clearance within the conventional metal industry	Pre-sorting is usually required due to dedicated melt furnaces and differences in melt temperatures of the different metals Melting of mixed metal components (such as small electric motors) is normally not economical	Off gases Slag
	Molten salt oxidation	Emerging technology Alternative to traditional incineration of organic waste Complete destruction of organic material Lower operating temperature Low levels of gaseous emissions Costs are relatively low	Limited commercial experience Requires specialized techniques for adequate conditioning of the salt product Limited to small and medium waste programmes	Salt residues Off gases
	Thermochemical	The powdered metallic fuel can be used for problematic waste streams such as irradiated graphite, spent ion exchange resins, polymers and biological waste in selected areas and in situ applications. Avoidance of emissions of radionuclides, heavy metals and chemically hazardous species Low environmental impact Relatively low cost	Not fully matured through broad implementation	Off gases

An example of a flow chart for managing solid radioactive waste is given in Fig. 7.

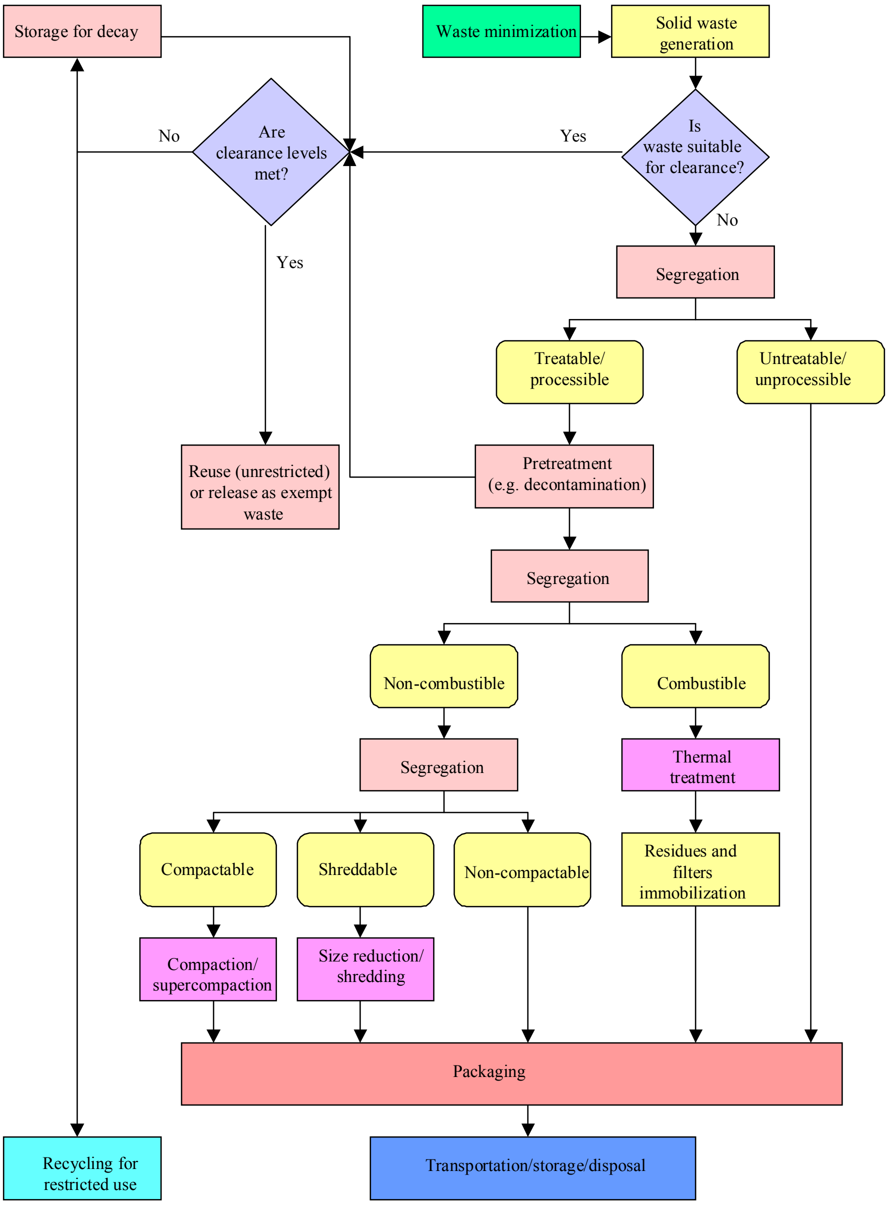


FIG. 7. Management steps for solid radioactive waste.

Both compaction and supercompaction technologies are described in details in Ref. [41]. *Compaction* involves compressing the waste into containers or boxes in order to reduce the volume. Low force compaction is the least expensive volume reduction process, and operation is easier than high force compaction. Compaction units are also amenable to automation, which can improve operational efficiency and radiation protection aspects. High force compactors can achieve marginally better reduction factors, whereas super compactors achieve highest volume reduction, close to the theoretical density of the materials (e.g. by minimizing the voidance). Both high force and super compactors typically compress the waste inside of drums.

From a technical viewpoint, the same technique may be applied as a treatment or a pretreatment step, depending on the required sequence in the overall waste management scheme. For instance, shredding could be considered as treatment when applied for volume reduction of waste before packaging, and as pretreatment when applied before incineration. In another example, low pressure compaction may be applied as a treatment method when used before supercompaction as a precompaction step.

Thermal treatment (incineration, pyrolysis, plasma, etc. [41, 42]) may provide the best potential for effective volume reduction of generated solid waste. Thermal treatment improves the homogeneity and quality of the waste form obtained after treatment and conditioning. Considering the high overall costs of waste disposal and the growing requirements for improved quality of the final waste form, the benefits offered by thermal processing become very significant.

Thermal methods may also have disadvantages restricting their applications. In particular, the environmental safety requirements, such as gaseous effluent restrictions, can increase the complexity and cost of these technologies, which may not justify the application of incineration for relatively small volumes of solid waste. Generally, the permits or licenses from regulatory agencies will stipulate numerical emission limits or reference standards to be met. Requirements for data collection, analysis and reporting will often be very prescriptive. Monitoring of such parameters as particulate, radioiodine, tritium and ^{14}C may be required. Typical chemical parameters requiring on-line monitoring may include oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), sulphur dioxide (SO_2), and nitrous oxides (NO_x). Therefore, depending on the rigor of the regulatory requirements, the off gas monitoring system can become a complex, costly component of implementing the overall thermal treatment, which should be factored into the life cycle economic analysis.

For non-combustible and non-compressible solid waste for which delay and decay or decontamination is not a viable option, direct conditioning without prior treatment should be considered.

Melting waste metal scrap, with resultant homogenization of the radioactive material and its accumulation in the slag, may be considered as a means of achieving authorized reuse or removal of regulatory control [42].

Two *emerging technologies* – molten salt oxidation and thermochemical treatment – have demonstrated promising performance parameters, though they still have limited applications.

Molten salt oxidation is a flameless thermal desorption process [42]. The waste is introduced into a bath of molten salts, typically at temperatures between 500–950°C, which oxidizes the organic constituents of the waste. Carbon dioxide, nitrogen and water are produced. The end product is an organic free salt residue which captures radionuclides, metals and other inorganics. The production of acid gas emissions is inhibited by the formation of the stable salts.

Thermochemical processing technologies are used for treating and conditioning problematic radioactive wastes [43]. Thermochemical processing uses powdered metallic fuel (PMF) such as aluminium or magnesium, which reacts both chemically and physically with water present in the waste to form hydrogen gas and heat; the subsequent combustion destroys the organic material, resulting in solid slag or ash. The hydrogen gas burns because of the presence of oxygen, and in co-reaction the waste is combusted and brought into a slag-like form. The presence of excess metal powder suppresses the production of corrosive gases. The composition of the PMF is designed in such a way as to minimize the release of hazardous components and radionuclides in the off gas and to confine the contaminants in the ash residue. Thus, the thermochemical procedures allow decomposition of organic matter and capturing hazardous radionuclides and chemical species simultaneously [42, 43].

Treatment of solid radioactive waste may generate different solid, liquid and gaseous secondary waste, which requires subsequent treatment and conditioning. These wastes should be limited as much as possible; a volume reduction system would be completely useless if it were to generate more secondary waste than the original waste, or make secondary waste more difficult to process. Secondary waste should comply with the existing treatment provisions. Taken together, a well designed waste processing system will produce secondary waste that can be managed in the existing facilities; nearly identical treatment principles apply for the secondary waste as for the gaseous, liquid and solid primary waste.

4.3.5. Biohazardous/infectious waste

Some solid and liquid wastes may contain biohazardous or infectious materials in addition to radiological hazards. Precautions for handling these wastes should be respected. When processing biohazardous wastes, their infectious features and proclivity towards putrefaction insect attacks and microbial degradation should be controlled. Clearance of biohazardous waste from radiation regulatory control is unlikely to provide exemption from biohazardous waste regulatory control. As the main risks are associated with biological properties of such waste, its treatment is considered separately in this Section.

The goals of biohazardous waste treatment are the following:

- Biologic detoxification;
- Prevention of biological degradation;
- Volume reduction.

An important step in the treatment of biohazardous waste is neutralization of biological hazard by sterilization. A number of sterilization methods are regularly used in hospitals and they can be applied for treating biohazardous radioactive waste with some adaptation. Other methods are aimed at volume reduction of the waste. A flow chart showing the steps in managing biohazardous radioactive waste is shown in Fig. 8.

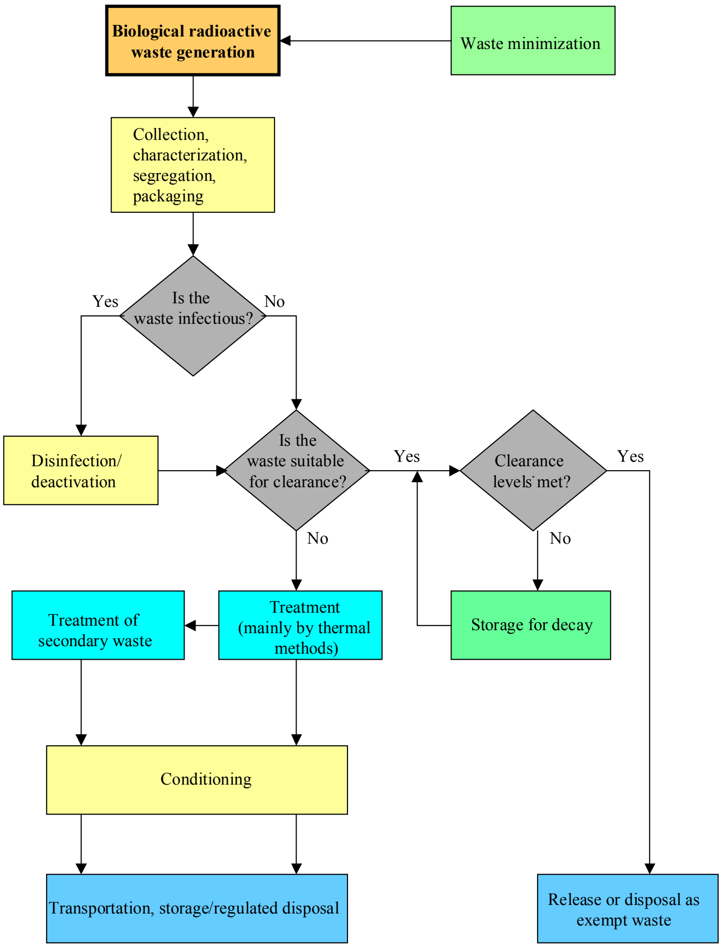


FIG 8. Management steps for biohazardous radioactive waste.

Treatment methods for biohazardous and medical radioactive waste are described in detail in Refs. [20, 44]. Their advantages and limitations are summarized in Table 13.

TABLE 13. TREATMENT TECHNOLOGIES FOR BIOHAZARDOUS RADIOACTIVE WASTE

Treatment method		**Advantages**	**Limitations**	**Secondary waste**
Thermal methods / Sterilization	Incineration	Effective reduction of the toxicity, mobility and volume Produces a totally sterile residue Inexpensive if used jointly with the available incinerator for other waste	Justified for high volumes of waste Need to meet the environmental requirements for discharges Difficulties with public acceptability and licensing	Ash Off-gases Filters
	Freezing/ refrigeration	Prevent putrefaction Remove liquids and leaves the solid waste for further treatment/disposal Commercial freezers or refrigerators can be used	Difficulties with large carcasses Requires rather expensive equipment	Liquid effluents
	Dry heat	Leads to coagulation of proteins (at 160^0C)	Small volume of a waste batch Long time of sterilization	None

Treatment method		Advantages	Limitations	Secondary waste
	Steam autoclaving	Regularly used in many facilities Low capital and operating costs Simplicity of operations	Relatively limited system capacity Appearance of odour and drainage problems Not suitable for most non-microbial pathogens	Liquid effluents
Chemical methods	Mummification	Prevent decomposition and putrefaction Commonly practiced	Some toxic solutions may be required	Liquid waste containing toxic chemicals
	Disinfection	Removes or destructs pathogenic microorganisms Easy to use Low cost for equipment	Use of aggressive chemicals Some bacterial spores may not be totally destroyed Shredding as a pretreatment stage is needed Good ventilation of the processing area is required	Liquid waste containing toxic chemicals Off-gases Solid organic waste
	Chemical decomposition	Alternative to high temperature incineration	No volume reduction	Liquid waste
Maceration/ pulverization		Change the physical form (from solid to liquid) Commercial liquidizers can be used	Secondary waste still require treatment and conditioning	Liquid waste
Intensive gamma irradiation		Easy to use for different waste Maintenance is minimized	High equipment cost Not widely available	None
Microwaves		The system is totally enclosed and runs under a slightly negative pressure Wetting the waste by steam injection facilitates the waste heat up process	Shredding as a pretreatment stage is needed Not recommended for volatile biohazardous waste, chemotherapy waste and pathological remains	None
Thermochemical treatment		Combines thermal destruction with chemical interaction of waste components with fuel. Easy to deploy. The slag obtained captures volatile components from off gas.	Requires special powder metal fuels.	None.

As wastes containing biological hazards are collected into lidded containers lined with plastic bags, special consideration should be given to sharp objects. When possible, these items should be collected in puncture resistant packages, properly labelled and treated separately.

Most microbiologically contaminated laboratory wastes are suitable for *steam autoclaving*, but this method should not be used where the radioactive content of the waste is volatile during steam treatment. This method is not appropriate for most non-microbial pathogens, animal carcasses or parts.

Chemical disinfection is useful for laboratory ware or similar materials, but it is not suitable for pathological waste and animal carcasses or parts.

Gamma irradiation seems to be a very attractive option for sterilization since is appropriate for pathological waste, animal carcasses and parts.

After deactivation or procedures aimed at preventing decomposition of its biological components, biohazardous waste can usually be treated using the same methods as for non-biological radioactive materials in order to meet the WAC.

Incineration is the preferred method for treating biohazardous radioactive waste of animal or human origins, as well as organic chemical waste. Incineration provides complete combustion of waste, producing totally sterile residues, with any emissions from the stack being kept to acceptable environmental standards.

Thermochemical treatment has been proved as an effective method to treat animal carcasses producing totally sterile slag residue, with minimal off gas emissions the composition of which can be kept in line with acceptable environmental standards.

In cases where incineration is not available or the volumes of human and animal wastes are so low that it is desirable to treat them as they are produced, it may be feasible to use *maceration/pulverization* to render these materials liquid, so that they can be discharged via a liquid radioactive waste route, including any necessary chemical deactivation to treat the biological hazard.

Compaction and shredding are not considered viable for treatment of biohazardous solid waste. The primary reason for this restriction is that any microorganisms contained within the waste may be spilled or released during these processes, and contamination may be widely dispersed.

4.3.6. Spent fuel

SNF may be stored as spent nuclear fuel waste (SFW) for eventual encapsulation and disposal or reprocessed to recover uranium and plutonium while conditioning remaining residue in the form of HLW containing mainly fission and activation products [45].

There is no specific treatment process for SNF, except that spent fuel elements are stored at the reactor site for a period of time to allow their intense radioactivity to decay and associated heat to decrease. SNF elements can be then moved to longer term storage facilities (dry or wet) before deep geological disposal. If not declared as waste, these could be shipped to a reprocessing plant after a suitable storage (cooling) period. The decay/cooling storage period at reactor sites varies usually from three to five years or even longer; afterwards, the spent fuel can be transferred to ‘away from reactor’ storage up to 50 years or more, depending on the national policies with regard to reprocessing or disposal.

If the fuel is reprocessed, the most active waste material is commonly called high level liquid waste (HLW), a solution resulting from nitric acid dissolution of the fuel containing more than 99% of the fission products and minor actinides (Np, Am and Cm) formed in the reactor, as well as a residual fraction of uranium and plutonium. Even if spent fuel were to be reprocessed systematically and plutonium recycled as MOX fuel in thermal reactors, after a number of cycles the remaining spent fuel will eventually be considered as waste due to gradual isotopic degradation of plutonium during recycling.

Other less active waste is produced during reprocessing (e.g. empty hulls, spacers, and insoluble components) which nevertheless contains significant amounts of long lived radionuclides (fission products, activation products and some residual fissile materials). LLW and ILW are also produced. Waste contaminated with plutonium should be managed, taking due note of the toxicity of the material for which technology is available. The processing of HLW is addressed in Section on 4.4 Conditioning.

4.3.7. NORM waste

Conventional industries generally produce large volumes of NORM containing residues, on the order of 10^4–10^6 t/a. This necessitates a different, more pragmatic approach compared to typical radioactive waste management which is based on the principle of concentration and containment [46]. For most NORM residues containment is not possible, and in many cases it is not waste but a useful recyclable residue. Therefore, for NORM residues the principle of dilution and dispersion should be preferred wherever possible; it saves resources and reduces waste volumes. Furthermore, concentration/containment and dilution/dispersion are complementary, not contradictory concepts.

Processing of NORM waste consists of pile stabilization by various processes in order to increase the safety of storage and disposal sites. Solid, large pieces of NORM waste, such as pipes from the oil industry, are fragmented for handling and transport purposes.

Liquid effluents are generated at all stages of the uranium production cycle that use process water and chemicals, including crushing, grinding, leaching, precipitation and tailings disposal and management. In addition, leaching of ore and mineralized waste rock by groundwater and surface water, respectively, can result in generation of acid mine water, which should also be contained and treated. The effluents contain radioactive and non-radioactive elements and compounds that, if not properly contained, can contaminate drinking water resources or enter the food chain, potentially harming the environment and endangering the health and wellbeing of human populations.

Scales and sludges, which are generated in small volumes but which may have activity concentrations reaching very high levels, such as those originating from the oil and gas industry, are usually held in storage pending the establishment of suitable disposal facilities.

Criteria for exemption of substances containing radionuclides of artificial origin are based on the premise that exemption will be the optimum option when the dose incurred by an individual is of the order of 10 μSv or less in a year [6]. For NORM, the situation is quite different. Owing to the existence of significant and highly variable levels of background exposure to radionuclides of natural origin, exemption is likely to be the optimum option over a much wider range of doses, typically doses of the order of 1 mSv or less in a year.

The use, reuse and recycling of NORM residues and NORM contaminated items – including, where appropriate, the dilution of NORM residues to reduce the activity concentration – is emerging as a legitimate and desirable option for minimizing the quantities of NORM that need to be disposed of as waste. In particular, the beneficial (and safe) uses of phosphogypsum as a co-product of fertilizer production are now very much in the spotlight and, in some countries there is already evidence of a shift in regulatory attitude towards this approach. However, when considering the use of NORM residues in the construction of dwellings as a component of either landfill material or construction material, the possibility of increased radon exposure needs to be carefully taken into account.

It has been demonstrated that NORM contaminated metal scrap can be safely recycled in a suitably controlled melting facility. This recycling option seems to be gaining greater acceptance by the steel industry.

4.4. CONDITIONING

4.4.1. Wasteforms

Conditioning includes those operations that produce a waste package suitable for handling, transport, storage and/or disposal [26]. Conditioning may include conversion of the waste to a solid waste form, additional immobilization of some solid waste, packaging of the waste form into containers, and, if necessary, an overpack. The *waste form (or wasteform)* is the waste in its physical and chemical form after treatment and/or immobilization (resulting in a solid product) prior to packaging. The waste form is a component of the waste package.

The *immobilization* of radioactive waste (solidification, embedding or encapsulation) to obtain a stable waste form is an important step in waste management that minimizes the potential for migration or dispersion of radionuclides into the environment during storage, handling, transport and disposal. Radioactive and chemically hazardous constituents in the waste can be immobilized into a waste form material through two processes: (1) binding them into the material at atomic scale (*chemical incorporation*), or (2) physically surrounding and isolating the material (*encapsulation*).

A number of matrices have been used for waste immobilization, including glass, ceramic, cement, polymer and bitumen [41, 47–57]. The choice of the wasteform depends on the physical and chemical nature of the waste and the acceptance criteria for the storage and disposal facilities to which the waste will be consigned. Several factors should be considered when selecting a wasteform material for immobilizing a specific waste stream. The key considerations include the following [51–53]:

— *Waste loading*: The waste form should be able to accommodate a significant amount of waste (typically 25–45 weight %) to minimize volume, thereby minimizing the space needed for storage, transportation and disposal.

— *Ease of production*: Fabrication of the waste form should be accomplished under reasonable conditions, including low temperatures and, ideally, in an air atmosphere, using well established methods to minimize worker dose and the capital cost of plant.

— *Durability:* The waste form should have a low rate of dissolution when in contact with water to minimize the release of radioactive and chemical constituents.

— *Radiation stability*: The waste form should have a high tolerance to radiation effects from the decay of radioactive constituents. Depending on the types of constituents being immobilized, the waste form could be subjected to a range of radiation effects, including ballistic effects from alpha decay and ionizing effects from decay of fission product elements.

— *Chemical flexibility:* The waste form should be able to accommodate a mixture of radioactive and chemical constituents with minimum formation of secondary phases that can compromise its durability.

— *Availability of natural analogues:* Since direct laboratory testing of the waste forms over the relevant time scales for disposal (typically 10^3–10^6 years) is not possible, the availability of natural mineral or glass analogues may provide important clues about the long term performance of the material in the natural environment, thereby building confidence in the extrapolated behaviour of the waste form after disposal.

— *Compatibility with the intended disposal environment:* The waste form should be compatible with the near field environment3 of the disposal facility. The near field environment provides the physical and chemical conditions that are favourable for maintaining waste form integrity over extended periods, which helps to slow the release of constituents and their transport out of the facility.

The main features and limitations of available immobilization processes are summarized in Table 14; additional details on technical options are presented in Refs [1, 47-57].

TABLE 14. WASTEFORMS FOR IMMOBILIZATION

Wasteform	**Features**	**Limitations**	**Secondary waste**
Glasses (Vitrification)	– Proven method to condition liquid HLW as well as ILW and LLW – High flexibility in terms of the glass formulation range – High reliability of the immobilization process – High glass throughput – High durability of the final waste form – Small volume of the resulting waste form	– High initial investment and operational costs – Complex technology requiring high qualified personnel – Generally not economical for LLW and ILW – Need to control off gases – Need to control variations in waste feed – High specific energy consumption	Off gases Filters Scrub solutions Used melters
Ceramics	– Possible to incorporate higher levels of actinides than borosilicate glass – Waste form is more stable and hence is more durable than glass – Expected to be suitable for long term isolation since it simulates natural rocks	– Limited experience. Most efforts have been research-based – There are not known commercial installations in operation at present – Generally considered not economical for LLW and ILW – The ceramivc (e.g. Synroc) waste form should be tailored to suit the particular characteristics of the nuclear waste to be immobilized	Filters Off gases Scrub solutions
Glass-composite materials (GCM's)	– Combine features of both crystalline and glassy materials – Higher waste loading – Higher compatibility – Higher stability compared glasses	– Limited experience	Off gases Filters Scrub solutions Used melters
Cements	– Widely used method for variety of LLW and ILW High flexibility – Low cost – Simplicity of the process – Low temperature precludes volatile emissions – High radiation stability, impact and fire resistance of waste forms	– Increase of volume (low waste loading) – Low retention of some fission and activation products Poor compatibility with organic materials and high salt content	None
Bitumen	– Mostly used for LILW, Chemical precipitates, Low heat and low alpha wastes – High flexibility – High compatibility with organic materials – High waste loading – Low leaching rate of waste forms compared with cementation	– High temperature process – Sensitivity to some components – Low fire resistance –	Filters
Metals	– Extensively proven technology for conditioning of metallic waste – The end product can be well categorized – The end product is typically homogeneous and stable	– Pre-sorting is usually required due to dedicated melt furnaces and differences in melt temperatures of the different metals	Off gases Slag

Glass is being used worldwide to immobilize HLW from reprocessing of SNF and targets [54]. The immobilization process, *vitrification*, is a continuous process capable of handling large volume waste streams. Vitrification is currently deployed on a large scale for lower activity waste streams and has become the reference process for the conditioning of HLW. Given the positive results obtained with vitrification of HLW, several projects are under way for the vitrification of slurries, low- and intermediate level solid waste, and mixed waste. It offers volume reduction, destruction of organic constituents including hazardous materials, immobilization of radioactive and hazardous components, and advantages for storage, transportation and disposal. Vitrification processes are sufficiently 'robust,' which means that they accept almost any waste after a minimum of up-front characterization, with reproducible characteristics of the end product and acceptable off gases. Vitrification can also be performed in situ as a special case (e.g. with legacy waste or contaminated soil).

Crystalline ceramics are inorganic, non-metallic solids that contain one or more crystalline phases. Single phase crystalline ceramics can be used to immobilize separated radionuclides (e.g. plutonium-239) or more chemically complex waste streams (e.g. HLW). In the latter case, the atomic structure of the ceramic phase should have multiple cation and anion sites that can accommodate the variety of radionuclides present in the waste stream. These materials are potentially attractive for immobilizing long lived alpha emitting actinides such as plutonium, neptunium and americium, however, some of these materials are susceptible to radiation damage effects associated with alpha decay from actinides [55]. Multiphase crystalline ceramics (e.g. *Synroc*) consist of an assemblage of crystalline phases. Individual phases are selected for the incorporation of specific radionuclides, with the proportions of phases varying depending on the composition of the waste stream. An individual phase can host one or more radionuclides, including solid solutions of radionuclides. However, not all phases will host radionuclides. Ceramic materials and methods of fixation were developed or are in the stage of developing. Ceramic products are crystalline in nature and therefore thermodynamically stable, though they are more sensitive to radiation damage.

Glass composite materials (GCM's) contain both crystalline and glass phases [51-53]. Depending on the intended application, the major component may be a crystalline phase with a vitreous phase acting as a bonding agent. Alternatively, the vitreous phase may be the major component with particles of a crystalline phase dispersed in the vitreous matrix. GCMs can be formed by a number of processes, including melt crystallization (controlled or uncontrolled), multiple heat treatments or by encapsulation of ceramic material in glass. GCMs offer several potential advantages over glass for use as waste form materials, including increased waste loadings, increased waste form density and smaller disposal volumes. These waste forms can also be used to immobilize glass immiscible components such as sulphates, chlorides, molybdates and refractory materials that have very high melting temperatures. They can also be used to immobilize long lived radionuclides (e.g. actinides) by incorporating them into the more durable crystalline phases; short lived radionuclides (e.g. many fission products) can be accommodated in the less durable vitreous phase [54].

Cements are inorganic materials that set and harden as a result of hydration reactions [52, 57]. Cements are used to immobilize waste that has relatively low levels of radioactivity (i.e. low or intermediate level radioactive wastes). Higher activity wastes can result in radiolysis and production of hydrogen gas from the breakdown of water or hydroxyl groups in the cement. Cementation is low cost and forms a major part of both solid and liquid (mainly aqueous) LLW and ILW immobilization technologies. The range of applicability of cements should be considered in view of the characteristics of the environment and of the initial waste. The cement may display pH buffering properties, and consequently, control mobility of most of the radionuclides in the disposal environment. The quality of cemented waste forms is continuously improving. They are also efficient for the immobilization of alpha bearing waste. The disadvantages relate to the relatively high porosity and leachability for some radionuclides of the end product, as well as the volume increase rather than decrease which may result.

Some waste treatment methods, such as plasma arc melting or molten metal techniques, result in both a high volume reduction and very stable waste forms.

Bitumen, a viscous hydrocarbon and a major component of asphalt, has been used to solidify and stabilize radioactive materials [50, 52]. Bitumen immobilizes waste by encapsulation; it does not bind the waste chemically. The advantages of bitumen as a waste form are simplicity of production, low operating cost and leach resistant characteristics. However, bitumen does not perform well with dehydrated salts, such as sodium sulphate, sodium nitrate, magnesium chloride and aluminium. It can also be a fire hazard, especially when oxidizing wastes like nitrates are involved.

When spent fuel is not reprocessed (once through option), SFW conditioning consists of volume optimization (rearrangement of the fuel rods) and envelopment in a multi-component barrier consisting of various *metals* (copper, lead) and the packaging canister [45]. Several different types of metallic materials have been studied as potential waste forms. Like crystalline ceramics, metal waste forms can consist of single or multiple phase assemblages and the waste form itself can be granular or monolithic. Metal waste forms can be fabricated sintering or casting. Each of these techniques has drawbacks; in particular, it can be difficult to find metal compositions and processes that effectively wet and encapsulate dispersed phases or fines.

4.4.2. Waste packages

The *waste package* is the product that includes the waste form and any container(s) and internal barriers (e.g. absorbing materials and liner), as prepared in accordance with requirements for handling, transport, storage and/or disposal. These requirements can be different for each step indicated above or they can be combined in one set of parameters that combine conservative requirements for each step.

If there may be a significant delay before an acceptable disposal route becomes available, the container should provide integrity during the predisposal storage period and should be capable of allowing for:

(a) Retrieval at the end of the storage period;

(b) Transport to and handling at a disposal facility;

(c) Performance as required in the disposal environment.

If a container is not initially designed to meet the relevant acceptance criteria for transport, storage or disposal, an additional container or an overpack will be necessary to meet the acceptance criteria. Care should be taken to consider the compatibility of the waste package and the overpack with respect to the WAC.

Waste packages are often produced when no disposal facility exists, and therefore no applicable disposal WAC are available to guide the design and preparation of the packages. In this case, it may be necessary to develop waste package specifications in place of the WAC. These specifications are considered as a design output, and are intended to control the radiological, physical and chemical characteristics of the waste package to be produced.

Waste specifications are usually oriented towards the performance or control of specific facility processes and may be used as a contractual vehicle to control subcontracted operations. Waste specifications, like the WAC, should take into account intended storage/disposal facility parameters and transport regulations, and incorporate relevant parameters of the WAC (or in lieu of the WAC, when they have not been developed).

It should be noted that the requirements on waste packages imposed by the IAEA transport regulations [19] meet many of basic requirements of the generic WAC. The place of WAC in the conditioning process is shown in Fig. 9.

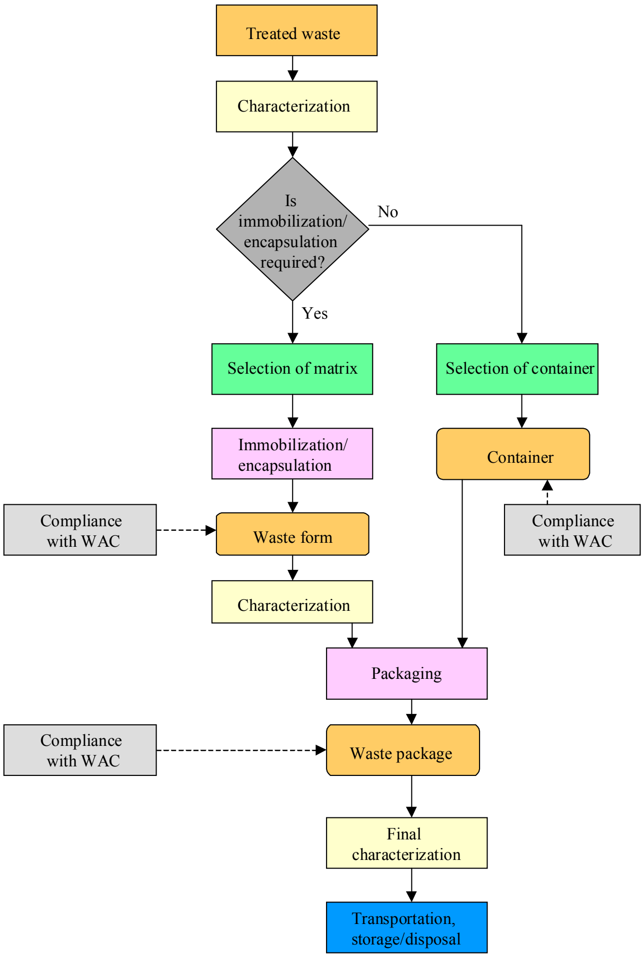


FIG. 9. Management steps for waste conditioning.

4.5. STORAGE

Storage is an integral part of the waste management strategy and should be provided for conditioned waste as well as for untreated/unconditioned (primary) waste. In this publication the discussion is restricted to radioactive waste package prepared for interim storage, including conditioned spent fuel, HLW and sealed radiation sources; decay storage of unconditioned waste is also included. Storage for short periods for processing purposes and area storage of LILW awaiting transport to the available final are not discussed in this publication.

Radioactive waste to be placed for storage has to comply with certain requirements established by the operator of a storage facility. In general, these requirements are that:

(a) The waste should be packaged in such a way that the package integrity can be assured during the entire planned storage time;

(b) The surface dose rate and contamination level of the storage package should comply with the requirements of the storage facility;

(c) Each storage package should be uniquely and durably identified.

The design features of storage facilities may vary greatly depending on the objective of storage, characteristics of the stored waste and period of storage [58]. The design of storage facilities should meet national regulatory standards and basic safety principles. In this context, the facility should be capable of maintaining the ‘as received’ integrity of the waste package until it is retrieved for disposal. The storage facility should protect the waste from environmental conditions, including extremes of humidity, heat and cold or any other environmental condition, which would degrade the waste form or container. Local climatic conditions may result in the need for cooling or dehumidifying of the store atmosphere, in order to avoid possible deterioration of the waste packages.

As far as the siting of a storage facility is concerned, it should be situated above the groundwater level, and certainly not in a flood plain. In areas of high rainfall, the facility should be constructed with appropriate systems to protect against intrusion of groundwater.

The main features and limitations of storage facilities for untreated and conditioned waste are given in Table 15; additional details on technical options are presented in Ref. [1]. Waste storage facilities by design vary from a simple steel safe to a sophisticated engineered facility what is reflected in the Table 15.

TABLE 15. WASTE STORAGE METHODS

	Storage method	Feature	Limitations
Decay storage of unconditioned waste	Safe, cabinet, room, ISO container, plastic containers, tanks	Used for decay storage of short lived unconditioned (liquid and solid) LILW and DSRS Low cost and simple construction Suitable for waste contaminated with radionuclides with a half-life up to 100 days.	Segregation of waste with regard to chemical compatibility Separation of storage areas for different categories of waste Applicable to limited volumes of waste May require shielding depending on dose rate
	Existing buildings	Can be used for all types of short lived unconditioned waste Sufficient storage space Facilitates a provision for separate storage of different waste categories Suitable for waste contaminated with radionuclides with a half-life up to 100 days.	May not be economical choice if extensive upgrading is required Licensing could be difficult
	Wet storage in water filled basins	Used for SNF and high activity sealed sources (e.g. 60Co) Good shielding to protect personnel and environment Centralized away from reactor facilities can provide high capacity for SNF storage	High cost High degree of technical expertise to design and operate such a facility Needs water purification and cooling system
	Dry storage	Used for SNF Used in the form of shielded casks Can be built inside a building or in the open Possible to use as dual purpose (storage and transport) casks	Requires cooling system Long procedures for initial licensing

Storage method		Feature	Limitations
Storage of conditioned waste	Subsurface storage (engineered shallow trenches)	Used sometimes for low dose rate LILW Low cost and easy operations of waste emplacement Not a prudent solution unless adequate environmental monitoring is implemented	Implementation of environmental monitoring measures could be expensive Not a practical solution for high dose rate LILW because of difficulty to retrieve and carry out inspection of waste packages. Storage time is limited High cost of waste retrieval Need for favourable climatic conditions
	Area storage (open vaults)	Placement of waste packages on the ground or on a constructed base Requires waste to be packed in durable containers Can be used for high dose rate LILW packages with adequate shielding (containers/walls)	Need for favourable climatic conditions Waste containers subject to corrosion under environmental conditions Storage time is limited
	Engineered storage (buildings or structures specifically provided for storage of waste packages)	Widely used storage solution in most Member States. Can be used for low dose and high dose rate LILW as well as for conditioned HLW Building design can be tailored to the climactic conditions, waste characteristics and quantities Provision of suitable environmental conditions possible to protect waste packages from degradation Provision for cooling of heat generating waste Suitable for long term storage Easier to meet WAC requirements	High cost of design, construction and operation, especially for HLW

Untreated waste materials are often stored due to practical reasons (e.g. to allow short lived radionuclides to decay) or as a buffer in view of optimal use of the treatment facilities. Storage for decay is particularly important for radioactive waste resulting from medical uses of radioisotopes since many radioisotopes are short lived and the activity of the waste produced is well defined. Practical experience shows that on site decay storage is suitable for waste contaminated with radionuclides with a half-life up to 100 days. Where large volumes of short lived radioactive wastes are produced, it may be more convenient to partition the short term decay storage facility to provide areas for storage of wastes according to their half-life.

Storage of conditioned radioactive waste in engineered facilities is characterized by the fact that it is controlled, that the material is retrievable, that maintenance and, if required, secondary packaging (overpack) remains possible, and that the material can be transferred to a final location in the future. Conditioned wastes including SNF, vitrified HLW and long lived waste have been safely and securely stored in a number of countries for several decades. Such storage could continue for many more decades, given proper controls and supervision as well as repacking of some waste and periodic refurbishment of stores.

In recent years, some countries have begun to consider whether the roles of storage might be expanded to provide longer term care of long lived solid radioactive waste and spent fuel.

Consideration of such expanded roles is linked to discussion of alternative strategies for the long term management of long lived solid radioactive waste and SNF, i.e., that final disposal is not necessarily the end point or that it might only be implemented after an extended period of storage.

In general, long term storage involves packaging radioactive wastes and storing them in purpose built facilities. Stores can be either above ground or below ground in the form of a single central facility or a range of local facilities. Above ground facilities can be designed to withstand foreseeable attack. With periodic refurbishment, long term interim stores might last for 100 years or more, depending on the design.

There are various motives for considering long term storage, though the most common include:

(a) Immediate and practical reasons, e.g. the need to gain greater public acceptance for disposal strategies and (in countries with smaller amounts of radioactive waste) that disposal would be more economical if a larger volume of waste is accumulated;

(b) Future strategic reasons, e.g. related to the possible development of regional or multi-national final solutions or developments in technology.

Planning for extended periods of storage (involving multiple renewals of storage facilities), introduces significant uncertainties over which the present generation can have relatively little influence. One of these uncertainties is the possibility that such storage might become the end point by default (instead by design), which is considered by many to be unsatisfactory and, inherently, unsafe.

Other disadvantages of this option relate to the possible degradation of waste packages owing to radiolysis, oxidation and other reactions, which would result in the potential release of some radionuclides, as well as the loss of information over time, especially if different waste batches are mixed together.

4.6. TRANSPORTATION

Solid or solidified waste should be adequately packaged and contained for transport by road, rail, air or sea in accordance with the national legal requirements. These national legal requirements should be based on the requirements established in Ref. [19] or in international agreements.

The on site transport of radioactive waste may not need to meet all the requirements for off site transport, because the shipment is under the control of the facility operator at all times. Operators should establish requirements and authorizations to ensure the safety of on site transport and although such an exposure is unlikely, take into account in the site emergency procedures the possible exposure of a member of the public as a consequence of the on site transport of waste.

4.7. DISPOSAL

Disposal is emplacement of waste in an appropriate facility without the intention to retrieve it. Disposal is generally applied to wastes in solid form placed in a suitable container and which may be first conditioned to a suitable stable waste form to facilitate safe handling, storage and disposal as part of a multi-barrier approach which can include the engineered disposal configuration and geological environment, with the aim of minimizing the risk of migration of radioactive materials to the biosphere. Some countries also use the term *disposal* to include *discharge*s of effluents to the environment [26, 59-61]. However, liquid or slurry wastes which cannot be discharged would normally be conditioned to a stable solid form for disposal.

The selection of a disposal option depends on many factors, both technical – such as waste characteristics and inventory, and administrative – such as the radioactive waste management policy, overall disposal strategy in the country (how many facilities), national legislative and regulatory requirements, political decisions and social acceptance and the conditions of the country such as climatic conditions and site characteristics, availability of suitable host media.
All disposal designs aim to prevent or reduce interaction between water and waste. There are many ways of doing this: choice of site (arid region, unsaturated, mountainous site, etc.), choice of depth (near surface above/ below grade, intermediate depth, deep geological), water resistant cap (runoff drainage layer, clay barrier) or long lived containment (borehole disposal concept (e.g. BOSS) concept).
A primary issue also is protection of inadvertent human intrusion and the degree to which a combination of depth of disposal, institutional controls and engineered barriers can be relied upon to prevent or minimize this exposure scenario.
Decisions on disposal technology selection should follow a graded approach. The following principles would typically apply in the implementation of such an approach:

- Wastes are disposed using the simplest disposal concept available, consistent with the hazards present and for which safety and environmental protection can be demonstrated;
- The most hazardous wastes are disposed using greater levels of engineering to provide for increased containment and/or are disposed at greater depth to increase isolation from the surface environment;
- Where existing disposal facilities are available, consideration is given to using them before developing new disposal facilities. This may require additional analyses and regulatory authorizations not addressed by existing WAC and operating procedures.

The IAEA Waste classification scheme (Fig. 10) provides a general system of classification accommodating various waste types and disposal solutions and gives a useful initial consideration despite that it simply identifies boundaries with associated quantitative guidance but does not prescribe specific disposal solutions for certain waste types (as specific safety assessment for each disposal facility is required) [15].

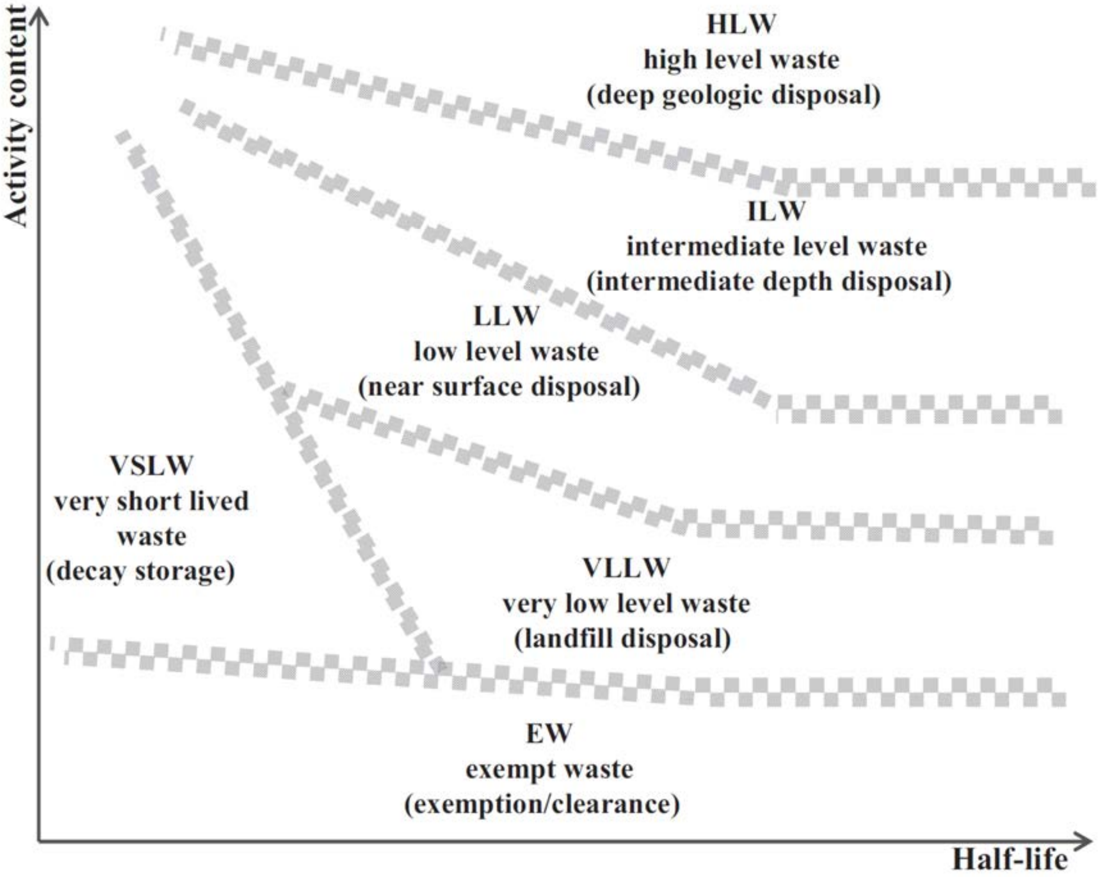


FIG. 10. Schematic of IAEA radioactive waste classification scheme [15]

LILWs can arise in a wide variety of forms and types and a diverse range of disposal solutions have been proposed and implemented for these waste categories, examples being: landfill, unlined or lined trenches, engineered surface or subsurface facilities, relatively shallow cavities, former mines, disposal in geological formations and borehole disposal. In all cases it is important to recognize the unique hazards of the specific subcategories of LILW, for example ILW containing predominantly short lived radionuclides may not require the same disposal methods as ILW containing predominantly long lived radionuclides. In case of DSRS the half-life (short or long lived) and the activity plays a key role. The following sub-section provides an overview of relevant disposal approaches for the various waste categories.

4.7.1. Overview of disposal approaches

Increased levels of activity and longer half-lives require increased measures to be taken to isolate the waste from inadvertent human intrusion and to minimize the migration of activity back to the biosphere. Increasing depth of disposal with increasing hazard level of the waste is a key parameter used to achieve these goals. However, it is noted that depth is just one of the factors that should be considered for the safety of waste disposal: the properties of the host rock formation, the waste characteristics and engineered features of the facility, regulatory constraints, national policy, etc. are other factors of equal or greater importance.

Normally three depths are considered suitable for disposal of radioactive waste, depending on the half-life and activity of radionuclides: near surface (shallow), intermediate, and deep (geological). Disposal facilities could be of a trench type, vaults, tunnels, shafts, boreholes or mined repositories. A depth of 30 m is used to differentiate between near surface disposal and disposal at intermediate and greater depths. This depth is widely accepted as the lower level of the 'normal residential intrusion zone' (i.e., a depth beyond which human intrusion is limited to drilling and significant excavation activities, such as tunnelling, quarrying and mining) [60]. Deep facilities are generally considered at depths greater than about 300 m (depths generally associated with geological repositories) and intermediate depth facilities in the range from about 30 to 300 m below the surface.

These depths only serve as examples as site specific conditions and safety assessments will dictate the actual facility depth and the need for an engineered barrier system (EBS). The combination of engineered barriers and natural barriers can contain radioactive material until it has decayed to insignificant levels, and provide sufficient isolation and containment to ensure an adequate level of protection for people and the environment.

In the absence of institutional control, a depth of 30 m is considered the minimum necessary to achieve waste isolation. This should therefore be the minimum depth required for waste that might constitute a security risk. However, for waste that would otherwise be eligible for near surface disposal and for short lived radionuclides (where the waste may no longer constitute a hazard after, perhaps, one hundred years) another option is disposal at a shallower depth together with institutional control. Engineered anti-intrusion barriers that are mechanically strong and heavy may also be useful in enhancing isolation.

Higher activity and longer lived waste requires a greater degree of isolation [15, 16]. Specifically, radium, americium and plutonium are of particular concern for disposal because the half-lives of these radionuclides are longer than the period over which many engineered containment features will be effective. Consideration of greater depths and the use of or enhancement of engineered barriers raises the possibility of using intermediate depth and deep geological repositories.

The main features of various disposal approaches are given in Table 16.

TABLE 16. WASTE DISPOSAL METHODS

Disposal method		**Features**	**Limitations**	**Waste subject to disposal**
Landfill sites used for domestic and industrial wastes		Simple and easy to construct and operate No institutional control for disposed wastes Existing facilities can be used	Poor containment and isolation	Exempt waste VLLW
Near surface facilities	Simple near surface facilities (trenches)	Excavated trenches covered with a layer of soil Simple and inexpensive Used historically for short lived LLW Activity concentration limits should be established	Erosion, intrusion and percolation of rainwater may affect the performance Decay to negligible levels during institutional control period (e.g. 100–300 years) is required Risk of fast migration of radionuclides to biosphere	Waste containing radionuclides with very short half-lives (VSLW), e.g. those often used for research and medical purposes

Disposal method		Features	Limitations	Waste subject to disposal
	Engineered near surface facilities	Multi-barrier approach to enhance the safety of disposal Engineered vault repositories Long experience with operation Ease of waste emplacement and increased efficiency in the management and closure of the repository	Institutional control (e.g. 100–300 years) is required Erosion, intrusion and percolation of rainwater may affect the performance	LLW with short lived radionuclides at higher levels of activity concentration, and also long lived radionuclides, but only at relatively low levels of activity concentration.
	Near surface borehole or shaft facilities	Alternative or complementary to near surface vaults. Economical option and also minimizing the probability of human intrusion	Size and quantity of waste packages is limited Institutional control for up to e.g. 300 years is required	DSRS
Intermediate depth facilities	Intermediate depth shafts or boreholes without EBS	Attractive disposal option for small volumes of waste such as radioactive sources The depth is adequate to eliminate the risk of erosion, intrusion and percolation of rainwater Flexibility in design Possibility to use existing disused cavities (e.g. mines)	Limited or no contact between percolating water is required Applicable in very low permeability host rocks, with little or no advection of groundwater Good backfilling and sealing is required Extensive characterization of the site required	Disused sealed radiation sources such as ^{90}Sr, ^{137}Cs, ^{238}Pu and ^{241}Am
	Intermediate depth shafts or boreholes with EBSs	Attractive disposal option for small volumes of waste such as radioactive sources	Significant water inflow or the geotechnical characteristics of the geological materials is allowed Waste containers and packages are important elements in the EBS	Disused high activity sealed sources
	Intermediate depth repositories	Massive concrete vaults or silos, with additional EBSs such as clay backfills and buffers	High cost Extensive characterization of the site required	ILW – waste that will not decay sufficiently within the period of institutional control
Deep facilities	Deep boreholes without EBSs	Containment of radionuclides is provided by the geological barrier No requirement for supplementary EBSs Lower flow, more stable chemistry and longer potential return paths to the biosphere	High cost Limited volumes of disposed waste	Disused high activity and long half-life radioactive sources
	Deep boreholes with EBSs	Containment of radionuclides is provided by the geological barrier Use of higher flow environments encountered in more permeable geological formations is possible.	High cost Limited volumes of disposed waste	Disused highactivity and long half-life radioactive sources

Disposal method	Features	Limitations	Waste subject to disposal
Mined geological repositories	May comprise caverns or tunnels with varying types of EBSs Containment of radionuclides is provided by the geological barrier Suitable for all waste categories Enhanced confinement	No operational experience for HLW and SFW High capital cost Assurance of site integrity for above 10 000 years required Extensive safety and performance analyses required Suitable geological media required	High level vitrified waste and encapsulated spent fuel Long lived LILW Disused sources of any activity and half-life

4.7.2. Landfills

Landfills have been used for the disposal of both exempt and VLLW. Exempt waste is the waste that meets the criteria for clearance, exemption or exclusion from regulatory control for radiation protection purposes as described in Ref. [7]. Exempt waste is acceptable for disposal in landfill sites used for domestic and industrial waste (and for hazardous waste if appropriate). VLLW is radioactive waste which does not necessarily meet the criteria of EW but does not need a high level of containment and isolation and therefore is suitable for disposal in near surface landfill type facilities with limited regulatory control.

4.7.3. Near surface facilities

4.7.3.1. Simple near surface facilities

Simple trenches have been used for many decades for the disposal of short lived LILW. They are generally considered appropriate only for those wastes and disused sources that will decay sufficiently within an anticipated period of institutional control (generally between 100 and 300 years) to represent no risk to the public, as determined by safety assessments. The design and function of such repositories are described in Refs [61-63].

4.7.3.2. Engineered near surface facilities

Large scale (typically thousands of cubic metre capacity) near surface engineered vault repositories have similar containment objectives and are used for similar types of radioactive waste as simple trenches. Their engineering is intended to allow ease of waste emplacement and increased efficiency in the management and closure of the repository. As with simple near surface facilities, the design and function of such repositories are described in Refs [61–63]. The issue of post institutional control intrusion can still be a dominant factor in waste acceptability.

For the near surface disposal option, a performance assessment is also required to determine either that the activity of the radioactive waste can be contained until it has decayed, or, if some migration is anticipated, that consequent doses are acceptable.

4.7.3.3. Near surface borehole or shaft facilities

Near surface shafts and/or boreholes can be considered as an alternative or a complement to near surface vaults. These disposal options are economical and also help to minimize the probability of human intrusion. If necessary an EBS can be added to the design and construction of these facilities to provide additional protection against radionuclide migration and human intrusion. More heavily engineered near- facilities have been designed with the specific intention of reducing the likelihood of intrusion by placing a massive concrete plug or cover over a large shallow shaft or borehole. For example, a reinforced concrete slab at least one metre thick is considered to be a deterrent to inadvertent intrusion. These intrusion resistant designs [61-63] could be helpful if institutional controls break down before the typically envisaged 300-year period; however, they do not offer sufficient guarantee against intrusion to be considered for disposal of higher activity or longer lived waste as compared to those suitable for disposal in near surface repositories.

4.7.4. Intermediate depth facilities

4.7.4.1. Intermediate depth shafts or boreholes without EBSs

Radioactive wastes that are not suitable for near surface disposal facilities because they will not decay sufficiently within the period of institutional control may be suitable for disposal at greater depth in disposal units characterized by one of several configurations.

With the exception of deep tunnels and mines, it is uncommon to find construction work (e.g. deep foundation engineering) carried out at depths greater than 30 m [64], so disposals at depths greater than this are only vulnerable to intrusion by deep drilling for water or mineral exploration – a much lower probability. As a result, the intrusion exposure risks posed by higher activity waste disposed of at intermediate depths are small.

Shafts or boreholes to depths of several tens of metres or more are relatively simple to construct and can offer an attractive disposal option for small volumes of waste such as radioactive sources [65]. Evaluation of such options needs to consider the stability of the hydrogeological system over the time period of concern for containment, which may be several hundreds or thousands of years depending on the types of radioactive sources to be disposed of.

Very low permeability host rocks, with little or no advection of groundwater, can also provide adequate containment without the need for additional EBSs. Some clay and claystone formations at intermediate depths can provide such an environment, and evidence of lack of flow can be obtained from pore water environmental isotope analyses and evaluation of any fracturing that may be present in the rock.

The isolation capability of this option depends on the ability to provide good shaft or borehole backfilling and sealing. The use of natural materials that reconstitute the original properties of the penetrated rock formations is recommended for all or some part of the sealing system. This may involve removal of some lining or casing to allow sealing against the host formations.

4.7.4.2. Intermediate depth shafts or boreholes with EBSs

If the disposal borehole/shaft is subject to significant water inflow or the geotechnical characteristics of the geological materials do not allow the excavation to be sufficiently stable, an EBS needs to be emplaced to provide a level of containment commensurate with the hazardous life of the waste.

Waste containers and packages are important elements in the EBS and need to be designed to complement the other elements of the containment system, both human made and natural. The design of containers and packages should be closely related to the definition of WAC for the specific disposal option. The actual composition of the EBS has to be defined on the basis of the specific characteristics of radioactive waste and the geological environment. The requirements are essentially to use the right combination of materials and to enforce appropriate quality assurance measures.

4.7.4.3. Intermediate depth repositories

There are some disposal facilities for radioactive waste in large rock cavities at depths of several tens of metres, generally in hard crystalline rocks such as granite (e.g. in Sweden and Finland). They are designed to contain short lived LILW. The containment provided by such repositories often comprises massive concrete vaults or silos, with additional EBSs such as clay backfills and buffers.

This type of containment should be adequate for the disposal of many if not all types of radioactive waste. For emplacement of high activity waste in a mined, intermediate depth repository, it is necessary to consider packaging and activity concentrations that suit the thermal characteristics of the host rock and EBSs of the repository. In addition, disused mines and/or caverns can be considered for intermediate depth disposal.

4.7.5. Deep facilities

4.7.5.1. Deep boreholes without EBSs

Deep boreholes without EBSs have not been widely used for the disposal of radioactive waste. The purpose of using deeper boreholes at depths typical of geological repositories would be to achieve greater isolation for limited volumes of radioactive waste, including disused radioactive sources, in an environment that is characterized by lower flow, more stable chemistry and longer potential return paths to the biosphere. In a very low permeability environment (some clay and claystone formations), there may be no effective water movement at depths of a few hundreds of metres. In such conditions, provided an adequate borehole seal can be constructed, the geological barrier provides containment of radionuclides and there is no need for supplementary EBSs beyond those needed to emplace the radioactive sources into the borehole and to maintain borehole stability during emplacement operations (casing and cementing).

The option is particularly suited to the highest activity and long half-life radioactive sources, for which long containment periods are required (e.g. ~10–20 half-lives or more). For example, strong ^{226}Ra sources could require isolation for 20 000 to 30 000 years. The depth and design of disposal also significantly reduces the likelihood of inadvertent intrusion, resulting in exposures to high concentrations of radionuclides before sources have decayed. If a facility of this type were developed for such sources, it would also be technically suitable for the containment of any weaker, shorter half-life sources in the disposal inventory, if this appeared to be a sensible solution economically and logistically.

4.7.5.2. Deep boreholes with EBSs

As with the previous option, such facilities have not been widely used for the disposal of radioactive waste. The objective would be the same, i.e., to move radioactive waste to an environment that is characterized by lower flow, more stable chemistry and possibly longer return paths to the biosphere compared with the disposal options at shallow or intermediate depths.

For this approach, additional EBSs are emplaced around the radioactive source containers so that adequate containment can be achieved in the higher flow environments encountered in more permeable geological formations. As with the previous option, if it appears to be feasible economically and logistically this route is technically suitable for the containment of any weaker, shorter half-life sources in the disposal inventory.

4.7.5.3. Mined geological repositories

Many countries that have nuclear power industry wastes to manage are developing mined repositories comprising caverns or tunnels with varying types of EBSs. They are designed to contain long lived LILW, HLW and spent fuel. The containment provided by all such repositories is expected to be adequate for the disposal of all types of radioactive waste, provided that legal and regulatory requirements on repository inventory permit (some countries have strict constraints on the types of waste that can be placed in specific repositories which are purely legal and unconnected with safety and performance). In addition, disused deep mines and/or caverns could be considered for geological disposal

4.7.6. Screening of disposal options

Taking into account the available disposal options it would be possible to describe a simple process for their screening (shown in Fig. 11) and for identifying the most appropriate one(s). Consideration should be given to the entire radioactive waste source inventory in the country. Consideration of only one type of waste at a time may lead to the identification of a number of separate disposal options, whereas logistical and cost considerations may lead to the choice of one disposal option for the entire waste inventory.

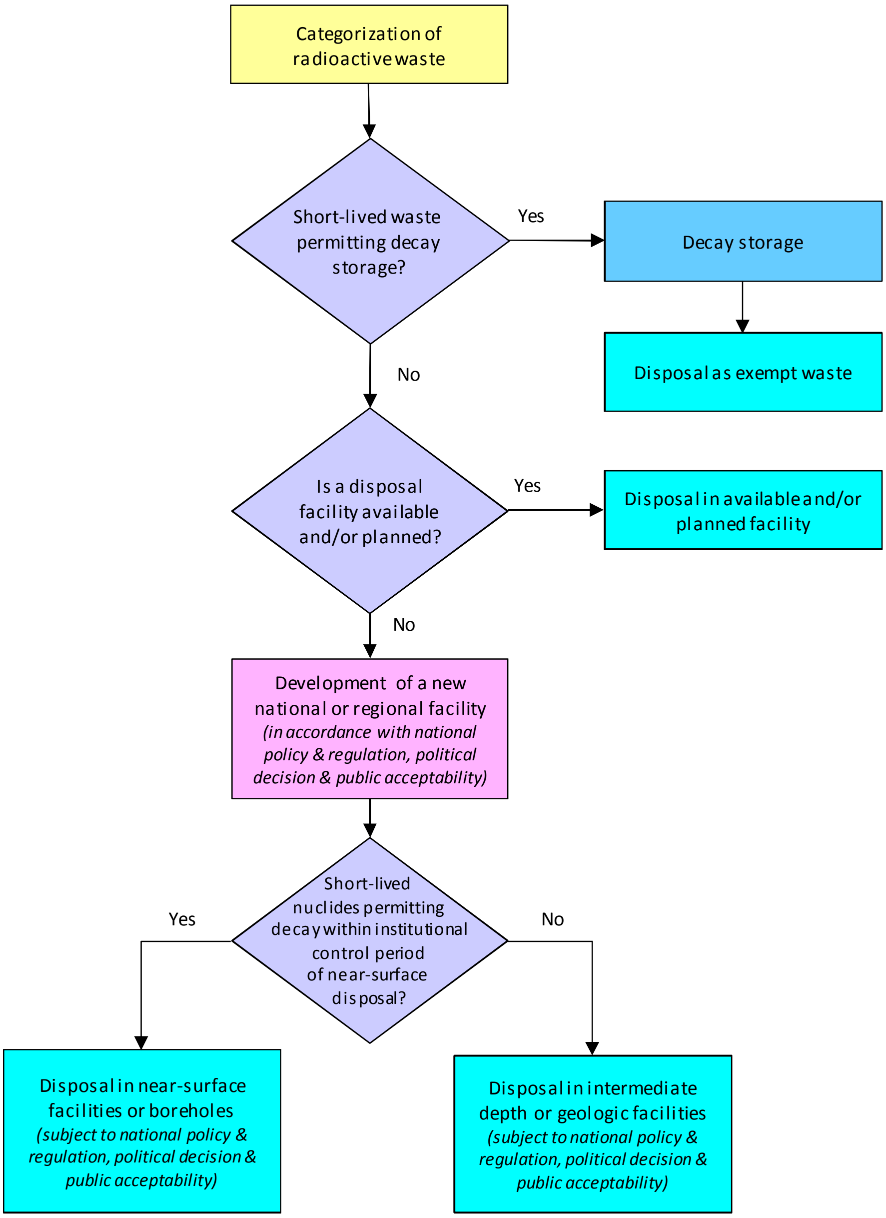


FIG. 11. Screening of disposal options.

Table 17 presents an example of a simple matrix screening approach using appropriate criteria for identifying a suitable disposal option. Safety is the fundamental objective of radioactive waste disposal and several options can be excluded from the perspective of safety considerations. Other options can be ruled out on the grounds of technical reasons (not feasible, difficult to implement, etc.). Based on the generic safety considerations and the characteristics and volume of waste, potentially acceptable or preferable disposal options can then be identified. There might be options which need to be more closely assessed from technical and economic aspects.

TABLE 17. EXAMPLE SCREENING MATRIX FOR INITIAL IDENTIFICATION OF FEASIBLE DISPOSAL SOLUTIONS. COURTESY OF PETER ORMAI, IAEA

🟥 **Not possible for safety reasons**	🟪 **Not possible for technical reasons**	⬜ **Possible but needs to be assessed from technical or economic aspects**	🟢 **Acceptable**	🟩 **Preferable**

Radioactive Waste Stream		END POINT						
		Decay Storage	**Surface Trench**	**Tailing Dam**	**Engineered Surface Facility**	**Intermediate depth disposal**	**Geological repository**	**Borehole disposal**
VSLW	Low volume	🟩	🟢	🟢	🟢	⬜	⬜	⬜
	Large volume	🟩	🟢	🟢	⬜	⬜	N/A	N/A
VLLW	Low volume	🟥	🟩	🟩	🟢	⬜	🟪	⬜
	Large volume	🟥	🟩	🟩	🟢	⬜	🟪	🟪
LLW	Low volume	🟥	🟢	🟢	🟩	🟩	🟢	🟢
	Large volume	🟥	⬜	⬜	🟩	🟩	🟢	⬛
ILW	Low volume	🟥	🟥	🟥	🟥	🟩	🟩	🟢
	Large volume	🟥	🟥	🟥	🟥	🟩	🟩	🟥
SNF/ HLW		🟥	🟥	🟥	🟥	🟥	🟢	🟥
DSRS	Short lived	🟢	🟢	⬜	🟩	🟢	⬜	🟢
	Long Lived	🟥	🟥	🟥	⬜	🟩	🟩	🟩
	SHARS[1]	🟥	🟥	🟥	🟥	🟩	🟩	🟩
NORM	Low volume	🟥	🟩	🟩	🟢	🟢	⬜	⬜
	Large volume	🟥	🟩	🟩	⬜	⬜	⬜	🟪
Uranium M&M	Low volume	🟥	🟢	🟩	🟢	🟢	🟢	⬜
	Large volume	🟥	🟢	🟩	⬜	⬜	⬜	🟪

The process described in Fig. 11 and Table 17 lead to a preliminary identification of a disposal option. It does not consider additional factors such as the cost, available geological settings, complexity of site characterization, resources required to demonstrate site specific safety, public acceptance, transportation, occupational exposures and other factors that should be considered in final decision making. Also, it does not include consideration of the

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[1] SHARS – Shielded high activity radioactive sources

alternatives that may be available when options are linked to potential disposal sites. Therefore the process in Fig.11 and Table 17 is used only to identify and screen options for input to a broad decision making methodology.

Factors to be considered in reaching a decision on a disposal concept include:

(a) The inventory of radioactive waste that requires disposal and the likely future arisings of waste that may need to be disposed of;

(b) The national infrastructure for managing radioactive materials;

(c) National policy and strategy regarding the disposal of radioactive waste;

(d) Regulatory requirements governing the disposal of radioactive materials;

(e) Possible arrangements or the potential for sharing disposal solutions on a regional basis;

(f) The conditions of the country such as climatic conditions, availability of suitable host media with respect to potential disposal solutions;

(g) The technical and financial resources available for disposal;

(h) Social, political and ecological issues.

In the first step all radioactive wastes are identified and categorized according to their radiological properties, as discussed in Section 3. The key considerations in this step and subsequent steps are the half-life and activity of each waste stream in the disposal inventory.

Options for combining or segregating types of waste to produce batched inventories should be considered if they could be designed to match a range of available disposal options. Then wastes that may not require disposal in a waste disposal facility are identified on the basis of their half-lives and activities. These wastes are those that could decay to safe levels during a relatively short period (a few tens of years) of monitored storage. Such storage would be followed by disposal as EW according to national regulations and practices. This waste could also be disposed of in existing near surface, intermediate depth or geological repositories.

Radioactive waste containing radionuclides with longer half-lives and higher activities than those discussed above will require disposal as radioactive waste in licensed waste repositories. In considering a disposal option for these wastes, disposal at existing or planned national facilities is preferable. Acceptance of waste at such disposal facilities depends on the repository's WAC, available disposal volume, cost of disposal and local societal considerations.

If no repositories are available or likely to become available in the near future, a new facility might be required to accommodate greater volume of waste. This facility could be regional or a national repository. In either case the remaining steps in this process of identifying and screening disposal options are the same.

The next step is to assess whether or not the remaining waste inventory under consideration will decay to safe limits within the envisaged institutional control period for near surface facilities. In this publication it is assumed that all near surface disposal facilities are subject to a period of institutional control.

Typical institutional control periods range from 100 to 300 years, but some facilities have used extended institutional control (e.g. to 500 years), or no control period. In practice, the duration of a site specific institutional control period should be established in consultation with authorities prior to making the decision on disposal options. Once the institutional control period has been established, an assessment can be made as to whether or not the waste inventory will decay to safe limits within the designated time period.

The definition of safe limits will depend on the facility's characteristics and the scenarios under consideration. For example, it may not be necessary for decay to reach clearance levels within the institutional control period but only to reach acceptable levels consistent with scenarios and exposure routes appropriate for the facility.

Near surface disposal is appropriate for waste with radionuclides that will decay to safe limits within the institutional control period. Therefore, the next step in the process for those sources is to choose the type of near surface facility that is appropriate for the specific waste. The volume of waste to be disposed of is a key consideration at this stage. Disposal in shallow boreholes can be considered for small volumes of waste. On the other hand, if the total volume of waste is sufficiently large that it cannot be disposed of in shallow boreholes, consideration of disposal in shafts, with or without EBSs, may be necessary. These wastes could also be disposed of in intermediate or deep disposal facilities.

For radioactive waste which will not decay to safe levels within the institutional control period, deeper disposal facilities that offer additional long term protection are needed. Again, the first option is to identify existing deeper facilities that may be usable for waste disposal. Disused mines and caverns may provide the degree of safety required for the sources. Such caverns and mines exist in a number of countries in environments which reduce the potential for migration into the biosphere.

Where disused mines and caverns do not exist, new facilities will have to be developed. Aside from safety a major consideration in the development of such a new facility is the minimization of cost and associated resources. For small volumes of waste (e.g. disused radioactive sources), disposal in deeper boreholes may be the preferred option. If the total volume of all sources to be disposed of in a given country is small enough to fit within a single borehole, this deeper borehole solution will clearly make sense for the entire inventory.

If the volume of waste is too large to be disposed of in boreholes, it may be necessary to consider disposal in shafts. Shafts are essentially large boreholes, but they are based on a different drilling technology and the costs associated with their development are greater than those for drilling boreholes.

Where a wide range of radioactive waste has to be disposed of in a given country, an efficient and flexible disposal facility may use several designs at the same site. For example, near surface pits or vaults and variable depth boreholes may be used at a single site. This solution may also be appropriate for countries that already have licensed near surface repositories at which these additional facilities for source disposal could be located.

Radioactive waste storage and conditioning facilities might also be located at the same disposal site.

Once a decision is taken concerning the disposal of particular radioactive waste, its packaging needs to be assessed. Any existing packaging may be judged to be adequate or may need modification, based on the proposed disposal option. The design of disposal packages for radioactive sources is determined by operational and post closure safety considerations and, if the disposal is to take place in disposal units with limiting dimensions (such as boreholes), by size limitations. Radioactive waste packages that are acceptable for disposal would be expected to meet the relevant WAC for the disposal facility. The following considerations are thus relevant mainly for packaging and for developing WAC for dedicated disposal facilities - principally shafts and boreholes deeper than the near surface options.

Waste package size and design and the requirement for other engineered barriers will vary according to whether shaft or borehole disposal is selected, the nature of the radioactive sources, and the isolation capacity of the host rock. These requirements need to be established by means of a facility specific operational and post closure safety assessment.

The package might be expected to contribute to the isolation of the radioactive waste by preventing or limiting the release of radionuclides into the geosphere. Two approaches can be applied to ensure longevity of the containment: use of corrosion resistant materials, and use of a thick walled container that would require a sufficiently long time to corrode. In both cases the effects of the physical and geochemical environment in the disposal zone play an important role.

The matrix in which the radioactive wastes are immobilized will have a significant effect on the properties of the waste package and can strongly influence its required performance.

4.7.7. Disposal of NORM waste

NORM waste is generally deposited in consolidated and over-covered piles or sludge beds, or purpose designed repositories with lined cells and protective capping [42]. As it is not feasible to move such large amounts of material, the waste tends to be disposed of on the site of its generation. Capping and some engineered structures may be used to prevent erosion and to limit the leakage of radioactive gases. In some cases, the waste has been disposed of by using it to backfill disused underground mines.

There is growing evidence to suggest that bulk wastes contained in properly engineered surface impoundments have very low radiological impacts. However, their environmental, safety and financial liability implications can be seriously underestimated. This has been demonstrated in the case of phosphogypsum stacks, where recent developments have suggested that the stacking option is not optimal and that more attention should be given to beneficial uses of the material.

Landfill disposal has been demonstrated as being an appropriate option for dealing with many types of NORM residue for which the quantities and activity concentrations are moderate, including most types of furnace dust with enhanced concentrations of ^{210}Pb and ^{210}Po. Normal landfill facilities are generally suitable, but the presence of non-radiological contaminants such as heavy metals may require the use of landfill sites specially designated for hazardous waste.

NORM residues from the chemical extraction of rare earths from monazite are produced in significant quantities and have characteristically high activity concentrations. It has been demonstrated that such wastes can be suitably disposed of either in earthen trenches or in engineered cells, depending on the activity concentration.

4.7.8. DSRS

The safe management of DSRS includes the following activities:

- Identification;
- Collection;
- Either return to a suppler or another user;
- Conditioning;
- Interim storage;
- Disposal.

The preferred practice is to return the disused source to a supplier or other organization for further use. Most new contracts for the purchase of sources contain a clause for the return of the sources once they are disused. However, this method is not available for many old sources as the original suppliers may be unknown or defunct. Also in some cases for which financial constraints have hindered the return of disused sources, the cost of packaging and transportation may be considerable.

In some countries, for example, it may not be possible to dispose of long lived disused sealed sources because deep geological repositories are not available. In this case return to the suppliers or recycling (overseas) may be the best, if not the only, option. Encapsulation of disused sealed sources in an irretrievable form (e.g. by direct encapsulation in cement) will only serve to complicate future handling of the waste. Encapsulation of sources in containers that are large or varied in size may have negative impacts on transportation, storage or disposal if it is necessary to repackage the source. It is much simpler to employ small packages of uniform size. If larger packages are required, then the variety of sizes should be limited to one or two types to facilitate handling of SRS which cannot be returned to a supplier or to another user.

Conditioning can be carried out either on site or at a specific conditioning facility. There are simple methods for conditioning of disused sources in a metallic drum filled with a cement grout [66]. Large sources used for sterilization and irradiation should preferably be sent back to the supplier. Immobilization of such type sources is typically done using metallic matrices such as lead or lead based alloys [52, 67, 68]. The recommended conditioning method for radium sources is either immobilization in a metallic matrix (lead) or encapsulation in welded stainless steel capsules and placing the capsules inside a metallic 200 L drum filled with concrete for shielding purposes.

A particular problem exists with the disposal of powerful (so-called Spent High Activity Radioactive Sources, SHARS) or long lived DSRS. Often existing near surface repositories do not accept such type conditioned spent sealed sources for disposal because of the long time periods required to achieve exemption or clearance levels. Reference [67] discusses management approaches for SHARS and long lived DSRS.

The flowsheet in Fig. 12 depicts the steps that are required for the management of disused sealed sources.

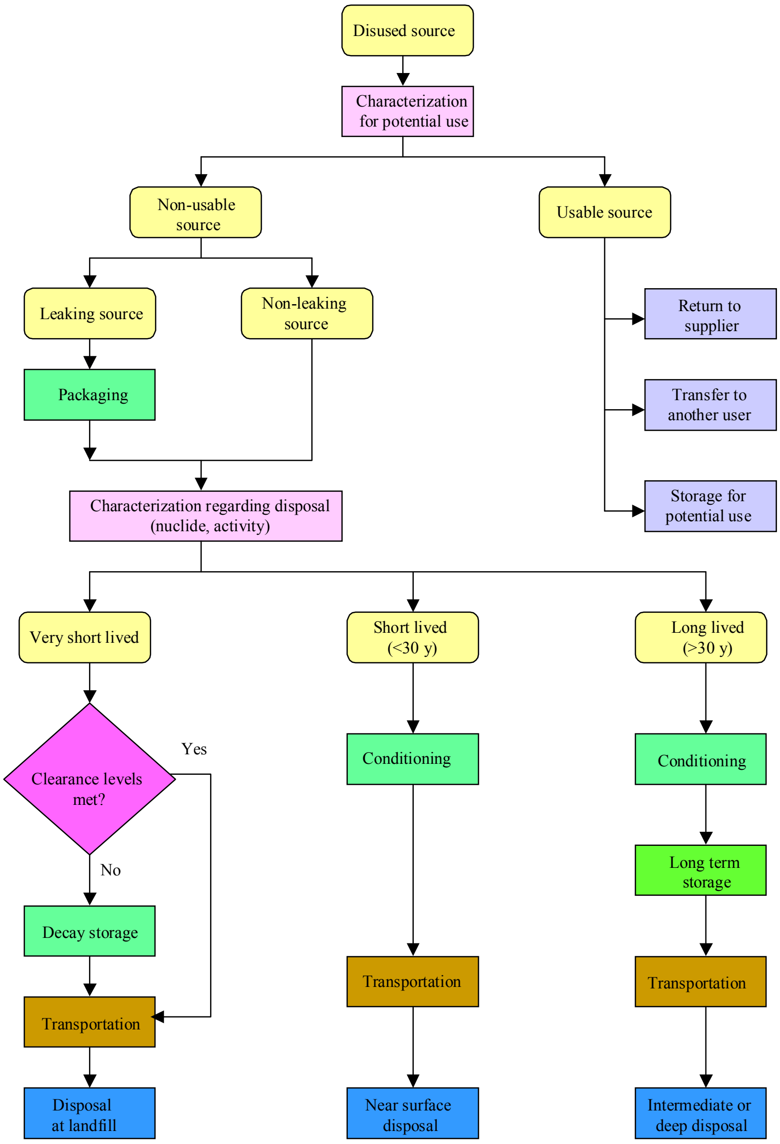

FIG. 12. Management of DSRS.

References [67-69] provide further guidance on management and disposal options for DSRS, including discussion of the borehole disposal concept (BOSS) which may be suitable when no national repository for wastes of the relevant waste category exists or is planned.

5. SELECTION CRITERIA

5.1. POLITICAL AND SOCIOECONOMIC CRITERIA

5.1.1. Compliance with regulations

Legal requirements have a significant influence on the selection of waste management technologies. In most countries, the management of radioactive waste should be conducted within an extensive framework of regulations, rules and norms issued by national and/or state governments or regulatory authorities. The national regulations often relate to nuclear safety, dose limitations of radiation exposure, transport and disposal requirements, whereas specifications for handling, treatment, conditioning and storage are imposed by state nuclear competent authorities or national waste management organizations. It is necessary to integrate the requirements imposed by different regulatory authorities and assure compliance with them during design, construction and operation of waste management facilities.

Consistent with national regulatory requirements, a safety assessment of the facility and its operation, as well as an environmental impact assessment, are normally required for new waste management facilities and practices. Such assessments should demonstrate compliance with national regulatory requirements and provide a basis for the Regulatory Body to review and approve the facilities or practices.

If a waste treatment/conditioning facility is located away from the nuclear facilities generating the waste, it will be transported to this facility according to the national transport regulations. Moreover, only in very rear cases disposal facilities are collocated with waste conditioning facilities. It means that the waste packages produced for eventual disposal should also be transported to the repository. The transport regulations in many countries are based upon IAEA Safety Standards Series No. STR-1 [19]. IAEA regulations specify the requirements for packaging and labelling, define shipping categories of radioactive materials according to their radioactivity content, and determine acceptable radiation dose levels. The waste packages prepared for disposal and to be transported to the repository shall comply with the transport regulations or additional packaging shall be provided.

International legal instruments have a significant influence on radioactive waste management in Member States. States that are parties to international conventions need to comply with their requirements, which may restrict or require certain waste management activities or options. In this respect, the Joint Convention on the Safety of Spent Fuel Management and the Safety of Radioactive Waste Management imposes binding obligations on Member States party to it [70].

5.1.2. Financial resources

A basic non-technical factor, which may greatly affect the selection of a waste management technology, lies in the financial resources of the Member State and its willingness to commit them to an established and progressive waste management programme. The lack of adequate funding could result in non-compliance with regulations and safety requirements, or inability to provide most basic services. A Member State should not embark on a programme leading to use of radioactive materials (including nuclear power generation) until the financial impact of that decision is fully understood. The cost, eventually borne by its citizens, may be high.

The structure and mechanism of funding may vary from one country to another. A government that promotes the use of nuclear energy/applications typically supports related R&D and regulatory control of the waste. The waste generator, to a certain extent, may be charged with a certain portion of the cost of management by the central waste management operator. Countries which rely on the import of equipment and materials for processing (e.g. radiation monitors, gamma spectrometers, chemicals, steel drums) may be affected by import controls and currency depreciation.

The cost of different technologies can vary greatly. Consequently, the choice of technology may be greatly influenced by economic considerations [18]. In an effort to take account of cost considerations effectively, the total life cycle cost should be considered. Total life cycle cost covers:

- All costs for investment, depreciation, operation, decommissioning, and manpower;
- Costs associated with handling of secondary waste;
- Costs related to surveillance and monitoring;
- Costs for additional research and development, demonstration, validation and/or adaptation.

Waste processing and disposal, and all intermediate steps of waste management, are costly activities. Reliable cost figures may not be available during initial stages of planning, but in any case volume reduction will reduce the volume – and thus, the cost – of waste material to be disposed. To the extent possible, all cost components should be considered so that potential areas for optimization can be identified, especially for nuclear activities which generate large amounts of radioactive waste.

Nonetheless, the selection of waste management technologies should not be governed solely by cost considerations. For example, more efficient treatment and conditioning processes can result in higher volume reduction, but may increase the exposure of operating personnel; safety, among other priorities, should always be taken into consideration. Furthermore, more expensive options may be selected to meet other technical requirements, such as the availability of materials, compatibility with existing equipment or conformity to national practices.

The higher cost of the most advanced waste management methods – which could best satisfy long term requirements – should not be an obstacle to their adoption. Experience has shown that inadequate waste packaging/immobilization and/or poor storage/disposal site physical characteristics can result in loss of isolation before the end of the waste's hazardous life, leading to additional costs that could have been prevented.

5.1.3. Manpower and personnel competence

It is important to consider the availability of manpower with a certain level of personnel competence for operation, maintenance and for secondary interventions, such as facility and product surveillance. The level of the competence available locally will influence the selection of waste management technologies. For example, in small facilities operating for limited waste generating programmes, the availability of qualified manpower may be a challenging criterion in the selection of a waste management technology.

The difficulty of retaining trained personnel should also be taken into consideration. Waste management activities in some Member States are relatively small, and key personnel are often attracted by better offers from other waste management agencies external to the country. Moreover, trained personnel are often multidisciplinary, and are moved to the job where they are most needed.

5.1.4. Physical infrastructure

The extent to which waste management technology options can be adopted greatly depends on the availability of basic physical services, including transport, communication and on site services. Accessibility to a site, availability of a transportation system and local factories which may produce components (e.g. waste containers) needed for the waste management facilities, are some examples of infrastructure constraints which can affect the process of selecting optimum waste management technologies.

5.1.5. Research and development

All technologies used in the nuclear and radiochemical industry have been underpinned by extensive R&D programmes. R&D programmes are expensive and demand highly qualified staff, and new processes will require extensive development to support design and licensing. With the worldwide deployment of many mature technologies that have proven and robust processes, the use of 'Best Practice' may limit the scope or even the need for further R&D. However, selection of an 'immature technology' will require some R&D investment.

For small and limited producers of waste, scientific investigation may be limited to ensuring the waste is compatible with the process, e.g. treatability testing or characterization of waste; these services could be performed by contractors.

5.1.6. Public involvement and political acceptance

The establishment of a waste management facility generally requires public participation in order to gain public acceptance. Failure to inform and involve the public and political decision makers can result in rejection of a particular waste management technology or the proposed area designated for the development of a waste management facility.

An effective public information programme will be a useful effort in addressing concerns among members of the public. To the extent appropriate, the public should be brought into the process of site and technology selection. Neglecting such measures can result in a negative impact on public perception, especially when there is organized opposition to the construction of nuclear facilities.

There is also a compliance obligation in conjunction with the 1998 Aarhus Convention on public access to environmental information [71], which requires availability and accessibility of information and provide the general public with the right to be involved in a decision making process on environmental matters. Compliance with the requirements of this convention may reduce the negative perception of planned waste management facilities and installations. The public should be informed at appropriate stages of facility development and societal issues should be addressed throughout these steps.

5.1.7. Facility location

Facility location is also an important factor in technology selection. Three main choices for the location can be taken into account: (1) on site facility; (2) centralized (national or regional) facility; and (3) mobile facility.

On site management may involve handling, treatment, conditioning, and storage without movement of the waste from the site of its generation, and may also include on site disposal. While this option eliminates the hazards associated with transportation to centralized facilities, it involves the development and maintenance of redundant capabilities for waste management for each facility operating. Also if disposal is not permitted locally, on site storage is mandatory and accumulation of waste with concurrent safety problems may become a concern.

Centralized management may govern many of the waste management steps, including the transfer of waste to a single location accessible by all waste generators. For this purpose, a transportation system will be needed for transferring the waste from the generation sites to the central facility. Generators will then be required to prepare the waste according to specifications for transport and criteria for acceptance of waste by the central facility.

To minimize the amount of waste transferred to a centralized facility, a mixed system of on site storage for decay and packaging for transport based on total activity and half-life could be introduced.

The third solution is the use of mobile systems, which can be transported among multiple nuclear sites for processing campaigns. The application of mobile technologies increases flexibility in choosing the optimum waste management approach for the actual needs of the local plant or country, and helps to control implementation costs. Typically a mobile system is used at a site for one to three months, but in some situations it may remain at the same site for several years (e.g. when using a supercompactor to recover some of the storage capacity of a ten year accumulation of drummed and stored waste).

The geography of a State can influence the suitability and the location of waste management facilities. For example, the location of a central facility may be affected by the distance to the main waste generators (in order to optimize transport of radioactive waste) and a large territory may affect the decision on establishing one or more centralized facility(ies), as the cost and difficulty of transport would be too high. Also, high population density and extensive use of land resources for agriculture may have an impact on the site selection for a waste management facility. In such a case, the waste processing facility may be designed to accommodate these particular constraints.

5.1.8. Opportunity for international cooperation

The availability of waste processing techniques and capacities in other States (especially in neighbouring States) should be considered when selecting a waste management technology. It may be possible to send the waste to another country, e.g. for treatment and immobilization, or to hire equipment from neighbouring countries to facilitate, a process such as volume reduction. Bilateral or regional cooperation agreements and projects can save money and reduce potential hazards to the population. Regional waste processing centres, storage facilities, and even disposal sites can provide a significant step forward in bringing the benefits of nuclear energy many countries of a region.

Other forms of international cooperation to achieve the waste management objectives include exchange of staff and agreements to accept certain types of waste, e.g. spent fuel from research reactors or DSRS. These agreements may be made by one country on behalf of another for a number of reasons, including, but not limited to non-proliferation agreements, technology transfers or international cooperation.

The IAEA Technical Cooperation programme provides considerable assistance to Member States in the field of radioactive waste management by supplying typical tools and equipment. The programme also makes it possible to train local waste management personnel through different mechanisms and to provide qualified expertise on technical issues related waste management issues.

5.2. TECHNICAL CRITERIA

5.2.1. Scale of technology application

The quantity of waste and its rate of generation will have a considerable influence on the scale and design of the waste management facility. In general, large quantities of waste will require specialized, more dedicated facilities and equipment. The application of advanced technologies may not be economically justified in some waste management schemes when there are insufficient waste volumes to be processed. When the volume of waste to be treated is large, a high efficiency treatment facility should be considered. Embodied in the scale of application is a choice between a facility co-located with the waste production sites, a central facility to which waste is transported, or a mobile facility that moves to generating sites.

On the other hand, small volumes of waste will require simpler, less expensive and more generic equipment and facilities. When the volume is low, high investment may not be justified and other approaches can be considered, such as mobile treatment equipment (including skid mounted equipment), transporting waste to a central waste processing facility (national or regional), or use of an alternative treatment method.

Some processes may be restricted to small scale applications by design, such as those which require manual handling (e.g. preparation of disused radioactive sources for storage/disposal) or new processes for which extrapolation to a large scale application may require further development and evaluation. Some equipment may have limited throughput, for example, bounding monitoring time by physical size and residence time; in this case alternative monitoring arrangements or multiple parallel units may be desirable. Other processes are characteristically large scale, such as supercompaction of solid waste, evaporation of aqueous effluents, etc.

5.2.2. Maturity of the technology

Although there are numerous technological options for management of radioactive waste, reliable information about the maturity of the various processes should be collected. Mature technology refers to technology that has been in use long enough that most of its initial faults and inherent problems have been removed or reduced by further development. In some contexts, it may also refer to technology which has not seen widespread use, but whose scientific background is well understood.

One of the key indicators of a mature technology is its ease of use for both non-experts and professionals. Another indicator is a reduction in the rate of new breakthrough advances related to it. Whereas inventions related to a (popular) immature technology are usually rapid and diverse – and may change the whole use paradigm – advances to a mature technology are usually incremental improvements only [72].

In the nuclear industry there are always cost saving and risk reducing advantages to using mature technologies and avoiding first of a kind processes, over sophisticated solutions and extensive development programmes. This is particularly true for generators of small volumes of waste, who can benefit from established best practices associated with mature technologies, which can lower costs and risks. Moreover, a large investment is often required to provide a new processing technology, which would have to be economically justified.

5.2.3. Robustness of the technology

Robustness is the quality of being able to withstand stresses, pressures or changes in procedure or circumstance. A system or design may be said to be ‘robust’ if it is capable of coping well with variations (sometimes unpredictable variations) in its operating environment with minimal damage, alteration or loss of functionality. Its application to radioactive waste management refers in general to the reliability in varying conditions of operation and maintenance, but in particular to:

- Sensitivity of the technology to the composition and variation in nature of the input waste (e.g. slurries, combustible and non-combustible solids, aqueous waste concentrates, ion exchangers);
- Sensitivity to operating parameters;
- Dependence of the process on up front detailed characterization of input materials;
- Complexity of startup, maintenance, shutdown and decommissioning operations.

Deficient robustness may have to be compensated by careful pretreatment, e.g. by segregation, homogenization and characterization of primary waste, or local availability of other processing technologies or more qualified operators. Since the pretreatment intervention is costly and may lead to additional personal exposure, robustness, even if it is adequately defined, is an important criterion in the selection process.

If a process is not robust it will require detailed characterization of the waste before treatment, may not accommodate changes in the waste characteristics, and may require personnel with high qualification and training.

5.2.4. Flexibility and adaptability of the technology

Flexibility is an attribute of various types of systems. In the context of engineering design, one can define flexibility as the ability of a system to respond to potential internal or external changes affecting its value delivery, in a timely and cost effective manner. Thus, flexibility for an engineering system is the ease with which the system can respond to uncertainty in a manner to sustain or increase its value delivery. Uncertainty is a key element in the definition of flexibility. Uncertainty can create both risks and opportunities in a system, and it is with the existence of uncertainty that flexibility becomes valuable.

Adaptation of technologies that are used within other (non-nuclear) industries, applied to a different waste stream, or applied to actual waste management needs is also an important factor which facilitates successful use of well developed processes.

These criteria address a balance between a small, simple, specific technology (to which the generator of a single waste stream might resort) to a larger, more versatile unit that might be used at a central treatment facility. Flexibility represents the difference between a well tuned technology that is highly effective for one waste stream and another that is applicable for many waste types. For example, biological processes may be able to degrade and destroy specific toxic organic materials (e.g. polychlorinated biphenyl and polycyclic aromatic hydrocarbons) and can operate at low capital cost, while an incinerator can destroy virtually all organic materials but carries a relatively high capital cost.

The field of application will also influence the technologies selected. For example, a waste that can be readily handled can use simple, manually operated technologies. A HLW will require substantial levels of shielding, which in turn may necessitate the use of low maintenance systems and remote handling technologies. Waste bearing high levels of α-contamination may require technologies that can be deployed in glove boxes or contained cells.

5.2.5. Complexity and maintainability

The principles of simplicity of design and operation are particularly important in the nuclear industry. Complex technological processes are not better than simple ones. Features that such a simple process might exhibit are:

- Few or no moving parts;
- Commonly available reagents for use;
- Stable process, easy to control;
- No need to have an exceptional level of technical competence to operate;
- Easily accessible components.

A complex process will often have high capital and operating costs and lower plant availability due to maintenance needs. The technical factors that will influence maintenance (including for example, removal, decontamination, repair, replacement, etc.) and the process downtime might be:

- Simplicity;
- Radiation resistance (hardening);
- Corrosion resistance;
- Wear resistance;
- Contamination resistance.

Failure to consider these factors could result in unacceptable system failures and downtime.

5.2.6. Integrated programmes

An integrated programme is one in which a collection of technology development activities with related technical disciplines or potential applications is managed as an integrated development process. Typically the technology products associated with an integrated programme are applicable to single or select related operational steps. An example of an integrated programme is one examining the waste processing component destruction that includes the technology development process for supercritical water oxidation, molten salt destruction and supercritical CO_2 reduction, as well as technology products for pretreatment and waste processing steps.

Technologies from outside the nuclear industry – including academia, commercial industry (both domestic and foreign), research establishments, hospitals and other governmental agencies – can be transferred into the integrated programme technology development process. Nuclear industry oriented technologies can also be transferred to other potential applications, such as environmental remediation.

An integrated demonstration provides a mechanism for focusing technology development efforts and developing a waste management system. Typically the integrated demonstration will be conducted at a ‘host’ site, addressing a problem that is of high national priority and/or is common to numerous sites. While most of the demonstration efforts will be conducted at the host site, there will be participation by sites that have common or similar problems or resident technical expertise or other capabilities applicable to the demonstration. Thus certain supporting efforts may be conducted at these sites and will be coordinated and integrated into the integrated demonstration.

An integrated demonstration also serves as a mechanism to integrate various technologies into a system that can address all operational steps. This system view includes examining interface requirements between technologies and support requirements such as training, maintenance, special support equipment, management of secondary waste streams, etc. Understanding the interactions of the various technologies as a system allows for a better optimization of the system to be implemented and for the transfer of the system or component technologies to other applications or to other sites.

5.2.7. Safeguards and nuclear safety

The technical factors in this section are of particular importance for Case A and Case B Member States where waste containing fissile materials will be processed. Typically these criteria will include:

- An ability to confirm the concentration and quantity of fissile material throughout the process (e.g. accountancy tank);
- Control of fissile mass in a unit process by geometry or fissile content monitors;
- Shielding;
- Containment;
- Restriction of access.

5.2.8. Site availability and location

Site availability and location have implications for both waste treatment and disposal. Several socioeconomic and technical factors should be taken into account, including geology, hydrogeology, hydrogeochemistry, seismicity, climate, proximity to natural resources (mineral, drinking water, forests, etc.) and primary materials (water, power, personnel, etc.). The technology choices will depend on the availability of sites. In their planning processes, Member States dedicate a significant degree of effort to selecting a site that is both fit for the purpose and technically acceptable. The types of technical decisions made against these criteria might, for example, be a greater reliance on engineered barriers for groundwater control in an area with a significant groundwater flow compared to a site in an arid region. These factors will be taken into account in any performance assessment of a site or activity.

As with site selection, intrusion is an issue both for operating sites (inadvertent or malicious access to facilities) and disposal sites (largely inadvertent access to waste by mining, drilling, water extraction, geological survey, etc.).

The response might include a security system for operating a site. For a repository that has been closed, massive barriers (engineered) in geological remoteness might be appropriate.

6. METHODOLOGIES FOR TECHNOLOGY SELECTION

The selection of pretreatment, processing, storage and disposal technologies is necessarily bound into an overall strategy for waste management, and this in turn may be part of a larger scheme embracing many waste types. To achieve a satisfactory waste management strategy, waste management components should be complementary and compatible with each other [1].

Many aspects have to be addressed; the challenge is to achieve the optimal solution in a logical, structured and justified way. An existing IAEA publication has already reviewed the most important factors affecting the selection and implementation of waste management technologies [73]. As it was mentioned above, the technology for waste management should be commensurate with the use of nuclear materials in the State [74].

The extent to which waste management efforts are considered necessary is essentially based on the nuclear activities being pursued in a State.

For a State that makes use of but does not produce radionuclides (Case D), efforts could be minimal and complex technologies would not be required. With multiple isotope applications, only the volume of waste and its diversity in nature would increase; the technology (or technological) inputs for managing waste would be substantially similar.

For a State seeking to operate research reactors (Case C), some significant technological applications will be needed for waste management, mainly due to the presence of radionuclides (mainly fission products and some activation/corrosion products) of somewhat longer half-lives (up to 30 years). Some of the nuclides would need to be isolated from the human environment for a period of about 300 years. However, after necessary conditioning the volume of waste from research reactor operation will be small enough to manage with interim storage provisions for up to a few decades until a disposal option is developed.

If a State chooses to operate nuclear power plants for producing electricity (Case B), a considerable degree of existing technological competence would support management of both spent fuel and radioactive wastes.

If a State seeks to reprocess the spent fuel or condition the spent fuel for direct disposal (Case A), it should carefully examine the technological infrastructure available within the State and externally in preparation for the need to isolate HLW (either from reprocessing or from spent fuel conditioning) from the biosphere for several thousands of years.

In any case, it is important to ensure that all three basic waste management routes (i.e. clearance, authorized discharge or use, and regulated disposal or transfer) as well as national waste management policies and strategies are taken into account and evaluated for all waste streams generated at a facility or site, rather than for individual waste streams. In addition, most national regulators now demand an assessment of possible technologies and a justification of the selected technology.

The process of selecting a waste management technology typically starts by collecting and assessing available data on all potentially influencing factors, including applicable regulations, waste properties, waste routes and associated good practice indicators. A set of possible technological options is then devised, together with a preliminary waste management plan for implementing each option. These plans can be relatively brief at this stage but should be sufficiently defined so that the associated major hazards and risks can be visualized. The next step is to perform technology selection studies, for which formal decision aiding techniques and ‘workshop’ discussion sessions can be employed.

Selection of a preferred or optimized waste processing technology is best achieved through the evaluation of the general criteria and constraints in terms of their attributes for a specific waste stream or facility (see Table 18). This evaluation can benefit from the use of formal decision aiding techniques that address the influencing factors and associated good practice indicators. Commonly used techniques are discussed in this section. (It should be noted that some constraints might eliminate specific technologies, as addressed in Section 4).

TABLE 18. TECHNOLOGY RELATED CRITERIA AND ATTRIBUTES

	Criteria	**‘Good practice’ attributes**
1	National policy and strategies	Compliance with the intent of national polices and strategies In the case of insufficient national policies and strategies, compliance with international ‘good practice’
2	Regulatory framework	Compliance with the requirements of the regulatory framework In the case of insufficient regulatory framework, compliance with international ‘good practice’ Clearance levels are set up Mechanism for authorized discharged is established
3	Funding and cost	Both direct and indirect costs (e.g. stakeholder involvement and public acceptance) addressed Total cost of the viable technology evaluated or compared and technology selected/eliminated in terms of main cost factors Adequate financial resources or financial security and funding mechanisms available for the funding of viable technology
4	Health, Safety and Environmental (HSE) impact	HSE impacts of viable technologies known and considered in the selection of technologies; HSE impact optimized by reducing exposure of the workforce and the members of the public The need for transportation of radioactive material is minimized
5	Waste characterization	Identification of all sources of waste generation Waste characterization developed and can be implemented at all stages of the waste management process
6	Waste management system	Waste management system exists and can support the newly introduced technology Storage/disposal facilities available Operational waste generation control programme in place
7	Human resources	Availability of suitably qualified and experienced personnel Consideration of lessons learned from implementation of other technologies
8	Social impacts and stakeholder involvement	Technologies discussed with stakeholders and considered in a transparent way All stakeholders involved in the selection of a technology and reasonable consensus reached
9	Technical factors	All technical factors affecting the selection of a technology (e.g. maturity, robustness, complexity and maintainability etc.) are taken into account
10	Physical infrastructure	Physical structure is available and can support the newly introduced technology

6.1. LINEAR DECISION TREE APPROACH

When evaluating the various influencing factors for a specific technology option, a simple ‘decision tree’ approach can be adopted. The limitations of a linear approach are that influencing factors may only be considered independently, and in descending order of priority. Project selection decisions require multiple, generally non-linear, objectives to be optimized simultaneously. In addition, factors that are mutually influential cannot be considered in combination. An example of the simplified decision tree approach for the selection of a suitable technology for a particular waste stream is given in Fig. 13. (Note that not all criteria and constraints are presented in this figure).

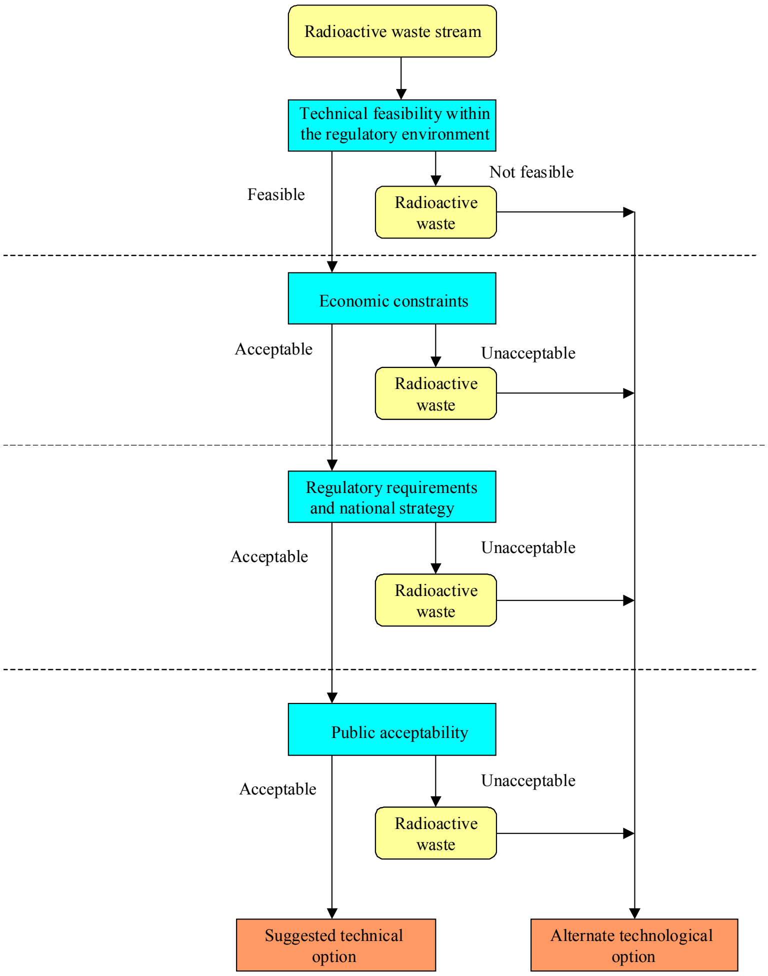

FIG. 13. Linear decision tree approach for the selection of a technology for a particular waste stream.

6.2. COST BASED APPROACH

6.2.1. Methodology

A proven project management methodology widely used in both nuclear and other industries involves dividing the project into phases and establishing a detailed Work Breakdown Structure (WBS) for each phase. The WBS allows the logical development of a detailed cost estimate based on each contributor to the costs, e.g. acquisition costs for each piece of equipment and labour costs for each process (e.g. engineering, environmental approvals). The

WBS is used as a basis to understand all aspects of the work involved and is the basis for developing the schedule of the project. The WBS includes the costs for each project, including estimates of non-facility or process costs such as infrastructure needs (roads, transport equipment, etc.).

Each waste management facility goes through three phases: a *pre-operational phase* of planning, design, construction, and commissioning; an *operational phase;,* and once its function is no longer required, a *post-operational phase* consisting of decommissioning and dismantling. In the nuclear waste management field, ongoing monitoring costs can also be incurred for many years during the post-operational phase.

While it is not possible to present a comprehensive description of the cost based approach, the basic flow chart below (Fig. 14) provides a useful guide for further detailed work. This report represents guidelines for estimating the costs of radioactive waste management and shows how cost estimates can be used to screen alternative technologies and processes or life cycle management options for managing radioactive waste. The report also shows how detailed costs of each process step can then be used to develop the total overnight costs of waste management for a particular waste stream, and how present value techniques can be applied to the overnight cost estimates in order to assess the relative economics of different life cycle management options for a particular waste stream. Factors which can affect the uncertainty in overnight cost estimates are also described, as well as how those uncertainties differ between projects and programmes to be implemented in the short term (less than10 years) and in the longer term (greater than 10 years).

Develop alternative waste management planning scenarios

Facility life assumptions and operational plans
Forecast of waste arising by type
Facilities needed e.g. storage buildings, disposal facilities
Opportunities to optimise/trade-off processes
Note: scenario must meet safety and regulatory requirements

Develop "screening level" cost estimates for each scenario

Cost estimates by process, technology or facility – utilize benchmarking information if available
Overall screening level cost estimate for life cycle of each waste stream
Note: Before scenario are chosen for detailed costing, "screening level" cost estimates can be used to identify favourite scenarios

Select one or two scenarios for detailed costing and further analysis

Develop detailed cost estimates for each process, utilising work breakdown structure
Overall detailed cost estimate for life cycle of each waste stream
Note: For detailed cost estimating a well developed and detailed work breakdown structure is recommended

Estimate present value of cost each selected scenario

Inputs:
Detailed "overnight" cost estimates (including cost flows) for each process/life cycle cost estimate by waste management stream, including fixed and variable costs
Labour and material escalation rates
Discount rates to be used (may be prescribed by regulation)
Current status of funding (if calculating funding requirements)
Outputs:
Present value of costs
Annual funding requirement by waste stream (if necessary)
Financial guarantees needed (if necessary)

Perform risk assessment

Key inputs:
Cost estimates uncertainty (i.e. ranges)
Economic indices uncertainty (i.e. ranges)
Timing uncertainty (e.g. in-service dates of facilities)
Output:
Confidence ranges around cost estimates and present value of costs of each scenario(s) chosen as an input to decision making

Select preferred waste management plan

FIG. 14. Process for developing plans, completing cost estimates and economic assessments.

Three basic cost categories associated with most undertakings, whether it is establishing a process (e.g. segregation process to separate ILW from LLW) or constructing a facility (e.g. storage or disposal facilities for radioactive waste) are:

— Up front investment costs related to such items as research and development, siting and land acquisition, design engineering, licensing activities (including community consultations), equipment acquisition, facility construction and closure (for disposal facilities);

— Operations and maintenance costs associated with the operation of the equipment or facility (e.g. waste processing operations, transportation costs, license renewals, environmental monitoring), as well as facility modifications and expansion costs such as design engineering, equipment acquisition costs, environmental assessment costs associated with the modification or expansion, etc;

- Post-operational costs associated with the decontamination of equipment and/or decommissioning of equipment and facilities at the end of their useful lives, managing the wastes from decommissioning the facility and post-closure ongoing monitoring.

A graded approach is suggested for application of the methodology. In using the methodology, it is important to bear in mind whether the costs estimates are being prepared for one or more specific waste management facility projects (e.g. a LLW storage building, an incinerator installation, a supercompactor, etc.), or whether the intention is to prepare a cost estimate for the full life cycle management of a particular waste stream or for the whole waste management programme (for which a particular entity is responsible, e.g. waste generator, waste management organization, the State).

Specific waste management facility projects are often planned for implementation in the short term, and the project or set of projects does not necessarily represent the whole waste management programme for the particular waste stream. In other cases, e.g. where a programme cost estimate is prepared for the full life cycle management of a particular waste stream or for the whole waste management programme consisting of several waste streams, the complexity of the cost estimating process and the long timelines result in significant uncertainty.

In general, each of the cost elements to be estimated will have the following cost components:

- Labour costs, i.e. the costs associated with people required to execute the process, construct the building(s), drive the transport vehicle(s), etc.;
- Material and equipment costs (e.g. building materials, equipment such as pipes and heat exchangers, tunnel boring machines, transport and work equipment, etc.);
- Other costs (e.g. utilities, supplies, etc.).

Moreover, depending on the stage of the cost estimating process, a contingency amount should be added either to each cost element or to the overall cost estimate.

As previously discussed, each waste stream can be processed through many steps, and several alternative routes with different cost characteristics (e.g. variable and fixed costs proportions) and risk profiles can be developed for a given type of waste. When all of these factors are considered, several hundred alternative processes (and hence, several hundred life cycle management options) can be developed for each type of waste. Therefore, it is essential to limit the number of alternatives considered to those which are feasible and operate within the constraints imposed by regulatory, economic and other constraints.

For Member States with well established waste management programmes and processes, the development of the total cost of the waste management for a particular waste stream can be obtained by summing up the estimated costs of the process steps. Total costs can also be broken down into fixed and variable costs, according to actual fixed and variable components.

Member States with large multi-site nuclear power installations can also benefit from inter-site comparisons of waste management volumes and associated costs, and can use this benchmarking information to identify opportunities for improvement. However, for Member States which are in the process of developing a preferred waste management strategy among several hundred possibilities, the process of developing the total cost for waste management becomes more complicated and may require the use of computer simulation techniques to identify the most cost effective and least risky route.

6.2.2. Risk assessment

The consideration of costs should include risk assessment. Risks may be inherent in any of the internal or external factors that could affect the success of the project, such as staff and customer resistance to change, immaturity of a new technology, personnel limitations, technology failures and expected changes in the technical, political or management environment [75, 76].

A performance estimate should include a list of the expected benefits of developing the system. Typical benefit categories include 'faster,' 'better,' and 'cheaper.' Therefore, the analysis should describe precisely how products or activities will be better, how much faster they will be, and how much less they will cost.

The analysis should also include a statement of how each benefit will be evaluated. Some measures will be relatively easy to describe in quantitative terms, especially those in the cheaper and faster categories. Others that we usually think of as qualitative (e.g. 'customer satisfaction') can often be translated into measures through surveys and interviews.

Cost, risk and performance analyses are needed to support a final decision on technology selection. Decision makers need to be able to anticipate costs and benefits of a technology prior to making a decision on project implementation. The results of cost–benefit and cost performance analyses also form an important part of the project evaluation. After the project is completed, these measures can be used to evaluate whether goals were achieved within the expected budget. This assessment is an important factor in planning for future activities.

6.2.3. Limitations

A comprehensive analysis of the project's impact may be difficult to prepare because of the complex environment in which public sector programmes reside and the many factors that may affect the intended outcomes of the project [75, 76].

Project managers are often more experienced with cost analyses, and it may be easier to develop projects that fit into the 'cheaper' and 'faster' categories. While these are definitely important, many innovative applications also address the 'better' category, which often requires more resource intensive assessment methods.

6.3. MULTI-ATTRIBUTE ANALYSIS

In addition to costs, other criteria and constraints are involved in the technology selection process. The application of MUA [5, 75, 76] is an effective and efficient approach to showing the impact of each technology option in terms of good practice attributes, which can also help with reaching conclusions that address all influencing factors. Such analysis involves assigning numerical ratings and weightings to the factors, followed by comparison of the resultant total scores for the options. If necessary (e.g. when two options have very close scores), a sensitivity analysis can be performed to check whether or not the preferred option is a robust choice. A simple scoring of the criteria in a given option allows options to be discarded or considered further. Regardless of the approach taken, it is necessary to produce a justifiable and auditable selection methodology.

MUA models are mathematical tools for evaluating and comparing alternatives to assist in decision making about complex alternatives; they can be particularly useful when groups are involved. To perform the analysis, all the attributes needed to evaluate the alternatives should be identified and assigned a weight that reflects their importance to the decision. For example, a value of 3, 2, or 1 might be assigned to each attribute according to its importance (alternatively, 100 points can be assigned and distributed).

For each attribute, each of the alternatives can be scored, e.g. on a scale of 1–10. The score for each alternative is then multiplied by the weight of that attribute; that total represents the value (or utility) of that alternative, and can be compared to the same calculation for the others. If it is a group process, each member of the group scores the attributes for each alternative and the group's ratings can be totalled or averaged. The result of an MUA analysis is a score for each option, which represents a relative, numerical ranking of the options (see Table 19).

Any evaluation of the various technological options should take into consideration a wide range of issues (such as those that are identified in Section 5), with special emphasis on the constraints imposed by the safety requirements and the resources available at the time of technology implementation. Furthermore, non-safety related matters (such as recycling of material as opposed to disposal) should be considered in the selection process. Where relevant, safeguards related issues should also be considered, e.g. in the decision making process for an optimal decommissioning strategy. The diversity of types of nuclear facilities makes characterization of the site and facility a critical step in the technology selection process because the waste generated defines the scope of the proposed project.

This analysis should be based on realistic estimates of the costs and radiation doses associated with a waste management facility that meets all the applicable safety requirements, including the cost of maintenance, surveillance and physical protection.

TABLE 19. EXAMPLE OF A GENERIC DECISION MATRIX WITH AQUEOUS WASTE TREATMENT OPTIONS

Option	**Feasibility of method**		**Availability of technology**		**Cost**		**Possibility for clearance or authorized discharge**		**Availability of technology for treatment and conditioning of secondary waste**		**Public acceptance**		**Final score**
	Weight (%)	Score	Weight (%)	Score	Weight (%)	Score	Weight (%)	Score	Weight (%)	Score	Weight (%)	Score	Score
Chemical precipitation	A_1	B_1	C_1	D_1	E_1	F_1	G_1	H_1	I_1	J_1	K_1	L_1	Σ_1
Ion exchange	A_2	B_2	C_2	D_2	E_2	F_2	G_2	H_2	I_2	J_2	K_2	L_2	Σ_2
Evaporation	A_3	B_3	C_3	D_3	E_3	F_3	G_3	H_3	I_3	J_3	K_3	L_3	Σ_3
Membrane processes	A_4	B_4	C_4	D_4	E_4	F_4	G_4	H_4	I_4	J_4	K_4	L_4	Σ_4
Biotechnological processes	A_5	B_5	C_5	D_5	E_5	F_5	G_5	H_5	I_5	J_5	K_5	L_5	Σ_5
Electrochemical processes	A_6	B_6	C_6	D_6	E_6	F_6	G_6	H_6	I_6	J_6	K_6	L_6	Σ_6
Combination of evaporation and membrane processes	A_7	B_7	C_7	D_7	E_7	F_7	G_7	H_7	I_7	J_7	K_7	L_7	Σ_7
Combination of chemical precipitation and ion exchange	A_8	B_8	C_8	D_8	E_8	F_8	G_8	H_8	I_8	J_8	K_8	L_8	Σ_8

An MUA model can also reveal the consequences of changing the attributes, their weights or the scores received. Since the criteria are open for all to see, it is possible to make any number of changes and review the results. For example, if it appears that some attributes are weighted too heavily, the weights can be adjusted to produce different results.

An advantage of MUA modelling is that it clarifies the basis on which the alternatives are being evaluated. This is particularly important in group decision making scenarios for which many viewpoints and selection options have to be considered.

Technology selection studies (even when using formal methods such as MUA) involve aspects that are inherently subjective and challengeable. Involving the public and other stakeholders in the technology selection process can strengthen and consolidate support for an ultimate decision.

Workshop sessions (sometimes called brainstorming sessions or decision conferences) can provide a practical and motivating way forward. In such sessions, a panel of relevant experts (including experienced operators) agrees on the list of influencing factors and then applies decision aiding techniques to assess the impact of these factors on each of the technological options. It is important to produce a report of the workshop sessions that describes the technique adopted, the considerations addressed and the results obtained. This report can be a valuable aid in support of the waste management plan and the associated safety justification.

The technology selection process and the subsequent detailed planning process are best approached by ensuring that the planning team clearly understands the underlying safety logic. This logic can be applied to each of the candidate options (at an appropriate level of detail) as part of the process of selecting a preferred option. The key point is to ensure that there is a demonstrated connection between the characteristics and amounts of radioactive waste at generation, the proposed technologies, associated risks in implementing these technologies, the resultant safety management arrangements, and costs. Analysis of the risks involved logically determines the requirements for key aspects such as additional or modified equipment, staff training, procedures, work instructions, maintenance and security arrangements.

7. CONCLUSIONS

The following general conclusions may be drawn from the evaluation:

- Before embarking on the selection of a particular technology, it is essential to research the waste generation process thoroughly and understand the volumes and characteristics of the waste to be processed,, the legal and regulatory regime (as well as national policy), and disposal options available, among other key issues. This is essential to developing and comparing options objectively.
- The selection of a technology should be based on the evaluation of all relevant criteria and constraints. Constraints associated with financial and human resources could limit the waste management technologies. In this case, it may be necessary to choose technologies that do not meet 'best practices.' Other conditions and constraints which are not dealt with in this report may exist, and are important to include in site specific evaluations.
- When constraints occur, management has to proactively take steps to remove the constraints or to eliminate or minimize their impacts.
- Techniques such as multi-attribute analyses can help decision makers take into consideration all the relevant criteria, constraints and conditions, their interactions and relative importance when selecting the appropriate technology.
- A full economic assessment is crucial to choosing among options, even though obtaining accurate data can sometimes be difficult, especially when assessing long range factors such as operating costs, maintenance costs and decommissioning costs. Many economic analyses have focused only on initial procurement, failing even to take into consideration the high costs of installation and operation.
- The need for and cost of ancillary facilities or service requirements should be taken into consideration in the overall processing needs assessment and in the economic assessment. For example, if the objective is to obtain a final conditioned waste package suitable for disposal, and if the selected technology is designed only for pretreatment or treatment, then the selection and cost of the subsequent conditioning technology should be included in the overall evaluation.
- It is often more economical to make use of centralized or regional waste treatment facilities. This is especially true for technologies with a high cost and high waste throughput demand, whereby the processing of waste from many waste generators will make the overall technology cost more economical.
- Possible return on investment may be enhanced if multiple waste types can be processed by a selected technology. When an expensive processing technology is designed for a single waste type or a narrow range of small volume waste streams, the cost per unit of waste processed can be far more difficult to cost justify.

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ABBREVIATIONS

BOSS	Borehole disposal concept
BSS	Basic Safety Standard
DF	Decontamination factor
DSRS	Disused sealed radioactive source
EBS	Engineered barrier system
EW	Exempt waste
GCM	Glass composite material
HEPA	High efficiency particulate air
HLW	High level waste arising from reprocessing
HSE	Health, safety and environment
ILW	Intermediate level waste
LILW	Low and intermediate level waste
LLW	Low level waste
MOX	Mixed oxide fuel
MUA	Multi-attribute utility analysis
NORM	Naturally occurring radioactive materials
NPP	Nuclear power plant
SHARS	Spent high activity radioactive sources
SFW	SNF declared as waste
SFW	SNF declared as waste
SNF	Spent nuclear fuel
SRS	Sealed radioactive sources
PMF	Powder metallic fuel
TECDOC	Technical document
TENORM	Technically enhanced NORM
VRF	Volume reduction factor
VSLW	Very short lived waste
VLLW	Very low level waste
WAC	Waste acceptance criteria
WBS	Work breakdown structure

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ISBN 978–92–0–104717-5
ISSN 1011–4289