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IAEA-TECDOC-2039

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Addressing Challenges in Managing Radioactive Waste from Past Activities

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International Atomic Energy Agency

ADDRESSING CHALLENGES IN MANAGING RADIOACTIVE WASTE FROM PAST ACTIVITIES

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INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2024

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Printed by the IAEA in Austria
January 2024

IAEA Library Cataloguing in Publication Data

Names: International Atomic Energy Agency.
Title: Addressing challenges in managing radioactive waste from past activities / International Atomic Energy Agency.
Description: Vienna : International Atomic Energy Agency, 2024. | Series: IAEA TECDOC series, ISSN 1011-4289 ; no. 2039 | Includes bibliographical references.
Identifiers: IAEAL 24-01651 | ISBN 978-92-0-102724-5 (paperback : alk. paper) | ISBN 978-92-0-102624-8 (pdf)
Subjects: LCSH: Radioactive waste disposal. | Radioactive wastes — Management. | Radioactive wastes — Storage. | Radioactive substances — Safety regulations.

FOREWORD

Radioactive waste is generated from operating nuclear power plants, nuclear fuel production and processing facilities and when applying nuclear techniques and technologies in medicine, industry and research. The decommissioning and dismantling of nuclear reactors and other nuclear facilities also leads to the generation of radioactive waste. In some countries, radioactive waste is also generated from defence related activities. All such waste needs to be managed in a way that keeps people and the environment safe over long periods of time. The IAEA has been supporting its Member States in adopting safe and effective solutions for radioactive waste management.

One of the areas needing special attention in this regard relates to the management of some of the waste generated from nuclear activities and applications carried out in the past, when adequate knowledge, technological advances, modern safety standards and quality management systems were not yet in place. Member States are now increasingly recognizing that such legacy waste needs to be managed in a way that is aligned with current safety requirements. The Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, which came into effect in 2001 and aims to achieve a high level of safety worldwide in radioactive waste management, also binds the Contracting Parties to review the results of past practices and document appropriate decisions related to the need to intervene due to various radiation protection reasons.

This publication aims to support the safe and effective management of radioactive waste from past activities by presenting focused information on the specific challenges associated with such waste as well as information on how to develop and implement strategies to address those challenges with the help of a range of real world examples. These examples were selected from the contributions provided by the participating representatives of Member States. It is hoped that the information provided in this publication will be of interest to the waste management community, particularly to those responsible for the safe and effective management of radioactive waste from past activities in their respective countries.

The IAEA wishes to express its appreciation to the individuals who took part in the preparation and publication of this publication. The IAEA officer responsible for this publication was F.N. Dragolici of the Division of Nuclear Fuel Cycle and Waste Technology.

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CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Some of the wastes generated from past activities remain a considerable challenge for the IAEA Member States, including those with established nuclear power and associated fuel cycle programs as well as those with waste arising only from nuclear applications. Feedbacks from many Member States participating in IAEA Technical Cooperation projects and events related to radioactive waste show that the management of these wastes is one of their key challenges. The International Radioactive Waste Technical Committee (WATEC) that advises the IAEA on radioactive waste management program activities and directions also identified the timely management of legacy, historic and problematic wastes as being a priority for consideration in future predisposal programs.

There is no official IAEA definition for legacy waste, but it is usually understood and agreed to refer to waste generated through past practices and, in some cases, include historical waste in old storage and disposal facilities that were intended to be a temporary state or are no longer complying with the safety requirements. Contaminated structures can also be considered as legacy waste, for example vault walls, pond surfaces, redundant tanks, etc.

In this publication, the terms 'legacy waste' is used for the waste generated as a result of past practices and that is either:

- Waste which does not have an identified route for safe disposal;
- Waste which does not have a predisposal concept and/or does not comply with defined Waste Acceptance Criteria (WAC) for storage and /or disposal; or
- Waste that is conditioned, stored, or disposed of in a form that does not comply, or no longer complies, with current regulatory requirements.

Legacy wastes are often of unknown provenience with little or no record of their origin or content, not well characterized, unsegregated and stored in improper conditions.

Although similar principles apply for legacy waste as those applied for characterization and processing of all radioactive wastes, often legacy waste requires more consideration and can be more costly and time-consuming. Many factors contribute to the complexities that waste managers face when establishing and implementing plans for safe management of their legacy waste inventories.

Over the years, a wealth of information and experience has been accumulated on the principles and practices related to the successful management of legacy waste. Some of this information and experience has been captured in several IAEA publications in the past. For example, one of the publications deals with the retrieval and conditioning of different types of solid radioactive waste from old storage facilities [1] and another publication brings together information on technologies and on-going national projects for the retrieval of sludge, ion exchangers, evaporator bottoms, crystallized salt waste, etc. from tanks, containers, vaults, and basins [2]. In many Member States, several so-called "problematic" waste streams have remained largely unattended because such wastes are not amenable for conventional treatment. A compilation of worldwide efforts to develop innovative technologies for the processing of such "problematic" waste streams is presented in an IAEA publication [3]. Guidance provided in the IAEA publication on strategy and methodology for radioactive waste characterization is also useful for the characterization of legacy waste [4]. Disused Sealed Radioactive Sources (DSRS) are often found mixed with other radioactive waste in old storage or disposal facilities. Some years ago, IAEA published a Nuclear Energy Series (NE) which provides guidance on locating, identifying, and characterizing such radioactive sources [5].

While this information is useful, it is recognized that a systematic approach to address the challenges of legacy waste management and lessons learned from past and on-going efforts will be helpful to the end-users in the Member States. Therefore, the present publication is an attempt to fulfil this need by showcasing several situations where legacy wastes were safely managed as well as the approaches that were applied depending on the safety requirements and local conditions.

1.2. OBJECTIVE

The main objective of this publication is to collect and describe some typical characteristics of legacy wastes and identify the major challenges to their management. In support, information gained through analysis of varied experiences, case studies, good practices and lessons learned are given, aiming to provide guidance on strategies for Member States to overcome these challenges, successfully manage their existing legacy waste inventories, and minimize the risk of their creation in the future.

This publication seeks to assist Member States by providing guidance on approaches to overcome barriers to management of legacy wastes and provides examples of novel applications of existing technologies, and proven strategies that have been used by Member States to manage similar waste streams.

1.3. SCOPE

This publication presents examples of legacy waste types, strategic and technical challenges in managing such wastes, and approaches to address these challenges. Such wastes could be generated from nuclear applications, operation of research reactors and nuclear power plants, defence programs (only those wastes without a path to predisposal or disposal) and decommissioning of nuclear facilities.

Wastes with a defined predisposal/disposal concept (e.g., vitrified waste) and wastes that have been processed in compliance with a defined Waste Acceptance Criteria (WAC) [6] are excluded from the scope of this publication. Although not explicitly excluded from the scope of this document mining and milling wastes, accident waste and Disused Sealed Radioactive Sources (DSRS) are not the focus of this document as they are extensively covered in other IAEA publications (referenced throughout the document).

While the main focus of this publication is represented by the technical issues, it is recognized that non-technical aspects are also important and thus are briefly discussed. For both technical and non-technical consideration, it is supposed by default that all illustrating activities are to be performed in compliance with safety requirement stated in the IAEA Safety Standards that are not specially addresses in this publication. Examples and case studies are provided to illustrate successful management of legacy waste leading to a path forward, approaches in addressing the practical challenges and lessons learnt.

The document is intended to be a support for owners, planners and implementers of waste characterization and processing programs, laboratory managers and technicians, designers, operators, and regulators involved in the management of legacy waste in Member States.

This publication, offering approaches to address challenges in managing legacy radioactive waste, is a compilation derived from numerous relevant documents and knowledge of experienced professionals from multiple Member States. Reference documents contain a significant amount of valuable data used only in part here, and therefore, these references need to be consulted for additional details where appropriate.

1.4. STRUCTURE

The structure of this publication guides the reader through understanding various types of legacy wastes and their associated challenges, considering strategic and technical aspects of planning their management, and approaches to identifying, selecting, and implementing technical solutions. The publication comprises six main sections supported by a collection of case studies to practically illustrate the challenges and achievements in managing various types of legacy wastes.

Section 2 details some of the common characteristics and challenges associated with legacy waste in general before focusing on key issues specifically associated with solid, liquid, gaseous and wet-solid legacy waste.

Section 3 discusses avoidance of ‘legacy’ status for radioactive waste, then development of management strategies when it nevertheless has become legacy waste. It then explores prioritization criteria for management, differences due to inventory size, and ownership issues.

In Section 4 non-technical considerations such as legal, financial, organizational, ownership and stakeholder issues are briefly discussed.

Section 5 addresses the most important technical aspects to consider when developing and implementing strategies for addressing legacy waste challenges.

Section 6 discusses approaches used in identifying, selecting and implementing technical solutions and several examples are provided in support.

Section 7 summarizes the key conclusions regarding legacy waste safe management.

2. WASTE TYPES, CHARACTERISTICS AND ASSOCIATED CHALLENGES

As noted in Section 1, many Member States are facing the challenge of safe and effective management of legacy wastes that may have been generated from nuclear applications, operation of research reactors and nuclear power plants, defence programs (only those wastes without a path to predisposal or disposal) and decommissioning of nuclear facilities as well as support facilities (laboratories, research and development facilities, hot cells, others).

There is a great diversity in the types, characteristics and the amounts of these radioactive waste produced from the different activities. The waste might occur:

- in gaseous form, such as gaseous samples and sources in ampules;
- in liquid form, such as scintillation liquids and high-level liquid waste from spent fuel reprocessing and, in wet-solid form, such as spent ion exchangers and sludge;
- in solid form, such as medical waste (e.g., contaminated trash), waste generated in the medical research facilities and radiopharmaceutical laboratories, up to wastes generated from the fuel reprocessing.

The concentrations and half-lives of the radionuclides present in the waste can also vary over a wide range from the slightly radioactive, such as those generated in medical diagnostic procedures, to the highly radioactive, such as wastes resulting from fuel reprocessing. The volumes can be very small, such as waste from nuclear applications, or large such as waste from multiple reactors at a nuclear power plant.

This publication does not attempt to provide worldwide inventory of waste from past activities. Such information can be obtained from the published reports submitted by the Member States to the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

2.1. COMMON CHALLENGES

While the wastes are of a diverse nature, some challenges are common:

- Lack of record and knowledge – of the waste itself and of waste generation source;
- Unsegregated waste;
- Difficult to retrieve and/or characterize;
- Chemical and physical challenges further complicate the management of the radiological risks;
- Waste accumulated over time leading to changing conditions;
- Degrading conditions of the waste, waste packages and/or the containing structures;
- Not meeting/ no longer meeting disposal requirements;
- Lack of radioactive waste management (predisposal and disposal) concept;
- Incomplete national waste management policy and strategy;
- Lack of funding;
- Lack of priority;
- Lack of ownership;
- Liability – may become a burden on future generations.

There are also several challenges that relate to the specific nature of the waste stream, and some of them are discussed in the following as well as related case studies.

2.2. GASEOUS WASTES

Gaseous wastes are typically not a large volume of a Member's States inventory but can represent a significant challenge for storage and ultimate disposition. For example, in France, the inventory of gaseous tritiated waste from the "small producers" represents a small part of the total inventory of tritiated waste. This is a closed inventory of limited volume, but high activity, and cannot be accepted according to the Waste Acceptance Criteria (WAC) of the existing disposal facilities. The reference solution, according to the French waste management plan, would appear to be decay storage after stabilization for the small-sized ampoules. The creation of new storage facilities by the French Alternative Energies and Atomic Energy Commission (CEA) over a period of about forty years, fully comply with the short to medium term safety requirements, pending its future transfer to disposal facilities. Liquid and gaseous tritiated waste from small producers are to be declared in the category of waste without management route in the National Inventory. ANDRA, the French National Radioactive Waste Management Agency, has the responsibility to continue the work to consolidate the inventory of tritiated waste (solid, liquid, gaseous) from small producers and from the national defence forces. A final management route for all liquid and gaseous tritiated waste from the small producers outside the nuclear power sector is expected to be identified and documented by 2025 [7].

Treatment of radioactive gaseous waste is necessary to be conducted in such manner to ensure that radioactive releases into the environment fully comply with the authorized limits and that the dose levels to the public and effects on the environment are as low as reasonably achievable. Several technologies are available, but the choice of option need to be based on assessment and comparison of available technologies with reference to acceptance criteria [8].

2.3. LIQUID WASTES

Liquid wastes can be aqueous or non-aqueous. Aqueous wastes can be of widely different chemical composition, from acidic to alkaline, having low to very high dissolved solids content, etc. The radioactivity content can also vary over a wide range and can be due to a single radionuclide or a mixture of radionuclides. Non-aqueous wastes include oils and solvents.

Small volumes of liquid wastes can be found stored in bottles, carboys, etc. while large volumes are usually stored in underground or above-ground tanks.

Some of the challenges associated with liquid wastes are listed below:

- Elevated environmental risk;
- Stratification (formation of layers) in storage tanks that are not routinely mixed;
- Precipitation of salts;
- Drying out of residual tank heels leading to friable radioactive material;
- Corrosive nature;
- Most susceptible to changes over time;
- Leakage of tanks;
- Need to be treated before disposal if they don't meet discharge requirements;
- Mixtures of organic and inorganic liquids.

In the USA, high level radioactive liquid wastes resulting from past defence efforts are stored in large carbon steel tanks (~3.8 million L). Early tanks were of a single shell design while later construction included a second shell to provide further protection against leakage. The stored waste is caustically adjusted in an effort to preclude waste tank corrosion. However, due to the age of the tanks some leaking has occurred. Efforts were concentrated on removing waste from single shell tanks and/or tanks that have exhibited structural issues. During a regular inspection at the Hanford's oldest double shell tank (containing radioactive and hazardous chemical waste), several leaking points from the inner shell were identified (Figure 1) [9]. The leaks were discovered in 2012 and in 2017 the waste was retrieved from the AY-102 tanks and transferred to tanks that were structurally sound.

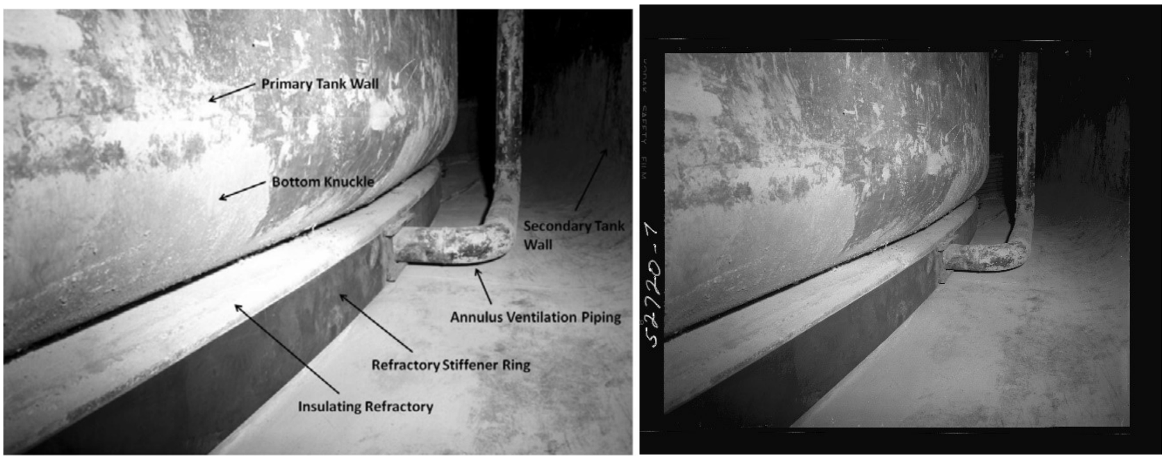

FIG. 1. Leaking points identified near annulus riser in Hanford AY-102 waste tank (Photo courtesy of Washington River Protection Solutions, United States of America).

2.4. WET-SOLID WASTES

Wet solid wastes include spent organic and inorganic ion exchange media, sludge, filters, and putrescible waste. Sludges came from various processes and origins such as chemical treatment of liquid wastes, precipitation of solids in storage tanks, etc. These wastes can be found stored in tanks, containers, ponds, or lagoons.

Spent ion exchange materials are a special type of radioactive waste as they are containing high concentrations of radioactivity requiring special handling and treatment arrangements. The past practice was mainly limited to their disposition in drums (or other types of packages), removal from the columns and storage in tanks for future processing or directly as disposable ion exchange columns without any treatment.

Some challenges associated with wet-solid waste are as follows:

— Spent ion exchange media in tanks:

  - Retrievability;
  - Agglomeration;
  - Degradation of tanks;
  - Degradation of the waste (via radiolysis, chemical and biochemical reactions);
  - Gas generation;

  - Mixing of ion exchangers from different sources/campaigns – not homogenous for characterization;
  - Rheological properties.

— Sludge:

  - Retrievability;
  - Agglomeration;
  - Degradation of tanks;
  - Degradation of the waste (via primarily biochemical reactions);
  - Gas generation;
  - Stratification – not homogenous for characterization;
  - Rheological properties.

— Putrescible wastes:

  - Small volumes of putrescible wastes can be generated (e.g., wildlife culled on sites or waste arising from research activities);
  - May not be suitable for direct disposal in all VLLW/LLW disposal concepts.

A relevant example related to the sludge management is coming from The First-Generation Magnox Reprocessing Plant (FGMSP) at Sellafield Ltd. The FGMSP, at Sellafield, is an open-air pond and was constructed between 1950 and 1960 for storing, cooling, and preparing the Magnox fuel for reprocessing. Operations ceased in 1986, and in present here are stored spent nuclear fuel, sludge, intermediate level waste and pond water. All these wastes need to be safely removed and processed through separate routes, therefore several solutions were developed, documented, and implemented to safely manage the legacy wastes.

There is approximately 1500 cubic meters of radioactive sludge lying at the bottom of the pond. The sludge primarily contains Magnox corrosion products, predominantly magnesium hydroxide and also some significant quantities of uranium fuel corrosion products (if the uranium fuel material is <6 mm is considered part of the sludge inventory). Significant efforts have been made to characterize and mobilise the sludge to enable it to be pumped into modern standard buffer storage facilities. The sludge is mixed with water to turn it into a slurry. Sludge retrieval started in 2015 using the Additional Sludge Retrieval (ASR) equipment and it is considered a significant milestone in the remediation of FGMSP [10].

There are many types of legacy sludges on the Sellafield site to be retrieved and packaged and, as a result was established a Sludge “Centre of Expertise” - a joint technical and engineering centre acting as a hub for the dissemination of experience across Sellafield Ltd [11].

Another solution to manage these types of wastes is related to the co-precipitation sludge from decontamination of reprocessing effluents in France. The reprocessing operations of Uranium Naturel Graphite Gaz (UNGG) Reactors and later UOx fuel both in La Hague (UP2-400) and Marcoule (UP1) led to the production of huge amounts of so-called co-precipitation (STE - Station Treatment Effluent) sludge. STE sludge comes from the chemical co-precipitation process used to remove the radionuclides from the liquid effluents. The chemical composition of the resulting sludges slightly changed over the years and can vary from one facility to another, but STE sludges mainly consist of barium sulphate, transition metal ferrocyanides, calcium carbonate, cobalt sulphide and some other hydroxides [2].

The retrieval of the sludge from the existing storage silos is to be done in two large staging tanks. The sludge is retrieved in the form of slurry and further homogenized to ensure consistency in the physical, chemical, and radiochemical characteristics of the waste batch. The next step is drying and compressing into pellets to be finally transferred into qualified waste packages along with sand to fill void spaces. Important quantities of STE-type sludges have already been conditioned into a bitumen matrix, a baseline solution for packaging these wastes. Lately, the conditioning in bitumen matrix was considered unacceptable by the French safety authorities due to the risk of radiolysis in bitumen-immobilized sludge. As consequence, large amounts of legacy sludge, for which the bituminization process is no more allowed, are still to be retrieved and conditioned [12] and cementation is considered as a technically feasible alternative.

Figure 2 below illustrates the retrieval and conditioning of 9000 cubic meters of co-precipitation sludge from 7(seven) silos of the effluent treatment facility in La Hague reprocessing plant.

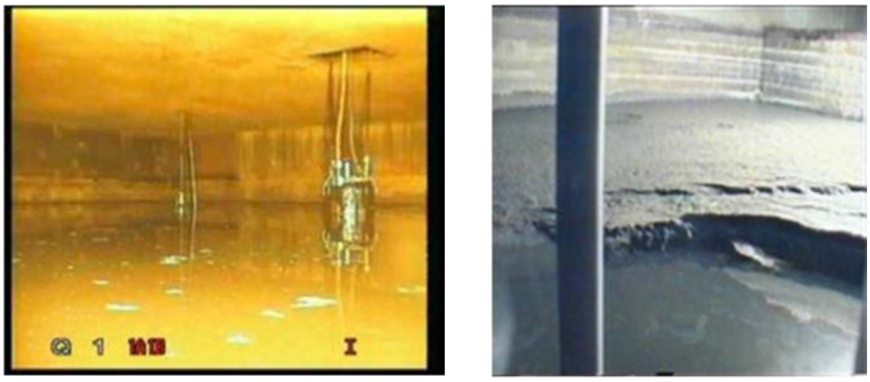

FIG.2. Sludges inside one of the pits (left); Sludges inside one of the pits after supernatant removal (right) (Photo courtesy of ORANO DWMD, France).

2.5. SOLID WASTES

Solid wastes include solid wastepaper, plastic, wood, metal, soil, contaminated equipment, disused sources, etc., and can be found in raw unprocessed state, or in conditioned and containerized state. In some cases, the waste could be damp or wet. Often legacy solid wastes are stored mixed including mixtures of raw and conditioned waste, waste from different sources, chemical and physical natures, ages, activity levels and contamination sources (alpha wastes mixed with beta/gamma wastes). Fig. 3 and 4 provide typical examples of storage of a variety of unpackaged and packaged waste without proper segregation or labelling. Figure 3 is showcasing the situation at the RADON facility in Tammiku, Estonia as of 2006 – meanwhile the wastes were removed from the facility and managed accordingly. Due to improper emplacement or storage, some of the waste may be damaged leading to increased handling requirements and the potential for contamination, for example in the case of damaged or unshielded radiation sources [5].

FIG. 3. Example of radioactive waste (in 2006) in RADON facility in Tammiku, Estonia (Photo courtesy of Estonian Waste Management Organization A.L.A.R.A)

FIG. 4. Solid waste stored in Hangar 1 at Vinca site, Serbia illustrating a wide variety of wastes stored in varying containers. (Photo courtesy of Public Company Nuclear Facilities of Serbia - PC NFS)

Some challenges associated with solid wastes are as follows:

— Raw waste:

  - Mixed wastes (radioactive and hazardous);
  - Physical state and size (range from fine powders to large components);
  - Organics (gas generation);
  - Galvanic corrosion;
  - Moisture/water content;
  - Difficult to characterize;
  - Difficult to retrieve.

— Unsuitably processed waste:

- Conditioned but not complying with disposal specification (swelling of bitumen, unacceptable cement);
- Waste previously buried.

— Containerized waste:

- Corroded containers;
- Pressurized containers;
- Non-conformant with WAC for disposal.

For packages which are deformed due to the effects of gas pressurization, or if chemical processes in the package damaged the waste container, repackaging or overpacking will be required to comply with the in-force waste acceptance requirements for storage, transport and/or disposal.

3. WASTE MANAGEMENT STRATEGY AND PLANNING

Before a challenging waste can be managed safely and appropriately, it is necessary to establish a credible and technically sound strategy for treatment and to plan the method to reach a stable endpoint.

The ultimate goal is to have a waste package that is suitable for disposal, or for "disposal ready" storage if disposal is not yet available. Investing the effort to have a qualified waste package, it will reduce the hazard associated with the waste in its current form.

It is important to establish the full costs, schedule, and scope of the legacy waste projects (as for any other project) to allow involved organizations to properly plan for the work. The facilities lifetime plans may also be affected by this legacy waste project, particularly if new infrastructure needs to be constructed for the processing of the legacy waste. This will affect the decommissioning plans for the facility, as well as the site footprint and utility infrastructure, therefore the potential impacts need to be assessed at an organizational level to effectively integrate with all the other work happening at the facility.

3.1. APPROACH TO STRATEGY DEVELOPMENT

Developing the strategy involves identifying, or even developing the lifecycle map for the specific waste (Fig 5).

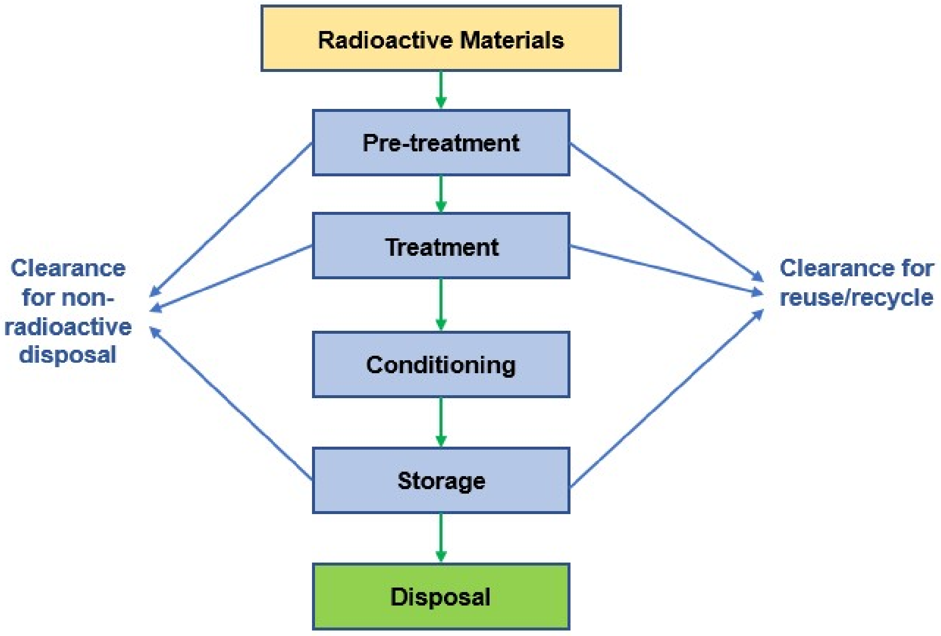

FIG. 5. Radioactive materials lifecycle displaying steps in the process

This is mainly to illustrate that having a strategy including predisposal to disposal steps is an important premise to avoid legacy waste accumulation. Waste managed in accordance with the strategy will not be legacy waste. Later sections in this document will showcase that this "wiring diagram" depiction of waste strategy is also useful in determining a recovery plan for a legacy waste problem. It can be utilized to identify where within the strategy the identified legacy waste is, and whether the steps in the strategy can be continued (with further work) or backed out of to start again at a prior step, or if a new strategy connecting the current step to disposal has to be developed to restore the legacy waste back on path for compliant disposal. An example of how the United Kingdom (UK) has developed and documented its Waste Management Strategy is further discussed.

The UK has produced and managed radioactive waste for decades and the UK nuclear legacy sites are managed under the Nuclear Decommissioning Authority (NDA) umbrella [13]. A single radioactive waste management strategy has been developed, providing a high-level framework to enable decision taking on implementing safe, environmentally acceptable, and cost-effective solutions that reflect the nature of the radioactive waste involved.

This single strategic approach provides a consolidated position and greater clarity of the strategic requirements, promotes cross category waste management opportunities, supports a risk-based approach to radioactive waste management and provides an integrated program to deliver supporting waste management infrastructure.

The strategy articulates the strategic positions and preferences against each of the waste management lifecycle stages as described in Figure 6 below.

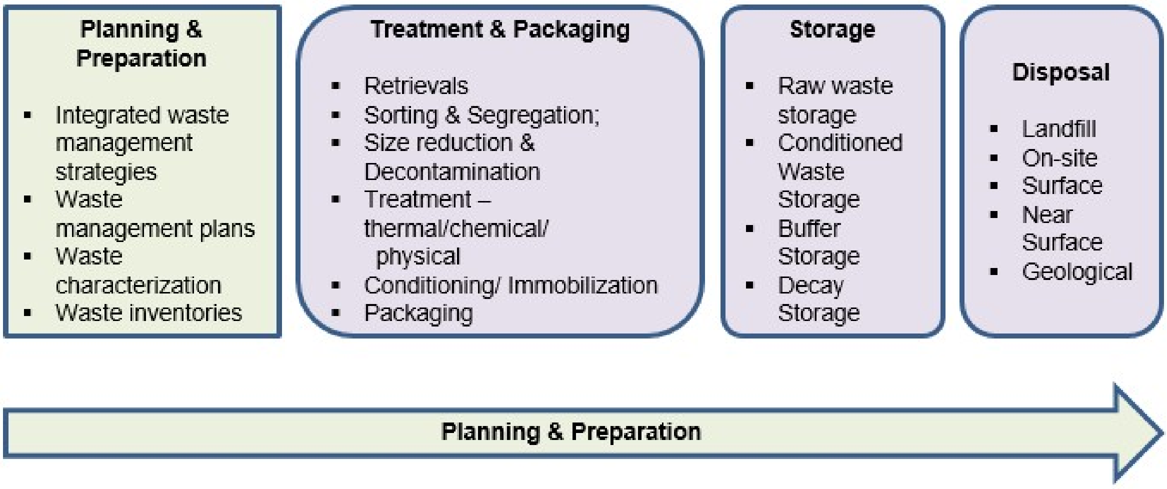

FIG.6. United Kingdom Integrated Waste Management Strategy, Nuclear Decommissioning Authority. Adapted from ref. [13]

Implementation of the strategy allowed the creation of an integrated program which was used to drive waste management behavioural change across the UK legacy nuclear sites. In addition, opportunities arose to prioritize waste management at LLW/ILW and VLLW/LLW boundaries. The more integrated approach to radioactive waste management coupled with a proportionate risk-based approach provides for better coordination across the UK nuclear industry and reduced lifecycle costs.

3.2. APPLICATION OF THE WASTE HIERARCHY

The Waste Hierarchy is a framework used to inform strategic thinking, highlighting the order in which options for dealing with waste will have to be considered. The hierarchy is applied throughout industry and is not limited to the nuclear sector.

When decisions about waste management need to be taken, it is important to consider:

- safety as a top priority;
- centralised and multi-site approaches;
- the implementation of waste hierarchy principles and criteria.

The waste hierarchy sets out the priorities in managing waste materials based on several criteria, one of the main being their environmental impact. In simple words, it is always preferable to avoid producing waste and/or the options to reuse or recycle materials need to be implemented to limit as much as possible the disposable waste amounts. The Waste Hierarchy structure applied at Sellafield site (UK) is based on the following approach:

- Safety and Risk Reduction (top priority)
- Avoidance
- Minimisation
- Reduction
- Re-use
- Recycling
- Recovery
- Abate
- Disposal (less desired)

For a number of facilities at Sellafield, ‘Safety and Risk Reduction’ is considered the most important priority, such that if a strategic option is identified which is not necessarily the best from a waste minimisation viewpoint but which provides essential safety and risk reduction, then that strategic option may be considered the most appropriate option [14].

As with the conventional waste hierarchy those options at the top demand the greatest consideration and provide the greatest benefit. As you progress further down the next step, the options for waste management become less favourable.

Another difference is the segment that reads ‘Abate’. Prior to waste being discharged into the environment, any opportunity for abatement has to be explored. This is predominantly applicable for the treatment of gaseous and aqueous wastes, thus reducing the impact to the environment upon final discharge. Finally, the nature of the Sellafield site inevitably means that a lot of the waste already exist. In such instances the application of the waste hierarchy focuses on minimizing the volumes of wastes where possible, reusing and recycling wastes and on avoiding the unnecessary creation of secondary waste.

Where possible wastes are minimised or avoided (e.g., removal of excess packaging before materials enter active areas, use of plastic pallets, etc) and the amount of waste destined for disposal is also minimised through treatment options such as compaction or size reduction, using on site facilities or off-site incineration facilities for some types of process wastes.

Decontamination techniques are also used to enable reuse/recycling or management as a lower category of waste. In addition, waste segregation is implemented at all sites and is a key component supporting the optimisation of waste management.

The application of the waste hierarchy requires a balance of priorities including protection of health, safety, security and the environment, value for money, affordability, and technical maturity.

3.3. ESTABLISH THE CORE OF THE PROBLEM

The existence of legacy wastes is a result of a range of reasons. It is important to understand the issue that caused the legacy to have been generated, to ensure that same issue does not a) halt progress in dealing with the current issue and b) lead to future legacy wastes being generated.

There are three basic questions that need to be answered when determining the state of the legacy waste:

- How did the waste become a legacy issue?
- What was the original plan to process this waste?
- Is any processing required to make it compliant with disposal criteria?

3.4. ESTABLISH PRIORITIES TO DETERMINE THE MANAGEMENT APPROACH

When developing a strategy for legacy waste management it is important to consider the prioritization of work to ensure that a logical and methodical approach is used. Clear prioritization of work will allow waste management organizations to plan for and allocate appropriate funding and resources to each stage and potentially carry lessons learned, personnel and equipment from one campaign to the next.

For most existing legacy waste situations there will be a range of options available in how the problem could be resolved. There may be a range of options at each state of the lifecycle. As examples:

- Retrieval of wastes or manage in-situ;
- Condition immediately or store as unconditioned waste in order to move wastes from a hazardous environment into modern fit-for-purpose buffer storage while developing or maturing a technical solution;
- Package into a disposable form immediately or take a stepwise approach;
- Disposition via existing disposal or diversion routes.

It worth to be recognized that, for some circumstances, to retrieve and condition legacy wastes an increased overall risk may need to be tolerated. Retrieval of waste may require containment (e.g., containers, facilities etc.) to be breached or retrieval equipment may need to be housed on aged facilities. This is reflected in the approach adopted by Sellafield Ltd.

Selection of the options at each stage of the lifecycle will depend on the specific circumstances and will be driven by the national/local/company priorities. For example, if limited funding is available, or timescales are short, a choice could be made to simply transfer to modern standard storage.

There are various ways to prioritize the work to be done when managing legacy waste, each way has merits, and the appropriate priorities will vary depending on the precise needs and current situation of each Member State. Once priorities are identified based on a suitable logic, a step-by-step plan can be developed that best suits the needs of the Member State. The logic used to prioritize the work has to be consistently applied, leading to a clear and stable approach that avoids many projects being started at once without a clear, integrated view across all waste management activities. In some cases, the regulator will set the priorities for the operator in others the regulator may agree the priorities set by the operator.

The sections below detail some of the possible prioritization logics that can be used when developing a legacy waste management strategy. The positive and negative points of each logic are discussed. It is important to stress that all the approaches are valid, and suitability will depend upon the specific needs of each Member State.

3.4.1. Prioritization based on hazard/inventory

Often the highest hazards in legacy waste are also among the most challenging waste streams, requiring extensive research and development of new or innovative technologies. This can lead to slow progress and high costs. It may, therefore, be more appropriate to manage the highest hazards once experience is gained elsewhere and could be applied in these cases. This approach may be most suitable for Member States with:

- Higher hazards;
- Greater experience in waste management;
- Knowledgeable public and political stakeholders;
- Available funds and research capability.

In the UK the funding and resource needed for legacy waste management are prioritised based on risk. This approach aims to give the public confidence that higher hazards are being managed promptly to reduce the risk of harm to the environment or the public. When progress is made, a clear and measurable reduction in the liability is seen.

3.4.2. Prioritization based on potential for success

Member States decisions to prioritize legacy waste projects can be based on choosing those that are most likely to be achievable in an expected time period (e.g., simple waste streams, lower dose rate items or projects that overall require less funding). The major achievements of such campaigns are the increased public and political confidence, and the opportunity to train the workforce before seeking funding for more challenging waste streams. Pursuing this logic can, however, lead to further degradation of waste conditions for the more challenging streams, which drives to increasing the hazard and challenge posed in future.

This approach may be most suitable for Member States with:

- Cautious stakeholders;
- A developing workforce;
- Available disposal routes for LLW and below;
- Legacy waste that is not expected to degrade or pose significant hazard in short term;
- Clearly identifiable” easy-wins.”

“Easy-wins” may be waste projects that are prioritized even if the hazard present is less than other wastes or facilities. Examples of projects where this may be undertaken could be because of a desire to reduce the site footprint or to facilitate early site clearance.

At Berkeley Nuclear site in the UK, approximately half of the nuclear licensed site footprint was historically used for buildings specializing in research and development including examination of materials following irradiation within the reactor core. As the Magnox power stations began to reach the end of their natural life and were sequentially shutdown and defueled, the need for this work was reduced and facilities were closed and decommissioned.

Many of the services were shared with the nuclear reactor buildings on the adjacent site, so unfortunately, there was no recognized reduction in the maintenance and security arrangements following closure of the facilities. Magnox undertook an extensive program of work to effectively sever all links between the half of the site where the R&D had been undertaken (and a nuclear license was no longer required) from the half of the site where the reactors and stored waste remained (license was still required). In performing this site separation Magnox delivered substantial annual budgetary savings by reducing overhead and support costs and facilitating reuse of the site as a Further Education College. A similar approach has been undertaken at Harwell where much of the original licensed site has been released for reuse as a commercial business park.

At Winfrith, early site clearance is seen as an “easy-win” to allow complete delicensing of a large site of Special Scientific Interest and an Area of Outstanding Natural Beauty. The waste is mainly contained within isolated facilities across a large site, but rather than maintain interim storage at that location, waste will instead be transferred to a suitable store at Harwell site [15]. In this way, the decommissioning “mission” at Winfrith site (scheduled for completion in 2023) can be declared complete and significant lifetime costs savings and safety, security and environmental impacts are avoided.

3.4.3. Prioritization based on volume of waste

Prioritization of large volume waste streams can be of benefit as it can allow a Member State to significantly reduce its legacy waste inventory earlier and create more space for future operations. Campaigns to manage larger volumes of waste can also be more cost effective if a methodology that favours high throughput is selected.

This approach may be most suitable for Member States with:

- Large volumes of accumulated waste;
- Waste from decommissioning;
- Limited storage for raw waste;
- Available disposal routes or safe long-term storage;
- Clear definition of WAC for disposal or disposal ready storage.

3.4.4. Prioritization of liquid wastes

Liquid waste and liquid waste storage vessels, as discussed in Section 2, are most likely to degrade over time. It may be in a Member State’s interest to prioritize retrieval and processing of these wastes to avoid continued degradation.

This approach may be most suitable for Member States with:

- Large volumes of accumulated liquid waste;
- Ageing liquid storage tanks;
- Known leaks of liquid waste to the environment.

3.5. DEFINE THE ENDPOINT- IS A FINAL DISPOSITION SOLUTION AVAILABLE?

To successfully implement the waste strategy, it is important that there is clarity with respect to the desired endpoint. This will be either an existing approved disposition route with clearly understood the WAC or a disposal concept with developed, justified, and approved WAC. For some Member States, there may be no disposal concept available. All these situations are deeper discussed below.

If the legacy waste contains short lived isotopes, for example medical waste or Co-60 disused sources, depending on the initial activity, it may be feasible to store the legacy waste as it is and wait for the waste to fall below the clearance levels and then dispose it to conventional waste disposal facilities.

3.5.1. Approved disposition route available

In an ideal situation, the objective would be to produce disposal compliant waste packages in real-time as radioactive wastes are generated. If radioactive waste disposal capacity is available, compliant waste packages can be disposed of immediately with no requirement for interim storage. In many cases where disposal capacity is not yet available, alternative arrangements are necessary. This situation has contributed to the generation of legacy waste challenges, specifically when the wastes have been stored in conditions that are not compliant with a defined disposal concept, or where the requirements for disposal are not explicitly understood. It is essential that an acceptable endpoint for all wastes is defined to avoid the continued accumulation of problematic wastes.

3.5.2. No current disposition route available but disposal concept available

Where a disposal facility is not available, many Member States have used the approach of establishing a disposal concept on which to base an assumption of the future WAC. The disposal concept will vary from one Member State to another and will be influenced by factors such as accumulated volume of waste, associated levels of activities, availability of appropriate environmental attributes (e.g., geography and geology) for disposal, the opinion of the local population, etc. A disposal concept could be as simple as a surface facility where waste is emplaced then covered over, or it might involve substantial engineering to excavate an underground network of tunnels and several hundred meters underground vaults.

In the UK, a set of disposal concepts have been identified for several possible geologies. An assessment process has been established that enables the waste producer and the future implementer of a disposal facility to gain confidence that investment in plant to retrieve and package waste will lead to development of waste packages suitable not just for the short term but also, as far as possible, for transport to and disposal in a Geological Disposal Facility (GDF) [16].

3.5.3. No disposal route nor disposal concept available

There may be cases where in the interest of safety, some works need to be carried out to improve the condition of legacy wastes in storage when there is no documented disposal concept yet available. This may be particularly relevant in countries with small nuclear programs, without a proper waste management infrastructure.

In the absence of a disposal concept, actions that are undertaken in the interests of immediate improvements in safety need to avoid, where possible, activities that preclude future predisposal steps once the disposal concept is known. The application of an appropriate knowledge management system is equally important in this context.

If a documented disposal concept is not available and is a need to start activities to avoid an increase in hazard, it may be a good practice to consider the requirements for treatment, knowledge management and storage of the waste that have been undertaken in other Member States. Observing approaches undertaken elsewhere can help inform potential options to be considered. However, one should be cautioned against simply adopting a WAC or disposal concept from elsewhere without evaluating its applicability within one's own circumstances. Individual requirements within WAC often have very specific reasons for their inclusion, often pointing to local geography and geology, regulatory framework, or other requirements.

Without an evolved disposal concept, there are no assurances that recovered wastes will be acceptable for disposal, and they may indeed still be legacy wastes. There is a risk that despite significant investment in recovery activities the ultimate objective will not have been reached and the wastes may require further rework in the future. For this reason, it is important to define an alternative endpoint that reduces the hazard currently associated with the waste but minimizes the risk of future re-work once a disposal concept become available.

For newcomers to nuclear power programs the principle is highlighted in [17] - Section 3.17 which describes development of disposal concept and requirements under phase 2 and 3 milestones:

- Under phase 2: "National strategies should be established for all expected radioactive waste streams, and the government should revise as needed the laws and regulations for radioactive waste management." [17]

- Towards the end of phase 3: "Existing, enhanced or new facilities for the storage or disposal of LLW and ILW should be fully operational and prepared to receive radioactive waste from the nuclear power plant." [17]

To avoid accumulation of wastes in storage that are not compliant with the defined disposal concept, the establishment of a methodology to assess waste treatment against the disposal concept is essential. Having this process is critically important because it determines what predisposal steps are acceptable and will include specification for ongoing storage [16]. Once the disposal concept has been established and acceptable storage criteria determined, any new waste can be managed in accordance with these requirements, thereby, ceasing further accumulation of legacy waste.

As the implementer and future operator of a geological disposal facility in the UK, Radioactive Waste Management Ltd (RWM) will be responsible for the development of WAC for the facility. As no site has yet been selected, the information necessary to define WAC is not available; the package specification is developed in such a manner to guarantee that the wastes can be converted into passively safe and disposable forms as soon as possible, and they define the requirements for waste packages to comply with the needs for transport to and disposal in a GDF.

At present, no GDF is in operation, but several are under different phases of development and/or implementation (from planning to construction). Consequently, the operational and environmental safety characteristics are sufficiently defined to enable specification of comprehensive Waste Acceptance Criteria (WAC). In the interim, progress is necessary to continue with retrieving and conditioning the Highly Active Waste (HAW) to reduce hazards and to enable decommissioning and clean-up of redundant facilities.

RWM's disposability assessment process consists of a series of technical evaluation topics and safety assessments. The waste producer is responsible to document that the packaging is compliant with the required specifications and safety cases. Once is fulfilling these requirements, a Letter of Compliance (LoC) which indicates that is expected that the packaged waste will meet the waste acceptance criteria for any future GDF, is issued by RWM.

Where packaging proposals are compliant with its packaging specifications and safety cases, RWM endorses the waste producer's proposal with a LoC which confirms that.

The Disposability Assessment Process (schematically presented in Fig. 7) is essentially a risk management process used by waste owners and site operators to gain confidence that investment in plant to retrieve and package waste will lead to waste packages suitable not just for the short term but also, as far as possible, for transport to and disposal in a GDF. It also helps RWM to optimize the design of the GDF, considering the type of waste packages proposed for disposal [16].

Additionally, when the assessment process is applied early in decision making on waste management choices, it allows identification of any significant issues that may challenge disposability. By identifying those issues early, the technical work can be undertaken without delaying implementation of the waste management approach.

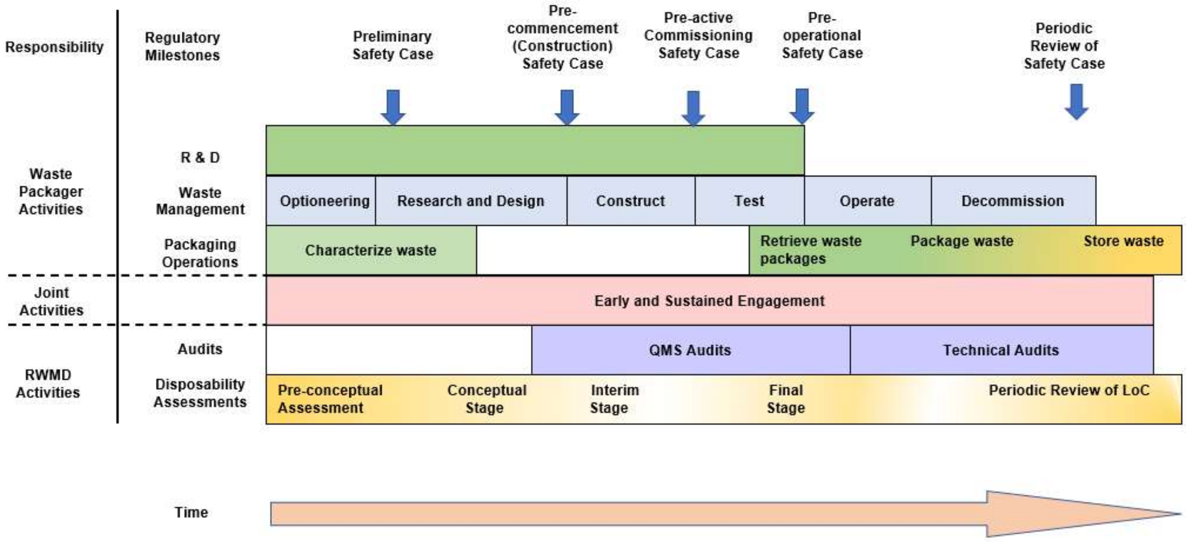

FIG.7. Indicative interaction between RWM and the waste packager on an idealized packaging project. Adapted from ref. [16]

In case that the WACs for a facility are changed, this might lead to wastes that were packaged for disposal becoming a legacy waste with no available disposal route. Such a situation is highlighted by the Sea Disposal Packages practice which due to the 1983 ban led to be stored on site until a disposal solution became available.

Between 1949 and 1982 low-level radioactive waste was dumped in the North-East Atlantic from vessels by several European countries (United Kingdom, Belgium, France, Switzerland, The Netherlands, Sweden, Germany, Italy). This approach changed in 1983 with the adoption, under the 1972 London Convention, of a voluntary moratorium on the dumping of radioactive waste at sea [18,19].

From about 1982, until the ban was finally ratified, United Kingdom Atomic Energy Authority (UKAEA) prepared further Sea Disposal Packages for deep sea disposal. In addition to those Sea

Disposal Packages containing radioactive wastes generated at Harwell, Sea Disposal Packages were also prepared containing wastes from other sites, e.g., Dounreay, Winfrith, Sellafield, Amersham, Aldermaston, Chapelcross, Rosyth and Chatham. While some of these Sea Disposal Packages have subsequently been subject to further sentencing or treatment (some as LLW), the majority remain in storage, awaiting final disposal.

The wastes consist of a wide range of materials including steels, PVC, polyethylene, aluminium, rubber and cellulose. The materials are present in a wide range of items/forms including un-immobilised fines, cemented monoliths, sheets, tubes, pipes, sealed sources, watches, weights, pellets, filters, ion exchange columns and bags. The sea disposal drums themselves make a substantial contribution to the waste and comprise steel and concrete.

The present challenge consists in understanding the inventory of wastes in the drums and to develop arguments that would underpin a management approach. The simplest might be to overpack the drums in larger containers, as opposed to a process of cutting the drums, open, retrieving the contents and treating the wastes. In accordance with the Nuclear Decommissioning Authority (NDA) 2016 inventory, it is intended that the concrete lined drums will be size reduced and that the waste will be repackaged. It is expected that after size reduction approximately half will be re-categorized as LLW, and the remainder will end up in 500 L drums [20].

3.5.4. In-Situ Waste Stabilization

In-situ disposal may be possible for waste, which was previously conditioned, stored or buried. This option can be applicable for waste which does not meet current criteria for disposal, but with engineering solutions for the disposal location, could be brought up to current disposal standards.

Previously, there have been trench disposal sites which were not lined prior to waste emplacement and were not effectively capped. This was leading to water ingress into the waste, degradations of packages and possible contamination of the local area through dissolution and sub-surface water flows.

One of the remediation options for this scenario could be to create a better engineered cap over the trenches to prevent water ingress and slow the migration of radionuclides out of the wastes. The more robust capping of storage trenches would convert the storage site to a safe and compliant disposal site provided the safety case can show that it meets an acceptable performance assessment. This concept, among others is explored in detail in the IAEA technical document related to near surface repositories upgrading works [21].

In considering in-situ disposal, the end-state of the site need to be clearly known, whether the site is required to be green field, brown field or under institutional control. If the end-state of the site is undecided, creating a disposal site mean that it will be under institutional control for some period and then possibly become a brown field site. Creating an on-site disposal facility will require a new safety case and will have to follow all the requirements, technical and non-technical, to establish, operate and monitor it.

3.6. MINIMISE THE SCALE OF THE LEGACY WASTE CHALLENGE

Ideally the immediate step to take is to stop generation of legacy wastes. This is not always possible, for example where the legacy waste is a secondary waste from a required process. For example, ion exchange resins can be generated to reduce the activity concentrations in legacy ponds to minimize the dose to workers.

One area to avoid is continuing to condition and/or process waste which generates an irreversible waste form.

3.6.1. Avoidance of accumulation of liquid wastes – process where possible

Liquid wastes can be particularly problematic when accumulated over long time periods. Because liquids are highly mobile, they pose increased risks to the environment due to breaches in containment (e.g., leaks from tanks). Although this is often mitigated through provision of more robust containment (e.g., double walled tanks) long term accumulation of liquid wastes in tanks is advisable to be avoided. Over time, liquids often stratify, making characterization, retrieval, and processing more complicated. Phases can separate, with solids accumulating as sludge at the bottom. Sludge can solidify to an extent that makes it very difficult to retrieve in the future. Electro-chemical processes can result in increased corrosion potential at phase change layers.

The best approach is to use tanks as short-term accumulation only to optimize processing, and continually process liquids as they are produced.

3.6.2. Ensure establishment of adequate knowledge management procedures

One of the factors contributing to legacy waste challenges is lack of confidence in characterization information due to historic weaknesses in knowledge management. Preservation of records information is extremely important. Wastes generated today to disposal standards that include specification of required records may no longer be compliant at time of disposal if confidence in the provenance of the records has been lost.

It is important that practical, consistent information to be collected for all wastes. Records need to be collected and maintained to inform and enable future decisions. Are various levels of records, for example: generic (information on the plant or process that generated the waste), campaign (the apparatus set-up for a series of packages from a common waste source), and package level (the individual characteristics of each portion of the waste).

The record specification has to be developed to support the disposal concept and a gap analysis need to be carried out to identify shortcomings in available data. If necessary, further characterization will be performed to complete the records.

3.6.3. Maintenance of retrieval and inspection options until clearly disposable

When wastes are put into storage, retrievability has to be always considered. This is particularly relevant for un-containerized waste storage systems. There are many examples of storage silos or tanks where the original design provided only for access for the waste to be put in storage with no consideration of how to retrieve for further processing and conditioning for disposal. For example, RADON-type disposal systems were developed in the former Soviet Union and the robust design was used in many countries. However, the design of the facility precludes ready access for waste retrievability if further processing or conditioning of waste is required for ultimate disposal. In these situations, the task of further pre-disposal steps will be considerably more difficult as safe methods of retrieval will have to be developed after the fact. It is much better to have retrievability built into the design in the first place.

The design of RADON type repository was used for both disposal and storage of low and intermediate level radioactive waste and Disused Sealed Radioactive Sources (DSRS). The vaults of this type of repositories are below the ground level with a volume of 200 m^3 or 400 m^3. The basements are made of concrete plates, the walls are made of monolithic reinforced concrete or concrete blocks. The repository is divided into cells (sections) by concrete or wooden walls. The top is covered by reinforced concrete plates, sand, and an asphalt layer.

In total, there are 35 RADON facilities in the world. The design is robust and generally provides good isolation of radioactive wastes from the environment. Further enhancements, as illustrated in Figure 8 below at the Maisiagala radioactive waste storage facility, provide even more environmental isolation. However, the design does not offer ready retrievability for any wastes that require further conditioning or processing for final disposal [21].

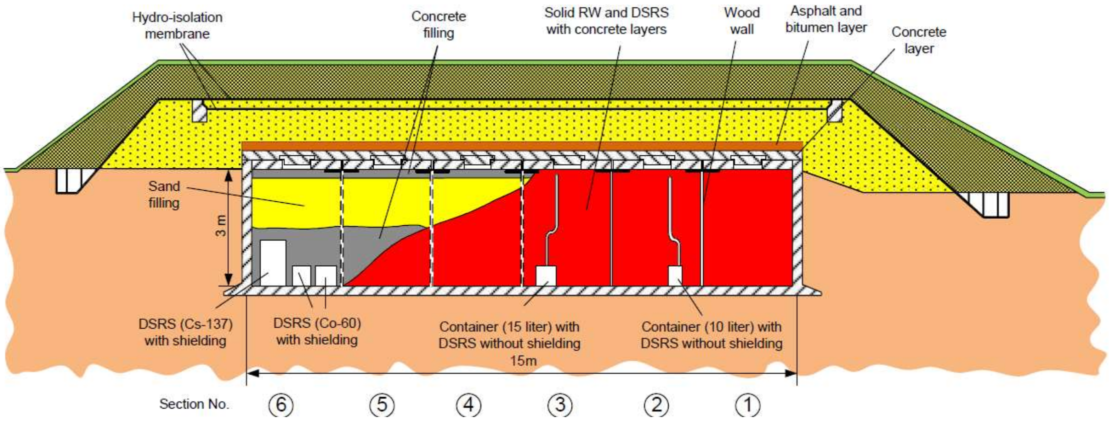

FIG.8. RADON facility with upgraded safety in Lithuania with two hydro-isolation membranes cover (Photo courtesy of Ignalina NPP)

Along with retrievability, the ability to monitor and inspect the waste is important to be able to demonstrate that package conditions are not evolving in such a way that their integrity is threatened. This is particularly important for situations where the storage period is anticipated to be prolonged or is not yet defined. This could include consideration of spacing arrangements for containers in storage to permit access, remote cameras, the ability to recover individual packages for periodic inspection, the storage and monitoring of inactive simulant packages, etc.

3.6.4. Design and maintenance of appropriate storage structure

Storage is necessary whether or not a disposal concept is in place, therefore consideration needs to be given to the anticipated time when disposal will be available, including the potential for delays. Examples of legacy waste challenges in the past associated with storage include degrading storage structures, less than adequate infrastructure, or lack of up-to-date management systems in place or maintained.

To maintain stored wastes in a disposal ready condition, the supporting structures and systems need to be periodically monitored and contingency options for intervention have to be available when necessary. Design intent of an interim storage facility is fundamental, and an assessment needs to be undertaken to identify foreseeable scenarios where ideal storage conditions may be compromised. The design of the storage facility has to take into account these scenarios, for example, this could include climate control systems (temperature and humidity) to minimize the risk of corrosion of metallic containers or to design the store to be refurbished without the need to move waste whilst still protecting workforce from excess dose (e.g., double skinned roof). During design activities, it is advisable to avoid features that require regular maintenance to ensure the integrity of the store (e.g., the roof of a building could be shaped so that rainwater runs off without the need to install drainage channels at height).

3.6.5. Avoidance of conditioning/treatment that forecloses future options

Decisions taken today need to be carefully evaluated not to foreclose future waste management and treatment options. Significant uncertainty surrounds what future waste disposal routes will be available, where they will be located as well as what waste treatment and conditioning technologies or packaging options may mature in time for use. New waste routes, technologies or packaging have the potential to offer waste lifecycle benefits. Consideration is therefore being given to waste management approaches which balance the need to meet long-term safe storage of the waste before disposal whilst not foreclosing the options for its future waste management.

It is important to consider the implication of unconditioned waste storage on sustainability and intergenerational equity and the placing of undue burden on future generations. When considering unconditioned waste storage and making the case, the waste generator will have to decide whether the approach is leaving to the future generation an opportunity (e.g., through better waste diversion, greater numbers of waste routes, technology that enables volume reduction or reclassification of work) or a liability (i.e., deferring the work with limited or no opportunity to get further benefit from handling the waste unconditioned).

In France, early conditioning remains a priority when the appropriate technology is available – it can lead to a lower lifecycle cost and ensures that the burden of completing waste packaging is not left for future generations. It also means that the design of the final disposal repository will be such that the wastes already packaged are suitable for disposal.

But there are examples where the risk to treat/condition or overpack remains. Examples include:

- For bitumen, the main technical issues in operation of the deep disposal facility are exothermic nature, the hydrogen production, and post-closure swelling. Selective emplacement to mitigate the fire risk may be needed or reconditioning (e.g., through thermal treatment).
- For organic alpha waste, the main technical issues relate to gas production and the production of organic soluble compounds leading to the potential to increase solubility in post-closure. Again, thermal treatment might be an acceptable conditioning approach.
- For co-precipitation sludge which used to be bituminized, the main technical issue for conditioning is the potential chemical reactivity of the salts. Again, thermal treatment might be an acceptable conditioning approach.

Delayed conditioning is more affordable in the short term, and it also allows time for new technologies to be developed and/or the WAC to became available for a disposal facility. For very complex waste, an incremental step may be needed to address short term priorities (such as retrieval of the waste from silos or tanks).

Certain treatment or conditioning methods could make future work on the wastes difficult or impossible. For example, while encapsulation in concrete can be part of a robust disposal concept, use of concrete without a disposal specification can make matters more difficult. The presence of concrete can rule out non-destructive assay as a valid future characterization means and will make sample collection and preparation for destructive analysis difficult. Noting that certain parameters of concrete can be important in some disposal concepts (such as compressive strength and leachability) in such cases prior use of concrete that is out of specification will make future conditioning difficult. Other encapsulation methods (e.g., bitumen) can also create future challenges if they are not part of the agreed disposal concept. It is best to avoid such conditioning steps until a future date when the disposal concept clearly identifies what methods will be acceptable.

Sometimes immobilization can lead to a low-quality product requiring further work to recondition and stabilize the waste. For example, as part of past activities in Canada, liquid wastes from dissolution of High Enriched Uranium (HEU) targets for Mo-99 production were stabilized in small cans with cement powder. The objective was to only stabilize the liquids. The resulting cement was of very low quality with essentially no mechanical integrity. Thus, the waste in this form is expected not to be suitable for disposal. Investigations are underway to assess the feasibility for processing into a waste product suitable for disposal. Two routes are taken into consideration based on solid technical justifications: 1) crushing the cement product and re-stabilising using an accepted cement formulation in a qualified container; 2) leaching the High Enriched Uranium out of the crushed cement for recovery and reuse, and to create further a qualified cemented product from the leached residues [22].

The options to stabilize or passivate the waste to reduce the risk of an increase in hazard need to be considered. In many situations, the presence of moisture can promote mechanisms that can cause waste to degrade (e.g., corrosion, gas generation, etc.). In such cases, a solution is to dry the waste to a level where these mechanisms are reduced, without posing any additional hazard introduced by making the waste more friable.

3.6.6. Consider whether segregation is beneficial

In most of the cases is useful to segregate stored wastes based on material type, source facility, level of hazard, level of activity, etc. This could make it easier to process similar wastes together in campaign when the next predisposal steps for that waste stream have been identified. It is also the case that in many situations, wastes that are co-located can often be treated by the same method to achieve the desired endpoint. In some situations, it may be desirable to deliberately mix compatible waste streams for treatment to increase the packing efficiency and reduce the overall number of packages for storage or disposal.

Another option for minimizing the amount of work required for a legacy waste site is to conduct selective retrievals. In this option, the legacy waste which is buried or stored can be characterized and an assessment made on the disposability of all the wastes in that facility. There will be variation in the legacy wastes stored in facilities over time and as operators became more familiar with the disposal technique. This means that some of the waste may no longer be considered radioactive, or by removing some material the facility can demonstrate that it meets the current disposal criteria. Targeting the non-compliant wastes, and removing them, could lead to the situation that the rest of the waste facility can be upgraded to the current standards, or an in-situ disposal case may be made for remaining waste [1].

There are also disadvantages and risks associated with segregating wastes. Segregation of waste will require operator intervention which may lead to additional doses to workers and also to secondary wastes generation.

An example of Risk Based Waste Management Framework [23] is presented and explained in Figure 9 and the support notes.

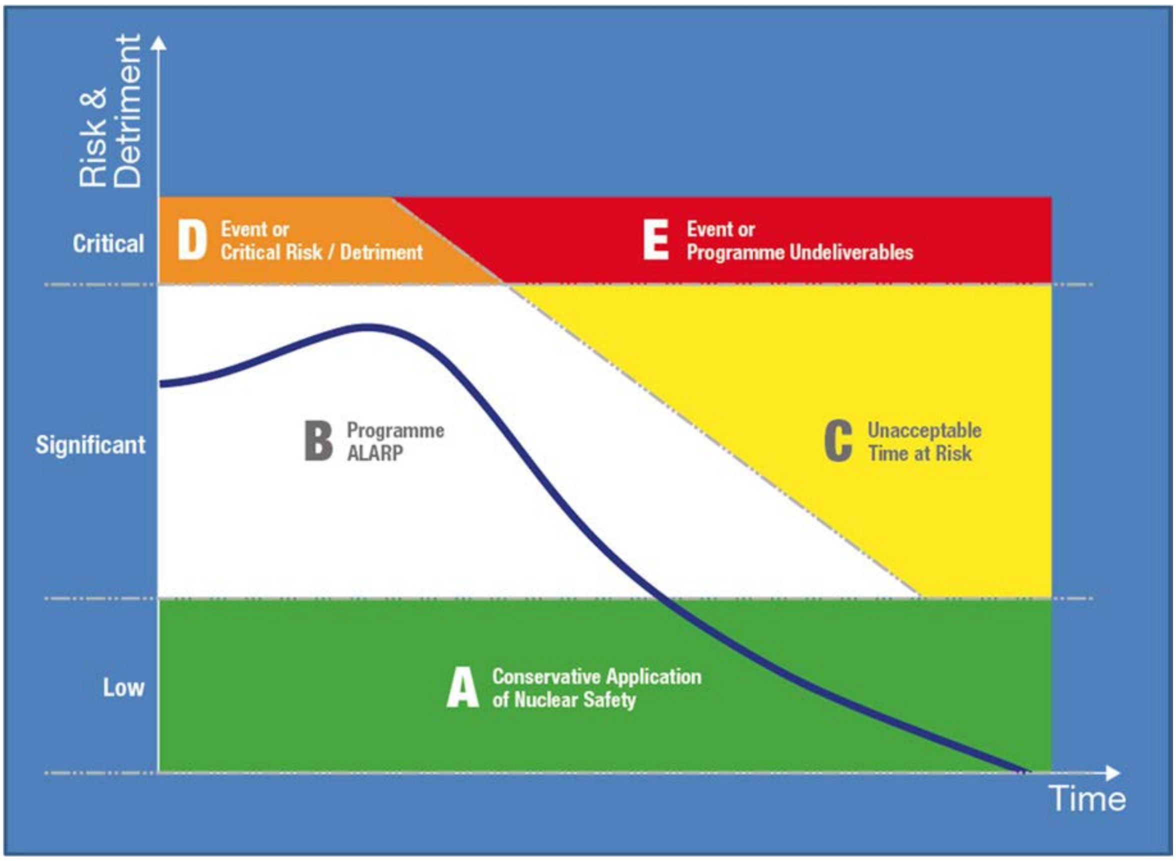

FIG.9. Risk Management Curve. Adapted from ref. [23]

The Sellafield Risk Based Waste Management Framework is made up of 5 regions:

- Facilities in Region A operate at a level of risk which is small because of their: robust construction, layers of engineered protection and disciplined approach to safe operations and maintenance.
- Facilities in Region B are those where the current level of detriment or risk to the workforce, public and/or environment cannot be tolerated. There will sometimes be a transient increase in risk to deliver an overall programme of risk and/or hazard reduction. An example is adding 100’s tonne infrastructure on the top of the Magnox Swarf Storage Silo.
- If facilities move into Region C, prompt management action is required, following bespoke process to either avert an emergency arising or to quickly move the facility back into the acceptable region.
- An event that moves a facility into Region D represents a programme risk or detriment, but the programme is recoverable.
- A facility moves into Region E if it has exceeded its baseline risk tolerance and the programme became unrecoverable without a major work or strategic change. This could be for example the facility suffering a catastrophic failure which causes the site emergency arrangements to be involved. It does not need to be an actual event on the facility leading to consequences to workforce, public or environment.

3.7. SCALING APPROACH

Often waste streams are similar across various Member States and looking to apply technologies and approaches used elsewhere can allow waste managers to understand the technologies available to them. However, it is important to note that approaches used for high volumes of waste may not necessarily be economically viable for small volumes and vice versa. For example, a Member State with a smaller inventory or waste stream may favour an approach resulting in more robust and expensive packages rather than investing money in an expensive or elaborate technology. Another example may be that a country with a larger footprint or more land available for a disposal site may prioritize volume reduction much less than a country with a large inventory and limited space for storage and disposal. The use of mobile technologies (as discussed in detail in Section 5) can also be more viable in the case of smaller inventories or volumes of waste.

4. NON-TECHNICAL CONSIDERATIONS

Consistent with nationally and internationally agreed principles and standards, the radioactive waste needs to be safely managed in a regulated manner. In implementing a proper radioactive waste management system is necessary to establish organizational and administrative arrangements which are defining the competencies, responsibilities, and activities of the involved institutions.

As with all radioactive waste management programs, compliance to jurisdictional regulations such as funding, politics and stakeholder acceptance are important to consider for successful completion of projects. In the case of legacy waste management, these non-technical challenges can be further complicated as the liability has been passed forward from past generations. Some areas of particular interest in the case of legacy waste management are discussed in this section but a detailed discussion of the factors affecting the selection and implementation of waste management technologies can be found in an IAEA publication [24].

4.1. LEGAL

In accordance with the national and international laws, directives and agreements, the Member States Governments are responsible for defining the national policy, developing the strategy and for establishing a national regulatory framework addressing the radioactive waste management competencies and responsibilities. The responsibility for implementing the national program and the support strategy, for establishing the relevant regulations and for defining the safety principles rest within each Member State. Some considerations include:

- Definition of waste/nuclear activities to allow for certain practices (e.g., defining clearance levels);
- Specific bans on certain materials or activities;
- Laws to define criteria and restrictions for transport, import or export of material;
- Delineating laws at all levels (local, regional, state, national or international);
- Clear definition of laws and regulations to avoid conflicts.

4.2. FINANCIAL

All Member States are faced with funding challenges with respect to radioactive waste management and it is important that all work is built into well-justified and reasoned funding plans on a national and a site-by-site level with consideration given to the prioritization of work.

Legacy waste management, particularly in countries with small inventories or small nuclear industry, can rank low in the national funding priorities and the required funding may be beyond the capabilities of the Member State. In these cases (or if there is an immediate need for action due to public or environmental safety implications), it may be possible to seek assistance from the international community through, for example, the European Union (EU), the IAEA Technical Cooperation Projects or through special funded projects for non-proliferation (grants). In the site-specific funding plans development, all work required to take the waste from its current state through to disposal need to be taken into consideration. Costs to include in a funding plan are:

- Project management and support;
- Procurement of equipment and material;
- Research and development;
- Pre-disposal actions;

- Site restoration, clean-up and landscaping;
- Storage Facility (construction, operation and maintenance);
- Disposal facility (construction, operation and maintenance);
- Environmental and radiological monitoring and inspection;
- Transportation;
- Security;
- Other costs (consulting fees, regulatory fees, permits, insurance, overheads).

Decommissioning and waste management may often be funded as single projects, hence reports on financial aspects of decommissioning are likely to be relevant [25, 26]. Guidance for developing such a plan is provided in some IAEA publication [24, 27].

Another issue to be considered refers to the availability of a skilled supply chain which may have the capability to carry out the requisite work. The supply chain may be international in nature as Member States with large nuclear industries will already have a wide-ranging supply chain in place.

4.3. HUMAN RESOURCE AND TRAINING

Ageing workforces and historical and socio-economic factors may have led to a reduction in trained personnel with a lack of new engineers entering the industry. Before any waste management plan can be carried out a sufficiently trained workforce needs to be available for planning and carrying out the work. International support is available through IAEA TC projects and other similar initiative to carry out training in Member States. National programs can also be developed working with universities and institutes to promote careers in waste management. An example is a program set up by the Nuclear Decommissioning Authority in the UK and later commercialized, that specifically recruits graduates into waste management and decommissioning organizations and provides two years of training and placements throughout the industry to fast-track training of young people.

4.4. STAKEHOLDER INVOLVEMENT

Planning, building, and operating a facility for the treatment of legacy waste streams generally involves interaction with a wide range of individuals including subject matter experts, designers, constructors, regulators, end users (operators and managers) and supporting organizations, and frequently, the public. Some areas of interest in the case of legacy waste management will be highlighted but a detailed discussion can be found in an IAEA publication regarding stakeholders' involvement through the lifecycle of nuclear facilities [28].

4.4.1. Regulators

The national regulatory body is responsible for the licensing and monitoring of the various radioactive waste management facilities. Every country needs to define appropriate regulatory responsibilities, which could include the role of the regulatory body related to specification, acceptance, concurrence, or approval of WAC. However, in general pre-disposal requirements for legacy waste does not exist and, therefore, the preparation and approval of waste forms for both safe long-term storage and disposal of LILW requires the regulator involvement.

4.4.2. Pre-disposal operator

The pre-disposal operator is responsible for the processing of the legacy wastes in accordance with government policy, regulatory requirements, and public acceptance. This in turn requires the establishment of an appropriate, safe, and compliant strategy for all the processing actions necessary for conditioning of the legacy waste. In the case of historical waste, it has to be emphasized that the characterization of raw waste undertaken by the waste generator is a crucial input for further processing of the waste. The pre-disposal operator, thus, need to liaise with the operators or caretakers of the legacy waste and the storage or disposal facilities regarding the receipt of waste, addressing:

- The anticipated inventory and characterization need;
- Compliance and interpretation of the WAC;
- The anticipated waste form and characterization requirements;
- Establishment of a quality assurance/control system and procedures (addressing technical, organizational and administrative measures) to ensure that the WAC are met to the satisfaction of the waste receiver, which will include liaison and agreement with waste receiver and permitting audits;
- Preparation of a data file for each waste package and completion of the waste receivers' documentation according to their requirements;
- Transfer of waste with documentation to the receiving facility when it is feasible and timely to do so.

WAC for conditioning and storage are derived from WAC developed for a conceptual disposal facility, with packages being made suitable for long-term storage until such a facility is available. Additional information on this issue can be found by consulting IAEA publications [29, 30, 31].

4.4.3. Storage facility operators

Storage for conditioned legacy waste would typically be in an interim storage facility pending transfer to a disposal facility. The storage facility will apply its own WAC regarding the design and operational configuration for handling, placement, and monitoring of the conditioned waste forms. The storage facility operator will be expected to demonstrate fulfilment of the WAC (particularly for long-term storage), the maintenance of comprehensive waste records such that full characterization information, together with waste condition monitoring information obtained during the storage period, may be passed to the disposal site operator (additional information can be found by consulting IAEA publications [32, 33, 34]).

However, since there would be no additional conditioning of the legacy waste package for disposal, the characteristics of the waste packages will largely correlate with the WAC of the designated disposal facility, with additional criteria related to its own design, environmental conditions, and safety requirements.

4.4.4. Disposal operator

The disposal operator is responsible for the repository design, construction, operation, and post-closure arrangements. All these phases need to comply with national regulatory requirements, with a particular focus on those which are related to the overall safety of the repository. The disposal operator is, therefore, responsible for specifying appropriate WAC for legacy waste to satisfy these requirements. A key aspect of the disposal site operator's responsibility for WAC specification is the addressing of issues which affect the long-term repository safety such as waste form stability, leach rates, and information on long-lived radionuclides which are the main inputs for the long-term dose determinations.

Among the disposal operator responsibilities, the followings are essential:

- Understand and assess the (full) range of wastes anticipated to be accepted;
- Design, construct, and operate the facility to safely dispose of the waste, having an established and documented safety case;
- Generate the WAC so that wastes will be shipped/transferred in accordance with design and safety case requirements (including transport), in close liaison with the waste generator to ensure the WAC are understood and achievable;
- Establish an agreement for receipt of wastes according to the WAC, the agreement process including reviewing and accepting the processing operator's quality assurance procedures being applied and qualification of the waste producing route, with auditing as required;
- Receipt of wastes for safe future management (taking title for the disposed wastes), including verifying that waste packages to be disposed of (or stored pending disposal) are compliant with the disposal waste acceptance requirements;
- Maintain full records of waste for future waste management purposes.

Additionally, the disposal operator could provide, as required, direction for and oversight of activities relating to classification of waste for storage or disposal or categorization of raw treated/conditioned and untreated waste. More information is available in several IAEA documents [35, 36, 37].

4.4.5. Public Acceptance

Public acceptability of operations at nuclear power plants and other institutions handling radioactive materials is important and the public represents a key stakeholder group. The nuclear power plants, in most of the cases, have in place well-developed, consultative procedures and public education programs to facilitate the introduction of new processes or facilities to the public; many of them are involving the public in the decision-making process itself.

In several Member States the national legislation may require formal public consultation. It is, therefore, critical that before the treatment of legacy waste to consider public participation at the inception of defining new technologies or prior to significant onsite construction to provide assurance to the public that safety and environmental requirements will be met.

4.5. ORGANIZATIONAL ASPECTS

The considerations and decisions regarding the management of legacy waste can impact several stakeholders, potentially challenging their program, resources, or compliance strategies. Therefore, one of the most critical aspects of developing and implementing a successful treatment program for legacy waste is early, direct involvement of parties that will affect, or be affected by, the development and operational processes. Cooperation with the waste generators, waste processors, storage operators, regulators, and any other institutions or organizations involved is paramount. This interface requires careful review, evaluation, and development of an interface agreement which has to be documented and clearly communicated in a timely manner to affected parties.

4.6. SECURITY

Legacy sites require adequate security arrangements to guard against human intrusion, uncontrolled dispersion of waste and the threat of malicious acts. This is particularly important due to the remote nature of some legacy sites where any loss of security can easily go unnoticed without adequate control.

4.7. OWNERSHIP OF WASTE

It is recommended that responsibilities with respect to legacy waste are well understood and defined before work is started. In the case of legacy waste is possible to have a diverse range of waste owners and/or even a lack of clarity as to the owner of the waste as original producers may have become insolvent or the liability may have been handed on to another party. Generally, responsibility for any waste without a clear owner (sometimes referred to as orphan waste) defaults back to the state. An example of a state government taking ownership of legacy waste issues is given below where the French government owned bodies acted to ensure safe storage and treatment of legacy radium sources.

On December 1, 1999, at the request of the French Health Ministry, OPRI (Office de Protection contre les Rayonnements Ionisants) and ANDRA launched a national campaign to collect the radium containing medical devices, formerly used in brachytherapy. The rationale behind this campaign was related to the risks involved in a careless handling of these objects and the increasing number of reported scattered radium medical devices in the last years. The campaign was initiated by a call of the owners (hospitals, caring centres, retired doctors) to a toll-free number. Priority was given to private citizens possessing the devices as they were not in a position to keep them in suitable storage conditions. The entire operation was based on safety protocols, working and handling procedures and compliance with the transport regulations. A total number of 517 objects with a total activity of 1.32×10^{11} Bq have been collected in 90 operations [38], transferred and safely stored at the French Alternative Energies and Atomic Energy Commission (CEA) - Saclay site before their transfer to ANDRA facilities. As a mission of public service, ANDRA is still collecting these radium objects.

4.8. INTERNATIONAL COLLABORATION

Considering the many challenges associated with legacy waste management – including financial, organizational, and technological challenges – a collaborative approach can be beneficial to address those challenges. The IAEA is a good example of an organization that facilitates international cooperation in this area by:

- Facilitating the sharing of knowledge, international expertise and providing direct assistance to the Member States through its Technical Cooperation Programme;
- Developing joint solutions to common problems through Coordinated Research Projects;
- Facilitating financial assistance from donor countries and other international organizations.

The European Union (EU) also facilities collaborative work to address common problems in the EU Member States. Two examples of international cooperation to address legacy waste challenges are presented below, as well as the examples presented under chapter 6.4. on recycling metal in Sweden from the Berkeley Boilers, UK.

4.8.1. European project THERAMIN: Thermal treatment for radioactive waste minimization and hazard reduction

As it was previously highlighted, radioactive waste safe management is challenging to both waste producers and waste management organizations. Thermal treatment can provide significant volume reduction, and the main applicable technologies include in-container vitrification, gasification, plasma treatment and hot isostatic pressing. THERAMIN EU project provided a framework for sharing of information and development of practices for all these methods [39].

THERAMIN objective, under five main work packages, was to identify which wastes could benefit from a thermal treatment, which processes are under development in participating countries, and how these can be combined to deliver a wide range of benefits. The result was an EU-wide strategic review and assessment of the value of thermal technologies applicable to a broad range of waste streams (ion exchange media, soft operational wastes, sludge, organics and liquids). Moreover, based on the EU-wide database of thermally treatable wastes, it was possible to document the strategic benefits of thermal treatment, to identify the challenges, synergies, opportunities, timescales and cost implications to optimize the radioactive waste management.

R&D facilities in thermal treatment were the major project beneficiaries as well as the as called End User Group (waste producers and waste management organizations). The mobility and training of staff for the development of the next generation of engineers and scientists, as well as technical and scientific events to disseminate the findings and results were among the project milestones. Another important goal was to establish a pan-European network of expertise on thermal treatment, to facilitate the technology transfer, and ultimately to assess the possibility for sharing of facilities between countries facing similar problems.

4.8.2. The Vinca-VIND Programme

Operation of the RA nuclear research reactor at the Vinča site in Serbia until 1983 resulted in the generation of spent nuclear fuel and many types of radioactive waste that need to be properly managed. The Vinca Institute Nuclear Decommissioning (VIND) programme was established in 2002 to undertake the decommissioning of the Vinca RA research reactor, repatriation of spent nuclear fuel and management of radioactive waste at the site.

The multi-phase VIND programme was supported by the Serbian government as well as by several international donors including the European Commission (EC), United States of America, UK, Slovenia, Russian Federation, and other donors, in partnership with the IAEA through the IAEA Technical Cooperation Programme [40].

Following the successful repatriation of spent research reactor fuel to the Russian Federation in 2010, the programme has now moved to the management of the radioactive waste inventory at the Vinča site, respectively the wastes contained in Hangar 1 and 2 (Figure 10) and in the surrounding area.

FIG.10. Hangars 1 and 2 and the new processing facility from Vinca site (Photo courtesy of Public Company Nuclear Facilities of Serbia - PC NFS)

The focus of current radioactive waste activities includes retrieval, characterization and packaging of solid waste stored in old hangars and then moving them to a new storage facility that has been constructed and commissioned. The programme also covers capacity building for the operator staff.

5. TECHNICAL CONSIDERATIONS

Some technical considerations for safely managing legacy waste are discussed in this section. These considerations include characterization, segregation of the waste, retrieval, degrading conditions, chemical characteristics, dose rate, criticality, physical size, production of secondary waste.

5.1. CHARACTERIZATION – TACKLING LACK OF KNOWLEDGE

Characterization activities are routinely performed during all stages of the radioactive waste lifecycle: during generation (including waste retrieval activities), processing (treatment and/or conditioning), and storage/disposal. However, in the case of legacy wastes, characterization data is often incomplete or non-existent. A balance needs to be found between the impacts and cost of data gathering and the effects of uncertainties in data on the resulting decisions. It is particularly important to ensure that the commitment of resources, which may result in worker dose uptake and/or the production of secondary wastes, is only undertaken in situations where the output will provide net benefits.

Where comprehensive sampling and characterization is not practicable (e.g., on the grounds of optimization of radiological protection), the explanations and arguments have to be presented as to why any alternative approach is appropriate and supportable. Where necessary, reliance may also be necessary on other lines of evidence, such as knowledge of the provenance and history of the raw waste (where supported by records), knowledge of waste evolution during storage, the use of simulants and modelling techniques [41].

It is not practical to define a single procedure for waste characterization due to the highly variable nature of the wastes and the varying needs for waste characterization data. In general, characterization actions need to be performed with the followings in mind:

- What is the WAC (and rational behind it) to allow for storage, treatment and/or disposal?
- What data is needed to perform the safety assessment and safety case for the storage, treatment and/or disposal concept?
- What is already known and where are the gaps in the knowledge?
- What are the data accuracy requirements and detection limits requirements?

An example on the use of the Data Quality Objectives Process in Characterization on UK nuclear legacy sites is presented below.

The UK nuclear legacy sites are increasingly using the Data Quality Objectives [42, 43] DQO, process to improve waste characterization and inventory data. The DQO process is a method to ensure that the collection and analysis of characterization data meets the stated specific objective and provides consideration for several issues during the characterization planning stages.

Before the DQO process is initiated, several issues are to be considered in assisting the preparation for considering each individual step in the DQO process, including ensuring that the correct people are involved from the start. Who are the stakeholders, the decision maker, the technical experts, and staff with the appropriate statistical knowledge? In addition, gathering existing site data/knowledge eases the overall process although recognition has to be given to any resource or socio-political constraints.

It is a seven-step systematic stepwise approach which are shown below:

1. ***State the Problem*** – describe the conditions requiring characterization, including potential noncompliance with regulatory requirements. Develop a conceptual characterisation model, often in diagram form. Inform about the resource limitations, including time restrictions for the collection of data.
2. ***Identify the Decision*** – this allows a Decision Statement to be produced, identifying the purpose of the characterisation study and the potential actions required once the characterisation data is analysed.
3. ***Identify the Inputs to the Decision*** – identify the kind of information required and the sources of the information. In addition, determine the Action Levels, if any, and then confirm the proposed sampling and analysis methodology which may result in a Sampling and Analysis Plan.
4. ***Define the Boundaries of the Decision*** – this effectively bounds the scope of the characterisation and may include for example, a population of legacy waste packages, or the contents of a legacy waste store. The boundaries may also include timeframes, dose restrictions, technological and financial constraints.
5. ***Develop the Decision Rule*** – this step assumes that information from the previous 4 steps have been successfully gathered and are available. Can then determine an "if …… then …" decision rule applicable to the characterisation case required.
6. ***Specify Tolerable Limits on Decision Error*** – the purpose of this step is to specify quantitative characterisation performance goals to determine the probability of making errors in the decisions including sampling errors and measurement errors.
7. ***Optimise the Design for Obtaining Data*** – this step allows the DQO team to optimise the sampling and analysis plan, incorporating the type, location and number of samples required for characterisation.

The DQO process provides a systematic planning approach to obtaining robust characterisation data which meets all stated criteria, bearing the agreed constraints to the characterisation presented by the legacy wastes.

Several IAEA documents provide guidance on characterization objectives, methodologies, and applications [4, 5] so the details will not be provided here. Reference [4] introduces *"historical wastes" are those that are generated without a complete traceable characterization program or quality management system in place.* This is equivalent to "legacy wastes" as described in this document. Because of the lack of knowledge or detailed records of the wastes, this situation in many cases results in the most difficult from a characterization point of view – streams whose properties are both complex and variable in nature.

In providing guidance in how to best develop a strategy for waste characterization, in reference [4] several explanations are provided on how to best avoid the most difficult situation of complex and variable streams, as these are very expensive in both cost and time to characterize with accuracy and precision. Waste characterization is defined as the "determination of situation of the physical, mechanical, chemical, radiological and biological properties of radioactive waste to establish the needs for further adjustment, treatment or conditioning, or its suitability for further handling, processing, storage or disposal" [4].

It may be possible to make use of preliminary actions to inform the characterization plan. For example, preliminary characterization of the waste can be conducted to allow for retrieval and placement into an interim state for further processing or readying for disposal. This can be as simple as visual inspections to ensure container integrity or analyses to ensure safety (e.g., contamination smearing or dose rate measurements). Once the waste is safely placed into an interim state further detailed analyses could be conducted to facilitate processing or disposal. In some cases, retrieval may also permit sorting and segregating at this stage into like material types; an action that will become very important for certain types of non-destructive analysis that could be streamlined later.

It can be expeditious to characterize wastes during retrieval if this makes the waste more accessible and if characterization equipment (e.g., gamma scanning) can be easily deployed. It may also be practical to sample during retrieval to obtain a representative sample for off-line analysis. This method is most appropriate for homogeneous wastes such as liquids or well mixed solids or wet solids.

Both destructive and non-destructive analyses are routinely employed. Again, it is important to align the used techniques with the data requirements for the specific objective and in some cases both techniques may be needed on a specific waste type to meet the requirements to allow for storage, treatment, or disposal. Reference [4] provides in depth information on many destructive and non-destructive analysis techniques with useful examples of their application.

It is important to work with regulatory bodies and/or the disposal implementer to understand and decide which are the relevant radionuclides and other species that need to be quantified. Once a list of analyses is determined, the methodologies to be used to determine the presence and concentration of the constituents can be specified.

5.1.1. Non-radiological characterization

In addition to radionuclide characterization, the assessment needs to be extended to physical, chemical, and biological considerations including for example the following:

- Leaching rate of waste form;
- Physical / mechanical stability of waste form;
- Volume or percentage of void inside the waste package;
- Chemical or other hazardous constituents;
- Biological, pathogenic, and/or infectious materials;
- Free liquid content;
- Flammable materials;
- Restriction on gas release;
- Solubility and chelating agents;
- Organic content;
- Chemical reactivity and swelling potential;
- Sorption of radionuclides.

The presence of many of these components (i.e., chemical or other hazardous constituents, biological, pathogenic, and/or infectious materials, flammable materials) is based on process knowledge and the implementation of a quality assurance system by the waste generator. In addition, visual checks can be performed and/or imaging techniques can be used.

5.1.1.1. Physical Characterization

Physical characterization is the determination of many of the following physical and mechanical properties of the waste:

- Physical form (solid, liquid, gas or mixed phase);
- Volume;
- Weight;
- Density;
- Shape;
- Material type (including quantities and types of metals, PVC, cellulose, etc.).

For solid radioactive waste, if it is un-containerized or need to be repacked as part of retrieval, then visual checking and segregation during the retrieval and/or repacking steps can be utilized to obtain this information, and this is a very reliable approach.

If the waste is containerized and it is highly undesirable to open the container for further investigation, then there are methods that can be employed to extract physical information, albeit with limitations. For example, a parameter such as density can be estimated by weighing the package and dividing by the package volume. This is just a rough approximation and often not very useful as in most of the cases density is not uniform across materials within a container. It does not infer material types. This approach is sometimes used to correct for self-shielding in gamma scan measurements but does not yield the highest accuracy in results.

X ray and/or tomographic scanning technologies have lately developed such that detailed 3-D images of container content can be constructed. These technologies are very expensive, and thus not widely accessible, and require hours to even days of scanning time to get very high resolution. There are also limitations with respect to resolution when packages contain very dense materials (e.g., lead or concrete) or distinguishing between materials of similar density (e.g., aluminium and polythene) which can be particularly important when neutron interrogation is being employed.

Contents confirmation of waste is often carried out by using X ray inspection apparatus, being an attractive technology for inspection of low level and intermediate radioactive waste package inspection and may even deal with high level waste packages in some cases.

The use of non-destructive X ray imaging techniques in waste characterization is an important component in the assurance that WAC for the safe long-term waste disposal are met. Radiography provides a direct picture and even measure of material density. It can then be used to confirm the physical form of the waste and identify some prohibited items. Free liquids can be located and identified in limited volume of waste packages, presently up to 200 L drums (Fig. 11). Developments are performed for large size and dense waste packages, such as concrete cylindrical container and metal boxes. Detection performances needed in the frame of homeland security pushes forward developments useful for waste characterization.

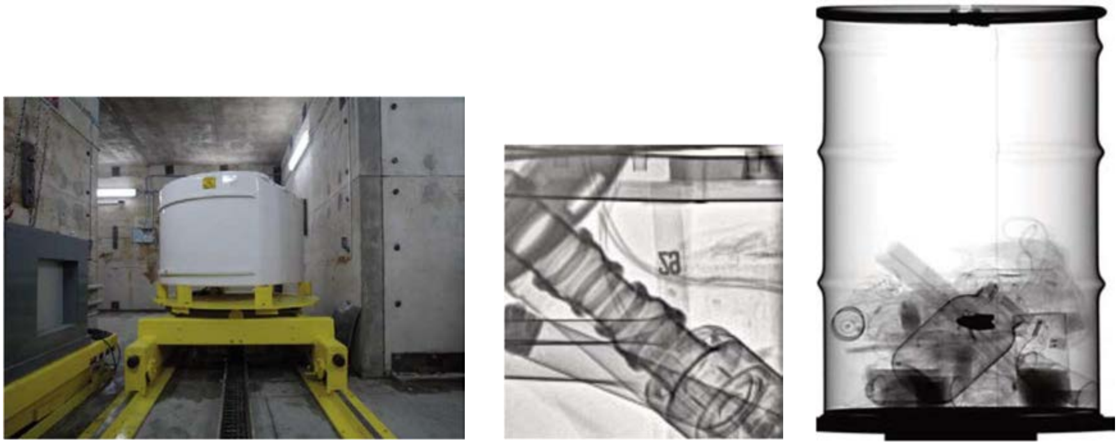

FIG.11. Digital X radiography system with imaging (photo courtesy of VJ Technologies). A glass flask is seen, and it might be possible to detect free liquid at its bottom (Photo courtesy of VJ Technologies, USA)

5.1.1.2. Chemical Characterization

For solid radioactive wastes, chemical characterization refers to determining some waste properties by addressing the followings:

- Does it contain gaseous emission materials?
- Does it contain prohibited hazardous materials?
- Does it contain hazardous materials that are required to be treated?
- Does the waste contain reactive or incompatible materials?

For many of these questions, the ultimate origin of the generation of the radioactive wastes can provide clues to narrow down the investigations. For radioactive facilities that are engaged in a narrow range of activities (e.g., fuel production plants) it may be possible to narrow down the list of potential problematic items or materials to be looked for. For wastes from multiple sources or research facilities the list may be quite broad.

Quite often simple approaches are utilized in conventional waste management and environmental remediation can be useful when dealing with radioactive wastes. Visual signs of staining from organic contaminants (oils or other hydrocarbons), signs of reactions between incompatible materials or evidence of corrosion from acids or bases. Vials or other similar small containers could contain liquids that would prompt additional investigations.

If liquid radioactive wastes are present, then are some typical properties that need to be analysed:

- If is organic or inorganic;
- Conductivity;
- pH;
- If is mixed – percentage weight;
- Turbidity;
- Dissolved oxygen;
- Chemical Oxygen Demand (COD);
- Total Organic Carbon (TOC);
- Total Dissolved Solid (TDS);

- Total Nitrogen;
- Total Suspended Solid (TSS);
- Chemical constituents (cations, anions, organic extractants and solvents, complexing agents, surfactants, etc).

5.1.2. Radiological Characterization

The radioactive properties of the waste need to be known to the extent that it can be robustly classified in terms of the waste category e.g., LLW or ILW and is facilitating the assessment whether decay to a lower waste category is possible within a reasonable timescale, and hence to inform decisions on its future management and disposal.

For quantitative analysis (determining the amount), the newest and most appropriate technique are mathematical efficiency calibrations (like ISOCS, ISOTOPIC, GESPECOR and others), which allow the user to obtain an estimation of the activity.

For unknown or complex vector waste, it may be possible to perform a gamma spectrometric measurement using a High-Resolution Gamma Spectrometry Germanium detector [4]. This allows the best qualitative discrimination between the different nuclides that are easy to measure. Next considerations are to be considered during this approach:

- Depending on the dose rate, the distance between detector and waste sample, or a correct collimator it has to be selected such that the maximum dead-time in the spectrum is not higher than 15% to allow clean discrimination between the possible nuclides.

- The list of nuclides that are to be investigated and reported, as a minimum:

  - the typical fission products (long lived, e.g., Cs-137) activation products (e.g., Co-60), and corrosion products;
  - other long lived Disused Sealed Radioactive Sources (DSRS) industrial and medical nuclides, like Ra-226 (and daughters), Ir-192, Am-241 (main 59 keV line and secondary lines);
  - Special Nuclear Material (SNM) or Transuranic (TRU)-actinides, e.g., U-235, U-238, Pu-239, Pu-241, Cm-247;
  - notice that some nuclides are indicative for different types of applications: as example Cs-137, that can be indicative of any fission produced waste, but also as industrial or as medical source; Am-241 that can be indicative of industrial alpha source (smoke detector), industrial neutron source (Am-Li/Be geology), actinide (as daughter of Pu-241);
  - Important reflections: if no gamma nuclides can be found but is a certain dose rate given by the waste, the origin of the radiation might be caused by e.g., bremsstrahlung from a beta source (like Sr-90), or e.g., Compton radiation from a highly shielded gamma source.

5.2. HISTORICAL RECORDS AND KNOWLEDGE MANAGEMENT

Over time, there can also be a loss of knowledge of stored legacy waste. Records systems may have become obsolete or written documentation lost or destroyed via fire or improper keeping conditions. Human process knowledge may have been lost due to any ageing workforce and subsequent retirements. In some cases, there may have been no documentation at all for these wastes. Often historical records may not reflect the actual situation, waste may have been deposited outside of normal process or the characteristics of the waste may have changed over time making it difficult to identify the waste from existing records.

Too often, inadequate recording led to the necessity to conduct additional works, as is highlighted in the example described below [44].

Radioactive waste in Poland originates from a research reactor, scientific and educational institutions, industry, and hospitals. The waste comes from various applications involving radioactive materials that are used in more than 5500 activities. The wastes are mainly low and intermediate level that are collected, processed, encapsulated, and prepared for disposal at the Świerk facility and then disposed at the National Radioactive Waste Repository in Różan. The Różan facility has been in operation since 1961 and is a serving as a near surface type facility for the disposal of low and medium level waste containing short lived beta and gamma isotopes, as well as a temporary storage for long-lived waste.

All the waste that is disposed of at Różan is either solid in nature or is encapsulated. In the early days of operation, little attention was given to waste segregation and records management for the disposed waste. Additionally, packaging was often inadequate. Some of the waste is not packaged and the rest is in the form of one of the following packages: 200 L drums, wooden case, plastic foil, 50 L drums, aluminium container, iron container, paraffin container, lead - iron container, plastic container, or glass container. The activity of some of the waste packages was not recorded on the records that accompanied the delivery.

The wastes deposited in facilities 2 and 3 and some in facility 1 pose a challenge as records on the activity concentrations and the type of radioisotopes are incomplete and some of the waste is not packaged or is in an unconditioned form. Before the closure of the Różan repository the waste from these facilities is intended to be retrieved, segregated, treated, and packaged to comply with waste acceptance criteria (WAC) for final disposal at Różan or meet the WAC for a future repository to be constructed elsewhere in Poland [44].

5.3. RETRIEVAL OF WASTE

Retrieving legacy waste can be challenging due to its location, accessibility, condition of storage containers or tanks and associated hazards. Often original vessels and storage locations were not designed with retrieval in mind and therefore the waste retrieval cannot be performed in the same way it was loaded.

For example, at the Hunterston Magnox site, historical waste was loaded through small posting ports at the top of 5 separate bunkers. During processing the waste is being accessed by controlled cutting operations into the bunker walls. After a bunker is emptied of waste, the operation is repeated to allow access to the next bunker.

Furthermore, the original waste handling equipment is often not maintained or is obsolete. New special apparatus or tools may need to be developed to facilitate retrieval. Mock-up testing can ease deployment of new retrieval techniques. The IAEA document [1] is an information source on retrieval and conditioning of solid wastes from old facilities. The retrieval of liquid and wet solid wastes is well documented in the open literature (for example retrieval of liquid waste from USA DOE high level tank wastes is available and describes methods and tools to retrieve these challenging wastes) but also in retrieval of fluidizable radioactive wastes from storage facilities [2].

Prior to initiating the retrieval process, a support infrastructure needs to be established to either stage the waste for further processing or to package for disposal. In some cases, the new location could be another store where the waste will be more safely managed or stored in a manner that meets current requirements.

Several safety requirements need to be considered during retrieval operations and subsequent waste handling to ensure worker safety. First, package or container integrity needs to be ensured during moving or lifting operations. When applicable, dose rates need to be monitored and ALARA principles employed. For some wastes, especially alpha-bearing wastes, the potential of gas build up needs to be considered.

Chapter 2 of this publication provides examples of the types of legacy wastes and storage scenarios. It is evident from these examples that the nature and storage environment vary considerably often requiring “one of a kind” solutions for waste retrieval.

5.3.1. Opening of containers, segregation, or co-packaging of wastes

There is often a question as to how much intrusion into containerized waste needs to be exercised. As it is often the case, the answer may be “it depends”. Some intrusion, or even segregation or repacking may be appropriate to adequately characterize the wastes. Some segregation may be required to separate incompatible materials, or to ensure compatibility with the conditioning matrix.

Legacy situations vary from retrieval of intact containers with little recorded information from a storage building (e.g., a drum store), to retrieval of unpacked wastes from a trench where any ability to identify discreet items or packages has been lost. Storage locations could also contain containers that are so degraded making the situation equivalent to bulk wastes. There may be a tendency to be reluctant to open the intact containers for analysis purposes. Unfortunately, characterization techniques that can be employed relatively cost effectively and quickly to intact containers all rely upon a certain amount of information about the contents of the container. If nothing is known about the contents of the containers, then in order to perform an effective characterization, at least some will require to be opened. The challenge will be in obtaining enough information that is representative for the population of containers. If, upon opening a small number of containers, the properties of the contents are shown to be highly consistent, then it may prove to be the “lucky” situation where a simpler characterization strategy can be employed. Caution, that even in this situation, a periodic opening of containers throughout the campaign is necessary to be considered, to provide assurance that as the population of legacy containers is worked through, the degree of consistency in container contents remains, otherwise, a change in characterization approach during the campaign may be necessary.

The following are examples for which a “yes”, “maybe” or “don’t know” answer could result in the need to open containers for further analysis:

- Do the physical material properties between containers vary a lot?
- Are there materials that could interfere with non-destructive analysis (e.g., very dense metals like lead for gamma measurements, or hydrogenous materials or strong absorbers for neutron measurements)?
- Are there incompatible materials packed together in containers?
- Is it possible that prohibited materials are present (e.g., reactive, explosive, pyrophoric or prohibited controlled chemical substance such as mercury)?
- Is it likely that difficult to measure radionuclides are present, and if so, the concentrations are consistently scalable to easy-to-measure radionuclides?

For the case of severely degraded or unpacked wastes, a large degree of additional handling of the wastes for conducting repackaging operations will be necessary anyway. In this situation, applying segregation while retrieving the wastes will in many cases assist with characterization. Additional visual indications, along with sampling for destructive analysis for difficult to measure radionuclides, or for the presence of chemical or other hazardous materials can also be performed during the repacking steps.

Segregation during retrieval may also be required for other purposes. Legacy wastes are often comingled or improperly stored. An important first step is to segregate the wastes, if practical. For example, segregating the waste is necessary when they cannot be co-disposed together. Several categorization schemes can be used to separate the wastes. The wastes can be separated by material type, process origin, hazard, or dose rate. The segregation method applied has to facilitate storage, processing or disposal and support meeting facility safety requirements and complying with regulatory requirements. It is best to segregate the wastes as early as possible after generation to avoid comingling and record keeping issues.

In some instances, it may be desirable to combine separated wastes to improve package efficiency. Key questions to be considered whilst assessing whether wastes can be co-packed are listed below:

- How will the waste package radionuclide inventory be controlled to ensure compliance with specified activity limits?
- How will records be generated to demonstrate the waste package compliance with the Waste Product Specification?
- Is there confidence that all components of the waste can be conditioned to a level commensurate with the requirements in the Waste Product Specification? Are (additional) conditioning trials required to gain, or increase this confidence?
- Has a Quality Plan(s) been prepared to control waste package manufacture?
- At the time of manufacture is the waste package dose rate acceptable against the site Safety Case?
- Has the decision process to co-package waste been accurately documented to inform future custodians of the package?
- Do any of the waste streams contain materials or items that are excluded from or limited by the Waste Product Specification (e.g., hazardous materials, sealed regions, bulk oil)? If so, how will they be managed?

A relevant example is showcased by the strategy applied at the Bradwell site in UK where Magnox has waste stored in various locations that originally were planned to be retrieved and processed separately. Consequently, it became evident that the internal volume in many containers was not fully utilized. As the cost of individual containers is relatively high, the feasibility of “topping off” containers with other wastes that had yet to be retrieved was investigated. An assessment was undertaken on the likely compatibility of waste types and a Waste Product Specification was submitted to RWM to confirm acceptability against the UK Disposal WAC.

By following this process at Bradwell it was shown to be acceptable to co-package sludge, reactive metal, sand, gravel, ion exchangers and other miscellaneous contaminated items within the same container [45]. Following loading the containers were conditioned by vacuum drying to passivate the waste form in accordance with the agreed Waste Product Specification.

By implementing this new waste minimization strategy, the interim storage facility (ISF) was able to continue taking waste from two other Magnox sites in the southeast – a change which brings along safety, environmental and financial benefits [45].

5.3.2. Size Considerations

Legacy wastes come in all shapes, sizes, and configurations. Large waste items often result from decommissioning activities. These large items can usually be readily handled when there are disposal options available for these wastes. However, when disposal options are not available, these items will have to be stored in a safe and manageable condition. This could present significant challenges for a waste management organization. Size reduction can sometimes be employed but could result in the introduction of other hazards including industrial and worker dose issues. For example, in France, ANDRA, the disposal implementer, has already successfully addressed several dismantling issues such as dealing with large components. Outsize wastes such as reactor vessel heads and other equipment items are disposed of in the Centre de L'Aube (CSA) without first being cut up for packaging in standard packages.

Alternatively, finely divided (i.e., material fines) and small waste materials can offer additional hazards for waste management. Fine powders are very dispersible and therefore need to be packaged in a manner that precludes release (e.g., multiple packaging layers). These powders are also more reactive in a finely divided form. It is often advantageous to immobilize small or finely divided materials; however, conditioning and treatment of these materials can be complex and expensive. Simpler immobilization processes such as grouting typically result in a volume increase that are consequently increasing the storage and/or disposal costs. In some cases, it may be advantageous to use double containment or special containers to manage very fine materials vs. immobilizing the fines.

5.4. DEGRADING CONDITIONS

Legacy waste by its nature is highly variable and contains many problematic constituents. Many of these constituents result in degrading conditions for the waste over time. In extreme cases, the waste may have changed so significantly that it is hard to identify or no longer recognizable.

In some cases, waste degradation can cause the packages to degrade or result in unsafe conditions for subsequent waste package handling. Mild steels were used in containers for many legacy wastes. The presence of corrosive species (e.g., chlorides) can cause major loss of integrity for the containers.

The immobilization of radioactive waste in bitumen can sometimes lead to swelling of the waste form and deformation of the waste container. In the followings is explained the phenomenon of swelling caused by self-irradiation leading to the generation of radiolytic gases and subsequent swelling of the bitumen matrix.

In a few countries including France and Belgium, for some radioactive waste types was selected bitumen as encapsulation material. Selected for its containment properties (as well as its low solubility in water, chemical inertness and low permeability), several types of radioactive waste were insolubilized by co-precipitation in bitumen. In France, the encapsulation process was consisting in extruding the high-temperature radioactive waste slurry with bitumen. The mixture that resulted (BWP - Bituminized Waste Product) was further dehydrated online and then poured into a steel drum. Due to the self-irradiation process some changes were induced, such as the production of radiolytic gases with a high hydrogen content, which depends on the type of bitumen (between 75 and 95%). Once the gas solubility limit in the material is reached, the nucleation of hydrogen bubbles occurs homogeneously, and the swelling process is facilitated in the matrix. In the attempt to predict the degree of swelling of bituminized waste drums, several models were studied and proposed. While all these theoretical models are consistent with the experimental, they still require several adjustable parameters. An important outcome was that it was possible to showcase that the swelling is dependent on the origin of the bitumen, or more specifically on its grade and composition [46].

As mentioned, gas generation in alpha-bearing wastes can be a concern. For example, TRU waste drums that are exhumed at DOE sites for repackaging and eventual disposal at Waste Isolation Pilot Plant (WIPP) are visually examined and then placed into containment where the drums are punctured using a spark-free puncture system and any evolved gas is analysed prior to further handling.

External environmental conditions can also lead to changes in the waste and/or waste packages over time. Water egress via rain, groundwater or condensation can interact with the waste containers and/or the waste. In extreme cases, this can dramatically change the characteristics of the waste. Temperature fluctuations over time can also impact the waste and/or waste containers.

In some cases, the storage location can be compromised by external factors mentioned above. Examples of corrosion of waste containers through water ingress at the Dounreay LLW storage pits [47] and temperature fluctuations leading to degradation of LILW boxes in Canada [48] are highlighted below.

During the 1960s LLW contained in mild steel drums was consigned to the Dounreay LLW storage pits [47], with some of the earlier filled pits containing uncompacted drums with void spaces. These pits, once full, were profiled with a top cover to ensure surface water was diverted to an engineered drainage system. However, with constant groundwater infiltration, many of the mild steel drums corroded and collapsed, resulting in the top cover gradually changing from a "dome" shape to more of a "dish" shape, at which point water infiltration increased due to rainwater. Infill was added to restore the "dome" profile to shed surface water.

Learning from this experience, UKAEA acquired a super compactor, and storing of super compacted drums in newer pits continued. This mitigated the potential for collapse of the pit profile but did not end the accumulation of legacy waste as this type of waste would still require remediation in the future. Further accumulation of this type of legacy waste at Dounreay was finally ended when a disposal concept and WAC similar to LLW repository near Drigg was adopted and the path to a Dounreay LLW repository was established. From that time forward, storage in the pits was replaced with characterized compliant packages (based on IP-2 ISO containers of varying height) stored in above ground storage buildings awaiting construction of the Dounreay repository, which commenced receiving waste in 2015.

The ultimate solution for this legacy waste challenge will involve retrieval from the storage pits and reworking of the waste for compliant emplacement in the LLW repository.

The second example is related to the above ground storage of mild steel B-25 style boxes of LILW at the Chalk River Laboratories (CRL) in Canada which is typically performed in shielded but unheated buildings. Temperature fluctuations in Canada can be seasonally extreme between -30 °C and +30 °C. The frequent temperature cycles and high relative humidity can lead to condensation developing on the steel and potential for corrosion of the packages over time (Fig. 12). This provides a question regarding integrity of container over lengthy time periods and underscores the consideration of package inspection for this type of storage arrangement. This effect was not foreseen, and obvious signs of corrosion have been observed after storage periods of sometimes less than 10 years) [48].

At the time this waste was received into storage, and during the period storage, a path to disposal was not yet available, and hence no WAC for disposal. WAC for storage did not require detailed characterization, particularly for non-radioactive hazards and the storage methods are not necessarily ensuring preservation of container integrity. Since the launch of the regulatory process for the proposed Near Surface Disposal Facility at CRL, WAC for disposal have been developed for LLW and waste received into storage needs to meet the WAC for disposal, and storage arrangements includes provisions for preservation of container integrity up to time of disposal.

FIG.12. Corroded containers after a decade storage period (photo courtesy of AECL Canada)

External or environmental events can also make a disposal location no longer suitable for the intended purpose. In these situations, one approach can be to re-engineer the disposal location (as in the below example - the legacy licensed ILW disposal shaft at Dounreay in UK) or retrieve the waste and to place them into a disposal location that meets current regulations.

Dounreay (UK) had a 65 m deep shaft residual from the construction of the liquid effluent discharge system [49]. This was chosen as a site to dispose of primarily ILW for many years under a disposal authorization. Following a small explosion in 1977, use of the shaft for disposal was discontinued and eventually the disposal license was withdrawn by the regulator and replaced with a storage license. Plans for safe retrieval and packaging of the shaft wastes have been developing for many years. By 2006 rings of boreholes surrounding the shaft were filled with pressurized grout to hydraulically isolate the shaft from the environment as the shaft was unlined and hydraulically connected to groundwater and the sea [50]. Facilities associated with the retrieval and packaging of wastes are progressing. Retrieval is anticipated to commence in the mid-2020s according to the current plan.

Furthermore, some storage locations exist whose original intention was to be disposal. With the increase in safety requirements and the evolution of safety standards, safety improvement actions are necessary to be implemented. In this condition, the legacy waste generally will have to be retrieved and repackaged. Since 1963, a RADON-type radioactive waste disposal facility has been in use for waste from medical and industrial applications in Estonia. The planned volume of the facility was 200 m^3. In 1995, the facility was temporarily closed. After several assessments it was clear that the facility does not fulfil the requirements for disposal facilities [5]. The possible assessment of alternative future scenarios included among others transportation of the waste to centralized interim waste storage and decommissioning of the site; conditioning of the waste and disposing it at the current site or doing nothing. After assessing the possible options, the decision was made to move the waste to the existing interim storage, condition it there and to decommission the RADON-type facility.

Degradation of packages or storage conditions can also occur due to the presence of chemical hazards within the waste.

5.5. CHEMICAL AND HAZARDOUS PROPERTIES

Many legacy wastes contain hazardous constituents that make treatment or disposal difficult. These include heavy metals such as lead, toxic species such as hexavalent chromium and mercury, carcinogens such as asbestos and organic solvents, etc. Some of these may cause little issue in waste management due to de minimis levels or low hazard of the species of concern. However, in many cases, the hazardous constituents may add additional safety and regulatory requirements for managing the waste. Although the presence of hazardous species can complicate treatment and disposal, there are several examples of Member States successfully addressing the issues and meeting requirements for disposal of these wastes. In the USA, a nickel-plating line sludge resulting from Al-U clad fuel production was vitrified and proven to be suitable for low level radioactive waste disposal by "delisting" the waste as hazardous in compliance with Environmental Protection Agency (EPA) regulations [51].

It may also be beneficial to perform research and development activities or develop models that can be used to predict chemistry changes that may occur over time. This may not be applicable to small quantity waste streams but could be proven helpful in managing large waste streams or very challenging wastes.

5.5.1. Reactive waste forms

Reactivity of the waste due to incompatible materials or presence of pyrophoric materials (e.g., fine metal powders) can also be an issue. Incompatible materials used in drums disposed at the Waste Isolation Pilot Plant (WIPP) in the USA resulted in a drum rupture and the release of airborne radiological material to the surface of the disposal mine. In the followings are presented two cases in which the wastes were mixed with incompatible materials.

On February 14, 2014, an event occurred at the Waste Isolation Pilot Plant (WIPP) in Carlsbad, New Mexico (USA) that, although did not result in significant worker safety issues or generation of significant radioactive waste, it is relevant in highlighting the potential issues with incompatible materials in disposal containers [52]. A small radioactive release occurred through an exhaust air duct due to the rupture of a waste storage drum in Panel 7 of the deep underground geologic repository. It was assumed that the drum rupture event was due to an incompatible mixture of a nitrate-based waste with an organic sorbent material used in the packaging process. The reaction may also have been catalysed by other waste materials present in the drum. To assist in the inspection of the event, an inspection camera system was fabricated that could reach 90 feet into the room with a swing rotation capability of 33 degrees. The system allowed for remote inspection of the ruptured drum and other drums within the room, as described in [52]. The recovery from the radiological release event was extensive and reopening the repository took place in September 2017. The primary lesson learned from this event centred on noncompliance of the waste generator with the WAC including lack of procedural and operational control. However, additional findings included inadequacies in the ventilation system design and safety management programs that compounded the effects of the incident.

The second example is related to the osmosis-induced swelling of bituminized hygroscopic salts in deep geological disposal conditions, namely the work carried out to study the behaviour of Eurobitum in an underground disposal facility.

The Bituminised Waste Product (BWP) - Eurobitum - from the former EUROCHEMIC reprocessing plant in Mol-Dessel (Belgium) contains large quantities of hygroscopic salts, mainly $NaNO_3$ and $CaSO_4$. In underground repository conditions the waste will come in contact with water causing the rehydration of the BWP dehydrated salts. This will result in swelling and, when no free space is available, in the appearance of a swelling-pressure [53], which might hinder the repository integrity and safety by stimulating preferential pathways for radionuclide migration. When BWP is hydrated in (nearly) constant volume conditions, the osmosis-induced water uptake results in an increasing pressure value that can be (in theory) as high as 42.8 MPa. The interaction between the swelling BWP and the host formation depends on the hydromechanical behaviour of both. The hydromechanical constitutive law of Eurobitum is not yet established and the works are still ongoing. In water uptake tests, the osmosis-induced swelling and swelling pressure increase and $NaNO_3$ leaching of small cylindrical bituminized waste samples are studied under constant total stress conditions (swelling) and nearly constant volume (swelling pressure) conditions. After about four years of hydration in nearly constant volume water uptake tests, pressures up to 20 MPa, were measured. Using a long-term model prediction related to the osmosis induced pressure evolution (at constant volume) (Fig. 13), it was estimated that a maximal pressure value of 20 MPa will be reached in approximately 5.5 years, after which the pressure would start to decrease. After 27 years the pressure would have decreased to a value of 2 MPa.

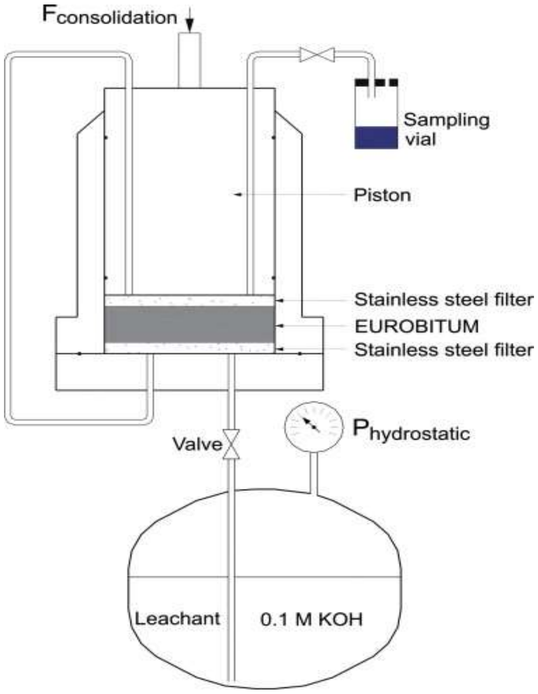

FIG.13. Schematic visualization of the experimental set-up for water uptake tests with BWP samples (Photo courtesy of SCK CEN, Belgium)

A continuation of the water uptake tests as well as the investigation of the effect of several parameters on the hydro-mechanical behaviour of the BWP will allow to further improve the understanding and model predictions. The final aim is to conclude on the safety of geological disposal of this waste form and to optimize the disposal design.

5.5.2. Flammable materials

The presence of flammable materials can also pose challenges for the storage, treatment, and disposal processes. In some cases, flammable materials can be destroyed by incineration. However, this is a relative expensive process and is not available in most countries for radiological materials or worth the investment for small quantity wastes.

5.5.3. Gas generation

As mentioned, gas generation due to radiolysis, hydrolysis, bacterial action or other degradation processes can occur in wastes that contain water or organics. In some cases, gas generation can be mitigated by drying the waste or precluding introduction of materials (e.g., organics) that can lead to gas generation. In other cases, measures may need to be taken to manage any gas that is generated in the waste. For example, vented High Integrity Containers (HICs) are often used for storing wet ion exchange materials.

5.5.4. Corrosion

The presence of corrosive species can lead to degradation of the waste and/or storage containers. Limiting the concentration of corrosives in the waste (e.g., chloride content limits) can be used to mitigate deleterious corrosion effects to containers. Microbial effects and galvanic corrosion are also common mechanisms found in legacy wastes that lead to degradation of waste and/or containers. Where corrosion is likely or possible, periodical inspection and surveillance programs need to be in place.

5.5.5. Hazardous chemicals

Special protective measures may be required for handling and treating radioactive wastes also containing hazardous chemical species. However, in some cases protective measures used to address the radiological hazard may be adequate. When handling these mixed wastes, it is important that the radiological control personnel and industrial hygiene personnel work cooperatively in ensuring that worker and environmental safety is maintained.

Mercury is an example of a hazardous element that is common to legacy wastes. The toxicity of the waste containing mercury is mainly linked to the chemical toxicity of mercury. The aim is to develop physical-chemical stabilization treatments such as to avoid any volatilization of the mercury into the atmosphere or leaching into the ground. In France, the various processes are tending towards stabilization in the form of mercuric sulphide, classified as non-hazardous.

5.6. DOSE RATE AND ENVIRONMENTAL MONITORING

Dose rates monitoring and their subsequent management are required to ensure worker and public safety. Dose rates are often of most interest to regulators especially for monitoring of radiological effects to the public and the environment. Therefore, it may be beneficial to employ special dose rate measurement equipment (e.g., gamma cameras) during waste retrieval or other activities where conditions may be changing. Although mining wastes are not in the scope of the publication, recent work in Iran involved the mapping of dose rates in the Gachin uranium mine (Iran) to ensure worker safety and to support decommissioning efforts. Results of the dose rate monitoring were presented to the regulatory body and will be used to facilitate environmental remediation.

Environmental Monitoring of Radionuclides Contamination in Gachin Uranium Milling and Mining Facility is carried out to allow for Planning of Legacy Waste Management [54].

Many years of uranium ore exploration, mining and milling processes in Gachin uranium mine has resulted in a considerable land area requiring remediation. Mining of radioactive ores for uranium production was initiated in 2005 and the mine was closed in 2016. To deal with the legacy of past mining of radioactive ores, the environmental monitoring and waste characterization of old mining site are set as a priority for Atomic Energy Organization of Iran (AEOI). The mining of uranium ore by surface methods and conventional processing techniques produces a wide variety of waste materials, including milling residues, tailings, waste liquors from the milling operation, rock piles, below-grade ore heaps, open pits and remaining extracted ores in surface depot, abandoned processing equipment and facilities.

A two-year monitoring of the Gachin uranium production site was carried out, including terrestrial gamma radiation dose measurement, uranium, thorium, and potassium mapping. The obtained information was useful in developing plans for decontamination and decommissioning (Fig. 14) which were presented to the regulator to move forward with the environmental remediation project.

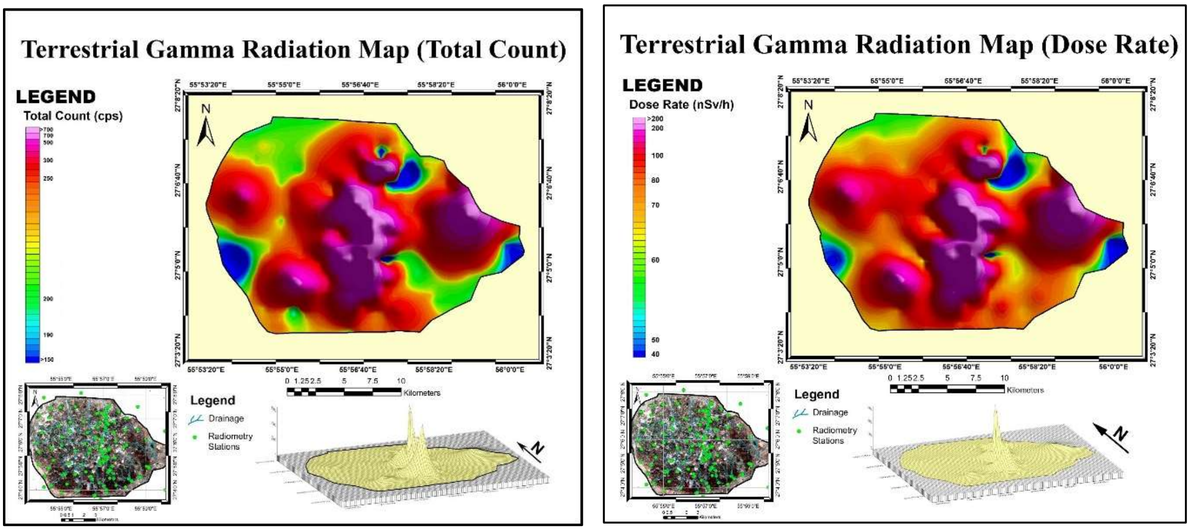

FIG. 14. Right - Terrestrial Gamma Radiation Map (total count); Left - Terrestrial Gamma Radiation Map (dose rate) at Gachin uranium production site (Iran) (Courtesy of IRWA, Islamic Republic of Iran)

It is often an aim in waste storage and disposal to reduce waste volume or consolidate wastes. This is especially pertinent in Member States with limited land mass or storage or disposal sites. However, this can sometimes be problematic if increased dose rates result in the need for increased shielding, result in the need for special tools or remote handling, limit exposure times for workers and lead to an increase in off-site dose. Therefore, cost benefits analyses are necessary to be conducted any time dose rate becomes a factor in managing legacy wastes.

In some cases, segregation of wastes can be used to help manage dose rates. Lower dose rate materials can be arranged around higher dose rate materials to provide shielding. Alternatively, special areas can be designated in a facility that utilizes increased shielding to handle especially high dose rate wastes.

Dose rates measurements are carried out and need to be carefully considered across all waste management activities – storage, conditioning/treatment, transportation, and disposal. For example, transportation may be a limiting factor for dose rate, so it may not be advantageous to condition or package wastes that could limit the amount of materials that could be transported.

5.7. WASTE PROCESSING APPROACHES

The predisposal activity's main objective is to produce a waste form that is compliant with the waste acceptance criteria for the designated disposal site. The end-state of the waste and the site need to be considered when identifying the disposal approaches.

5.7.1. Select and implement the appropriate predisposal technologies

There are a range of waste processing options that are in use across Member States and have a high level of technical maturity for a wide range of legacy wastes. These include cementation, compaction and entombment, and detailed information can be found in an IAEA publication dealing with selecting the proper technical solutions in managing the radioactive wastes [55].

The route to implement the appropriate predisposal technologies is influenced by many factors such as:

- understanding the legacy waste from the history;
- understanding how to process and condition the waste;
- understanding the technologies;
- decision making processes (including how to choose the proper technical option when there are several possibilities);
- funding;
- legal issues;
- regulatory compliance.

Referring to the strategy for legacy waste management and the lifecycle of the site, it will indicate the priority given to the specific legacy waste stream. The financial and political circumstances will indicate the level of money which can be spent on the legacy waste. The safety, security and regulatory framework will dictate how the legacy waste will be processed. The legal landscape will define some activities which may be involved in the conditioning process (e.g., emissions from incinerators) and may impact the disposal pathway.

The solution that is developed has to be adequate for the risk and the level of complexity. Having the perfect solution will never be feasible for legacy wastes, as there is always a challenge with these wastes, or they would have been disposed of earlier. The solution needs to make the waste form compliant with the waste acceptance criteria, or an approved step on the way to the waste acceptance criteria.

The solution chosen, before being implemented, is required to be technically documented and sustained by an experimental programme, developmental work and/ or reliance on proven knowledge and operational experience. The underpinning will need to include evidence that demonstrates that the process will create waste products that provide the relevant safety function across any potential variations in waste feeds.

As part of development work both inactive and active development trials need to be conducted, at both small-scale (laboratory) and full-scale trials (e.g., on development rigs or plant prior to active commissioning).

5.7.2. Use of mobile or temporary plant

Legacy wastes are often of a set and limited quantity. Therefore, it may not be justifiable to build extensive new infrastructure, with all the expense and risk required to operate, manage secondary wastes and decommission new plants, when predisposal operations could be conducted in limited campaigns using existing, modular or mobile facilities. Mobile or temporary systems to process the waste can be considered with consent of regulators and other key stakeholders. The advantage of using an existing mobile system is that the costs are substantially reduced as the equipment is being hired, rather than built; the regulatory approvals for the process are in place, in principle; footprint for waste processing facilities is saved which is particularly useful on crowded sites; and the equipment can move to several locations making the logistics and transport easier across a legacy waste stream common to several sites. Temporary systems are often of modular design resulting in significant cost savings and can be rapidly deployed. The IAEA publication on Mobile Processing Systems for Radioactive Waste Management [56], contains useful information on mobile systems.

5.7.3. Sharing of plant or resources between sites

Similarly, if it is possible, it may be desirable to transport raw waste for processing to a central location that is shared between multiple waste owners. Reducing the number of treatment facilities by centralization creates the capability to address common issues in the same way. This is particularly important for Member States where relatively small volumes of waste at multiple sites require treatment infrastructure that is prohibitively expensive for one facility to design, construct and operate. Obviously, this option for processing waste relies on sufficient information being available for a suitable transport solution to be identified and implemented.

For Member States with similar wastes located at different sites where the use of mobile plants is proven not to be practical, it may be possible to develop one solution that can be applied at all sites with lessons learnt from a “lead” site being carried forward to subsequent sites. In this case although plant may not be transferable, the gained knowledge and personnel can be.

5.7.4. Production and management of secondary wastes

Conditioning and treatment processes can result in the generation of secondary wastes that require management. Thermal processes typically require advanced off-gas systems to treat volatiles and emissions from the treatment. Incineration processes result in an ash product that although greatly reduces waste volume, could produce challenges in handling the ash with concentrated radionuclides and fine physical size. Therefore, the need to condition the waste and the management of the by-product from waste treatment, has to be carefully assessed. Ion exchange processes and complexing processes are routinely used to remove specific radionuclides from liquid wastes and the resulting ion exchange media and agglomerated solids need to be subsequently managed. It is important to ensure that processing of waste does not lead to unacceptably large volumes of secondary waste or secondary waste that cannot comply with the established WAC. Decommissioning wastes need to be considered when planning legacy waste management. Secondary waste may also be produced from any R&D activities carried out related to legacy waste management.

5.8. CONTAINER SELECTION

Waste containers play a key role in ensuring safety in several stages of the radioactive waste management system, from storage of the raw waste through to its disposal. The containers may be designed for relatively short or long lives, depending on the stage or stages of the waste management system in which they are involved. They are intended to play a significant role by restricting or preventing the release of radionuclides.

The choice of container will depend on the infrastructure available on site, during transport and at the disposal location. Examples of consideration include:

- In many cases, the disposal organization will identify a small number of waste containers that are acceptable and can be managed safely within the safety case of the disposal location.
- The mass of waste containers (when loaded with waste) can range from a few hundred Kg to 10’s of tonnes. The heavier containers will require cranes or very large stacker trucks to move them between locations on-site and possibly access to a rail network for off-site transport.
- If shielded stores are available, then it may be possible to use containers with minimal shielding. If wastes can be demonstrated to be Low Specific Activity or Surface Contaminated Objects, then transport in an Industrial Package is possible. These packages will generally have larger cavities than Type B containers. Additional information and guidance can be found in Regulations for the Safe Transport of Radioactive Material, 2018 Edition [57] and [58].
- If a Type B container is needed, this can be achieved using a transport flask, similar to those used for the spent fuel transport.

The waste container and the waste are key elements in the overall performance of the waste package, they are strongly interconnected, each generally depending on the robustness of the former. In Figure 15 is schematically represented how the use of a less robust container led to the need to increase the required contribution of the waste form to overall waste package performance [59].

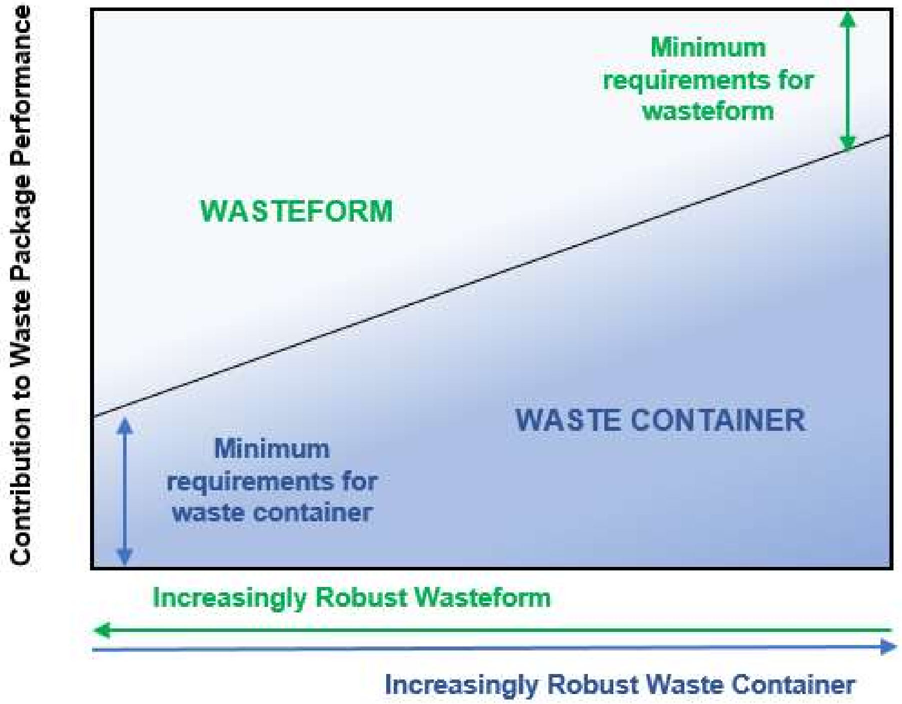

FIG. 15. Interconnection between container robustness and waste form characteristics leading to overall waste package performance. Adapted from ref. [59]

This is relevant to some legacy wastes:

- Where treating and conditioning the solid wastes is a challenge, then potentially a more robust container might remove the need for a number of processing steps.
- Legacy waste packages could be overpacked thus providing a more robust container, without the need to open the legacy packages to rework the wastes.
- For sites with no shielded stores, a heavily shielded container can be stored in fit-for-purpose store, reducing the cost (although the containers will individually cost more).

An analysis of the interdependencies of all the requirements as well as the need for a collaborative approach in developing an adequate waste package for all related waste management steps is further discussed in [60], trying to define a methodological approach guide in designing the waste package, by considering all the parameters and constraints to find the best balance between technical feasibility, costs and public acceptance.

RWM Ltd. Has produced a three-level guidance [61] on how waste packages are specified for the UK disposal concept which outlines the hierarchy of documentation:

- The Generic Waste Package Specification – define the requirements for the waste packages which are to be used in geological disposal;
- Generic Specifications – which refers to the application of the high-level packaging requirements (as defined in the Generic Waste Package Specification) to those waste packages which contain a specific type of waste;

- Waste Package Specifications– refers to the application of the general requirements (as defined in the Generic Specifications) to the waste packages which are manufactured using standardized designs of waste containers.

The Waste Package Specifications for the current range of standardized designs of waste container are included in the guidance as well as explanatory notes. The intent is that waste producers demonstrate that the containers they have chosen to package the waste are demonstrably compliant with the specifications. Three basic types of waste packages can be manufactured based on the current range of standardized waste containers:

- Unshielded waste packages - typically manufactured using thin walled (i.e., a few mm) metals containers. For the handling and transport of these unshielded waste packages remote handling tools and shielded overpacking containers are needed in order to compensate their low radiation shielding properties.
- Shielded waste packages - generally manufactured using reinforced concrete or thin-walled metal containers with integral concrete shielding. Consequently, they are suitable for handling and transport without any special additional radioprotection measures.
- Robust shielded waste packages - manufactured using thick walled (i.e., 50 mm or greater) cast iron containers. These types of packages are providing sufficient shielding and do not require any remote handling techniques or additional shielding measures for transport purposes.

5.9. STORAGE OF RADIOACTIVE WASTE PENDING DISPOSAL

Legacy radioactive waste predisposal technologies may include storing of radioactive waste. The fundamental requirement in the provision of storage for radioactive waste is that safe and secure storage facilities will be available for the expected waste amount and estimated storage periods.

The storage of radioactive waste for different time periods can occur for many administrative and / or technical reasons:

- To facilitate the decay of short-lived radionuclides up to the established levels of release from regulatory control (clearance) or authorization for discharge, or recycling and reuse can be issued;
- To optimize the transfer to a treatment and conditioning or disposal facility by collecting a sufficient amount of radioactive waste;
- To collect further information on the waste while in storage;
- To provide long term storage of radioactive waste in case of no suitable disposal facility is available.

Where many decades of long-term storage of waste are required, the control of environmental conditions (temperature, relative humidity and constituents of the atmosphere) within the store may need to be controlled to protect the integrity of the waste packages and avoid degradation of the waste.

Consequently, a monitoring procedure related to surveillance and inspection need to be in place for the entire storage period. The surveillance and inspection activities will certify that the storage conditions are accomplished (as defined in the facility WAC).

In the case of raw waste storage, it is required to have in place measures and provisions that avoids deterioration and allows retrieval for processing and further disposal, whilst maintaining the safety standards levels.

In the case that the physical and chemical state of radioactive wastes in a raw form is degraded during accumulation, the practice of periodic inspection (performed through direct sampling and analysis) needs to be in place, to confirm that any such degradation will not affect the ability to retrieve and process the waste as planned.

The UK Nuclear Decommissioning Authority has developed and published an integrated approach related to the Interim Storage of Higher Activity Waste Packages [62] that includes extensive information on Package performance and design, store performance and design, storage system operations and storage system assurance. A particularly useful aspect of this guidance is the identification of good practices and approaches to the 28 key requirements identified for interim storage.

5.10. TRANSPORT CONSIDERATIONS

Transportation of radioactive materials is a highly regulated component of the nuclear industry with national and international regulations set within legislation to ensure the safe movement of radioactive materials on and off sites. IAEA Regulations for the Safe Transport of Radioactive Material [58] sets down the safety requirements, including the minimum standards transport packages that have to be met, which are linked to the radioactive inventory of the waste form to be moved.

Decisions on the strategic approach to deal with legacy wastes will include the need for transportation of the material to a greater or lesser degree – do you need to transport the waste to an onsite predisposal treatment facility or take a mobile treatment facility to the waste? Are the waste containers degraded and therefore requires transport overpacks to meet the dose rate and/or contamination requirements for shipments? Clearly setting out the strategic objectives for predisposal treatments bring the need for onsite or offsite transport into focus. Solid waste makes transportation easier but liquid waste can be pumped into large waste containers which are then bunded and placed into IP2 ISO containers for safe transport to a treatment plant if there is no pipework between the legacy waste tanks and the desired treatment plant.

Regardless of whether it is onsite or offsite transportation, the containment of the radioactivity through multiple barriers will be required and the radiation at the surface of the transport package has to comply with the safety case limits. This can be achieved by using transport overpacks which can be for individual waste drums or multi-package overpacks which can accommodate up to 4 waste drums. These overpacks can either be accredited for Rail and Air Mode (RAM) transport or can fit into transport packages such as the R74 or Mosaic flask.

Transport packages come in all shapes and sizes depending on the complexity of the radioactive hazards associated with the legacy waste form. Solid LLW can be moved in IP2 approved ISO freight containers which has the capacity to hold up to 70 x 200 L drums and will fit on a standard Heavy Goods Vehicle flatbed chassis. Solid ILW would require some radiation shielding and again this can be provided by the waste flasks such as the German Mosaic flask or the Belgian R74 waste flask. These transport packages can take 500 L drummed waste or accommodate waste boxes as required. The shielding provided increases the weight of the waste packages and, for handling purposes will be used either crane to lift to 30 tonnes or suitable forklifts available to move these shielded flasks. Typical solid waste containers are discussed in some detail in Section 6 of this document.

5.11. QUALITY MANAGEMENT CONSIDERATIONS

The consistent message throughout this document is that problematic wastes from past activities become no longer problematic once they have either been dispositioned to an agreed route or are in "disposal ready" storage to an agreed disposal concept. To achieve this state, the packages have either be demonstrated as fit for disposal today (direct disposal) or that they will remain fit for disposal at some point in future when disposal is available ("disposal ready" storage). Established quality management principles in radioactive waste management, therefore, clearly point to the requirements being essentially the same whether the near-term goal is disposal or interim storage pending implementation of an agreed disposal concept. Although regulatory requirements regarding quality management may vary between Member States the same principles apply.

Quality Management in terms of radioactive waste management can essentially be broken down into two main themes:

- Activities undertaken to help ensure that the waste meets the WAC;
- Activities undertaken to maintain confidence over time in the validity of recorded information about the wastes.

Indeed, some problematic wastes from past activities are problematic either directly or partly because of weakness in one or both themes.

Several considerations apply when demonstrating that the particular waste meets the WAC. Many of these involve the degree of technical robustness of the processes involved in assessing and packaging the wastes, as well as the degree of robustness in implementation and execution of such processes. Independent verification at multiple points in the process increases confidence. Some of these expectations are the responsibility of the waste producer, and some rest with the disposal organization.

Examples of responsibilities of waste producer:

- The WAC is documented and fully understood by the waste producer;
- The waste producer has procedures and processes in place to address each requirement in the WAC;
- Characterization methods are technically robust, and the limitations of the methods employed are well understood;
- Adequate controls are in place to ensure wastes that are appropriately segregated remain segregated;
- All personnel involved in assessing or packaging wastes have been adequately trained for the roles they undertake;
- Appropriate supervision and/or independent verification or oversight is employed to capture when processes are not undertaken as fully intended;
- Non-conformances are reported, and lessons learned shared to improve execution of processes;
- Individuals are rewarded for and held accountable to high standards of conformance in the execution of their work.

Examples of responsibilities of the waste disposal organization (assuming direct disposal):

- Review of the waste management plan of the waste producer and acceptance that the interpretation of the WAC is appropriate;
- Review of the implementation procedures of the waste producer to confirm acceptance that the methods employed will meet the requirements of the WAC;

- Review of the quality arrangements of the waste producer to determine the degree of additional independent oversight of the operations leading to production of waste packages;
- When receiving requests for shipment, review of waste producer documentation to confirm paper requirements are met;
- When receiving waste packages for disposal, performing appropriate verification that physical material received conforms to submitted documentation.

Additional considerations regarding storage when direct disposal is not available:

- Identification of packages in storage indefinitely preserved until time of disposal;
- Records of individual package contents indefinitely preserved until time of disposal;
- Link between package unique identification and records of package contents indefinitely preserved until time of disposal.

Note that these responsibilities may rest either with the waste producer, waste disposal organization (or some other organization) depending on who is tasked with waste storage. If it is not the waste disposal organization, note that there will be a hand-off in future at time of disposal where the disposal organization will want to independently verify the history of storage to have confidence in the quality of the waste being received.

The intent of the above context is to show that it is not enough for the waste producer to convince themselves that their activities result in “disposal ready” or “disposal compliant” packages. The waste disposal organization is the only organization that can make such determination, and, therefore, need to be involved in oversight of the entire waste management process. It is strongly recommended that the disposal organization be actively engaged in solutions involving storage of “disposal ready” wastes awaiting future implementation of the agreed disposal concept.

6. IMPLEMENTING TECHNICAL SOLUTIONS

As discussed in Section 5, there are many technical factors that are considered while developing a detailed strategy for managing legacy wastes. Depending on the size, complexity, and history of the nuclear programme of the Member State, the types of legacy wastes and their associated challenges can vary over a wide range. This section provides a compilation of examples of work carried out in the Member States to address some of those challenges, including waste characterization, records management, retrieval, treatment and conditioning, containers, transport, and storage. New promising developments resulting from on-going R&D activities are also discussed. It is expected that the agencies responsible for dealing with legacy wastes in the Member States will benefit from these examples.

6.1. WASTE CHARACTERIZATION

The purpose of characterization is to deliver verified and documented properties for radioactive waste. This process usually involves establishing the radioactive properties of the waste and waste package, as well as other properties of the waste, waste form and waste packages such as the physical, chemical and mechanical properties. This information may then be used to assess what further actions are required to manage the waste and establish the appropriate waste disposal route. Thus, characterization ultimately ensures compliance of the waste, waste form and waste package with acceptance criteria for any subsequent process based on the quality assured information of its properties.

In several cases, the gamma spectrometers (with the appropriate tailored method) are used for characterization of drums containing legacy radioactive waste and the method is accompanied by the use of assumptions and correction factors.

Generally, waste characterization involves the use of state-of-the-art assay methods and radiation metrology to verify the properties and characteristics of the waste. In addition, characterization comprises product quality control to verify the compliance of waste properties with the waste acceptance criteria (WAC) of a waste pre-disposal facility or a repository.

The mobile characterization units are effective tools to accomplish the needs in waste characterization through several sites. A relevant example is presented in the followings.

To support TRU waste disposition at Waste Isolation Pilot Plant (WIPP), a Central Characterization Project was conducted. An element of the project was to deploy the Mobile Characterization Solutions (MCS) unit at sites across the DOE complex (Fig. 16). The mobile system performs waste characterization at sites that lack equipment and/or supplement sites with their own systems. The mobile system was deployed at the Savannah River Site, Idaho National Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory and Argonne National Laboratory. The mobile system proved to be quite effective in expediting analyses and provided consistent methods for use at several sites.

FIG. 16. The Mobile Characterization Solutions (MCS) unit for TRU drum characterization – WIPP Overview, USA (Photo courtesy of Mirion Technologies)

Another technical solution, related to the characterization of facilities this time, is the use of remotely operated equipment's as in the next example.

After the 1957 fire at Sellafield's Windscale Pile the radioactive contamination levels were too high and therefore it was impossible to launch the decommissioning works. Even if from the time when the fire took place until the decommissioning works were scheduled to start was a significant time difference, it was still needed to use remotely operated equipment to establish a plan for cleaning and dismantling the chimney.

Remote Intelligence Survey Equipment for Radiation (RISER) combines two separate pieces of cutting-edge technology: drones and radiation-mapping software [63] as presented in Figure 17 below.

FIG.17. Sellafield: remotely operated unmanned aerial vehicle combined with radiation mapping software (Photo courtesy of Blue Bear Systems Research Ltd, United Kingdom)

The drone or unmanned aerial vehicle (UAV) can accurately manoeuvre inside complex industrial spaces and the collected data are transmitted to the mapping system. Based on these data a contamination mapping is performed, highlighting the contaminated areas as well as the radiation levels.

The solution was delivered through a consortium of Blue Bear Systems Research Ltd and Createc and was also deployed at Fukushima in 2018.

6.2. CREATING AND MAINTANING RECORDS

As discussed previously, it is vital to adequately document and maintain a record of the waste. Information such as history of generation, available characterization data, WAC that were applied and present status, need to be included in these records. In some cases, these records may have to be recovered due to loss or need to be generated to provide more comprehensive information.

A recovery project was conducted in Canada with a goal to increase confidence in the waste inventory after data was lost or found to be incomplete [64].

In response to a federal audit, a records recovery project was initiated in 2007. This effort was aimed at improving confidence in waste inventory data collected between 1956 and 1995 at Chalk River Laboratories, Canada. In 1995, a waste tracking database was implemented, and all waste records collected prior were paper records. The audit recommended converting the paper records into an electronic database system to better underpin the recorded liability of future decommissioning and waste management activities associated with the site. Acting on this recommendation afforded the opportunity to review multiple records where they existed for each container in an attempt to enhance the quality of recording information for each stored item. Note that due to a fire in an administration building in 1956, all waste records prior to 1956 were lost and this timeframe was not included in the scope of the action.

At the time this action was initiated, it was perceived that:

- Waste data collected from 1995 to present was high quality due to the use of a comprehensive waste tracking database and this data will be useful for the disposal phase.
- At the end of this exercise, compiled waste data for waste consigned to storage from 1956 to 1995 would be of higher quality and useful for the disposal phase.

Many years of effort were expended reviewing the paper records in archive for wastes received for storage between 1956 and 1995. At the end of the exercise in 2014, the following conclusions and lessons learned were observed:

- For wastes that contained recorded accountable quantities of special nuclear material several different records sources existed, and a comprehensive description of waste contents was possible to be constructed.
- For wastes that did not contain recorded accountable quantities of special nuclear material the level of detail in the records was very thin and with little value for disposal considerations.
- The level of detail in records near 1956 was on average very thin and it was concluded that there was little value in trying to reconstruct any records that were lost in the fire in the administration building.
- As the requirements for data for disposal were not known when this records recovery was initiated, the scope of the data review was based on what it could be done, and not what should be done. With hindsight and better understanding of the requirements for disposal and recognition of the many gaps in the recorded data, the level of records recovery was not planned to be as intensive as the end value of the verified records is very limited.
- Co-incident with the conclusion of this exercise, a project to acquire the next generation waste tracking database was being evaluated. A brief review of the data collected since 1995 when the electronic database was implemented showed gaps that were not initially perceived to be present, and it was assessed that only about 15% of the data collected since 1995 would be worth migrating. It was concluded that many quality gaps exist in the post 1995 data as well and that the data for all wastes currently in storage is unlikely to meet the requirements for disposal. The characterization for all wastes in storage will need to be revisited to some degree to dispose of these wastes.

In Lithuania, a PHARE project (The PHARE programme is one of the three pre-accession instruments financed by the European Union to assist the applicant countries of Central and Eastern Europe in their preparations for joining the European Union) was completed using technical experts to provide a more comprehensive database of the waste inventory using past historical records and new information.

During the PHARE project "Safety assessment and upgrading of Maisiagala repository in Lithuania" (2005) [65], radionuclide inventory of the repository was carefully analysed. Based on the available information on radioactive waste transportation passports and delivery notes, as well as expert evaluation of these records, the database of the radioactive inventory was developed. The database contains more than 4,000 records of about 300,000 items. The activity was estimated at different times to consider the half-life and different sorting by radionuclides, activity types, radioactive waste types, the date of reception to the facility, originating company and country.

6.3. CLEARANCE (INCLUDING FREE RELEASE AND CONDITIONAL CLEARANCE)

There are several strategies for disposing of waste, any of which may be valid for a specific legacy waste. The simplest disposal strategy is to have the legacy waste go through a radiological clearance process. If the Member State has a legislated clearance level or process, it may be possible to characterize the legacy waste and show that it is not considered radioactive and can be disposed of as a non-radioactive waste. In case of the very low-level waste, there are several international practices where the waste can be disposed at designated landfill sites.

In case of mixed waste, there may be additional hazards in the waste, and it might have to be disposed in a hazardous waste facility after discussions and approvals from relevant regulators. Many of the precautions which are required for hazardous wastes are also required for radioactive wastes.

Between 2001 and 2008 took place the decommissioning and demolition of the Post Irradiation Examination Facility at the Magnox Ltd Winfrith site. The decontamination of the building fabric to remove the contamination and to support the management of the resultant waste was performed using both remote and manual techniques.

The decontamination and segregation practices applied during the entire project led to the generation of approx. 10,000 tonnes of waste. The main part of it was classified as out-of-scope / exempt waste and only a small volume was managed as VLLW [66].

6.4. REUSE AND RECYCLE

The most common form of recycling of radioactive waste is through metal reclamation, exploiting surface abrasion technique, e.g., grit blasting to remove surface contamination or metal melting where the radioactivity migrates to the metal slag impurities, leaving >90% of the metal free from radioactivity. The volume/mass of radioactive waste arising from these metal recycling techniques or processes is greatly reduced compared to the original raw metallic waste form with the recycled metal product free to be mixed with virgin metal for use in industry.

A relevant example of recycling some certain types of radioactive waste is coming from the UK (Berkeley Boilers) [67] where soon after abandoning the dismantling strategy, a joint arrangement was agreed.

During operation of the Magnox power station at Berkeley, UK, 16 heat exchangers (or boilers) were positioned around two reactors to generate steam, with each boiler weighing some 310 tonnes. While operational, carbon dioxide coolant gas passed through the hot reactor core drawing off heat for transfer to the boilers to generate steam. The coolant gas system was operated under pressure, and it was believed that over the years contaminated material such as corrosion products and graphite dust from the reactor core was transferred and deposited in the boilers. This understanding was confirmed by the 1995 trial. The boilers themselves were outside the biological shielding at a significant distance from the reactor so the boiler metal itself was not activated. The main radionuclide associated with the contamination was Co-60 and it was located mainly within the reactor internals.

The original plan was that these boilers to remain in this state until 2074 when they would be removed during the final clearance of the site, at this time an assessment for the most appropriate disposal route would take place. In 2010, UK LLW strategy changed to place greater emphasis on early solutions to favour options such as recycling above disposal.

In 1995, a trial to dismantle one of the boilers on site was not entirely satisfactory as it took a prolonged period and dose uptake was higher than was desirable. Primarily for this reason and the change of emphasis to recycle material, a joint arrangement between Magnox and Studsvik was brokered by the UK Low Level Waste Repository (LLWR) to transport the remaining 15 boilers to Sweden for melting and release of some of the material.

In the Spring of 2012, the first 5 boilers were moved from Berkeley to Sweden through Berkeley village on multi-wheeled transports to a local dock before being transferred by barge to a larger vessel for ongoing sea transport to Studsvik.

In line with UK and Swedish solid LLW policy, secondary waste was collected into 200 L or 100 L drums and packaged in half-height and/or third-height ISO containers for disposal at LLWR. Secondary wastes were composed of the following:

- Residual boiler residues (dust) from operations;
- Segmentation residues from cutting;
- Blasting residues from contamination;
- Slag removed from the melting process;
- Dust from ventilation filters;
- Production consumables.

Secondary waste from each boiler was approximately 15 tonnes, representing a typical recycling rate of 95%. Overall, this project transported and treated over 4000 tonnes of metal in less than 36 months, saving more than 5500 m^3 of space at LLWR, the equivalent of 291 half height ISO containers.

Another example is dealing with the recovery of Caesium (Cs) from high level liquid waste and converting it in non-dispersive glass form for its utilisation towards societal benefits, i.e., health care sector in blood irradiation process (Cs glass pencils for irradiation), developed and implemented at Bhabba Atomic Research Centre - BARC, India [68].

Caesium contained in the radioactive waste generated from reprocessing of spent fuel, is considered for recovery. Due to the presence of other radioactive fission products, long lived minor actinides and inactive constituents added during reprocessing, the Cs recovery is a challenging and complex process. A chemical, based on calix crown ether which is highly selective for recovery of Cs from waste, has been developed and utilised for recovery of Cs from High Level Liquid Waste using solvent extraction process at engineering scale after extensively testing the efficacy of process on laboratory scale. Large amount of radioactive Cs has been recovered and a specially formulated borosilicate glass matrix was used for its conditioning. The vitrified Cs glass is poured in stainless steel pencils, which are subject to various stringent quality assurance checks, and further used as sealed sources in different medical or industrial applications.

6.5. RETRIEVAL OF WASTE

The waste retrieval operation is often the most difficult step due to various reasons such as limited access to the waste, handling and transport constrains especially due to the waste state as well as regarding technically difficult operations that requires detailed planning and preparation. The need for flexibility in the planning details (in terms of work, equipment, and techniques to be used) is a direct consequence of lack of information about the waste to be managed.

Given the broad differences among the various types of legacy wastes and facilities in which are content, tailored solutions (that will consider the waste forms, radiological context, others) will be applied for each site, and the techniques and equipment to be used will have to be adapted to the site-specific situation.

Several examples of projects involving waste retrieval and the tailored actions and tools applied, are presented in the followings.

6.5.1. Retrieval of sludge

The mobilization and removal of sludges from storage tanks is a key issue for its further treatments and conditioning, and tailored systems are developed and adapted to the nature of the sludge. A Remotely Operated Vehicle (ROV) (Fig.18) was developed for mobilization and removal of the STE2 viscous sludge stored in LaHague [69]. The vehicle is equipped with:

- local pumping system to pump out the sludge;
- dilution jet – used for reaching the appropriate concentration;
- corresponding to the correct operation of the pumping system;
- propellers to allow the ROV system to move onto the sludge surface;
- ballasts to allow the ROV to go down to the sludge layer to be retrieved and go back up to the surface.

The descent and the rise back of the ROV is monitored by video camera. Once pumped out of the silo the sludge is transferred by pipe to an agitation tank.

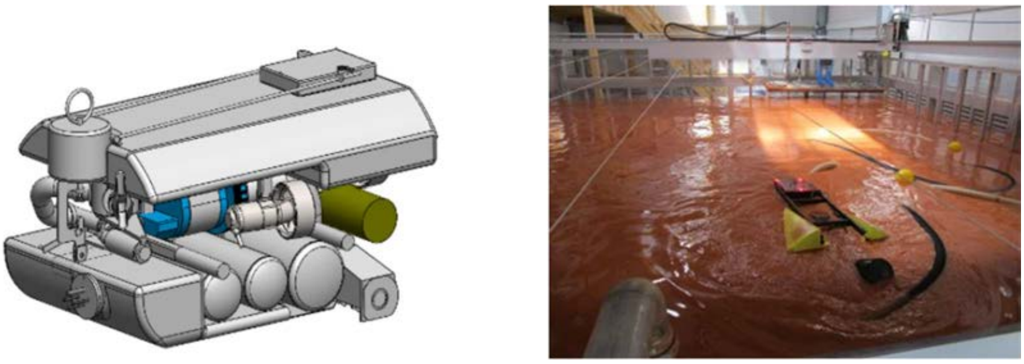

FIG.18. Left - Remotely Operated Vehicle used to retrieve the co-precipitation sludges currently in silos in La Hague Plant; right - Tests operation (Courtesy of ORANO, France)

6.5.2. Waste retrieval and conditioning from silos coming from past activities of gas cool reactor reprocessing operation

During the reprocessing of used fuel of French graphite moderated gas cooled reactors some specific wastes were produced. The fuel assemblies received in La Hague plant for reprocessing comprised a graphite tube containing a metallic uranium rod cladded by a magnesium alloy. Before reprocessing metallic uranium, assemblies had to be dismembered and thus graphite and magnesium alloys wastes have been produced. Wastes were stored together in silos in La Hague plant pending for processing (Figure 19).

The first operation was the upstream retrieval preparations: civil engineering works were implemented prior to operations and equipment installations (ventilation, electricity, sorting table) as well as the assessment of the retrieval technology to be used. Most of the wastes are graphite (about 92%), but other waste is present, amongst which reactive metals such as magnesium, aluminium and potentially metallic uranium. The operations started in 2019 and were retrieved 479 tonnes of bulk waste, mostly graphite, 16 tonnes of sludge, 1400 m^3 of effluents and 150 m^3 of solids and rubble. The implemented strategy was to separate the waste in function of their size, prior to a specific sorting table where aluminium will be removed. Magnesium wastes will be quantified thanks to the development of a shape recognition tool. The different separated waste streams will then be available for conditioning. The current strategy is to go for the final conditioning when the technologies are available [70].

FIG.19. Schematic of the technological fluxes concerning the retrieval and conditioning of wastes stored in silo 130 in La Hague (Courtesy of ORANO, France)

Some graphite is already disposed in surface disposal, so it is assumed that cementation of graphite is a mature technology. A specific cement formulation adapted to reactive metals was developed (supposed to compensate any sorting error) together with an innovative waste mixing solution.

6.5.3. Accessing the Pile Fuel Cladding Silo

The Pile Fuel Cladding Silo (PFCS) from Sellafield was commissioned with its associated plant and equipment in the early 1950s for use as a dry Intermediate Level Waste (ILW) storage facility for waste resulting from the de-canning operations of pile fuel and later Magnox. When tipping operations ceased in the 1960s the silo was left as a waste store under a regime of care and maintenance, with the concrete structure continuing to provide containment and bulk shielding for the waste.

The silo is a concrete structure 29 m long 10 m wide and 18 m high and is divided into six compartments each containing ILW. Each compartment is split into a north and south bay separated by a dividing wall. They were effectively locked vaults which were never designed to be opened.

To gain access to the waste within the silo's walls, Sellafield Ltd, has cut a hole at the top of each of the facility's six compartments. Silo containment doors have been lowered over the apertures and closed. These giant steel doors provide radiological shielding and maintain the inert argon atmosphere inside the silo until waste retrievals begin.

The waste removal is planned to be done using a crane that will be extended through the cut holes with a grabber attached to it (which will then dropped down to scoop the waste up lifting it out of the container, back through the hole) [71].

6.5.4. Retrievals from the Harwell Tube Stores

During Tube Store retrieval operations at Magnox - Harwell site, was observed the accumulations of contaminated water residing in some of the tubes. The water removal was performed using the on-site infrastructure and resources, requiring complex innovative solutions to accomplish the recovery, processing, and disposal in a single step [72].

In performing the work, the involved companies developed several different shaped and sized perforated bags to hold a water-absorbing material, in combination with a rapid setting compound, which ensured that only solid waste was removed from the tubes. After trials to ascertain the effectiveness of the different bags, the products were manufactured and supplied, turning it from a laboratory test to a commercial solution.

ILW generated at Harwell waste was originally placed in cans, which were then placed in tubes, in three tube stores constructed between 1952 and 1974. Initially, mild steel cans were used and in the late 1980's studies showed that waste cans within the storage tubes had degraded and some of the cans cracked, releasing waste contents into the tubes.

Most of the solid wastes have now been retrieved using a retrieval machine and processed into disposable waste products.

Liquid wastes were also generated as a result of accumulation of contaminated water residing in some of the tubes. An absorbent system (engineered to harden, resulting in a disposable product) was lowered into the tubes to remove water. A bespoke perforated bag containing water absorbing material was combined with a specially developed polymer, combined with a rapid-setting cement to provide long-term stability under high doses of radiation and, critically, would meet criteria for disposal.

6.6. WASTE PROCESSING

Once the waste is retrieved/removed, treatment and conditioning technologies need to be applied, to bring the waste to a final form that complies with the WAC of the storage or disposal facility.

Normally, this further processing is carried out using the standard techniques used in the radioactive waste management. However, if a needed technology is not available, the solution could be to buy or develop a specific technology to solve the problem of treating the retrieved waste in the most efficient way. Below are described some methods applied in different MSs, depending on a cumulus of conditions, requirements, and constraints.

6.6.1. Treatment and conditioning of the historical radioactive wastes at IFIN-HH - Romania

Before 1974, when the Radioactive Waste Treatment Plant from Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering (IFIN-HH) was commissioned, the radioactive wastes produced all over the country were collected and stored in an old military fort, close to the institute. Once the waste treatment capabilities were available, all the wastes were transferred for further treatment and conditioning. Up to 1985 when the Romanian National Repository Baita-Bihor (LILW-SL) was put in operation, almost 3.000 type A drums were produced and started the transfer for their disposal.

Due to various reasons, approx. 800 conditioned drums remained in unproper storage conditions at the institute for more than 25 years, suffering severe corrosion and damages. During 2007-2008, all the historical drums were characterized (by gamma spectrometry and checking the presence of neutron sources) and overpacked in 420 L drums (a product developed and licensed by IFIN-HH) (Fig. 20).

The whole reconditioning activity was finally completed in 2009 by transferring and disposing all drums which complied with the Baita Bihor repository WAC, on-site remaining only 4 drums (two drums contain Ra-226 sources and two drums contain neutron sources), which are kept in the storage facilities.

FIG.20. Historical waste drums reconditioning (Photo courtesy - Horia Hulubei National Institute for Research and Development in Physics and Nuclear Engineering (IFIN–HH), Romania)

6.6.2. GeoMelt In-Container Vitrification (ICV™)

The UK's National Nuclear Laboratory (NNL) and Kurion have completed cold and active commissioning of the GeoMelt In-Container Vitrification (ICV™) plant at NNL's Laboratory on the

Sellafield site. The technology offers the benefits of volume reduction, passivation and has the capacity to treat mixed contaminated waste cost-effectively.

A GeoMelt demonstration rig was used to convert mixed lower activity material into a robust, durable glass waste form. A cold run was performed at the National Nuclear Laboratory's (NNL) Workington facility and then moved to the active rig hall in NNL's Central Laboratory on the Sellafield site to tackle radioactive wastes, as presented in [73]. With a capacity of 500 kg, the demonstrator was successfully treating contaminated soil.

6.6.3. Plasma Melting Facility at the Kozloduy nuclear power plant in Bulgaria

At the Kozloduy NPP a plasma melting facility is installed and in operation, as a heat source to melt inorganic and organic waste generated by the decommissioning process, resulting in a slag as a robust end-product [74]. Treatment of the resulting flue gases is similar to the treatment used in conventional radioactive waste incinerators, such as the one installed at the Belgoprocess site in Dessel, Belgium. The Plasma Melting Facility was supplied by a joint venture between Spain's Iberdrola Engineering & Construction and Belgian radioactive waste management company Belgoprocess.

During the facility's commissioning, as part of installation testing, a cold run of 72-hour was performed. The test successfully demonstrated the compliance with the designed capacity and required volume reduction factor. There were also performed tests by pouring different quantities of hot liquid slag at a temperature of about 1300°C as well as safety tests.

The plant capacity is up to 250 tonnes per year. In the plasma, concrete debris, sand, inorganic granulates, insulation material and asbestos are melted, as well as metals which are melted and oxidized. They are transformed into a chemically inert and amorphous glassy slag. Liquids and organic materials are vaporized so the final product is organics-free. (LLW and ILW).

In the USA, *in-situ immobilization* has been deemed acceptable for certain facilities including waste tanks. Performance assessments are completed to ensure that the in-situ immobilization will meet requirements and appropriate agreements that are made with regulators to implement this technology option. Grout injection is used at the Savannah River Site to immobilize any residual material in waste tanks after waste removal and chemical cleaning processes are completed. More information on this process is given in ref. [75] and below.

In 1997, the first high level radioactive waste tank was closed at the Savannah River Site (SRS) in the USA The 1.3-million-gallon tank (4.9 million L) tank was cleaned by physically removing as much waste as possible followed by chemical cleaning. The tank was filled with a specialized cement-like grout to operationally close and remove the tank from service.

To facilitate closing, input was received from the public and agreements were made with the South Carolina Department of Health and Environmental Control and the USA Environmental Protection Agency. Performance assessments were completed to demonstrate that radionuclides would be immobilized for thousands of years.

To date, eight HLW tanks have been closed at SRS using this technology [76]. The success of this technology facilitated similar tank closure activities at Idaho National Laboratory and the Hanford Site.

6.7. LOCATION OF PREDISPOSAL OPERATIONS

Legacy wastes are often of a set and limited quantity. Therefore, it may not be justifiable to build extensive new infrastructure, with all the expense and risk required to operate, manage secondary wastes and decommission new plants, when predisposal operations could be conducted in limited campaigns using existing, modular or mobile facilities. Mobile or temporary systems to process the waste can be considered with consent of regulators and other key stakeholders. Temporary systems are often of modular design resulting in significant cost savings and can be rapidly deployed. The IAEA document [56] contains useful information on mobile processing systems.

Similarly, if it is possible, it may be desirable to transport raw waste to a central location for processing that is shared between multiple waste owners. This is particularly important for Member States where relatively small volumes of waste at multiple sites require treatment infrastructure that is prohibitively expensive for one facility to design, construct and operate.

For *retrieval and separation of TRU* waste at USA facilities, existing buildings are utilized and/or small temporary buildings are constructed on site which hold glove boxes, packaging and cask loading equipment [77]. The waste is placed in the gloveboxes and segregated into new packages which are then removed and conditioned through normal processes. Significant cost and time savings result from not constructing new structures for treatment of the whole waste and allows for applying simpler conditioning techniques.

Low level waste constitutes a large proportion of the solid waste generated at nuclear sites. To avoid accumulation of such waste at the generating site it is desirable to process this waste and send for disposal. Super compaction is a proven processing option that can provide significant volume reduction for compactable low-level waste. However, in many generating sites installation and operation of a super compaction facility might be considered very expensive. In such cases, the use of mobile super compaction services can be a viable option. There is considerable experience on the use of such systems. For example, at the Winfrith nuclear site in the UK, a 2000 tonne mobile super compactor has been used extensively to process more than 30,000 waste drums of 200 L capacity [78]. The compacted drums, known as pucks, were placed in standard ISO containers, and sent for disposal. The mobile super compactor was also used at other waste generating sites. Nucleco in Italy has also used mobile super compactor for volume reduction of low-level waste at NPP sites in Italy [79]. Other suppliers of mobile super compactors include Westinghouse (USA) [80], Tradebel Inutec (UK) and Babcock Noell (Germany).

Ion exchange resins are routinely used in nuclear power plants to remove impurities from the various water streams, including primary coolant system, spent fuel storage ponds, and liquid waste. After use, the spent resins will have to be managed as radioactive waste. A mobile system is being successfully used in France for the on-site conditioning of spent resins in an epoxy polymer matrix, moving from one nuclear power plant to another as per planned campaign schedules [56]. The conditioning is done in a shielded concrete container and the final waste package meets ANDRA specifications for near surface disposal. The mobile fleet consists of several trucks, including the conditioning unit on a road trailer, a road tanker containing process chemicals, and other systems (control station, workshop, etc) housed in ISO freight containers. While providing a cost-effective solution for the management of spent resin waste, use of this system is helping nuclear power plants in France to avoid on-site accumulation of such waste.

A transportable ion exchange facility has been used by the Bhabha Atomic Research Centre (India) for the *treatment of alkaline intermediate level liquid wastes* generated from past reprocessing operations [56, 81]. The facility was designed and constructed specifically for this application. It consists of a trailer mounted shielded cubicle containing filters, ion exchange columns, sampling stations and remote handling facilities. Other systems are also installed for fluid transfer and pre-treatment, chemical preparation, effluent collection and neutralization, and instrumentation and control.

The process involves metered transfer of waste from underground storage tanks to a particulate filter followed by a set of three shielded ion exchange columns. Two of these columns are filled with Resorcinol Formaldehyde Polycondensate Resin (RFPR), a selective ion exchanger developed specifically for the removal of Cs-137 that is the predominant radionuclide present in the waste. The third column is filled with a chelating resin for removing traces of Sr-90 also present. The effluent is monitored and sent for further treatment as required to meet authorized discharge limits. The activity loaded on the columns is eluted using a small volume of dilute nitric acid and the columns regenerated with alkali for use in the next loading cycle. The eluted activity is stored for further conditioning or recovery of Cs-137 for radiation source applications. After several cycles the resins get degraded at which point the columns are replaced. Engagement and removal operations of ion exchange columns are remotely controlled.

Several campaigns carried out at multiple sites using this transportable facility have resulted in the successful treatment of large volumes of liquid waste from past reprocessing operations.

6.8. CRITICALITY

The fissile radionuclide content of the waste has to be controlled to ensure that subcritical conditions are maintained under all possible conditions to be encountered at any time during conditioning and to ensure that the requirements of the waste package specification are met (waste package fissile mass limits are established for nuclear criticality control purposes). The radionuclides which need to be controlled for criticality reasons include readily fissile isotopes, uranium, and transuranic elements. Preventive care measures to avoid concentration of any remaining fissile material in conditioning processes (especially in liquid or volume reduction processes) are necessary to be implemented.

A case study involving fissile loading in drums containing Plutonium Contaminated Material is the Waste Treatment Complex at Sellafield which was designed and constructed to package Plutonium Contaminated Material for interim storage and future disposal, with operations starting in 1998. Plutonium Contaminated Material is comprised of materials which have been used in plutonium plant. A significant proportion of Plutonium Contaminated Material is secondary waste, which has not been in intimate contact with process fissile material. The current process transfers 200 L Feed drums suitable for processing from storage to the Waste Treatment Complex and positions them in the ‘super compactor’ within a glove box. The drum is then subject to high force compaction to reduce the volume of the waste material. Next, the pucks are placed into a 500 L Product drum, grouted, and left to cure. Normally, each product drum contains between 5 to 8 pucks.

To comply with the requirements for transport of the product drums in the public domain, and for disposal at the GDF, a limit is placed on the total fissile mass in the 500 L drum. To ensure that this limit is never exceeded, a combination of pucks is selected to achieve the compliance. This increases the complexity of plant operations as the fissile loading in the 200 L drums varies considerably [82].

6.9. R&D FOR WASTE CHARACTERIZATION AND PROCESSING

When managing waste, it is important to remember that adequate, safe solutions need to be identified and deployed. In many cases, these technologies are not advanced or elegant but provide the necessary solution to meet waste management requirements. Except for certain problematic wastes such as graphite or particularly exotic wastes, technologies for radioactive waste management exist. Using the research and development activities these technologies can be adapted, demonstrated, and deployed to address the specific needs of the Member States. Where a research need is identified it is important to develop a solution that is fit for the waste to be treated.

6.9.1. Use of thermal pre-treatment for waste sorting

Japan Atomic Energy Agency (JAEA) has stored TRU wastes generated from reprocessing and Plutonium fuel fabrication R&D activities in the Nuclear Fuel Cycle Engineering Laboratory. These wastes need to be segregated prior to processing. JAEA developed the thermal pre-treatment technology that can automatically unpack TRU waste and can remove hazardous materials [83]. A laboratory scale examination was conducted using the simulated waste. The simulated waste was heated with the air or nitrogen heated to 500 – 700 ˚C. Combustible materials such as papers, PVC and oils were removed and low melting point metals such as zinc, lead, and aluminium were separated by thermal pre-treatment. This technology could be useful for the pre-treatment of legacy waste.

6.9.2. PIVIC Process for thermal treatment

The PIVIC process (In-Can incineration, melting and vitrification process) purpose is to perform in a single reactor the incineration of the organic fraction of waste, the fusion of the metallic fraction, and the incorporation of the incineration residues in a glass matrix [84]. No waste pre-processing is required, the waste being directly loaded into the combustion chamber through the top of the introduction chamber (Fig. 21).

The waste is gradually lowered into the combustion chamber to directly control the incineration velocity. To perform the organics incineration, the water jacket combustion chamber receives an oxygen non-transferred plasma torch.

An IN CAN melting technology heated by direct low frequency induction is used in the fusion module. The power is deposited in the metallic phase from the waste found in the bottom of the crucible. The crucible is used as part of the process for the duration of its filling, and as primary container, a new container is placed after each filling.

The gases that are produced during the process are further treated in an afterburner chamber to complete the combustion.

The PIVIC project is a partnership between ORANO, ANDRA and CEA, which is supported by the French government program “Programme d’Investissements d’Avenir”. The objective of this project is to develop a process able to treat ORANO alpha waste (PCM). The industrial feasibility is not yet acquired, and so far, the tests were carried out only with surrogate wastes and not in industrial context.

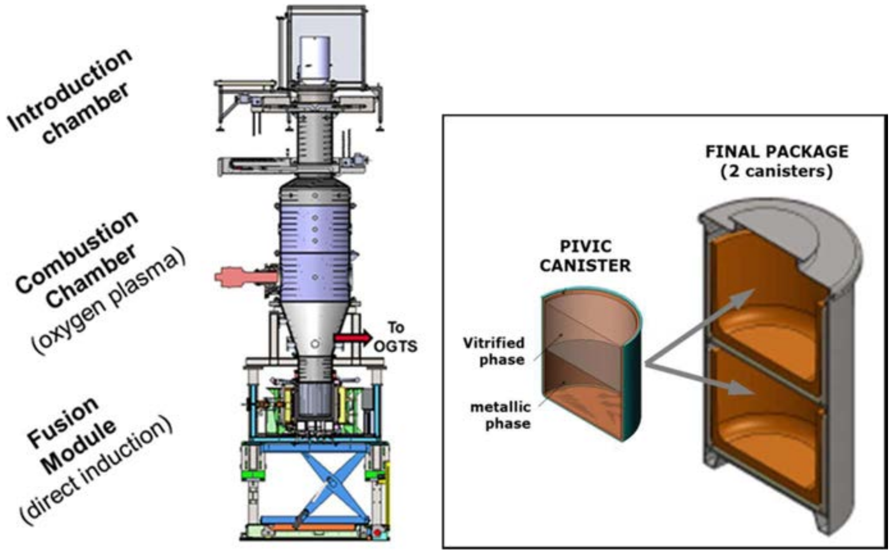

FIG.21. PIVIC process description (Courtesy of ORANO, France)

6.9.3. Encapsulation of ILW residue from fission Mo-99 production

Molybdenum-99 (Mo-99) is the parent nuclide for the most widely used radioisotope in nuclear medicine Technetium-99m. It is produced primarily in research, test or isotope production reactors by the irradiation of highly enriched uranium (HEU) targets. The production of Mo-99 via an alkaline-route in which the targets are dissolved in a sodium hydroxide solution, resulted in several waste streams. One of these is the uranium filter cake (residue), which contains fission products and minimal process chemicals. This ILW, containing more than 80 % enriched uranium, is currently stored inside hot cells and are considered problematic wastes [85].

Collaboration research between South African Nuclear Energy Corporation (NECSA) and Australian Nuclear Science and Technology Organization (ANSTO) was initiated to develop immobilization criteria for various candidate waste forms based on waste loading, porosity, aqueous leach resistance, mechanical properties for the encapsulation of this waste form. The types of waste forms investigated were glasses, glass-ceramics, ceramics, and cementitious products. For immobilization of the used High Enriched Uranium (HEU) - targets it was found that Synroc derivatives with waste loadings of ~45 wt.% were competitive if they contained some glass that aided reactivity (Fig. 22). Also, glasses that were pourable at temperatures of ~1300°C with waste loadings of ~25 wt.% were competitive. Cements and geopolymers all failed on proliferation grounds.

FIG. 22. Photos of the HIPed (left) and unHIPed (right)2DB canisters for future waste encapsulation (Photo courtesy of ANSTO, Australia)

6.9.4. Plasma melting technology for the treatment of miscellaneous waste materials

Japan Atomic Energy Agency (JAEA) has many drums of miscellaneous solid waste that is contaminated by various radioisotopes. These wastes have been generated by research activities and, therefore, vary in character. Thus, various radioisotope compositions are expected, and it is very difficult to apply the scaling factors to specify the wastes. Furthermore, there is insufficient information on the contents. Sampling and analysis are, therefore, essential for the radiological characterization.

JAEA has developed a plasma melting apparatus at the Nuclear Science Research Institute, Tokai R&D Centre [86]. A prototype unit of capacity 4 t/day has been constructed and tested for melting of non-radioactive materials. This apparatus can be applied for the melting of non-combustible wastes such as concretes, glasses, ceramics, and incineration ashes, which containing β- and γ-emitting nuclides. This technology may be used to homogenize the wastes and facilitate sampling of each melted batch. Further, a consolidated product may result from the melting process that may be suitable for disposal.

6.10. CONTAINERS FOR WASTE PACKAGING

When packaging waste for storage and eventual disposal consideration need to be given to the selection of a suitable container to comply with WAC. When a disposal concept has been defined, an appropriate suite of containers can be identified that are compatible with the concept chosen.

6.10.1. New Multi-Waste Container

During nuclear facility operation or their decommissioning, there are various waste types, volumes and activities that need to be taken into consideration. Among others one could have activated metallic waste, legacy waste, sludge, resins, orphan waste, etc. This will lead the generators to undertake multiple and costly waste management operations which include handling, reconditioning and/or material transfers between packages.

To address this issue, a new – highly flexible up to reversible – cask system, the TN-MW, is being developed as an “All in One Solution” by ORANO, France (former AREVA) [87].

TN - MW has a total weight of 10 tonnes (compliant with the IAEA regulations [57]), was designed and developed to provide flexibility and to be adaptable to the various needs of the nuclear industry.

From IP-2 and Type A containers to Type B(U) and B(U)F casks, the TN-MW cask system offers several options that can address the requirements of each step of the waste stream from on-site and international transport to long-term interim storage and final disposal.

6.10.2. Use of flexible packages to support waste retrievals

Sellafield Ltd. is retrieving large irregularly shaped metal (ILW and LLW) scrap items from two of the legacy ponds. The wastes are wet, with some adhering fuel bearing sludge. To contain the contamination as quickly as possible, a flexible packaging solution - Pac Tec bags is used. The working environment is extremely constrained in terms of space and access. The ability to use soft sided containers offer significant operational advantages.

The advantage for Sellafield Ltd. is that the bags are bespoke shaped for each waste item. The waste packages are then transported across site for onward management.

6.11. LARGE COMPONENTS

The management and disposal of large radioactive components can offer unique challenges. In some cases, size reduction can facilitate handling, storage and disposal. However, in some cases the robustness of these large components can be advantageous with handling and transport. In the USA disposal sites for large components are available and through cooperation with the Nuclear Regulatory Commission, nuclear power plant operators were able to complete decommissioning activities and disposal of large plant components.

Decommissioning of a commercial nuclear power plant results in large quantities of radioactive, hazardous, and conventional wastes. The wastes range from finely divided materials to very large structural components. The USA has successfully completed decommissioning of several nuclear power plants including disposal of wastes. Existing waste disposal options were identified and utilized for disposal of radioactive wastes. The Connecticut Yankee was one such reactor that was decommissioned including disposal of several large components. The decommissioning organization worked with the Nuclear Regulatory Commission to allow the components to be transported as-is, taking credit for the robust construction of the large structural components as the shipping packages. This allowed for disposal of the Connecticut Yankee reactor vessel at the Barnwell disposal site in South Carolina and steam generator components to the Energy Solutions disposal site in Clive, Utah and to the Barnwell disposal site [88].

6.12. TRANSPORTATION

The transportation of radioactive waste is often carried out employing several modes of transport. This is normally the situation where national waste strategies involve the use of centralised waste treatment, storage and/or disposal sites. Road and rail modes are often employed together, with road transportation used locally to move the radioactive waste packages to and from the railhead and the longer journey employing rail transport. Several waste transport containers can be moved on one rail transport maximising the cost benefit of rail transport. In some cases, returning solid ILW from international reprocessing contracts can lead to road, rail and sea transports being used. Examples of shielded RAM transport packages are contained in IAEA publications [89, 57].

6.13. STORAGE OF PACKAGED WASTE

Legacy radioactive waste predisposal technologies may include storing of radioactive waste. Across the Member States the storage approach can vary. Several approaches have been adopted:

- Heavily engineered shielded stores that are remotely operated using cranes;
- Lightly shielded stores with manual operations using forklift type mechanisms to emplace waste packages;
- Storage of packaged waste in existing buildings.

The storage of legacy waste varies across Member States. Those states with existing engineered stores can make use of any spare capacity within these stores to safely hold the legacy waste, provided the store WAC can be met. There may be a requirement to overpack degrading legacy waste packages/containers to comply with the storage safety case and the WAC as previously discussed in Section 5.

If there is no capacity in existing storage facilities, there may be a requirement to retrofit storage capacity into other engineered plants or facilities. It is important that the environmental conditions within the storage area chosen to ensure a dry and ventilated atmosphere to minimise any waste container corrosion issues, especially if a considerable interim storage period is envisaged.

In Member States where no disposal routes are available, there is a risk that there may be a considerable delay (possibly many decades) before such a route becomes available. As a result, in this situation the interim store containing legacy waste is required to be robust and engineered to allow safe storage for such a long period.

In many Member States heavily, engineered shielded stores are required to safely store solid ILW containers, which can be drums or boxes. In the two examples shown, one from Belgium and the other from the UK, remote handling cranes are used to emplace waste containers within the store.

Trawsfynydd site has a small number of 3 m^3 boxes of high dose rate ILW that could not be stored in their ILW store as the dose rates exceeded the conditions for acceptance. Therefore, the use of temporary shielding to store high dose rate wastes in a lightly shielded store was an option which was taken into consideration [90].

Concrete overpacks were used as final solution for placing the boxes, to facilitate the safe handling and storage. The overpacks are thick-walled reinforced concrete boxes that are providing the necessary shielding to reduce the exterior surface dose rates to levels that are in accordance with the regulations for the safe transport of radioactive materials. The overpack and lid weight is approximately 30.5 tonnes.

When the wastes are dispatched to the Geological Disposal Facility, the boxes will be removed from the overpacks and the overpacks will be sentenced as waste.

The storage of LLW drums and larger waste containers incorporates lightly shielded stores where manual operations are carried out, both in the emplacement of waste containers and for monitoring the condition of the containers over time (Fig.23). The waste containers are transported and emplaced within the store using forklift type machines, rather than remote cranes, simplifying operations throughout the stores.

FIG. 23. Conditioned solid LLW drums in COVRA (Courtesy of COVRA, The Netherlands)

7. CONCLUSIONS

Legacy waste remains a considerable challenge for many Member States, including those with established nuclear programs as well as those with only waste from nuclear applications. Many of the Member States - Counterparts in Technical Cooperation Projects related to radioactive waste cite the management of legacy waste as one of their key challenges. The International Radioactive Waste Technical Committee (WATEC) that advises the IAEA on radioactive waste management program activities and directions also identified the timely management of legacy waste as being a priority for consideration in future predisposal programs.

Over the years, a wealth of information and experience has been accumulated on the principles and practices related to the successful management of Legacy Waste. While all of this information is useful to the end-users in Member States, it is recognized that there is room for improvement in the way the information is organized and presented so that it becomes easier to use for specific needs in this area. The present publication is willing to be a response to these requests and addresses the absence of IAEA technical guidance in this area.

There is no official IAEA definition for legacy waste, but it is usually understood and agreed to refer to waste generated through past practices and, in some cases, include historical waste in old storage and disposal facilities that were intended to be a temporary state or are no longer complying with the safety requirements. These wastes are often of unknown provenance with little or no record of their origin or content, not well characterized, unsegregated and stored in less than optimal conditions.

To avoid a legacy waste problem, it is paramount to have a clear path to disposition. This is ideally achieved through disposition in an operating disposal facility or defining a clear disposal concept with evolved Waste Acceptance Criteria providing clear specification for acceptable storage leading to disposal. Alternatively, a clearly defined path to clearance or re-use is a means to preclude formation of legacy waste.

The following conclusions are derived from the strategies and examples provided in this document:

— Legacy waste issues are representing a challenge to many countries, however, there are numerous examples of successful approaches to deal with this type of material that are beneficial to be shared between Member States. Additionally, there are chronicled unsuccessful efforts where lessons learned can be derived.
— There are a variety of reasons why legacy waste has become an issue in Member States. In some cases, technical challenges have precluded a straightforward disposition path. However, more often, legacy wastes result from lack of funding, low priority or lack of a regulatory pathway for disposition.
— Before a challenging waste can be managed safely and appropriately, it is necessary to establish a credible strategy for treatment and to plan the method to achieve the desired endpoint.
— As with all radioactive waste management programs, compliance to jurisdictional regulations such as funding, politics and stakeholder acceptance are important to be considered for the successful completion of projects.
— It is advisable to manage the waste in a prompt manner, once they are generated, to avoid a legacy waste problem. If a disposal facility is available, prepare the waste for disposal and dispose of the waste. Alternatively, proper regulatory framework and mechanisms for clearance or re-use will tremendously contribute to the minimisation of the waste volumes to be disposed of.

- Characterization is a key challenge for legacy wastes and require commitment and dialogue between stakeholders. A balance between practicality and the amount of information to be collected need to be established as waste characterization efforts include the assessment of radiological, chemical and physical properties.
- If there is no disposal available and no disposal concept, development of an agreed disposal concept, and corresponding generic WAC are essential to be considered of utmost priority to avoid generating future legacies.
- If disposal is not yet available and long-term storage is a necessity, the development of storage facilities and waste packages need to comply with the current requirements and to anticipate the future needs. Wastes destined for long-term storage are necessary to be packaged consistent with the WAC and to meet requirements associated with the anticipated disposal concept so that repackaging is not necessary [16].
- If improvement of the safety of the waste is considered urgent, then it needs to be undertaken before a disposal concept is developed and agreed. The selection of technologies should consider those that are not likely to interfere with a quality waste product under the disposal concept to be realized in future.
- Documenting and maintaining records of legacy waste management are keys to ensure the waste does not become a legacy in future.
- If no technical solution currently exists, R&D can be undertaken to develop new techniques for managing and treating the wastes. However, for all new technologies it is important to keep disposition in mind while being developed.
- International collaboration can be helpful to managing legacy wastes particularly for countries with small inventories. The sharing of knowledge, R&D results, technologies, and facilities are all beneficial to solving legacy waste issues. The IAEA plays a major role in facilitating collaboration. Over the years, a wealth of information and experience has been accumulated on the principles and practices related to the successful management of legacy waste. A significant amount of this information and experience has been captured in IAEA publications. Technical Cooperation projects and Technical Meetings conducted by the IAEA are also excellent means to foster international collaboration.

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GLOSSARY

The IAEA Safety Glossary[1] is establishing the terminology used in the nuclear safety and radiation protection field. Some of them, used in the present publication, are presented below to help the reader by explaining their technical meaning:

Conditioning – Those operations that produce a waste package suitable for handling, transport, storage and/or disposal. Conditioning may include the conversion of the waste to a solid waste form, enclosure of the waste in containers and, if necessary, provision of an overpack.

Disposal system - The system of properties of the site for a disposal facility, design of the disposal facility, physical structures and items, procedures for control, characteristics of waste and other elements that contribute in different ways and over different timescales to the fulfilment of safety functions for disposal.

*Legacy waste (*only for the purpose of this document)* – Radioactive waste generated as a consequence of past practices and that is either:

- Waste which does not have an identified route for safe disposal;
- Waste which does not have a predisposal concept and/or defined WAC to achieve safe disposal; or
- Waste that is conditioned, stored or disposed of in a form that does not comply, or no longer complies, with current regulatory requirements.

Predisposal management - Any waste management steps carried out prior to disposal, such as pre-treatment, treatment, conditioning, storage and transport activities.

Pre-treatment – Any or all of the operations prior to waste treatment, such as collection, segregation, chemical adjustment and decontamination.

Processing – Any operation that changes the characteristics of waste, including pre-treatment, treatment and conditioning.

Segregation – An activity where types of waste or material (radioactive or exempt) are separated or are kept separate on the basis of radiological, chemical and/or physical properties, to facilitate waste handling and/or processing.

Treatment – In radioactive waste management, the IAEA uses the term “treatment” to indicate operations intended to benefit safety and/or economy by changing the characteristics of the waste. The basic treatment objectives are volume reduction, removal of radionuclides from the waste, and change of composition. Treatment may result in an appropriate waste form. If treatment does not result in an appropriate waste form, the waste may be conditioned to do so.

Waste characterization – Determination of the physical, mechanical, chemical, radiological and biological properties of radioactive waste to establish the need for further adjustment, treatment or conditioning, or its suitability for further handling, processing, storage or disposal.

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Characterization of waste, in accordance with requirements established or approved by the regulatory body, is a process in the predisposal management of waste that at various steps provides information relevant to process control and provides assurance that the waste form or waste package will meet the waste acceptance criteria for the processing, storage, transport and disposal of the waste.

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

Waste Acceptance Criteria **-** Quantitative or qualitative criteria specified by the regulatory body or specified by an operator and approved by the regulatory body, for the waste form and waste package to be accepted by the operator of a waste management facility. Waste acceptance criteria specify the radiological, mechanical, physical, chemical and biological characteristics of waste packages and unpackaged waste. Waste acceptance criteria might include, for example, restrictions on the activity concentration or total activity of particular radionuclides (or types of radionuclides) in the waste, on their heat output or on the properties of the waste form or of the waste package. Waste acceptance criteria are based on the safety case for the facility or are included in the safety case as part of the operational limits and conditions and controls. Waste acceptance criteria are sometimes referred to as “waste acceptance requirements”.

ABBREVIATIONS

ANDRA	Agence nationale pour la gestion des déchets radioactifs, France
BWP	Bituminised Waste Product
DQO	Data Quality Objectives
DSRS	Disused Sealed Radioactive Sources
EU	European Union
GDF	Geological Disposal Facility
HAW	High Activity Waste
JAEA	Japan Atomic Energy Agency
LLW	Low Level Waste
LILW	Low and Intermediate Level Waste
LoC	Letter of Compliance
ILW	Intermediate Level Waste
MSs	Member States
NDA	Nuclear Decommissioning Authority, United Kingdom
R&D	Research and Development
RAM	Rail and Air Mode (transport)
RWM	Radioactive Waste Management
RWM Ltd.	Radioactive Waste Management Limited, United Kingdom
TRUE	Transuranic Elements
UK	United Kingdom
UKAEA	UK Atomic Energy Authority
USA	United States of America
VLLW	Very Low Level Waste
WAC	Waste Acceptance Criteria

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