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DISPOSAL APPROACHES FOR LONG LIVED LOW AND INTERMEDIATE LEVEL RADIOACTIVE WASTE

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FOREWORD

It is widely accepted in Member States that radioactive waste of low and intermediate activity with limited concentration of long lived radionuclides can be safely disposed of in near surface facilities, either above or below ground levels. The safety of this concept is based on the performance of engineered and natural barriers combined with a period of institutional control of the repository. Waste that poses a potential risk in the long term due to its high activity or high content of long lived nuclides should be disposed of in geological formations at depth, allowing for unrestricted use of the land after the closure of the disposal facility. Some of the subsurface repositories may accept a certain amount of such a waste type. With the exemption of the Waste Isolation Pilot Plant (WIPP) facility in the USA, no other repository has so far been designed exclusively for this purpose.

When considering the wide spectrum of activities of long lived radionuclides present in waste, however, this simplified division between near surface and deep geological destinations does not seem to be completely practical. Therefore, a number of Member States are considering alternative approaches to the disposal of non-heat generating waste containing long lived radionuclides, ranging from adapting facilities to designing specific ones. The requirements for these facilities may vary significantly according to characteristics of waste to be accepted.

This report provides: an overview of waste categories and facilities to be considered for accepting long lived waste; advice on the key factors to be considered when selecting the appropriate approach to their disposal; and an outline of the procedure for selecting the relevant strategy for disposal of long lived low and intermediate level waste (LILW-LL).

The IAEA expresses its thanks to all those who were involved in preparation of the report and its revision, especially S. Hossain who revised the final report. The IAEA officers responsible for this publication were B. Neerdael and L. Nachmilner from the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

SUMMARY 1

1. INTRODUCTION 3

 1.1. Background 3
 1.2. Objective 4
 1.3. Scope 4
 1.4. Structure 4

2. SOURCES AND CHARACTERISTICS OF LILW-LL 4

 2.1. Sources of LILW-LL 5
  2.1.1. Nuclear fuel cycle 6
  2.1.2. Research, medical, industrial and other uses 6
 2.2. Important attributes 6
  2.2.1. Half-life and activity of radionuclides 6
  2.2.2. Radiotoxicity and chemotoxicity 7
 2.3. Waste classification 7
 2.4. Waste amount 8
 2.5. Waste form properties 9
 2.6. Waste processing 10

3. DISPOSAL OPTIONS 10

 3.1. General remarks 10
 3.2. Near surface options 11
 3.3. Geological disposal options 12
 3.4. Other practices 13
 3.5. Potential variants 13

4. OPERATING AND FUTURE FACILITIES 13

 4.1. Konrad repository, Germany 13
 4.2. Proposed closure solution — Richard repository, Czech Republic 15
 4.3. Mount Walton East intractable waste disposal facility, Australia 17
 4.4. Waste Isolation Pilot Plant (WIPP), USA 18
 4.5. Near surface facilities in the USA 21
 4.6. Examples of planned disposal facilities 23
  4.6.1. Near surface disposal 23
  4.6.2. Intermediate depth repositories 23
  4.6.3. Deep geological disposal 23
  4.6.4. The borehole disposal concept for disused sealed radioactive sources 24

5. KEY FACTORS TO BE CONSIDERED IN THE SELECTION OF A DISPOSAL CONCEPT 26

 5.1. Introduction 26
 5.2. Protection of human health 26
  5.2.1. Operational phase 27
  5.2.2. Post-closure phase 27
 5.3. Environmental protection 29
 5.4. Availability of geological environments 30

5.5. Availability of facilities and technologies 30
5.6. Economic and technical resources 30
5.7. Sociopolitical and ethical factors 31
5.8. Integrating the key factors to develop a repository concept and design 31
5.8.1. Developing the concept 32
5.8.2. Optimization and the role of safety assessment 32

6. CONCLUDING REMARKS 33

REFERENCES 35
CONTRIBUTORS TO DRAFTING AND REVIEW 37
STRUCTURE OF THE IAEA NUCLEAR ENERGY SERIES 38

SUMMARY

Separation of radioactive waste into two categories — that which is acceptable for near surface disposal and that which should be directed to a geological repository — seems simple, but complications can arise when defining the boundary between the two categories and, in particular, when deciding the most appropriate disposal route for wastes that contain relatively low concentrations of long lived radionuclides. This category of waste is generated within the nuclear fuel cycle, but can also arise in countries that do not operate nuclear power plants (NPPs). Wastes of this type may not be large in volume or high in radioactivity, but their radiological, physical and chemical properties can make their management difficult.

The objective of the report is to provide an overview of both proven and potential approaches for the safe disposal of long lived low and intermediate level waste (LILW-LL). It discusses the advantages and disadvantages of the various disposal options in terms of their abilities to comply with international safety standards and other influencing factors, such as the nature of the waste and the availability of suitable geological environment.

A number of radiological and non-radiological parameters can be used to characterize radioactive waste for disposal, but for the purposes of this report, the following, which are significant in considering different disposal approaches and options, have been selected and are discussed together with the sources of LILW-LL and a discussion on the classification of waste:

- Half-life and activity;
- Radiotoxicity and chemotoxicity;
- Waste amount;
- Waste form properties and waste conditioning.

Radiological properties are governed by the radionuclides present in the waste, and the risks induced by them decrease with elapsed time. Other properties depend on how the waste is processed and may also change with time. However, the potential impact of waste disposal on the environment depends on the combination of both groups of characteristics, together with the engineered and natural components of the disposal system. This provides some flexibility when selecting disposal approaches so that, for example, the consequences of adverse radiological characteristics can be reduced by selecting a suitable combination of waste form and engineered barrier system. This combination may reduce the reliance on retention of radionuclides in the surrounding geosphere and, therefore, allow an increase in the specific activity of long lived radionuclides that can be accepted for disposal.

An important factor in the management and disposal of LILW-LL is the concentration of long lived radionuclides in the waste stream. It is an accepted practice to dispose of radioactive waste with a limited concentration of long lived radioactivity in facilities located at/or near the surface, at sites with favourable geological characteristics, remote locations, dry climate, and/or engineered barriers or other features that impede or limit the eventual release of radionuclides out of the repository environment to acceptable rates and amounts. For higher concentrations, a more robust containment system is required. Ideally, the radionuclide containment function should derive from a multi-barrier system that employs both engineered and natural barriers to achieve the required passive safety.

A number of options have been considered and/or implemented for disposal of waste containing significant amounts of LILW-LL. There are currently several facilities in operation (e.g. the Waste Isolation Pilot Project and several near surface facilities in the USA), and others have been licensed (Konrad, Germany), or are in the process of being decommissioned (Asse and Morsleben in Germany). Almost all of these are subsurface (underground) facilities. Disposal of some waste in boreholes drilled from the surface may be a suitable option where waste volumes are limited. Depth ranges from a few metres up to several hundred metres, and diameters from a few tens of centimetres up to more than one metre have been achieved.

For countries with a limited amount of LILW-LL, disposing of the waste in a regional repository shared with other countries can be attractive. Since underground disposal, especially deep disposal, has high fixed costs that are independent of the volume of waste, significant economies could be achieved if a repository were shared between several countries.

In radioactive waste disposal, adherence to the principles of radioactive waste management is achieved by complying with the relevant safety requirements for near surface disposal and deep geological disposal. These requirements place various obligations on the government, the regulatory body, the disposal facility developer or operator, and the waste generator. All of these principles and requirements will influence the choice of a disposal option and on the resulting conceptual model. Other aspects, such as the waste inventory, national radioactive waste management policies and the nature of the available geologies, will also be important. Therefore, this report aims to describe the principles, safety requirements and other aspects, such as economic and technical resources, and sociopolitical and ethical factors (here called ‘key factors’) that, in practical terms, are likely to have the greatest impact on the choice of an option.

The national radioactive waste management policy of a Member State may prescribe or proscribe some radioactive waste disposal options. In general, this will usually simplify the decision making process. National policy may also prescribe the disposal site. When this is the case, the process of developing the repository concept may be simpler than would be the case if, for example, the concept had to be capable of being implemented at a range of sites. Stakeholder involvement will occur at some point, which may be early or late in the decision making process. The nature and extent of stakeholder involvement will also vary from one case to another.

Depending on a wide range of factors, the disposal of LILW-LL may be implemented via several disposal approaches. The decision making process begins with consideration of the national radioactive waste management policy and the characteristics of the waste itself. There is a general presumption that long lived waste should be disposed of at depth. Beyond this, the geological environment, the waste package and other engineered barriers will largely define the concept by contributing to the achievement of the required degree of safety.

1. INTRODUCTION

1.1. BACKGROUND

The Joint Convention [1] places a duty on its signatories to develop strategies for the management of their radioactive wastes to avoid, for example, the imposition of undue burdens on future generations. There is an international consensus that, for long lived wastes, this is best achieved through geological disposal, the goal of which is to ensure passive protection of humans and the environment from the radiotoxic species that the waste may contain. Only geological disposal allows the possibility of isolating radioactive waste for a period of time that is sufficiently long to allow the radioactivity to decay to safe levels.

In many countries, the preferred concept for short lived low and intermediate level waste (LILW-SL)[1] is disposal in near surface facilities. The safety of this concept is based on engineered and natural barriers combined with institutional control. This control may include active measures such as monitoring, surveillance and facility maintenance. Institutional control may also include passive measures such as the placement of markers and restricted use of the affected land. In broad terms, the combination of engineered and natural barriers together with institutional control aims to provide adequate containment of the radionuclides and isolation of the waste.

The management of LILW-SL has been solved in a number of countries through the construction and operation of near surface repositories, some of which are now closed and under institutional control. Questions remain, however, on how LILW-LL and high level waste (HLW) should be safely disposed of. It is generally recognized that spent nuclear fuel (SNF), HLW and high inventories of other LILW-LL should be disposed of at depths in stable geological formations. Some countries require that almost all radioactive waste be disposed of in geological formations, without regard to their radiochemical characteristics.

Separation of radioactive waste into two categories — that which is acceptable for near surface disposal and that which should be directed to a geological repository — seems simple, but complications can arise when defining the boundary between the two categories and, in particular, when deciding the most appropriate disposal route for wastes that contain relatively low concentrations of long lived radionuclides. This category of waste is generated within the nuclear fuel cycle but can also arise in countries that do not operate nuclear power plants (NPPs). Wastes of this type may not be large in volume or high in radioactivity but their radiological, physical and chemical properties can make their management difficult. Some examples of LILW-LL are given below:

— Waste generated during reactor operation;
— Decommissioning waste;
— Wastes from reprocessing plants;
— Wastes from radiopharmaceutical production;
— Wastes arising from accidents;
— Used sealed sources;
— Concentrates and waste from research laboratories.

In some countries, naturally occurring radioactive material (NORM) and technologically enhanced naturally occurring radioactive material (TENORM) may be considered long lived radioactive waste; waste produced by the mining and milling of uranium may also fall into these categories. The long term management of these materials is very much affected by their very large volumes. Since a number of IAEA reports already deal with these wastes (e.g. Refs [2–5]), they will not be considered further in this report.

For the purpose of this report, a *disposal option* refers to permanent emplacement of radioactive waste in a specific surface, near surface or geological environment by means of an engineered facility. The boundary between a near surface environment and a geological environment is considered to lie at about 30 to 50 m below the surface

[1] For a discussion of the classification of radioactive waste, refer to Section 2.3. The terms 'LILW-SL' and 'LILW-LL' are used according to the current IAEA recommendations of 1994, but a more recent work, still in draft, will update these recommendations, modifying these terms strictly on the basis of disposal options and proposing instead equivalent terms LLW (suitable for near surface disposal) and ILW (for disposal at intermediate depth, between a few tens and a few hundreds of metres), respectively.

or, in undulating terrain, 30 to 50 m below the local topographic low point. This range is based on the maximum depth of excavation considered likely for the foundations of tall buildings [6, 7].

Isolation and containment are specific safety requirements for safe geological disposal [8]. *Isolation* is the placing of radioactive waste beyond human use and interference. This may be achieved by disposal at a suitable depth below the surface or, in the case of surface and near surface disposal, by institutional control and anti-intrusion barriers. *Containment* is the confinement of the radionuclides in the waste allowing them to decay to harmless decay products. It is aided by engineered barriers and by disposal in a stable geological environment.

1.2. OBJECTIVE

This report provides an overview of both proven and potential approaches for the safe disposal of LILW-LL. It discusses the advantages and disadvantages of the various disposal options in terms of their abilities to comply with international safety standards and other influencing factors such as the nature of the waste, the availability of a suitable geological environment, etc. It is intended for decision makers, regulatory authorities and those individuals or institutions interested in selecting or planning a national system for the long term management of LILW-LL.

1.3. SCOPE

This report deals with disposal approaches for LILW-LL. For the purposes of this report, ‘long lived’ means a half-life of more than about 30 years and LILW is distinguished from HLW by a heat generation rate[2] of less than 2 $kW \cdot m^{-3}$, as described in Section 2.3. As mentioned above, NORM and TENORM wastes are not considered in this report.

1.4. STRUCTURE

Following this introduction, Section 2 describes some of the sources of LILW-LL and their main characteristics. Section 3 lists existing and potential options for the safe disposal of LILW-LL and details their principal design features. In Section 4, more detailed descriptions are given for some of these alternatives, based on concrete examples. Section 5 lists and describes the key factors that may influence the development of a safe disposal concept for LILW-LL. It also explains how a repository concept for LILW-LL might be developed by integrating these key factors. Finally, Section 6 highlights some concluding remarks.

2. SOURCES AND CHARACTERISTICS OF LILW-LL

A number of radiological and non-radiological attributes can be used to characterize radioactive waste for disposal [9]. For the purpose of this report, the following more significant ones for considering different disposal options and approaches for LILW-LL have been selected. They are discussed below together with the main sources of LILW-LL and a discussion on waste classification:

- Half-life and activity;
- Radiotoxicity and chemotoxicity;
- Waste amount;

[2] According to the new work mentioned in footnote 1 and in Section 2.3, this separation from HLW is now made, rather, on the level of activity concentration of around 10^4 TBq/m^3.

—Waste form properties and waste conditioning.

Radiological properties are governed by the radionuclides present in the waste, and the risks induced by them decrease with elapsed time. Other properties depend on how the waste is processed and may also change with time. However, the potential impact of waste disposal on the environment depends on the combination of both groups of characteristics, together with the engineered and natural components of the disposal system. This provides some flexibility when selecting disposal approaches so that, for example, the consequences of adverse radiological characteristics can be reduced by selecting a suitable combination of waste form and engineered barrier system. This combination may reduce the reliance on retention of radionuclides in the surrounding geosphere and therefore allow an increase in the specific activity of long lived radionuclides that can be accepted for disposal. Long lived radionuclides present in waste often belong to one of the groups indicated in Table 1.

2.1. SOURCES OF LILW-LL

With the exception of NORM and TENORM wastes, LILW-LL is generated in a wide spectrum of activities, such as

—The nuclear fuel cycle (fuel production and reprocessing, reactor operation and decommissioning);
—Nuclear research;
—Medical and industrial applications.

TABLE 1. SELECTED RADIOLOGICAL PROPERTIES OF SOME KEY LONG LIVED RADIONUCLIDES

Radionuclide group	Radionuclide	Half-life (a)
Natural long lived radionuclides	^{226}Ra	1600
	^{232}Th	1.41×10^{10}
	^{238}U	4.5×10^{9}
Transuranic elements	^{239}Pu	24 100
	^{241}Am	433
Fission and activation products	^{14}C	5700
	^{36}Cl	300 000
	^{59}Ni	75 000
	^{79}Se	65 000
	^{99}Tc	211 100
	^{126}Sn	10^{5}
	^{129}I	1.6×10^{7}
	^{135}Cs	2.3×10^{6}

2.1.1. Nuclear fuel cycle

Generation of LILW-LL within the nuclear fuel cycle is mostly associated with the handling of nuclear fuel (fuel manufacture, reactor operation, fuel storage and reprocessing), refurbishing and/or decommissioning of reactors (irradiated construction materials, such as core components), and related research and development activities.

Typical examples of such wastes are materials contaminated by the primary reactor coolant or activated by exposure to a neutron flux such as control rods, core grids, core barrels and detectors. Gas-cooled and RBMK reactors generate substantial amounts of irradiated graphite which may contain long lived radionuclides such as ^{14}C.

Significant amounts of LILW-LL are generated at reprocessing plants. The most radioactive of these are usually fuel cladding hulls, spacers and fines from the dissolution of spent nuclear fuel. Other materials include filters of various kinds as well as ion exchange resins, spent reprocessing chemicals, evaporator concentrates, sludge that may contain both transuranic elements and long lived fission products, and scrap and trash from handling of fissile materials.

LILW generated by nuclear accidents is characterized by its large volume and wide spectrum of radionuclides, and may be best considered in the context of environmental remediation.

Finally, the decommissioning of a reprocessing facility will also generate waste contaminated by long lived radionuclides (construction materials and concentrates).

2.1.2. Research, medical, industrial and other uses

Experimental research performed in support of nuclear power programmes generates radioactive waste, some of which belongs to the LILW-LL category. This waste is typified by its physical and radiochemical variability, and relatively small volume. It includes liquid and solid waste of different activity, including concentrates and organic liquids, precipitates, laboratory materials and equipment, disused glove boxes and filters. Other examples are disused components of research reactors, instrumentation from irradiation experiments, samples from reactor material monitoring programmes and decommissioning waste. Waste is contaminated by the whole spectrum of radionuclides generated during reactor operations (actinides, fission and activation products).

A small amount of LILW-LL is generated in radiopharmaceutical production. Waste produced by medical and biological research and applications may be problematic to dispose of due to its high biodegradability (organic tissues, carcasses, organic liquids). Typical long lived radionuclides used in this branch are ^{14}C, ^{36}Cl and ^{99}Tc, which are used in diagnosis, labelling and biological research applications [10, 11].

A number of long lived radionuclides are used in industry in the form of sealed radioactive sources. They are installed in different measuring devices (analysers, detectors), used for thickness measurements, eliminating static electricity, and for detecting moisture, and are widely used in geological investigations. Typical sources of this kind include ^{14}C, ^{63}Ni, ^{226}Ra, Pu/Be, Am/Be and Ra/Be neutron sources [12].

Disused smoke detectors and lightning preventors, which may contain 10^4–10^7 Bq of ^{241}Am (or sometimes ^{239}Pu) per unit, may also fall into the long lived waste category. If collected in large amounts, their specific activity may reach and even exceed the acceptance limits for most near surface disposal facilities.

2.2. IMPORTANT ATTRIBUTES

Radiological characteristics are the main decisive attributes when selecting an approach for managing radioactive waste, as discussed below.

2.2.1. Half-life and activity of radionuclides

Half-life is an important attribute that should be considered in categorizing radioactive waste because of its importance in determining the duration of the minimum containment period during which waste must be isolated from the environment.

It is common to classify radioactive waste according to its *activity*. Limits on the total and the specific activities of radionuclides contained in waste are normally specified in the waste acceptance criteria. These limits are laid down as a result of safety analyses carried out for a particular disposal option and a specific waste form. In general, specific activity is limited by human intrusion scenarios, and total repository activity is limited by natural releases of radioactivity.

It is relatively straightforward to discriminate between HLW/spent nuclar fuel (SNF) and LILW. It is more difficult to draw a strict line between long lived and short-lived LILW. The relevant regulations may help to resolve this difficulty. For each facility there will be a maximum allowable specific activity for long lived radionuclides in each waste package. There will, however, also be a maximum value set for the total content of long lived radionuclides in a repository. Either of these two limits could be the decisive factor in limiting the long lived activity of a waste package.

Long lived radionuclides are often difficult to measure. It is not simple to analyse these isotopes in already existing waste, especially in waste that has been previously treated and packaged. It is very important, therefore, to collect the necessary data on radionuclide content before or at least during the waste processing. For 'historical waste' that has already been conditioned and that exists in considerable quantities in some Member States, indirect methods should be employed to estimate the radioactive content. For example, one of the following procedures or their combination could be considered:

- Calculation;
- Checking documentation;
- Recording interviews with staff who were involved in waste processing;
- Measuring gamma inventories and estimating long lived radionuclide content provided that their mutual ratio is known;
- Checking records on produced or purchased radionuclides.

2.2.2. Radiotoxicity and chemotoxicity

In the context of radioactive waste disposal, the most important measure of radiotoxicity for a specific radionuclide is the effective dose coefficient [13, 14], which indicates the dose (expressed in sieverts per becquerel ($Sv \cdot Bq^{-1}$)) resulting from the intake (usually by ingestion or inhalation) of one becquerel of the particular radionuclide. An operational and post-closure safety assessment will be used to calculate the total dose to affected humans from the estimated intake. This will depend on the radiological inventory of waste and the mobility of the various radionuclides, i.e. their propensity to migrate from the confines of the repository (see the following sections).

In the past, most investigations of post-closure safety of a repository mainly focused on the radioactive constituents of the waste and on assessments of possible radiological consequences and impacts. However, the radionuclides present in the waste only form a minor part of the total mass. The major part of the mass is made up of non-radioactive constituents that may include toxic and/or chemically hazardous substances. These constituents may be persistent so that their hazard potential remains constant with time, i.e. no decay is expected. This has important implications for the disposal of radioactive waste, whether in near surface facilities or deep geological repositories.

Increasingly, national and international legislation addresses groundwater protection. Thus, the safety case for a radioactive waste disposal facility should take into account the consequences arising from the presence of toxic or chemically hazardous substances in the waste packages.

2.3. WASTE CLASSIFICATION

Current IAEA recommendations for waste classification are contained in Ref. [9]. This suggests three broad categories of radioactive waste:

—Exempt waste at or below clearance levels;
—LILW with activity levels above clearance levels and thermal output below 2 kW·m^{-3}; this may be further divided into:
  • LILW-SL;
  • LILW-LL;
—HLW.

LILW-SL has a restricted concentration of long lived radionuclides that is represented by a maximum specific alpha activity for individual waste packages of 4000 kBq·kg^{-1} and an overall average for a near surface facility of less than 400 kBq·kg^{-1} [9]. Existing guidance suggests that HLW and LILW-LL will be disposed in a geological repository, whereas LILW-SL can be disposed of to a near surface facility.

A more recent work [15] has updated the current IAEA recommendations for waste classification and explored the possibility of providing separate definitions for LLW and ILW, which is common practice in many countries.

These schemes may be compared with the approach used in the USA where there are five general categories of radioactive waste:

(1) Spent nuclear fuel from nuclear reactors and HLW from the reprocessing of spent nuclear fuel;
(2) Transuranic radioactive waste (TRUW) mainly from defence programmes;
(3) LLW;
(4) NORM, TENORM, and accelerator-produced radioactive material (NARM);
(5) Uranium mill tailings from the mining and milling of uranium ore.

This scheme reflects the fact that, in the USA, radioactive waste is largely categorized according to its origin and not necessarily according to its level of radioactivity. For example, LLW is defined as "radioactive waste not classified as high level radioactive waste, transuranic waste, spent nuclear fuel, or by-product material as defined in section 11e.(2) of the Atomic Energy Act of 1954" [16]. Furthermore, some LLW has the same level of radioactivity as some HLW. Of particular importance to this report is that current US laws and regulations do not refer to ILW. Consequently TRUW and LLW class B, C, and greater than Class C (GTCC) are used in this report as the US equivalents of the ILW category.

2.4. WASTE AMOUNT

The total amount of waste (volume or mass) is another important factor to be considered when choosing an appropriate disposal option. It may influence, together with radiological characteristics, the selection of both the predisposal and the disposal technologies. Typically, conditioning of a few pieces of spent sealed sources will differ from the technology applied for processing large volumes of LILW from, for example, NPP decommissioning. Also, the disposal option designed for accepting several cubic metres of waste is likely to be different from a facility intended for the disposal of thousands of cubic metres.

The volume of waste to be disposed can be affected by the conditioning process. Requirements on the type of the package and on the conditioning/stabilization technology can result in the final volume of processed waste being several times greater than that of the raw waste.

The waste volume to be disposed of will have to be assessed in the planning stage of the repository development or reconstruction. Inventories of existing (stored) and future waste arising will need to be compiled, taking into account decommissioning of existing and planned facilities. Waste volume is a cost issue and other related aspects such as transportation may also influence the option to be selected.

The external volume and total number of waste packages will usually be the most important determinant of the repository volume. Other factors are the shape of the packages and their handling requirements. In particular, the need for remote handling of packages may cause an increase in the excavated repository volume to provide space for handling equipment such as overhead cranes.

2.5. WASTE FORM PROPERTIES

Waste form properties, including non-radiological properties, are relevant to the assessment of waste disposal options and approaches. Factors to be considered include: the potential for mobilization of radionuclides, the chemotoxicity of the waste form(s) and its chemical compatibility with the disposal environment.

Radionuclides contained in the waste can be mobilized by water and, less often, may migrate via gaseous pathways (^{14}C, Rn). With respect to the groundwater pathway, the tendency of a radionuclide to be dissolved and transported depends on

- Its physical and chemical forms;
- The chemical characteristics of the disposal environment (e.g. high pH conditions caused by the presence of cement);
- The sorption characteristics of dissolved radionuclides on the adjacent engineered barrier materials;
- Non-radioactive components of the waste (e.g. presence of corrosive species and complexing ligands used in reprocessing);
- The resistance of the waste form to degradation processes (e.g. biodegradation and radiation stability).

When assessing the performance of the disposed waste, chemical reactions that may result in creation of mobilizing agents should also be taken into account. As an example, some complexing ligands not originally present in the waste may be formed due to the chemical interactions between the barrier materials and the waste itself. The most well-known example is the alkaline degradation of cellulose to isosaccharinic acid (ISA) [17] which can increase the mobility of otherwise nearly insoluble radionuclides by many orders of magnitude.

The evaluation of mobilization processes is complex and may bring unexpected findings. For example, radionuclides with a high solubility and low sorption ability, such as ^{36}Cl and ^{129}I, can be critical in safety assessments although they have low radiotoxicity. In contrast, highly radiotoxic plutonium isotopes are retained within the repository system due to their low solubility and high sorption characteristics and thus may contribute less to final dose of the critical group.

The concentration of chemically toxic components in the disposed waste may play a decisive role when selecting the disposal option. Most disposal facilities, with the exception of those designed for accepting 'mixed[3] waste' (e.g. the Clive facility, Utah, USA), prohibit the acceptance of toxic materials. However, when disposing of large amounts of waste, even compounds with low non-radiological hazard may become problematic. The principal problem of chemotoxicity is that it does not usually decrease with time and thus the engineered barrier system may provide effective containment of the waste for only a portion of the time during which the waste remain potentially harmful. In such cases, the geological barrier will be important in limiting the potential long term impact of the disposal. When assessing the risks of chemically toxic contaminants, the following aspects will be crucial: the nature and chemical form of the chemotoxic components and the exposure pathways and contaminant transport times [17].

Gases can be generated by three main processes:

- The microbial degradation of organic components of the waste (cellulose, hydrocarbons);
- Metal corrosion;
- Radioactive decay (radon).

For example, aluminium is expected to corrode in a high pH environment to produce hydrogen gas. Carbon steel behaves similarly under oxygen free conditions and at much lower rate. Some of the gases that are generated may themselves be radioactive, e.g. ^{3}H, ^{14}C in carbon dioxide or methane, ^{222}Rn. If gas is produced in large amounts, it could lead to a buildup of pressure that may be sufficient to damage barriers. Gas will tend to migrate due to buoyancy and, where this occurs, it could cause unwanted movements of repository pore water and/or the surrounding groundwater.

[3] Mixed waste contains both radioactive material and non-radioactive hazardous material.

2.6. WASTE PROCESSING

It is evident that the proper selection of a waste conditioning process may make a significant contribution to the long term safety of a disposal system. Conditioning can produce a waste form that is more chemically and physically stable than the primary waste. It can also provide an additional engineered barrier to radionuclide migration by reducing the mobility of radionuclides and other potentially harmful constituents of the waste. A basic requirement for selecting a conditioning method is that the resulting waste form (and its potential degradation products) should be compatible with the disposal environment and the other engineered and natural barriers.

Waste processing can also reduce the waste volume. For example, waste sorting and segregation can be used to re-categorize some of the waste as non-radioactive (concentration of radiocontaminants and release of the rest of waste as non-radioactive). Long lived radionuclides can be stabilized in the form of very low solubility compounds, and their chemotoxicity can be reduced by proper treatment resulting in less dangerous products. Chemical aggressivity can be decreased through different neutralizing chemical reactions.

It is widely agreed that, where they cannot be discharged to the environment, liquid wastes should be solidified and conditioned. This improves transport, operational and post-closure safety. Solid waste will often need to be treated and conditioned for similar reasons. Large components, for example, may need to be cut into pieces suitable for packaging and handling, and volume may be reduced by compaction or incineration. Incineration may also be undertaken to remove unwanted components of the waste (e.g. organic materials). However, incineration of radioactive waste, which requires the cleaning of off-gases and the processing of secondary waste, is by no means trivial. Thus, it might be simpler to dispose of solid waste with a certain content of organic materials, provided the solution is consistent with long term safety.

Cement mortar, bitumen and some polymers are used routinely for conditioning of LILW-LL. Vitrification has also been considered and used for some specific waste categories. Concrete containers with steel reinforcement, steel drums and steel boxes are commonly used for waste packaging. Their dimensions should fit the conditioning equipment and handling appliances, including transport casks, and the dimensions and shapes of the disposal spaces. Therefore, it is a considerable advantage to limit the number of different package types to a few standardized models.

Sealed sources are usually associated with some sort of device that may require dismantling so that the sealed source can be removed. This allows the non-radioactive parts to be discarded and the sources to be packaged so that they can be more conveniently handled. Sometimes, the waste package may contain shielding, often composed of heavy metals (cast iron, steel, lead, depleted uranium), concrete or a combination of these materials.

3. DISPOSAL OPTIONS

3.1. GENERAL REMARKS

An important factor in the management and disposal of LILW-LL is the concentration of long lived radionuclides in the waste stream. It is an accepted practice to dispose of radioactive waste with a limited concentration of long lived radioactivity in facilities located at/or near the surface, at sites with favourable geological characteristics, remote locations, dry climate, and/or engineered barriers or other features that impede or limit the eventual release of radionuclides out of the repository environment to acceptable rates and amounts. For higher concentrations a more robust containment system is required. Ideally, the radionuclide containment function should derive from a multi-barrier system that employs both engineered and natural barriers to achieve the required passive safety. Figure 1 illustrates the various components of a disposal system that are used in this report.

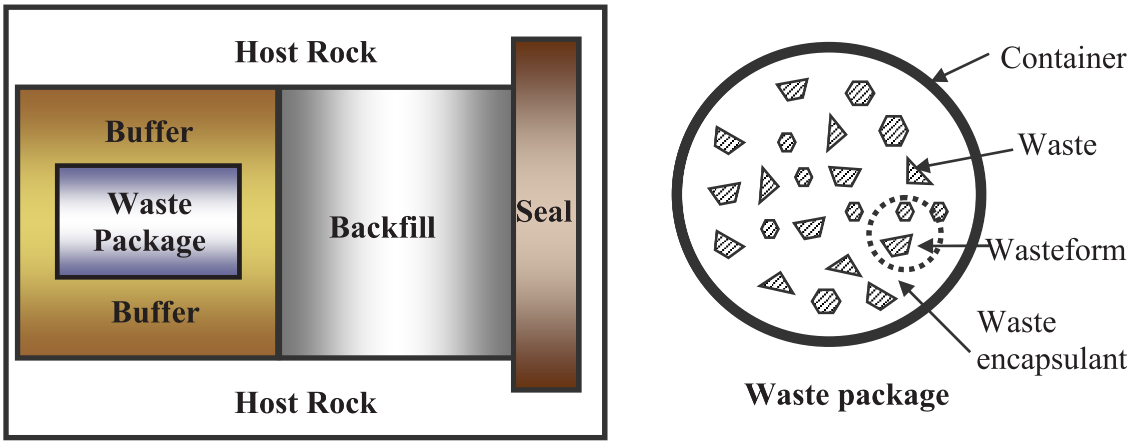

FIG. 1. Components of a repository system as used in this report.

A number of options have been considered and/or implemented for disposal of waste containing significant amounts of LILW-LL. There are currently several facilities in operation (WIPP and several near surface facilities in the USA), and others have been licensed (Konrad in Germany), or are in the process of being decommissioned (Asse and Morsleben in Germany). Almost all of these are subsurface (underground) facilities.

3.2. NEAR SURFACE OPTIONS

Activities such as the decommissioning of NPPs and other nuclear facilities as well as clean-up operations may result in significant amounts of low level waste with low content of transuranic elements and/or long lived activation and fission products. For this kind of waste, disposal in near surface facilities with limited engineered barriers at/or near the site where the waste arises might be a safe, economically attractive option. Containment of the radionuclides in the waste is guaranteed by emplacing it, appropriately packaged, above the groundwater table and by limiting or avoiding rainwater percolation with a sufficiently impervious cover. Often these low level waste facilities consist of trenches, especially in remote arid areas. Assessing the suitability of the site to demonstrate appropriate radionuclide containment and waste isolation is a necessary part of the licensing procedure of all repository sites. This will require studying the geological environment of the site, especially its hydrogeology in order to evaluate the contribution of natural barriers to containing radionuclides and diluting/retarding released radionuclides so that resulting radiation exposures are kept as low as reasonably achievable and below regulatory limits [18].

Landfill disposal may be suitable for very low level waste with very limited amounts of long lived activity. These facilities usually contain no complex engineered barriers or elaborated sealing. In such cases, the requirements on the waste treatment and packaging will also be less stringent. But adequate waste acceptance criteria (WAC) and quality control must ensure that the radionuclide content, especially the content of long lived activity, remains at very low levels compatible with the limited containment and isolation capabilities of this type of disposal.

For wastes with higher radioactive content, *trench disposal* has been often used. A trench can be divided into individual compartments to increase radionuclide containment and flexibility of operation. After filling, a waterproofing top cover is installed. Surveillance and monitoring are required after closure during the period of institutional control. Again, the WAC will limit the type, concentration and quantity of radionuclides allowed in waste packages, reflecting the limited retention capability of this type of site.

Recently implemented *engineered surface repositories* of the vault type incorporate more elaborate engineered barriers that aim to reduce the amount of water that could contact the waste. Such facilities are principally intended for the disposal of short-lived waste with the activity of long lived isotopes being limited to low concentrations that, typically, fall in the range 400 to 4000 $kBq \cdot kg^{-1}$, this limit being imposed through the WAC. This type of facility allows the economic disposal of large volumes of LILW, such as waste from the operation and decommissioning of nuclear power plants. Waste from other sources is also accepted provided that it meets the WAC. In 2003, the IAEA published a technical document [19] describing a practical approach for establishing WAC (activity limits for long lived radionuclides).

Engineered surface repositories are equipped with surface barriers (caps), vertical barriers (cut-off vaults) and sub-horizontal barriers (floors). There are other containment technologies that may be applied, including chemical barriers that retard migration of radionuclides without impeding the water movement.

After the waste is disposed of, the void spaces in vaults are usually filled with grout or some other backfill material. The engineered barrier system may include drainage collectors to channel out infiltrating water. Underground galleries may be installed to allow the functioning of the barriers to be checked. Additional barriers might be constructed around the disposal unit to control the movement of water.

Common to all surface repositories is a period of active institutional control following repository closure. Its purpose is to prevent human intrusion and damage to the facility from, for example, burrowing animals or erosion. This active control should persist for a period of time that is sufficient to allow the radioactivity to decay to values considered no longer a hazard. Active institutional control may persist for centuries. Passive institutional control may also be applied. This may include markers, controls on land ownership, and use and archiving of records.

3.3. GEOLOGICAL DISPOSAL OPTIONS

Waste with higher contents of long lived radionuclides is usually disposed of at depth in appropriate geological formations. The depth of *deep geological repositories* ranges between some hundred and somewhat more than 1000 m. In some cases, certain categories of long lived waste can be disposed of at *intermediate depth* (up to some 100 m).

Geological disposal has been carried out safely in a number of countries. The nature of the wastes and the waste forms acceptable at a given site depends on factors such as waste and site characteristics. Treatment and packaging of the waste provide both physical and chemical barriers to the radionuclide migration. The selection of backfill material to fill in void spaces depends on the design requirements and must consider its compatibility with the host rock. The repository may have the form of a tunnel, a chamber or a silo. It may be purpose-built or constructed in an existing mine. Walls can be covered, e.g. with shotcrete, and void spaces can be sealed with a low permeability material, e.g. grout or bentonite, to control groundwater movement. Furthermore, long term stabilization of excavated openings by backfilling may be necessary in some host rocks.

In principle, repositories in caverns provide a higher level of containment and isolation than surface repositories. Also, the likelihood of human intrusion after repository closure is much lower, since the access to a closed underground facility requires greater technical effort. Consequently, such facilities may be able to accept high concentrations of long lived radionuclides. A further advantage of deep disposal is that the need for institutional control after closure is much diminished — in most cases, the land can be put to a range of uses, including agriculture, immediately after closure.

Many different rock types could host a deep repository. Granite, salt, clay, tuff and other rocks have been considered and/or proposed, but only one site has actually been implemented, in rock salt (WIPP). A further site in a low-grade iron-bearing rocks covered widely by clay has been licensed, but is not yet implemented (Konrad). In developing a deep repository, two options are available: re-use of an existing mine or a new excavation. Of the four licensed deep geological repositories (not all of them for long lived waste), three are re-used mines (Asse, Morsleben and Konrad in Germany) and one is in a purpose-built facility (WIPP in the USA).

Disposal of some wastes in *boreholes* drilled from the surface may be a suitable option where waste volumes are limited. Disposal of sealed sources in such boreholes is the subject of a different report [20]. Depth ranges from a few metres up to several hundred metres and diameters from a few tens of centimetres up to more than one metre have been implemented. The waste would normally be contained within an engineered package because of the difficulty in ensuring appropriate conditions at the location of the waste in the borehole. Boreholes can be co-located in the area of a surface repository for short lived waste, which will help reduce the cost of disposal.

Shafts sunk from the surface to form a silo have been used for disposal of waste contaminated with transuranic elements at the Nevada Test Site. In this case, engineered barriers largely consist of the waste package. In Novaya Zemlya, a more highly engineered variant has been proposed for permafrost soil. Compared with other engineered surface repositories, such an approach would render the frozen, immobile groundwater an additional barrier to radionuclide escape.

Appropriately implemented geological repositories render the highest possible degree of waste isolation, and can therefore accept waste with high contents of long lived radioactivity. But the effort for implementation is high, so that their construction might not be justified for disposal of limited amounts of long lived waste. In some cases, co-disposal of LILW-LL with HLW may be economically attractive and feasible.

3.4. OTHER PRACTICES

A number of practices have been used in the past, mainly to deal with certain kinds of legacy waste in conditions requiring remediation measures. They are not recommended practices in situations in which the options mentioned above are available or could be easily implemented, but they can constitute an acceptable practice for remediation purposes. These practices include:

- In situ immobilization in tanks;
- In situ deep soil mixing;
- In situ vitrification.

3.5. POTENTIAL VARIANTS

For countries with a limited amount of LILW-LL, disposing the waste in a *regional repository* shared with other countries can be attractive [21]. Since underground disposal, especially deep disposal, have high fixed costs that are independent of the volume of waste, significant economies could be achieved if a repository were shared between several countries.

For relatively small volumes of waste, *long term storage* for up to 100 years and more can be considered an option. Such a solution may contradict the principles of sustainability and intergenerational equity, and assumes the fulfilment of a number of prerequisite conditions [22]. It may, however, be the best available solution at a given time until a repository becomes available. Such an interim storage has been implemented in the Netherlands, where a final solution for radioactive waste is not available at present.

4. OPERATING AND FUTURE FACILITIES

4.1. KONRAD REPOSITORY, GERMANY

From the very beginning, radioactive waste disposal policy in Germany has decreed that all types of radioactive waste are to be disposed of in deep geological formations. This includes short lived and LILW-LL. Re-use of mines is economically attractive so that, due to its favourable geology and hydrogeology, the Konrad mine was investigated for radioactive waste emplacement.

Konrad is an abandoned iron ore mine. It is located in the south of a large, poor quality iron ore formation in the federal state of Lower Saxony, in northern Germany. This formation was deposited about 150 million years ago. The overlying strata mainly consist of low-permeability clayish rock that completely covers the iron ore sediment. This forms a 200–400 m thick barrier that isolates the formation from overlying groundwater (Fig. 2). The iron ore is accessed by the mine workings at a depth between 800 m and 1300 m.

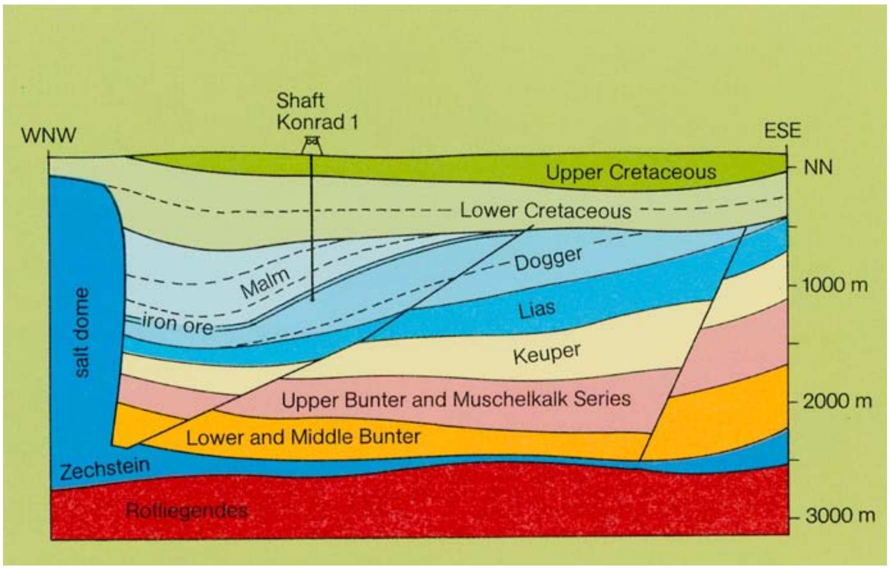

FIG. 2. Geology of the Konrad site.

The hydrogeological situation is characterized by a pronounced structure. The groundwater near the surface, locally influenced by human use, is mostly found in Quaternary deposits and is hydraulically connected to watercourses on the surface. The deeper groundwater levels consist of individual aquifers, separated by claystone with low permeability. As a result, the Konrad mine is exceptionally dry.

First investigations on the suitability of the Konrad site to host a repository were performed on behalf of the Federal Government from 1976 to 1982. These investigations confirmed the ‘presumed site suitability’, and the licensing procedure was initiated in August 1982, followed by a comprehensive investigation and planning programme.

This programme confirmed the suitability of the Konrad mine for the disposal of radioactive waste with negligible heat generation, i.e. waste packages that do not increase the host rock temperature by more than 3°C on average. This licence was granted by the Ministry of the Environment of Lower Saxony on 22 May 2002. Following a period of litigation ending in 2007, the site is currently being developed and will start receiving waste for disposal in 2013. All types of solid and solidified low and intermediate level waste including both short lived and long lived radionuclides will be disposed of at Konrad.

According to the site licence, the Konrad repository will be operated by means of two shafts. Shaft Konrad 1 will serve for air intake, material transport and personnel access. Shaft Konrad 2 will be used for exhaust air and waste package transport. The waste packages will be delivered to the site by rail or road. Subsequent to entrance control measures, they will be hoisted via shaft Konrad 2 to the underground disposal level, loaded on transport vehicles and shipped to the emplacement rooms that have a cross section of 40 m² and a length of up to 1000 m. Several disposal rooms form an ‘emplacement field’, as shown in Fig. 3.

The emplacement fields still to be excavated will be located outside the former mining areas, which are not suitable for waste emplacement, mainly due to mine safety considerations. The waste packages, standardized cylindrical and box shaped waste containers will be stacked in the emplacement rooms. The residual voids will be backfilled by pumping a mixture of crushed Konrad rock debris, cement, additives and water. There is no intention to retrieve the waste once disposed of.

In total, according to the investigations performed, waste package volume of about 650 000 m³ could be disposed of in the Konrad repository, but the site licence limits the acceptable waste volume to a maximum of 303 000 m³, in line with more recent forecasts of waste arisings. According to the results of the comprehensive site-specific safety assessment, the permissible total activity of alpha emitters amounts to 1.5×10^{17} Bq and that of beta/gamma emitters to 5.0×10^{18} Bq. Further information on the Konrad repository can be found on the web site of the German Company for the Construction and Operation of Waste Repositories (DBE) [23].

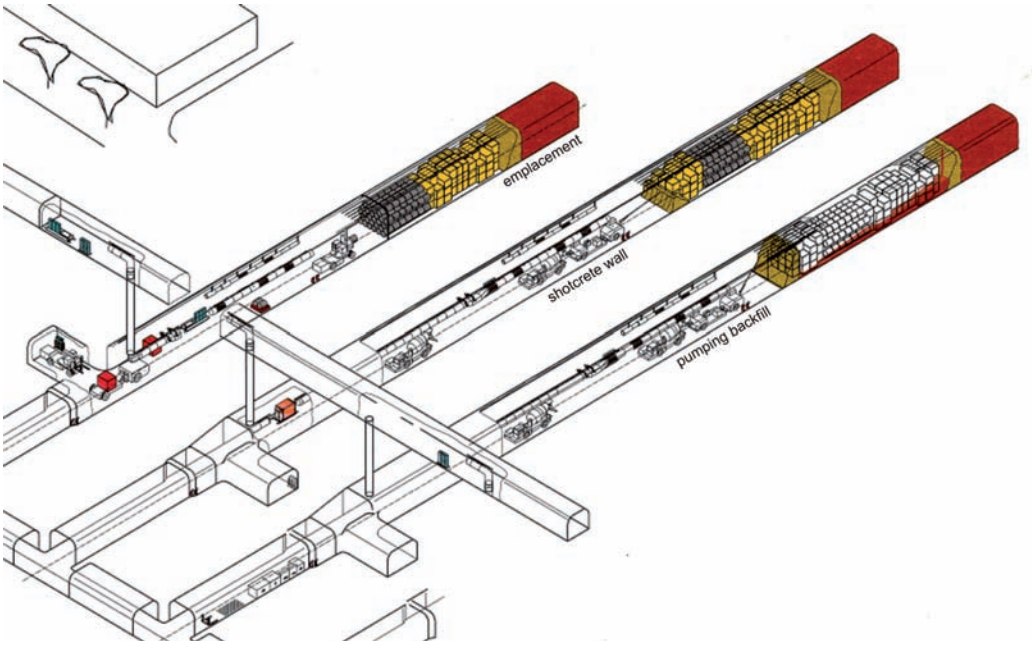

FIG. 3. Emplacement field in the Konrad repository.

4.2. PROPOSED CLOSURE SOLUTION — RICHARD REPOSITORY, CZECH REPUBLIC

The Richard repository is located near Litoměřice, a historical town on Labe River, in northern Bohemia. Richard, originally a limestone mine at shallow depth, was enlarged to host an underground facility for weaponry production during World War II. The newly created underground cavities then lay unused until nuclear research and the use of isotopes in medicine and industry in Czechoslovakia in the 1950s gave rise to the need for a repository for the resulting waste. In the mid-1960s, some of the abandoned chambers began to be used for the disposal of low level waste from hospitals, industrial radioisotopes and research involving radioactive materials. The waste was usually packed in standard drums as contact-handled waste. Most of the currently accepted waste packages consist of a 200 L drum with a 100 L drum cemented inside it, so that some 5 cm of concrete radiation shielding is provided. Figure 4 shows a disposal chamber in the Richard repository, filled with LLW. Further information about the Richard repository is included in Ref. [24].

As a result of past practices the site contains historical waste with a relatively high proportion of long lived radionuclides, mainly ^{241}Am, ^{239}Pu, and ^{238}Pu, which made up an important part of the activity inventory of about 10^{15} Bq. The preliminary closure concept anticipated the sealing of individual disposal chambers with walls separating them from the rest of the Richard mine. The chambers were then to be backfilled with very low permeability, high quality concrete. Later, all the connection tunnels were to be backfilled and the repository access tunnel carefully sealed. Further studies showed, however, that it would be very difficult to reach the required level of chamber backfill quality, especially in regard to permeability. Moreover, it cannot be shown that the required very low permeability is achieved everywhere in the chamber, since it is not accessible for testing after backfilling. A new, detailed analysis of the Richard safety case indicated the need for additional measures to improve waste containment while relaxing any difficult-to-achieve requirements, i.e. to optimize protection by improving the robustness of the waste isolation system.

This has led to the development of the enhanced closure concept in which radionuclide leaching and transport is substantially reduced and delayed by eliminating the driving force, i.e. any pressure gradient across the waste body that might develop after repository closure. To achieve this, a ‘hydraulic cage’ will be constructed around the waste disposal chambers to avoid the buildup of such a pressure gradient. The hydraulic cage consists of a high permeability layer completely surrounding the chamber so as to provide a preferential pathway for any groundwater that may be present (Fig. 5). With this system, water flow through the waste is avoided, not (as originally intended) by enclosing the waste in a very low-permeability cement matrix, but rather by eliminating the pressure gradient that drives the flow.

FIG. 4. Richard repository disposal chamber.

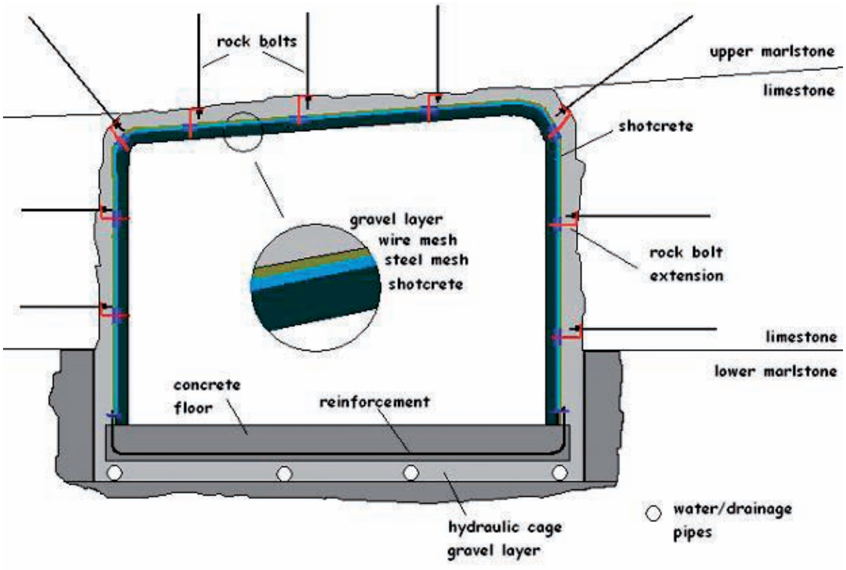

FIG. 5. Concept outline for the hydraulic cage realization.

After reviewing the different technical implementation alternatives, a robust solution for the construction of the hydraulic cage was developed that is analogous to techniques used for tunnel construction in high pressure environments. In principle, the empty chamber is first fitted with a gravel layer supported by a steel mesh attached to the walls with rock bolts. The steel mesh is covered with shotcrete and a concrete floor is emplaced. The waste packages are stacked in the chamber, leaving a certain space between the external waste packages and the chamber wall. The void space is then backfilled with low permeability concrete of standard quality. The gravel layer with high hydraulic conductivity completely surrounds the waste/concrete body. Drainage and monitoring systems allow the performance of the hydraulic cage to be monitored before final repository closure, so that the proper functioning of the system can be verified for a period of up to several decades.

The enhanced closure concept is to be tested at first in a few chambers. The planned work includes the preparation of the chamber system subdivided for technical reasons into several segments, the reconditioning of some of the historical wastes, its transfer into the prepared chambers, the isolation of the chamber segment by means of a concrete wall, and the backfilling of the disposal chambers with pumped concrete. During the backfilling process, the concrete temperature will be monitored at a number of positions in the chambers to verify that, during the concrete solidification, temperatures that could lead to cracking are not reached. The backfilling process will be also monitored and quality controlled by means of television cameras and by sampling and testing the backfilling concrete after solidification, which is now possible.

The safety analysis carried out for the enhanced closure concept showed an important optimization of the protection for the most likely scenarios of future development. In the case of one specific, rather unlikely scenario, a substantial reduction of the calculated radiation exposures was achieved, so that the relevance of this scenario was completely eliminated. Furthermore, the hydraulic cage significantly reduces the performance required from the concrete backfill to that of normal concrete. The hydraulic cage concept has therefore proved applicable to an existing LILW repository that, because of past disposal practices, contains comparatively high amounts of certain long lived radionuclides.

4.3. MOUNT WALTON EAST INTRACTABLE WASTE DISPOSAL FACILITY, AUSTRALIA

The Mount Walton East facility [25] has been in operation since 1992. This facility is designed for the disposal of both radioactive and chemical waste, but is legally prevented from accepting wastes from outside the state of Western Australia. The facility is operated on a campaign basis, covers an area of 25 km^2 and is estimated to have a capacity of 120 000 m^3.

There are two shafts at the site, 28 m deep, 2 m diameter and 5 m apart, and three trenches all located within a low permeability, natural kaolinitic clay horizon (see Fig. 6). The trenches have been used to dispose of materials contaminated with NORM, including steelwork from a dismantled phosphoric acid plant [26]. The shafts and trenches are all situated in the unsaturated zone.

Waste emplaced in the shafts is cemented into 60 L drums, which are then concreted into 200 L drums. Within the shafts, the drums are arranged in layers of three, each surrounded by a concrete backfill that is added after each layer has been put in position. The topmost layer is 8.5 m below the surface. Above this is 0.5 m of concrete, 8 m of previously excavated soil and (above ground level) a concrete cover (see Fig. 7).

Spent radioactive sources are an important component of the inventory of this repository. The total inventory of major radionuclides disposed of in this facility is given in Table 2. In this facility, the activity of an individual source could be fairly high (4 GBq average for ^{137}Cs); however, the average disposed concentration throughout the facility is consistent with current practice for near surface disposal [27].

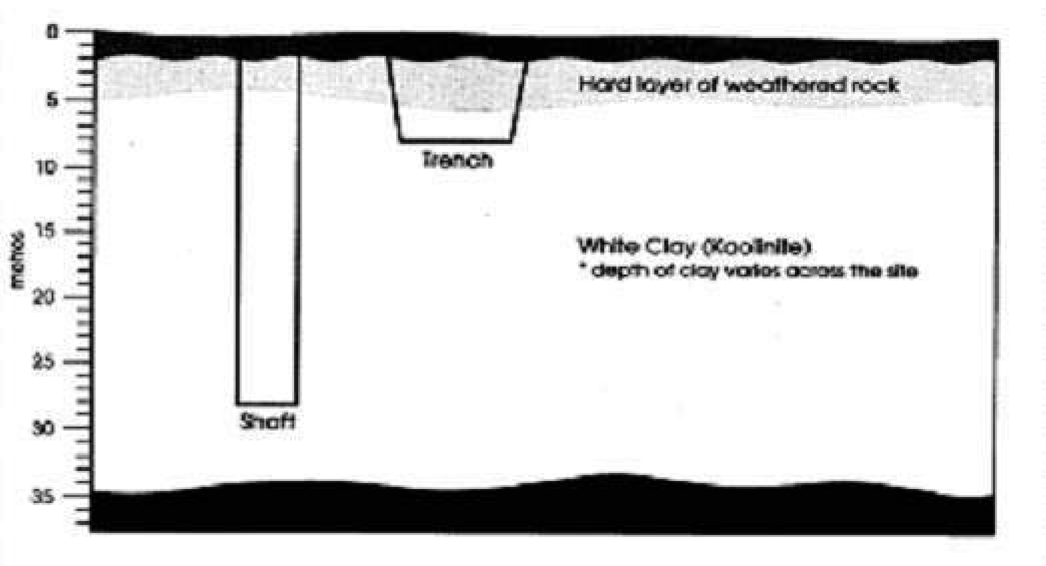

FIG. 6. Disposal units (borehole and trenches) at the Mt Walton East site in Australia.

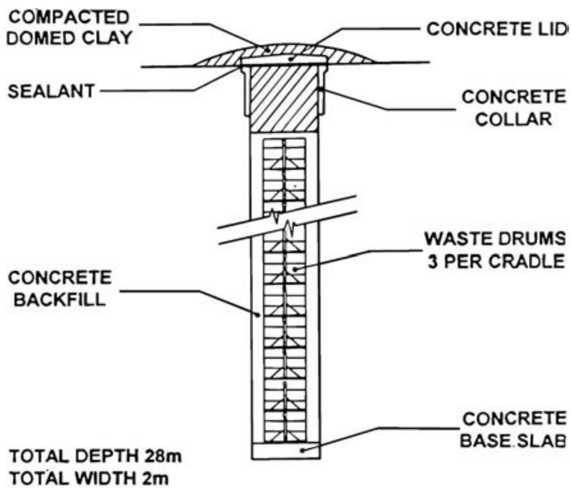

FIG. 7. Shaft disposal facility at the Mt Walton East site in Western Australia.

TABLE 2. TOTAL ACTIVITIES OF MAJOR INDIVIDUAL RADIONUCLIDES DISPOSED OF IN WESTERN AUSTRALIA'S MT WALTON EAST FACILITY [28]

Radionuclide	Inventory (MBq)
^{3}H	1.3×10^{8}
^{137}Cs	2.9×10^{4}
^{241}Am	1.1×10^{4}
^{226}Ra	1.9×10^{3}
^{60}Co	490
^{109}Cd	290

4.4. WASTE ISOLATION PILOT PLANT (WIPP), USA

The WIPP TRUW repository (Fig. 8) is the only currently operating ILW disposal facility in the USA. The WIPP site was certified by the USEPA on 18 May 1998 for safe management and disposal of TRUW [29] and it opened on 26 March 1999 [30]. The repository is situated approximately 650 m below ground level in the lower half of the 250 million-year-old Salado Formation. This is a 600 m thick, regionally extensive, undisturbed, virtually impermeable, bedded rock salt formation.

The current legal and regulatory frameworks governing TRUW disposal at the WIPP site [31–34] define TRUW as defence-generated radioactive waste containing at least 3700 Bq·g^{-1} of alpha-emitting, transuranic isotopes with half-lives greater than 20 years and exhibiting a maximum canister surface dose rate of 10 Sv·h^{-1}. They also distinguish between set volume and activity limits for the following two main TRUW categories:

(1) Contact handled (CH) TRUW, which may exhibit canister surface dose rates of up to 0.002 Sv·h^{-1} at the time of characterization.
(2) Remote handled (RH), which may exhibit canister surface dose rates between 0.002 Sv·h^{-1} and 10 Sv·h^{-1} at the time of characterization. In addition, the total volume of RH-TRUW is limited to 7080 m^{3} or 16.87×10^{16} Bq, but only 5%, i.e. 354 m^{3}, of the total RH-TRUW volume may exhibit a canister surface dose rate of 1 Sv·h^{-1} or higher.

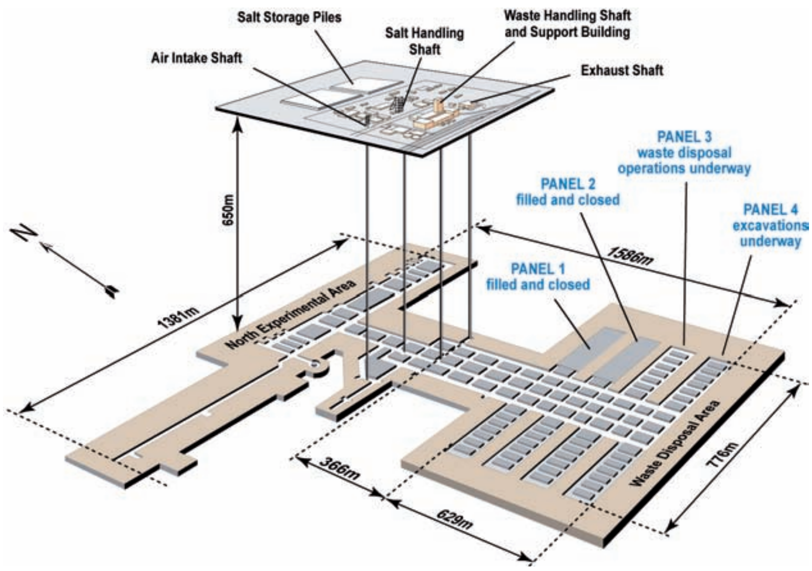

FIG. 8. Schematic illustration of surface and subsurface facilities at the WIPP site (courtesy of USDOE).

Finally, the current legal and regulatory frameworks define the waste form as a solid material containing less than 1% of free liquids.

Although the total volume of TRUW that may be disposed of in the WIPP repository is limited to 175 584 m^3, the total volume of TRUW requiring deep geological disposal remains to be established based on the ongoing environmental cleanup of former nuclear weapons complex sites. However, approximately 60% of the currently known CH- and RH-TRUW may contain regulated hazardous constituents (= mixed TRUW) and mixed TRUW is governed by regulations related to both the WIPP Land Withdrawal Act of 1992 (LWA) and the Resource Conservation and Recovery Act of 1976 (RCRA), which, in the case of WIPP, are enforced by the New Mexico Environment Department (NMED).

As mentioned above, TRUW can only be disposed of in a deep geological repository. The WIPP TRUW repository disposal concept is based on the disposal principles recommended by the National Academy of Sciences (NAS) in 1957 [35], i.e. deep geological disposal in a ‘stable’ salt vault/repository. As also mentioned above, disposal options for other types of ILW are currently being explored by the US Department of Energy (USDOE).

The baseline WIPP repository layout/design comprises eight separate panels (Fig. 9). Each panel hosts seven disposal rooms and each disposal room measures ~4 m in height, ~10 m in width, and ~91 m in length. As indicated in Fig. 8, the panels are excavated and filled in stages. For example, at the end of September 2005, Panels 1 and 2 had been fully excavated and filled with mixed and non-mixed CH-TRUW, Panel 3 had been excavated and was being used for mixed and non-mixed CH-TRUW disposal, and Panel 4 was being excavated. The baseline disposal scheme at WIPP is to first emplace RH-TRUW canisters in horizontal holes drilled in the walls of the disposal room with remote handled equipment (Fig. 9) and subsequently fill the disposal room ‘manually’ with CH-TRUW contained in either 208 L standard steel drums or larger standard steel waste boxes stacked three high (Fig. 10). A limited amount of magnesium oxide (MgO) ‘powder’ in bags is also emplaced in the void space between the walls of the disposal rooms and the outer perimeter of CH-TRUW containers (at the time of Fig. 10 MgO in super sacks and elongated circular sacks was placed on top of the container stacks and between the containers, respectively). The MgO is an additional engineered barrier to decrease actinide solubility.

It should be noted that only CH-TRUW is currently disposed of in the WIPP repository pending the authorization of RH-TRUW disposal. The USDOE submitted an application to dispose of RH-TRUW in 2004 that is currently being reviewed by the USEPA and the NMED. The disposal of CH-TRUW commenced prior to obtaining the regulator-approvals required for commencing receipt and disposal of RH-TRUW at the WIPP site, because the projected RH-TRUW volume was significantly smaller than the available disposal volume.

FIG. 9. Simulated emplacement of RH-TRUW in the WIPP repository (courtesy of USDOE).

FIG. 10. Photo of CH-TRUW and magnesium oxide backfill emplaced in one of the disposal rooms of the WIPP repository (courtesy of USDOE).

Since the 1999 opening of the WIPP site through 3 October 2005, WIPP had safely received 3969 shipments of TRUW for disposal. When filled to its current legal capacity, the WIPP repository will contain 175 584 m^3 of TRUW that may include up to 17 t of plutonium isotopes, some of which will have a half-life in excess of 24 000 years; and waste containers with external surface dose rates of up to 10 Sv/h. In other words, the TRUW emplaced in the WIPP repository is both long lived and highly radioactive.

It should be noted that, although the applicable regulation [33] allows for up to a 5 km lateral stand-off distance between the perimeter of the disposed TRUW and the area accessible to the general public (also referred to as the 'accessible environment'), the lateral distance between the perimeter of the TRUW and the accessible environment is only 2.4 km, which illustrates the excellent containment and isolation capabilities of the repository host rock (bedded salt), since the post-closure containment and isolation of the disposed TRUW is essentially provided by the natural barriers. Notwithstanding the short stand-off distance, the WIPP performance/safety analyses showed that the radionuclide releases during the 10 000 year regulatory period were less than one tenth of the regulatory limits and 1/768 of the average annual natural background radiation in the USA. In terms of performance/safety assessment, ^{239}Pu and ^{241}Am are the most important radionuclides.

4.5. NEAR SURFACE FACILITIES IN THE USA

Although other concepts have been pursued in the past, the only two current concepts for disposal of LLW in the USA are above ground and near surface disposal. They require, among other things, to avoid natural resources in the area, such as wildlife preserves; the site must be sufficiently isolated from groundwater and/or surface water and must not be in an area of geological activity (such as volcanoes or earthquakes). Regardless of design, all LLW disposal sites use a series of natural and engineered barriers to prevent radioactivity from reaching the general public and the environment.

As mentioned above, the United States Nuclear Regulatory Commission (USNRC) has established the technical baseline requirements for disposal of LLW and its definition of a 'near surface facility' is a land disposal facility in which radioactive waste is disposed of within the upper 30 m of the earth's surface. The following are the five most common land disposal options for LLW in the USA:

(1) *Shallow land burial* was used by all US LLW disposal facilities until 1995. Since then, as summarized below, other disposal options have been successfully used. In the shallow land burial facilities, which are sited in areas away from surface water and where travel of any groundwater is slow, the waste containers are placed in long, lined trenches, 8 m or more deep. The trenches are covered with a clay cap or other low-permeability cover, gravel drainage layers and a topsoil layer. They are then contoured and replanted with vegetation for drainage and erosion control. In addition, an intrusion barrier, such as a thick concrete slab, is added to the class C LLW trenches. The sites are carefully monitored to ensure performance in compliance with the applicable regulations and that there is no leakage. An example of a shallow land burial facility — the 200 W Area at the Hanford site — is shown in Fig. 11.

(2) *Modular concrete canister disposal* consists of individual waste containers placed within concrete canisters, which are then disposed of in shallow land sites. The array of canisters has an earthen cover. This additional engineered barrier system has been used at the Chem-Nuclear Systems LLC Barnwell facility in South Carolina (Fig. 12) since 1995.

(3) *Below ground vault disposal* uses a sealed structure built of masonry blocks, fabricated metal, concrete or other materials that provide a barrier to prevent waste migration. It has a drainage channel, a clay top layer and a concrete roof to keep water out, a porous backfill, and a drainage pad for the concrete vault.

(4) *Above ground vault or engineered berm* is a reinforced-concrete structure that provides isolation on the earth's surface. Its sides and top are between 0.5 m and 1 m thick, and it has a sloping roof to aid water runoff. For low-activity radioactive waste, above ground engineered berms that provide the same isolation as shallow land burial are in use. For example, Envirocare of Utah, Inc. (Envirocare) uses the above-ground engineered berms option (Fig. 13) at its Clive site in Utah for disposal of class A LLW.

(5) *Earth-mounded concrete bunkers* are equipped with a drainage system and covered with impermeable clay and topsoil, giving the facility a rounded shape. The waste is placed in below ground, concrete monoliths, and less radioactive waste is placed on top of the monoliths to create the mounds.

There is no deep geological disposal facility for LLW in the USA because the current USNRC regulation for land disposal of LLW [36] does not provide conditions for deep geological disposal of LLW (or disposal options for GTCC LLW). It does, however, allow for a case-by-case approval by the USNRC of deep geological disposal of class A, B, and C LLW. Options for safe disposal of GTCC LLW are currently being pursued [37]. In the absence of these options, GTCC can be disposed of in a deep geological repository in compliance with 10 CFR Part 60 [38].

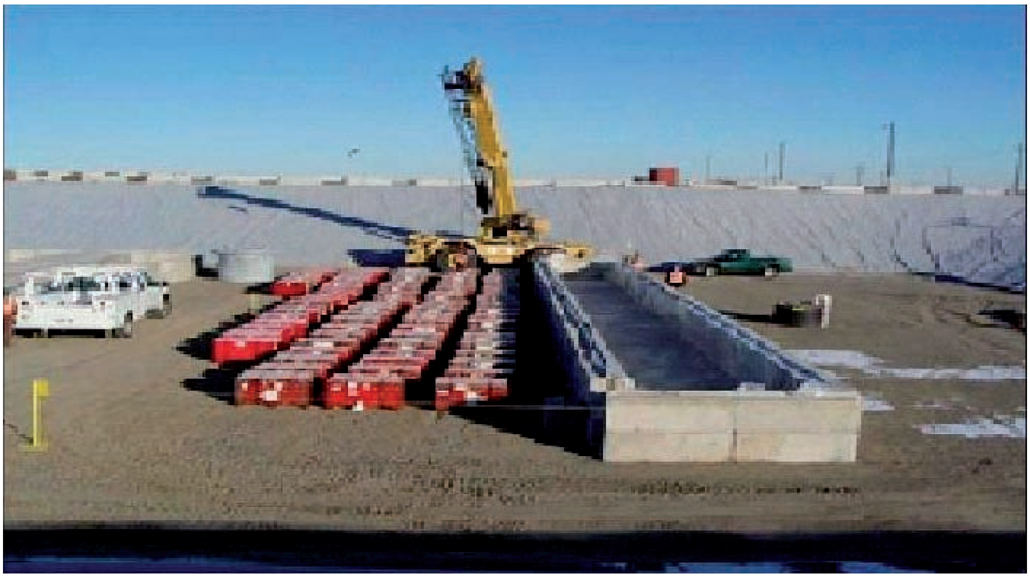

FIG. 11. The shallow land burial facility for LLW at the 200 West Area at the Hanford site.

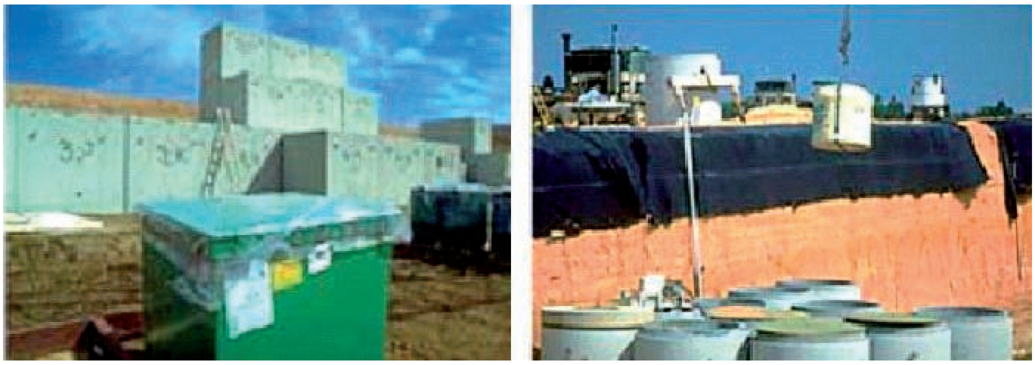

FIG. 12. View of the two types of modular concrete canister facilities for LLW disposal at the Barnwell site, South Carolina.

FIG. 13. The above ground berm for disposal of low activity (class A) LLW at the Clive site.

4.6. EXAMPLES OF PLANNED DISPOSAL FACILITIES

4.6.1. Near surface disposal

In France, future plans include subsurface disposal for LLW-LL, specifically radium bearing and graphite waste [39, 40]. In the case of radium, radon emissions in the closed near surface facility Centre de la Manche have led to more stringent WAC for radium-226 at the currently operating facility at Centre de l'Aube. Consequently, radium-containing waste from chemical and metallurgical industries and from rehabilitation of old sites is no longer acceptable for surface disposal. Graphite waste arises from the former gas-graphite reactor (GGR) system, in which graphite was used as a reactor moderator. These reactors were used from the beginning of the 1960s to the end of the 1980s, and some are currently undergoing decommissioning. The radioactive content consists mainly of short lived radionuclides (cobalt-60 and tritium) but there are also some long lived radionuclides (carbon-14 and chlorine-36).

The French Nuclear Safety Authority has approved the general design of the subsurface disposal facility but, to date, only for radium bearing waste. The Agence nationale pour la gestion des déchets radioactifs (ANDRA) is developing a trench design at a depth of approximately 15 m in a low-permeability clay or marl formation. At the end of the operational period, a cover made up of reworked clay would be installed to restore the initial topographic level. After resaturation, the cover will sufficiently contain the radon emitted by this waste. Moreover, the low mobility of radium and its progeny in clay will limit their migration. Although the problems raised by the two waste categories are basically different, a search for a suitable site for joint disposal of radium bearing and graphite waste has been launched and is being conducted in parallel with design studies. Preliminary safety assessments showed that for the disposal of graphite, the impact of chlorine-36 is sensitive to the thickness and permeability of the underlying formation. The long term impact of the disposal facility is directly proportional to the amount of chlorine-36, which makes it essential to determine the inventory as precisely as possible. In June 2008, ANDRA was officially requested by the French Ministry of Ecology, Energy, Sustainable Development and Regional Development to launch the campaign for identifying suitable sites for the implementation of a disposal facility for long lived low-level waste.

In Olen, Belgium, surface disposal is also the envisaged long term management option for waste with very low radium specific activity levels (with a mean estimated value just below 10 Bq/g). The expected volumes are relatively large (~100 000 m^3) [41].

4.6.2. Repositories at intermediate depth

Japan Nuclear Fuel Limited (JNFL) is planning subsurface disposal for operational and decommissioning waste in a rock formation at a depth between 50 and 100 m at Rokkasho Mura. A test cavern for confirmation of stability and three measurement tunnels for investigating the excavation disturbed zone have been constructed, and various measurements are ongoing [7].

Three facilities of this general type already exist, albeit for LILW-SL, in Finland and Sweden; these are the repositories at Forsmark in Sweden and at Loviisa and Olkiluoto in Finland.

4.6.3. Deep geological disposal

The UK Government has adopted deep geological disposal as the way forward. This concept aims at offering a coherent option for the very long term management of the UK's ILW and certain LLW while leaving open decisions on final closure of such an underground facility to future generations [42, 43]. A range of options are being considered at this stage. The concept described below is considered for a strong host rock. It envisages:

- —Emplacement in vaults excavated deep underground within a suitable geological environment (geological isolation);
- —A period of monitoring during which the wastes would be straightforwardly retrievable;
- —Backfilling the wastes at a time determined by future generations (using a specially formulated cement-based vault backfill to give chemical conditioning);
- —Sealing of the repository (geological containment).

To provide adequate containment of the wastes, the concept employs physical, chemical and geological barriers. The chemical barrier and in part the physical barrier are achieved through the extensive use of cement. This imposes high pH conditions throughout the wastes, which improves the near-field retention of many important radionuclides, leading to chemical containment. The geological barriers derive from the natural geological and hydrogeological setting, while the physical and chemical barriers consist of the waste package and the surrounding vault backfill material.

If a future generation were to take a decision to dispose of the waste in situ, it would then be necessary to ‘backfill’ (i.e. to completely surround) the waste packages with a specially formulated cement-based material, the Nirex Reference Vault Backfill (NRVB, or cementitious backfill here). This material would stabilize the waste stacks within the vaults and, most importantly, would chemically condition any inflowing groundwater to high pH.

Within the repository, gas can be produced by anaerobic corrosion of metals and microbial degradation of organic materials. The porous structure of the NRVB makes it gas permeable, thereby avoiding over-pressurization.

In Belgium, the reference solution for LILW-LL is deep disposal. The research carried out will determine whether disposal in the clay layers (such as the Boom clay in the north-east of the country) can guarantee the protection of people and the environment in the long term. The facility would consist of a network of underground galleries lined with concrete, together with access drifts and shafts. Drums of conditioned waste would be enclosed in groups in a big concrete container backfilled with cement mortar to fill the spaces between the drums.

4.6.4. The borehole disposal concept for disused sealed radioactive sources

For countries with no access to existing or planned disposal facilities for radioactive wastes, the only options for managing disused sealed radioactive sources (DSRS) is to store them indefinitely or to find an alternative method of disposal, if they cannot be returned to the original supplier. Although gathering and conditioning DSRS is a key step in sound management and increased safety and security, indefinite storage is not a sustainable solution. This problem was raised by the IAEA African Regional Cooperative Agreement for Research, Development and Training Related to Nuclear Science and Technology (AFRA) Member States during the mid-1990s, and in response, the IAEA funded the development of a fully engineered system for the borehole disposal of disused sealed sources (BOSS), as part of an IAEA AFRA regional project.

In principle, the BOSS disposal concept involves the sealing of DSRS in a stainless steel capsule, which is then sealed in a disposal container, also made from stainless steel (Fig. 14), and emplaced in a borehole with a diameter of 260 mm at depths ranging from 30 to 100 m below surface (Fig. 15). Several disposal containers are disposed of in the same borehole, spaced 1 m apart, using cement backfill. A casing is used to facilitate the disposal operation, after which the portion above the disposal zone is removed.

The BOSS system was developed using a reference source inventory, compiled from AFRA Member State inventories, and has been proven to be a safe, economic, practical and permanent means of disposing of DSRS. It is likely to be applicable to a wide range of sources and of hydrogeological and climatic environments. It should consequently be considered a viable waste management option for present-day management of these sources.

An international peer review of the BOSS system conducted in April 2005 [44] recommended further development of the concept to also allow for the disposal of high activity sealed sources and neutron sources, which pose particular handling and shielding problems during conditioning and disposal operations. The first implementation step was inititiated in Ghana in 2008.

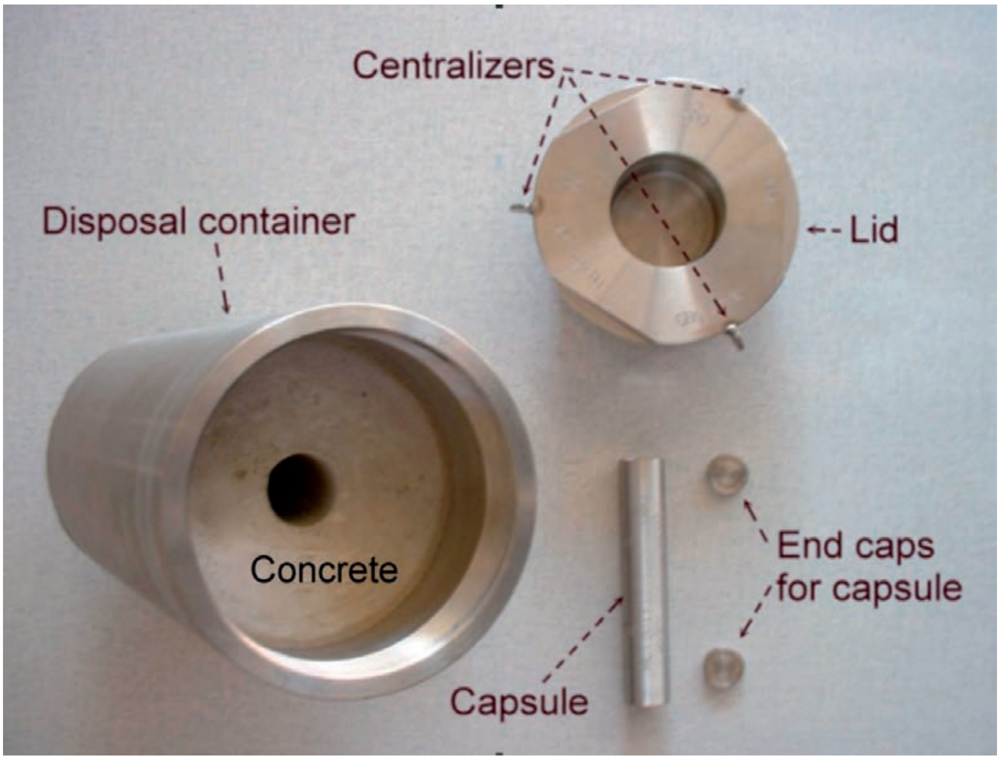

FIG. 14. Disposal container and lid showing concrete insert into which a sealed capsule is placed. Each capsule is fully welded and can hold several disused sealed radioactive sources.

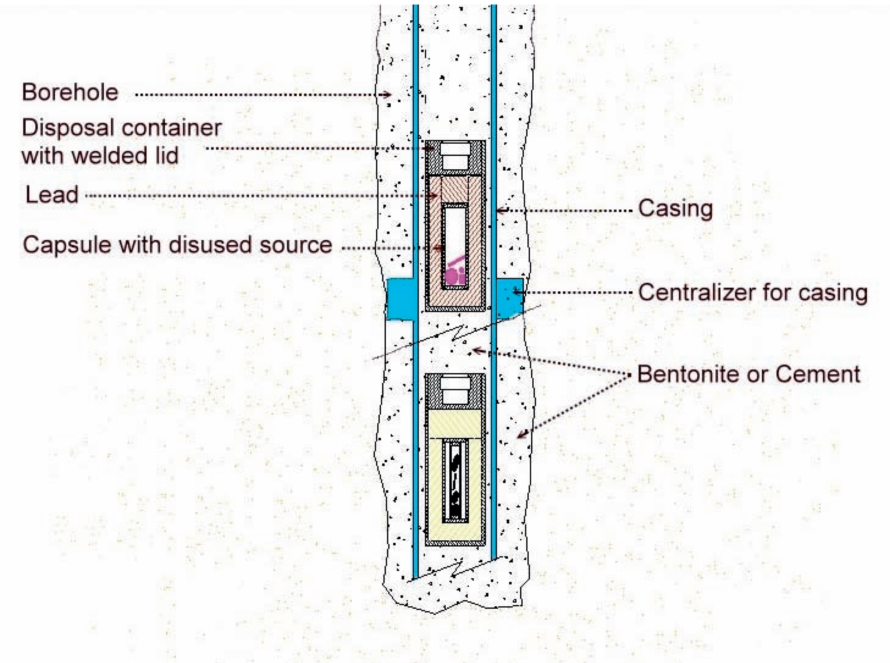

FIG. 15. Borehole disposal concept (BOSS).

5. KEY FACTORS TO BE CONSIDERED IN THE SELECTION OF A DISPOSAL CONCEPT

5.1. INTRODUCTION

In radioactive waste disposal, adherence to the Principles of Radioactive Waste Management [45] is achieved by complying with the relevant safety requirements for near surface disposal [18] and deep geological disposal [8]. These place various obligations on the government, the regulatory body, the disposal facility developer or operator and the waste generator. These obligations include:

— An appropriate legal, regulatory, financial and decision-making framework;
— An approach to safety that stresses the importance of passive safety, optimization of radiological protection, containment, isolation, diverse safety functions and the need for an underlying understanding of the features, events and processes that contribute to safety;
— An incremental and iterative approach to the design, site selection, site characterization, construction, operation and closure of a disposal facility that allows safety to be continually assessed, re-assessed and updated in the light of new technology and knowledge.

All of these principles, and the relevant safety requirements that follow from them, will have an influence on the choice of option and on the resulting conceptual model. Other aspects such as the waste inventory, national radioactive waste management policies and the nature of the available geologies will also be important. This section therefore aims to describe the principles, safety requirements and other aspects (all called ‘key factors’ in this report) that, in practical terms, are likely to have the greatest impact on the choice of an option. First among these key factors is the nature of the waste itself — the waste characteristics. This has already been discussed at length in Section 2; the other main factors follow.

5.2. PROTECTION OF HUMAN HEALTH

In considering the protection of human health, it is helpful to distinguish between two periods of time:

— The operational period of a repository — the period during which the repository, after construction, is operated and finally closed — when repository operation could result in radiation exposures to workers and to the general public;
— The post-closure period, which follows immediately after repository operation and sealing. Since there are no workers in this period, any radiation exposures that might occur will be to the general public.

In the context of radioactive waste disposal, protection and safety must be optimized so that the magnitude of individual doses, the number of people exposed and the likelihood of incurring exposures are kept as low as reasonably achievable economic and social factors being taken into account [46]. For the post-closure phase, where any radiological impact of the repository will only materialize far into the future, the kind of optimization used for operational safety is not feasible. Instead, constrained optimization is appropriate where the design is considered [47] to have been optimized if:

— Due attention has been paid to the post-closure safety implications of the various options during the development process;
— The assessed doses and risks for the design evolution of the system fall below the relevant constraints;
— The probability of events that might give rise to doses above the constraint has been reasonably reduced by siting or design;
— The design, construction, operation and closure programmes have been subjected to a quality management system.

The consequence of this approach is that, if these conditions are met, it is not necessary to seek further improvements in post-closure safety (i.e. lower calculated doses) by, say, searching for a ‘better’ site or additional engineering measures.

For both periods, it is necessary to evaluate safety (i.e. radiation exposures and non-radiological hazards) under both planned and unplanned conditions. In the operational period, planned conditions equate to normal operating conditions, whereas unplanned conditions primarily occur from accidents and emergencies. In the post-closure period, planned conditions are more usually described as the normal (or design) evolution of the repository, which should encompass all the expected changes in the engineered barriers and the natural system (including climate) over the period of interest. Where a number of evolutions are reasonably possible, there may be more than one normal evolution scenario adopted. For the post-closure period, unplanned conditions equate to less likely scenarios that will include, for instance, natural disruptive events, alternative climate sequences and human intrusion.

5.2.1. Operational phase

The safety case for the operational period should describe the means for controlling possible releases of radioactivity both in normal operation and during unexpected conditions, which will include, for instance, internal hazards such as fire, and external hazards, such as seismic events, flooding and aircraft crash. It is normal to have a requirement for non-radiological risks to be reduced to the same level as radiological risks.

The disposal option selected must comply with the fundamental safety principles, ensure that doses do not exceed regulatory dose limits, meet dose/risk targets for accident conditions and adhere to the requirements that human exposure be reduced in accordance with the as low as reasonably achievable (ALARA) principle. Where the exposure is highly hypothetical, it is important to consider a measure of risk that refers to radiation dose and to the likelihood of the event which gives rise to it. To satisfy the ALARA principle, measures necessary to reduce risk must be taken until or unless the cost of those measures, whether in money, time or resources, is disproportionate to the reduction in risk.

In general, operational safety in relation to the general public is unlikely to be a major factor in deciding which repository option should be selected. This is mainly because it is usually possible to introduce additional engineering measures to reduce risks to the public to an acceptable level. The situation with respect to worker risks is similar except that mining is a relatively high risk occupation. In addition to cost, this may be an argument for not constructing or using a geological facility if a surface facility was likely to be capable of meeting regulatory requirements.

5.2.2. Post-closure phase

National safety regulations for a repository should reflect the basic principles and safety requirements issued by the IAEA [8, 18, 45]. These regulations should describe the required level of safety for a facility. This will usually be expressed as a probabilistic risk of death or, in the case of exposure to radiation, it may be expressed in terms of dose. The regulators in many countries either specify a radiological risk of death of less than 10^{-6} per year, or an individual dose of less than 0.1–0.3 mSv/a to an individual from the most exposed group. However, because predictions of either risk or dose in the long term have considerable uncertainties, these predictions should be supported by ‘multiple lines of argument’, which demonstrate the robustness of the disposal approach with respect to safety.

Another important factor is the length of time over which safety must be demonstrated. Again, this varies from country to country. In some countries, it is required that the time at which the risk or dose is a maximum be determined and that the risk or dose at this time is demonstrated to be less than the regulatory requirement. Others argue that predicting detriments over time periods in excess of 10 000 years is so uncertain that it is not a useful basis for regulation and a cut-off at time periods of this order is specified.

Post-closure safety is usually a major factor in deciding on the repository option that should be selected, and a frequently used approach is to develop a normal scenario that describes the way the repository is expected to evolve over time. This might include, for instance, gradual degradation of the engineered barriers and changes in climate. Complementing this is a series of non-normal or less-likely scenarios that include events or processes that have a lower probability of occurring.

Normal evolution

Compliance with the national requirement must be demonstrated by a long term performance assessment for the repository and the waste inventory for which a licence is being sought. In normal circumstances, the most likely pathway for the radioactivity in the repository to reach humans in the long term is through the groundwater. Thus, the hydrogeology of the selected site is likely to be crucial to post-closure safety. For small amounts of long lived waste, adequate safety may be achieved by a surface or near surface facility but, where larger amounts of long lived elements are involved, deeper repositories may be required in order to find host rocks with a suitable hydrogeological setting and properties. Of course, hydrogeology is not the only determinant factor; other potentially important factors include rock competence, erosion, uplift and proximity to natural resources.

The normal scenario should include consideration of all features, events and processes (FEPs) that are likely to occur over the timescale of interest. These include extreme meteorological events and expected climate states such as might be expected to result from anthropogenic warming and future glaciations.

Less likely scenarios

Post-closure safety assessments must also be used to assess less likely scenarios that assess the possibility that the repository evolution may not follow the normal scenario. If the safety requirement is expressed in terms of risk, the total risk, including any possible combinations of FEPs, must be shown to be less than the regulatory constraint. Some of the potential events that should be considered are discussed below, inadvertent human intrusion being usually the most important of these:

— Inadvertent human intrusion;
— Aircraft crash;
— Seismic event;
— Tsunami;
— Extreme climatic conditions;
— Other natural effects.

Inadvertent human intrusion

It is necessary to consider the consequences of disturbance of the waste by human activities (human intrusion) at the end of the institutional control period. The likelihood of such an intrusion should be reduced by choosing a site with low resource potential. Should such an intrusion occur, a few individuals who take part in activities such as drilling or excavating into the facility could receive high doses. Still more important is the possibility that the intrusion could permanently disrupt the engineered barriers. The International Commission on Radiological Protection (ICRP) suggests [47] that, to assess the consequences of human intrusion, one or two stylized human intrusion scenarios should be evaluated. If the indicative annual doses from such scenarios are above 100 mSv, then, according to the ICRP, reasonable efforts should be made to reduce the probability of human intrusion or to limit its consequences. Where the calculated annual doses for stylized intrusion scenarios are below 10 mSv, these additional efforts are less likely to be required. The risk of human intrusion is normally expected to decrease as the depth of the repository is increased from the order of 30 m, where it may be affected by future construction activities on the surface, to greater depths, where intrusion would be limited to activities such as drilling or mining. On the basis of the approach adopted by the ICRP above, it is not possible to take numerical credit for the reduced risk obtained by locating the waste at a depth of 30 m or more, but achieving this depth may be considered to reduce the dose ALARA unless it results in a disproportionate detriment in terms of cost or another factor.

Aircraft crash

One of the hazards that could affect a surface repository is the crashing of an aircraft either accidentally or as a result of an act of deliberate sabotage. The considerations of this hazard are similar to those of human intrusion and, similarly, the risk is reduced if the repository is below the surface or if a protective barrier diminishing the consequences of the crash is installed.

Seismic events

The potential hazard due to seismic events should be reduced to acceptable levels by choosing a site where the probability of disruption from a significant seismic event is suitably low. Assessing the impact of such an event on post-closure safety will allow the overall risk to be determined and compared with the regulatory constraint.

Tsunamis

Coastal facilities may be affected by tsunamis. Such an occurrence is only likely to have a significant effect on a deep repository during the operational period — an obvious possibility is that the underground workings could be flooded. For a surface repository, a tsunami could again affect operational safety, but could also impact on post-closure safety by damaging the protective cap. In all these cases (operational and post-closure), safety assessment would assess both the probability of such an event and its likely consequence (in terms of calculated dose) so that, as before, the risk may be compared with the regulatory constraint.

Extreme climatic conditions

Where it is expected that extreme climatic conditions (e.g. glaciation) will affect a site, they should be assessed as part of the normal scenario. There may, however, be some unlikely sequences or more extreme climatic states that, because of their potential impact on post-closure safety, will need to be examined as part of a variant scenario.

Other natural effects

Other natural effects that might be considered to lie outside the normal scenario include higher rates of erosion and uplift, more rapid deterioration of the engineered barriers, significant changes to hydrogeology as a consequence of climate change, etc.

5.3. ENVIRONMENTAL PROTECTION

The environmental impact of a facility is most usually assessed in terms of:

- Its effect upon flora and fauna;
- Its effect upon human society;
- Whether the development represents an appropriate use of resources.

It is not self-evident that measures providing an adequate protection of human beings will also provide for adequate protection of flora and fauna, and several research programmes are currently in progress to assist the development of a system of radiological protection to protect flora and fauna. However, in the context of selecting a type of repository (as opposed to a site), there are currently no additional constraints associated with protecting flora and fauna that are more restrictive than those that are required to protect human beings. Thus, the protection of flora and fauna is unlikely to be a major factor in selecting a type of repository.

The creation of a repository, whether in the near surface or deep, could produce significant societal disruption in terms of site investigation and construction activities, visual amenity and possibly long term restrictions on land use. While such issues are important for site selection, they are much less likely to be crucial in terms of the choice of facility.

The greater the depth of a repository, the larger the amount of energy and resources consumed during its construction. This environmental impact will be reflected in the overall cost. An over-engineered solution — making a repository deeper than it needs to be, for instance — will unnecessarily deplete a country's resources and divert them from more deserving or justifiable ends.

5.4. AVAILABILITY OF GEOLOGICAL ENVIRONMENTS

'Geological environment' is here defined to include the geology, hydrogeology and geochemistry of a given location. Aspects that could have an effect on radioactive waste disposal in terms of geological environment are [48, 49]:

- Geological stability;
- Rock competence;
- Groundwater flow regimes;
- Geochemical environment;
- The availability of nearby natural resources.

The need for geological stability applies to all types of disposal facility. It can be a limiting factor in site selection in regions where there is significant seismicity, tectonism or uplift. It is conceivable that it could affect the choice of facility, but this is not very likely.

Rock competence is most important where facilities are to be created at depth, because low rock competence would increase the need for rock support and, consequently, the cost. Rock competence will also influence the optimum size of underground openings, which will impact on the size of waste package that can be disposed of. In some countries, hard crystalline bedrock may be the only available geology. Certainly, homogeneity of the formation also facilitates understanding what can make safety demonstration easier.

Groundwater flow is important because groundwater can act as a medium for the migration of radionuclides. The range of hydrological environments and the depth of the unsaturated zone will primarily depend on geology, topography and climate.

Geochemical environments are important for all types of facility because, for example, solutes in groundwater (e.g. chloride and sulphate) can react with the engineered barriers to degrade the repository performance.

5.5. AVAILABILITY OF FACILITIES AND TECHNOLOGIES

It is a widely accepted principle that the disposal of radioactive waste should be based on technologies that are currently proven and that the "waste management strategy should not be based on a presumption of … technological advance" [50]. In some countries, the use of proven technology in radioactive waste management is already a regulatory requirement. Repositories should only be licensed if they are in accordance with currently available technologies and do not rely on yet unproven ones.

The construction of a deep repository requires reasonable access to enable construction machinery, equipment, plant, construction materials and the waste to reach the site. Furthermore, excavation and operation will require utilities such as power and water. Near surface facilities are less demanding in this respect — there are many near surface facilities located in remote desert regions, for instance — but reasonable access is still a necessity.

5.6. ECONOMIC AND TECHNICAL RESOURCES

Cost is a factor in strategy selection, which influences decisions on the type of technology, packaging and number of facilities required. Any chosen waste management strategy must be economically viable; achieving a cost-effective solution is an important aspect in managing national liabilities and resources, but must not preclude achieving an acceptable level of safety.

Because skilled personnel are needed to design, construct, operate and close a disposal facility, their availability could, in principle, influence the choice of an option. In practice, however, this rarely figures as an important issue because of the high mobility of staff and easy access to the relevant technology. More often, this factor has been used as an argument for the implementing waste disposal by the current generation, as opposed to leaving it to future generations who may not have the technical resources, the skills, or the finances to do it.

5.7. SOCIOPOLITICAL AND ETHICAL FACTORS

Technical, environmental and financial factors will not be the only determinants of the choice of disposal option. Issues such as public acceptability and equity (fairness) may also have an influence. Such issues will often influence site selection and, by doing so, may severely limit the available geological environments. These factors may also affect the repository design by requiring, for instance, measures to improve the monitoring aspects and the retrievability of the waste. National policy may preclude surface disposal or dictate that all radioactive waste be placed in long term storage. Sociopolitical and ethical factors can, therefore, place strong constraints on the available options.

5.8. INTEGRATING THE KEY FACTORS TO DEVELOP A REPOSITORY CONCEPT AND DESIGN

The national radioactive waste management policy of a Member State may prescribe or proscribe some radioactive waste disposal options. In general, this will usually simplify the decision making process (Fig. 16). National policy may also prescribe the disposal site. When this is the case, the process of developing the repository concept may be simpler than would be the case if, for example, the concept had to be capable of being implemented at a range of sites. Legislative aspects may also constrain the siting procedure and programme development.

Stakeholder involvement will occur at some point, early or late in the decision making process, as suggested by its inclusion as an extended vertical box in the flow diagram shown in Fig. 16. The nature and extent of stakeholder involvement will also vary from one case to another.

Therefore, within the national policy framework and acknowledging the importance of stakeholder involvement, the principal starting point in the development of a disposal concept is the inventory of long lived waste and, specifically:

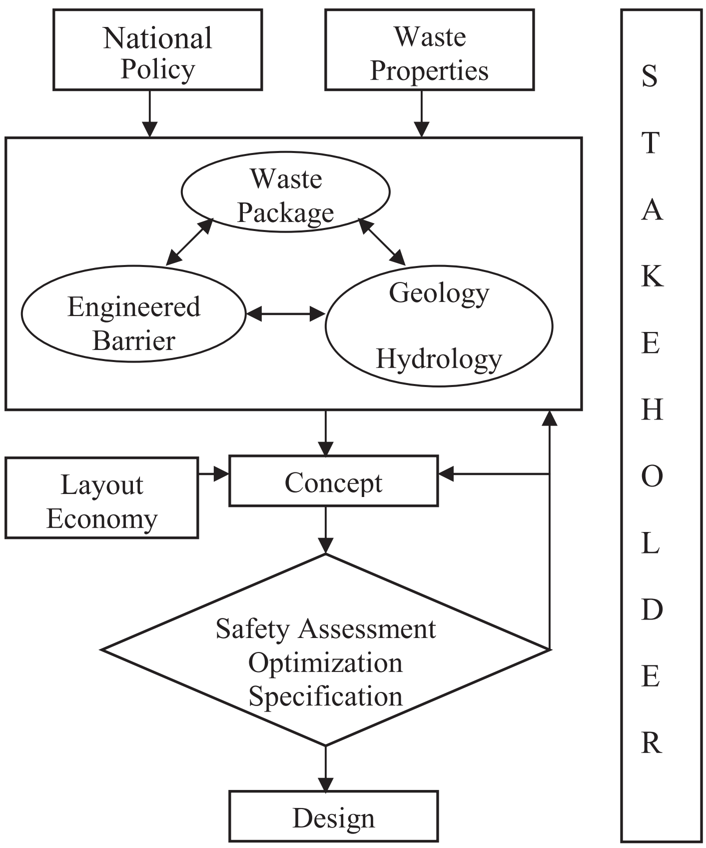

FIG. 16. Decision making process for the development of a repository concept and design for LILW-LL.

— The total activity (Bq) and the activity of long lived radionuclides;
— The waste volume;
— The condition of the waste (properties, conditioning);
— The current location of the waste.

5.8.1. Developing the concept

Three barriers will contribute to achieving the required degree of safety:

— The geological environment of the chosen or potential site(s) and, to some extent, the depth of disposal;
— The waste package, i.e. the chosen waste form, and waste container;
— The creation of other engineered barriers, such as the emplacement of a waste package buffer (cement, bentonite, magnesium oxide, etc.), the construction of a hydraulic cage, and backfilling and seals. In general, backfilling and sealing should aim to achieve an average permeability equivalent to that of the adjacent rock.

If one barrier provides a very high level of containment, less reliance may be placed on the others. How this is done is best described by example. In the cases of WIPP and Konrad, for instance, the geological environments allow the post-closure safety requirements to be achieved without relying on the integrity of the waste packages. In these cases, the prime function of the containers is to provide operational and transport safety. In the case of the Richard repository, the provision of a hydraulic cage allows the required level of post-closure safety to be achieved without having to relocate the waste to a new facility, i.e. without having to find another geological setting. Finally, the use of a specially formulated cement buffer (the Nirex Reference Vault Backfill) in the UK's geological disposal concept is intended to make it possible to dispose of the UK's intermediate level wastes while using ILW containers that are often vented (to allow release of hydrogen gas produced during waste encapsulation) and geological environments that may be commonly encountered in the UK.

5.8.2. Optimization and the role of safety assessment

Safety assessment is the basic tool used in the development of a safe repository concept and design. Important inputs/outputs from safety assessment include detailed knowledge of the design/site features and processes that provide the required level of safety (iterative process). These features and processes are likely to include:

— Factors contributing to radionuclide containment such as waste package integrity, solubility limitation, sorption, geochemistry and hydrogeology;
— Waste acceptance criteria, deriving activity limits for long lived radionuclides in disposal facilities.

Safety assessment is the most important tool in the process known as the 'optimization of radiological protection' — refining the concept and design to make the radiological impact "as low as reasonably achievable, social and economic factors being taken into consideration". But it is not the only tool, because repository designs should also be cost effective and easy to implement using proven technology, and safety assessment alone cannot address all these issues. When used to develop a repository concept and design, therefore, safety assessment must be used in conjunction with cost–benefit estimation, environmental imperatives and precedent practice.

What is acceptable in terms of cost and social impact will vary from one country and context to another. To this extent, techno–economic optimization is a judgmental process that will depend on the values of those who do the judging, i.e. it may be said to be value driven. It will therefore be important for a prospective implementer to determine, so far as possible, how optimization is to be interpreted by stakeholders and, especially, the regulatory body so that the required balance can be achieved.

6. CONCLUDING REMARKS

Depending on a wide range of factors, the disposal of LILW-LL may be implemented via several disposal approaches. The decision-making process begins with consideration of the national radioactive waste management policy and the characteristics of the waste itself. There is a general presumption that LLW should be disposed of at depth.

Beyond this, the geological environment, the waste package and other engineered barriers will largely define the concept by contributing to the achievement of the required degree of safety.

If one of these components provides a very high level of containment, less reliance may be placed on the others. Such considerations lead to a simple methodology that allows disposal concepts to be tested, refined (i.e. optimized) and detailed through the iterative use of safety assessment and consideration of how the concept and, ultimately, the design might be realized in practice.

REFERENCES

[1] Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, INFCIRC/546, IAEA, Vienna (1997).

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, Extent of Environmental Contamination by Naturally Occurring Radioactive Material (NORM) and Technological Options for Migration, Technical Reports Series No. 419, IAEA, Vienna (2003).

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, Protection of the Public against Exposure to Natural Sources of Radiation including NORM , IAEA Safety Standards Series IAEA, Vienna (in preparation).

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, Current Practices for the Management and Confinement of Uranium Mill Tailings, Technical Reports Series No. 335, IAEA, Vienna (1992).

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of the Radioactive Waste from the Mining and Milling of Ores, IAEA Safety Standards Series No. WS-G-1.2, IAEA, Vienna (2002).

[6] OECD NUCLEAR ENERGY AGENCY, Shallow Land Disposal of Radioactive Waste: Reference Levels for the Acceptance of Long lived Radionuclides. A Report by an NEA Expert Group, OECD, Paris (1987).

[7] YAMATO, A., “The current status of JNFL sub-surface disposal plan for relatively higher LLW”, Safety of Radioactive Waste Disposal (Proc. Int. Conf. Tokyo, 2005), IAEA, Vienna (2007).

[8] INTERNATIONAL ATOMIC ENERGY AGENCY, Geological Disposal of Radioactive Waste, IAEA Safety Standards Series No.WS-R-4, IAEA, Vienna (2006).

[9] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, Safety Series No. 111-G-1.1, IAEA, Vienna (1994).

[10] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Radioactive Waste from the Use of Radioactive Material in Medicine, Industry, Agriculture, Research and Education, IAEA Safety Standards Series No.WS-G-2.7, IAEA,Vienna (2005).

[11] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Radioactive Waste from the Use of Radionuclides in Medicine, IAEA-TECDOC-1183, IAEA, Vienna (2000).

[12] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Disused Long Lived Sealed Radioactive Sources, IAEA-TECDOC-1357, IAEA, Vienna (2003).

[13] INTERNATIONAL COMMISSION FOR RADIOLOGICAL PROTECTION, Dose Coefficients for Intake of Radionuclides by Workers, Annals of the ICRP, Publication 68, Pergamon Press, Oxford and New York (1994).

[14] INTERNATIONAL COMMISSION FOR RADIOLOGICAL PROTECTION, Age-dependent Dose Coefficients to Members of the Public from Intake of Radionuclides: Parts 1–3 Ingestion Dose Coefficients, Annals of the ICRP Publications 56, 67, 69, Pergamon Press, Oxford and New York (1989, 1993, 1995).

[15] INTERNATIONAL ATOMIC ENERGY AGENCY, Classification of Radioactive Waste, IAEA Safety Standards Series No. GSG-1, IAEA, Vienna (to be published).

[16] U.S. PUBLIC LAW 83–703, 1954. The Atomic Energy Act of 1954.

[17] INTERNATIONAL ATOMIC ENERGY AGENCY, Management of Low and Intermediate Level Radioactive Wastes with Regard to their Chemical Toxicity, IAEA-TECDOC-1325, IAEA, Vienna (2002).

[18] INTERNATIONAL ATOMIC ENERGY AGENCY, Near Surface Disposal of Radioactive Waste, IAEA Safety Standards Series No. WS-R-1, IAEA, Vienna (2005).

[19] INTERNATIONAL ATOMIC ENERGY AGENCY, Derivation of Activity Limits for the Disposal of Radioactive Waste in Near Surface Disposal Facilities, IAEA-TECDOC-1380, IAEA, Vienna (2003).

[20] INTERNATIONAL ATOMIC ENERGY AGENCY, Safety Considerations in the Disposal of Disused Sealed Radioactive Sources in Borehole Facilities, IAEA-TECDOC-1368, IAEA, Vienna (2003).

[21] INTERNATIONAL ATOMIC ENERGY AGENCY, Developing Multinational Radioactive Waste Repositories: Infrastructural Framework and Scenarios of Cooperation, IAEA-TECDOC-1413, IAEA, Vienna (2004).

[22] INTERNATIONAL ATOMIC ENERGY AGENCY, The Long Term Storage of Radioactive Waste: Safety and Sustainability, A Paper by International Experts, IAEA,Vienna (2003).

[23] GERMAN COMPANY FOR THE CONSTRUCTION AND OPERATION OF WASTE REPOSITORIES, http://www.dbe.de

[24] BIURRUN, E., HAVERKAMP, B., KUČERKA, M., “Closure of a Chamber in the Richard Underground Repository”, Waste Management ’05 , Tucson, AZ, 2005.

[25] HARTLEY, B.M., et al., “The establishment of a radioactive waste disposal facility in Western Australia for low level waste”, Nuclear Energy, Science and Technology Pacific Partnership (Proc. 9th Pacific Basin Nuclear Conf. Sydney, 1994).

[26] HUTCHINSON, D.E., TOUSSAINT, L.F., Near Surface Disposal of Concentrated NORM Wastes, Appl. Radiat. Isot. 49 3 (1998) 265–271.

[27] CROSSLAND, I.G., “Disposal options for disused sealed radioactive sources”, Safety and Security of Radioactive Sources: Towards a Global System for the Continuous Control of Sources throughout their Life Cycle (Proc. Int. Conf. Bordeaux, 2005), IAEA, Vienna (2005).

[28] AUSTRALIAN NATIONAL REPORT, Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management, 2003 (http://www.arpansa.gov.au/pubs/reports/jc040803.pdf).

[29] ENVIRONMENTAL PROTECTION AGENCY, Criteria for Certification and Recertification of the Waste Isolation Pilot Plant's Compliance with the Disposal Regulations: Certification Decision; Final Rule, Federal Register, **63** EPA, Washington, DC (1998) 27354–27406.

[30] DEPARTMENT OF ENERGY, Carlsbad Area Office, The Waste Isolation Pilot Plant — Pioneering Nuclear Waste Disposal, Rep. DOE/CAO-00-3 124 (2000).

[31] U.S. PUBLIC LAW 102-579, The Waste Isolation Pilot Plant Land Withdrawal Act of 1992 (1993).

[32] U.S. PUBLIC LAW 104-201, The Waste Isolation Pilot Plant Land Withdrawal Amendments Act of 1996 (1996).

[33] ENVIRONMENTAL PROTECTION AGENCY, Environmental Radiation Protection Standards for Management and Disposal of Spent Nuclear Fuel, High level and Transuranic Radioactive Wastes; Final Rule, Code of Federal Regulations, 40 CFR 191, EPA Washington, DC (1993).

[34] ENVIRONMENTAL PROTECTION AGENCY, Criteria for Certification of the Waste Isolation Pilot Plant's Compliance with the 40CFR191 Disposal Regulations: Final Rule, Code of Federal Regulations, 40CFR194, EPA, Washington, DC (1996).

[35] NATIONAL ACADEMY OF SCIENCES, National Research Council, Committee on the Waste Disposal of the Earth Sciences, The Disposal of Radioactive Waste on Land, Publication 519 (1957).

[36] NUCLEAR REGULATORY COMMISSION, Licensing Requirements for Land Disposal of Radioactive Waste, Code of Federal Regulations, 10CFR Part 61, NRC Washington, DC.

[37] DEPARTMENT OF ENERGY,Advance Notice of Intent to Prepare an Environmental Impact Statement for the Disposal of Greater Than Class C Low Level Radioactive Waste, Federal Register, **70** 90, USDOE, Washington, DC (2005).

[38] NUCLEAR REGULATORY COMMISSION. Disposal of High level Radioactive Waste in Geologic Repositories, Code of Federal Regulations, 10 CFR 60.

[39] GREVOZ, A., "Disposal options for low-level long lived waste in France", Disposal of Low Activity Radioactive Waste (Proc. Int. Symp. Cordoba, Spain, 2004), IAEA, Vienna (2005).

[40] GREVOZ, A., "The disposal of irradiated graphite in France", ibid.

[41] MINON, J.P., DIERCKX, A., DE PRETER, P., "Issues for the disposition of long lived low activity waste", ibid.

[42] NIREX, The Proposed Nirex Forward Programme, Nirex Report N/015, (2001).

[43] NIREX, Why a Cementitious Repository? Nirex Report N/034 (2001).

[44] WATRP REVIEW REPORT on the Borehole Concept for the Disposal of Disused Sealed Sources developed by the Nuclear Energy Corporation of South Africa (NECSA) in the framework of the IAEA TC Project RAF/4/015, 11–15 April 2005, NECSA, Pelindaba, South Africa (2005).

[45] INTERNATIONAL ATOMIC ENERGY AGENCY, Principles of Radioactive Waste Management, Safety Series No. 111-F, IAEA, Vienna (1995).

[46] FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS, INTERNATIONAL ATOMIC ENERGY AGENCY, INTERNATIONAL LABOUR ORGANIZATION, OECD NUCLEAR ENERGY AGENCY, PAN AMERICAN HEALTH ORGANIZATION, WORLD HEALTH ORGANIZATION, International Basic Safety Standards for Protection against Ionizing Radiation and for the Safety of Radiation Sources, Safety Series No. 115, IAEA, Vienna (1996).

[47] INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION, Recommendations of the International Commission on Radiological Protection, Publication 81, Annals of the ICRP, Pergamon Press, Oxford and New York (2001).

[48] INTERNATIONAL ATOMIC ENERGY AGENCY, Siting of Geological Disposal Facilities, Safety Series No. 111-G-4.1, IAEA, Vienna (1994).

[49] INTERNATIONAL ATOMIC ENERGY AGENCY, Siting of Near Surface Disposal Facilities, Safety Series No. 111-G-3.1, IAEA, Vienna (1994).

[50] OECD NUCLEAR ENERGY AGENCY, The Environmental and Ethical Basis of Geological Disposal of Radioactive Wastes, OECD, Paris (1999).

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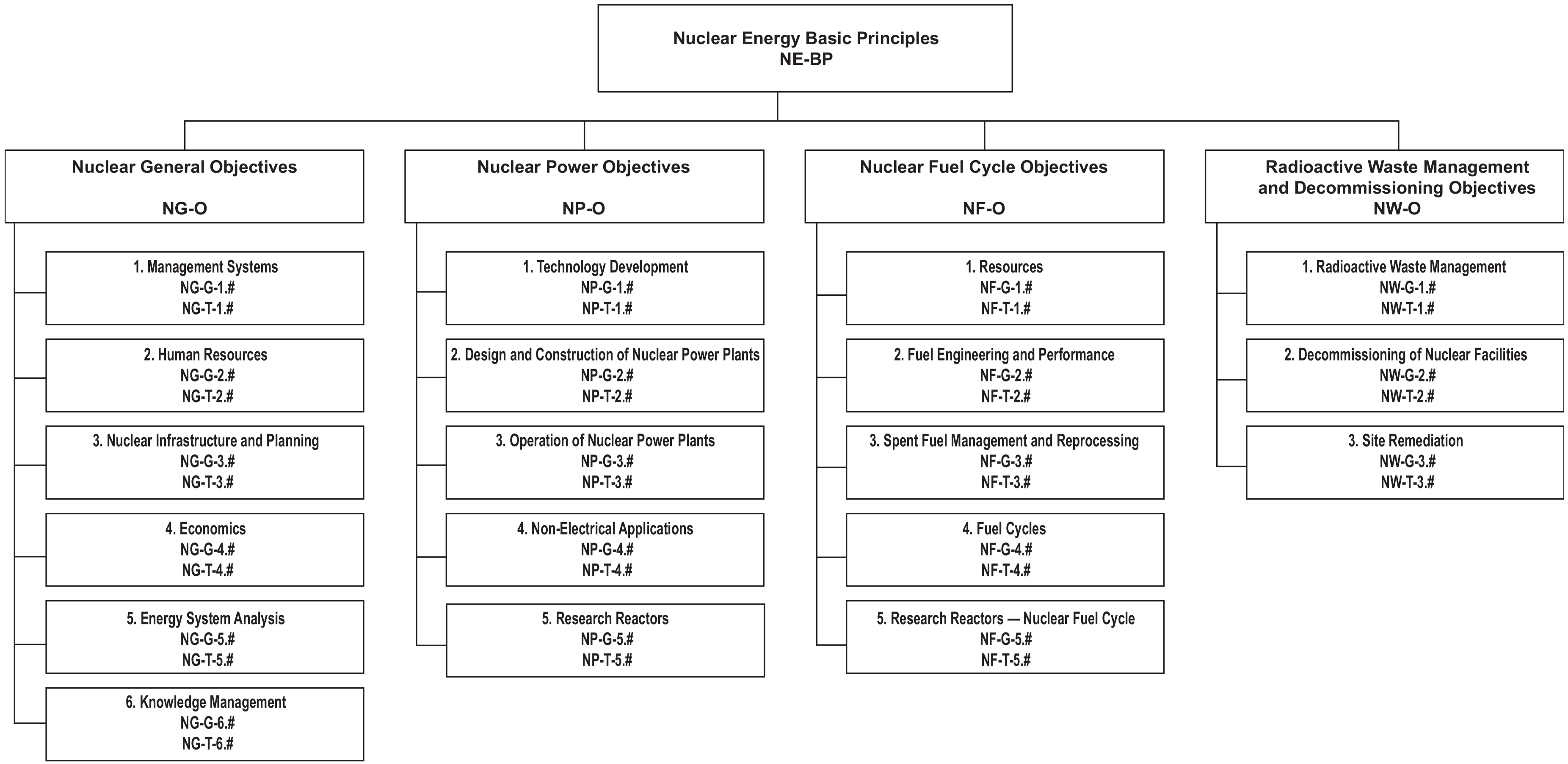

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