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Underground Disposal Concepts for Small Inventories of Intermediate and High Level Radioactive Waste

IAEA
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UNDERGROUND DISPOSAL CONCEPTS FOR SMALL INVENTORIES OF INTERMEDIATE AND HIGH LEVEL RADIOACTIVE WASTE

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INTERNATIONAL ATOMIC ENERGY AGENCY
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For further information on this publication, please contact:

Waste Technology Section
International Atomic Energy Agency
Vienna International Centre
PO Box 100
1400 Vienna, Austria
Email: Official.Mail@iaea.org

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FOREWORD

Near surface disposal of low level radioactive waste (LLW) is safely and effectively conducted on a routine basis in numerous Member States. Underground disposal facilities for LLW and intermediate level waste (ILW) are also in operation, while facilities for the underground disposal of high level waste (HLW) and/or spent nuclear fuel (SNF) are being planned and constructed. The latter are being pursued by Member States with nuclear power programmes that have generated significant quantities of this waste. The commonly accepted end point solution envisaged for programmes dealing with HLW/SNF is disposal in a deep geological repository.

The costs of constructing, operating and closing underground repositories suitable for ILW and/or HLW/SNF are generally of the order of billions of euros. Some of the costs — such as those for the construction and subsequent closure of access shafts or ramps — are fixed and are not proportional to the waste volume. This fact can render a mined deep geological repository economically unfeasible for comparatively small waste volumes of ILW and/or HLW/SNF.

This publication presents underground disposal concepts other than a mined deep geological repository that may provide a safe and economical solution for the relatively small inventories of ILW and/or HLW/SNF arising in a Member State without a major nuclear power programme. The concepts are evaluated for their potential suitability in a number of situations, including possible advantages and weaknesses and the maturity of concept development. Case studies are included for each of the discussed concepts. Some of the case examples are facilities that are being planned or operated; others, such as disposal in deep boreholes, are only conceptual examples.

The publication aims to provide Member States with a better understanding of disposal concepts they may consider for their relatively small waste inventory, as a starting point for their process of implementing an effective disposal solution. Only underground disposal is addressed. Near surface disposal facilities, suitable for LLW, have lower fixed costs, while total costs are likely to be reasonably proportional to the size of the waste inventory. It is important to emphasize that, although the concepts presented in this publication could offer a disposal solution with lower fixed costs, they will need to meet the same safety standards as any disposal project. This will require the site characterization, engineering developments and assessments needed to provide for a robust safety case.

The underground disposal concepts may also be of interest to Member States with large inventories of ILW and/or HLW/SNF that have smaller volumes of waste with properties making it unsuitable for co-disposal with other waste, possibly excess plutonium (if considered as a waste). For these waste streams, a separate, smaller scale disposal concept could effectively contribute to meeting the overall disposal needs of the national inventory.

The IAEA is grateful to all those who contributed to the production of this publication, in particular N. Chapman (Switzerland). The IAEA officer responsible for this publication was P. Van Marcke of the Division of Nuclear Fuel Cycle and Waste Technology.

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Every Member State that uses nuclear technology generates radioactive waste. This waste requires careful management to protect human health and the environment. Waste with a very short half-life can be kept in a storage facility until it decays to a safe level. Where the waste contains longer-lived isotopes, it can remain potentially hazardous for hundreds or even thousands of years. Safe storage cannot be guaranteed beyond timescales of even a few hundred years. Storage facilities require active measures, such as inspections, monitoring, maintenance and security. It cannot be guaranteed that future societies will have the knowledge and the resources for guaranteeing safe waste storage. In addition, passing on the responsibility for managing the waste to future generations is not in accordance with the sustainability principle of avoiding the imposition of undue burdens on future generations.

For waste that cannot be managed by decay storage, disposal is the only option providing a safe, secure and permanent solution. Waste disposal means placing the waste in an appropriate facility without the intention of retrieval [1-2]. A disposal facility needs to provide passive safety after its closure, meaning that no active safety or security measures are required to ensure that it maintains its isolation and containment functions.

Many near surface disposal facilities[1] for radioactive waste are in operation worldwide [3-4]. Several examples of the underground disposal of low-level (LLW) and intermediate-level waste (ILW) exist as well. No such facilities are being operated today for the disposal of high-level waste (HLW) and/or spent nuclear fuel (SNF), but several countries are making significant progress in developing, planning and constructing such facilities. Examples of advanced programmes are to be found in Finland, Sweden, France and Switzerland. These Member States are planning for the disposal of their ILW and HLW/SNF in mined geological repositories [5-8].

These countries have significant waste inventories. The amount of SNF waste stored in France at the end of 2015 was more than 13.500 tonnes [5]. The amount of SNF kept in storage, either in SNF pools at the nuclear power plant (NPP) or in storage facilities, in Finland, Sweden and Switzerland consisted, as of 2016, of approximately 14.000, 34.000 and 6.500 assemblies, respectively [6-8].

For countries with smaller inventories of ILW and/or HLW/SNF, disposal in a mined geological repository may not be viable. This is mainly because of the relatively high fixed costs for a mined repository, such as for the construction of access shafts and/or ramps plus their subsequent sealing and closure.

Therefore, Member States with such smaller inventories could benefit from alternative disposal options that provide for the same protection levels, while potentially having lower associated programme costs. In this regard, it is important to note that any alternative option found suitable for a small inventory would need to demonstrate the same safety performance as required for mined repositories. This will require extensive site characterisation and the development of a sound engineering concept and safety case [2]. Those activities will be part of any disposal

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[1] From the IAEA Safety Glossary [1]: A near surface disposal facility is located at or within a few tens of metres of the Earth's surface. A geological disposal facility is located underground, usually several hundred metres or more below the surface in a stable geological formation to provide long term isolation of radionuclides from the biosphere.

project and it is important to emphasize that there are no shortcuts around the related efforts and costs.

1.2. OBJECTIVES

This publication explores the disposal strategies and concepts that might be applicable for Member States with relatively small inventories of ILW and HLW/SNF, i.e., waste requiring underground disposal. The concepts are evaluated for their potential suitability in a number of situations, including possible advantages and weaknesses and the maturity of concept development. Case studies are included for each of the discussed concepts. Some of those case examples are facilities that are being planned or operated, others, such as disposal in deep boreholes, are only conceptual examples.

Near surface disposal concepts for LLW are not addressed, as significant experience exists for the disposal of this waste and the costs are typically more proportional to the waste inventory [9]. The issue of affordability for Member States with small inventories therefore mainly manifests itself with regards to planning and implementing underground disposal facilities.

1.3. SCOPE

In the context of this report, "small inventories" refers to inventories of ILW and/or HLW/SNF whose volume could make construction, operation and closure of a mined deep geological repository financially challenging, due to the fixed costs associated with constructing such a facility. It is up to the organizations responsible for the disposal of those inventories to decide for themselves if that is the case. Chapter 2 provides some examples of inventories that could be considered small.

The underground disposal concepts presented may also be of interest to Member States with larger nuclear waste programs that have a subset of waste with specific properties that make co-disposal in planned repository facilities undesirable. Such waste could include excess plutonium (if considered as a waste). For these waste streams a separate, smaller-scale dedicated disposal concept could offer a suitable alternative.

Predisposal activities such as waste processing, conditioning and storage are outside the scope of this report. Ref. [10] provides guidance on the processing and storage of radioactive waste in countries with small amounts of waste generation.

1.4. STRUCTURE

The term "small waste inventory" is further discussed in Section 2. This section provides some examples of what those inventories could be. Section 3 describes factors that can affect the selection of the disposal strategy to be pursued. Section 4 then addresses some strategic choices that might be available to a disposal programme.

Five disposal concepts are presented in Section 5 and these are then further described in Sections 6 to 10. The main conclusions are summarised in Section 11.

2. SMALL INVENTORIES OF INTERMEDIATE- AND HIGH-LEVEL WASTE

Potential sources of radioactive waste are:

- Nuclear applications;
- Nuclear facility decommissioning;

- Research reactors and nuclear power plants.

Other sources of radioactive waste, such as materials from military and defence programmes, or waste from accidents at nuclear facilities, constitute specific cases that are not explicitly addressed here. This report does also not explicitly consider waste arising as by-products from nuclear fuel cycle activities, such as commercial fuel fabrication. The Member States that generate these types of waste typically have major nuclear power programmes, with large associated waste inventories. This publication however does consider ILW and vitrified HLW resulting from SNF that is returned to the inventory holders.

This report uses the waste classification scheme of the IAEA [11]. This scheme is based primarily on considerations of long-term safety and thus, by implication, on appropriate disposal solutions for the waste. Where countries classify their waste differently[2], this is noted.

2.1. WASTE FROM NUCLEAR APPLICATIONS

Small inventories of radioactive waste are most commonly associated with the widespread application of nuclear technologies in medicine, agriculture, industry and research[3]. Although every Member State possesses such waste, their management may present a challenge, in terms of building up the necessary human and financial resources.

Many of these applications use radioactive sources, frequently in the form of sealed sources, where the radioactive materials are firmly contained or bound in a suitable capsule or housing, typically a few centimetres in size (see Fig. 1) [12]. Several Member States have arrangements for the return of spent radiation sources to the manufacturers, but almost all Member States also possess a legacy of non-returnable or orphan sources that will require disposal.

FIG. 1. Some examples of sealed radioactive sources (the pencil indicates the scale).

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[2] Some countries classify their waste into short-lived and long-lived ILW, whereby the short-lived waste can be disposed in a near-surface disposal facility and the long-lived is required to go in an underground disposal facility. In the IAEA classification scheme, such short-lived ILW that can be disposed in a near-surface facility, is, by definition, LLW.

[3] The radioactive waste generated by nuclear applications in medicine, industry and research is sometimes referred to as 'MIR' waste.

2.1.1. Medical applications

Radioactive materials are used in medical diagnosis and therapy in the form of unsealed sources, liquid solutions and high specific activity sealed sources housed in shielded assemblies. Radioisotope and radiopharmaceutical production to service medical (and other nuclear) applications is usually carried out in irradiation facilities such as research reactors and accelerators. Waste from isotope production is typically small in volume but can be highly radioactive and contain fission products, uranium isotopes and several very short-lived radionuclides. Most of the radioisotopes used for medical diagnostic procedures and treatments are very short lived and, in most cases, the only management required is decay storage. Radioactive medical waste tends to contain beta particle and gamma ray emitters. In diagnostic nuclear medicine several short-lived gamma emitters such as technetium-99m are used.

2.1.2. Industrial and agricultural applications

Industrial and agricultural applications mostly use sealed radioactive sources, both for irradiation (e.g., eradication of pests) and for detection and measurements (e.g., gauges and smoke detectors). These sources can contain alpha, beta, neutron or gamma emitters. Gamma emitters are used in radiography, while neutron emitting sources such as Ra-226-Be, Am-241-Be, and Cf-252 are used in a range of applications, such as oil well logging.

2.1.3. Research applications

Uses of radioactive materials in universities and other research establishments are widespread and involve sources, irradiated items and radioisotope labelled chemicals. A common use is in monitoring the metabolic or environmental pathways associated with materials as diverse as drugs, pesticides, fertilizers and minerals. A wide spectrum of radionuclides is available for research. C-14 and H-3 are commonly used in toxicological studies and I-125 is used to label proteins. Isotopes such as H-3, P-32, P-33 and S-35 are widely used for DNA sequencing.

2.1.4. Examples of waste inventories generated by nuclear applications

Cyprus allows the import of radiation sources only if there is a repatriation agreement in place for the spent material. However, it operates a storage facility for legacy sources used in medicine before such arrangements were in place, including four Category II Co-60 sources, several smaller sources from lightning rods and smoke detectors using radioactive isotopes, and sources used in education [13].

Greece also returns sources to manufacturers, but has accumulated around 161 orphan sources, 472 lightning rods., around a dozen drums of consumer items produced with radioactive elements and some Pu contaminated materials requiring disposal [14].

Jordan stores a total number of 369 disused sealed radioactive sources including 25 Am-241 and 13 Ra-226 sources [15].

Slovenia operates a central collection and storage facility for radioactive waste from small producers at Brinje. It has accumulated 53 tonnes of assorted waste in 832 packages (totalling 93 m3), including spent sources, dismantled smoke detectors and solidified (originally liquid) waste from medical applications [16].

South Africa has an inventory of around 10.000 disused sealed radioactive sources (DSRS) from medical, agricultural, industrial and research activities, including more than 800 category 1-sources [17].

Tajikistan has an inventory of 348 DSRS. Seven of those DSRS are category-1 sources (Co-60 and Sr-90).

2.2. WASTE FROM NUCLEAR FACILITY DECOMMISSIONING

The decommissioning of nuclear facilities, including power or research reactors, generates a wide variety of radioactive waste in terms of material, activity concentration, size and volume. The largest volumes of waste arise from demolition operations and decontamination operations. Decontamination (the removal of contamination from surfaces of facilities or equipment by washing, heating, chemical or electrochemical action, mechanical cleaning or other techniques) reduces waste volumes and dose levels in the installations thereby facilitating dismantling and demolition.

Austria only has LLW and ILW. This waste is generated by the use of radioactive material in medicine, industry and research and ongoing decommissioning activities, mostly at the Seibersdorf site. One example is the dismantling of the 10 MW research reactor ASTRA, which was completed in 2006. The total volume of LLW and ILW from all activities by 2045 is estimated at around 3600 m^3 of which 60 m^3 is long-lived waste [18].

Denmark is currently completing the decommissioning of three research reactors that were in operation since the 1950s at Risø, as well as a plant for fabricating fuel for two of the reactors, a hot-cell facility and a waste management plant. SNF from two of the reactors has been transferred to the USA under an agreement with the US Department of Energy. Denmark however still holds 4,9 kg SNF from the first research reactor, 233 kg of experimental SNF used for post irradiation experiments, in addition to operating, institutional and decommissioning waste which is mostly classified as LLW [19].

Thailand is decommissioning several nuclear facilities, including a former research reactor, resulting in a total of about 850 m^3 of accumulated waste. The research reactor will account for approximately 200 m^3 of waste and 109 SNF rods. An isotope production facility accounts for another 200 m^3, while decommissioning of a rare earth processing plant will generate about 400 m^3. An incineration facility will produce an additional 50 m^3.

2.3. WASTE FROM RESEARCH REACTORS AND NUCLEAR POWER PLANTS

Waste generated routinely by NPPs and research reactors consists of SNF, if declared as waste, and operational waste. In some countries, SNF is not regarded as waste, as it can be reprocessed. SNF contains fission products that emit beta and gamma radiation (e.g. Cs-134, Cs-137, Sr-90, Ru-106), actinides that emit alpha particles (e.g. U-234, Np-237, Pu-238 and Am-241) and neutron emitters such as Cf-251. It is highly radioactive and emits heat. It is typically kept in a fuel pool at the reactor site for several years, after which it can be transferred to a storage facility.

The quantities of SNF that are produced by modern nuclear power reactors depend upon several factors, such as the reactor and fuel type, the operational history, the fuel burnup (level of neutron irradiation of the fuel) and the initial enrichment. Modern light water reactors (LWRs) of 1000 MWe capacity, with an availability of 90%, an efficiency of 35% and a burnup of around 45 GW·d/tU, generate around 25 tonnes SNF per year [20]. Higher burnup (over 60 GW·d/tU) reduces SNF quantities further. Heavy water reactors that can use natural uranium generate larger quantities of SNF. A 1000 MWe CANDU reactor produces around 125 tonnes of SNF a year, but the specific activity and decay heat from CANDU SNF is much lower than that from LWRs.

Member States that choose to have SNF reprocessed abroad might receive back ILW and vitrified HLW. HLW can generate substantial heat, which needs to be taken into account when considering disposal options.

Operational low- and intermediate-level waste (LILW) from a nuclear reactor arises from the processing of primary circuit cooling water and storage pond water, equipment decontamination and routine facility maintenance. Waste generated from routine operations includes contaminated clothing, floor sweepings, paper and plastic. Waste from processing of primary coolant water and the off-gas system includes spent resins and air filters, as well as some contaminated equipment.

Waste can also be generated from the replacement of activated core components such as control rods or neutron sources. Once conditioned, the operational waste is mainly LLW, with only small quantities of ILW. The volumes produced depend on the reactor type with a typical 1000 MWe PWR generating about 100-200 m^3 of conditioned LLW and ILW waste per year [20].

Research reactors generally produce the same types of waste as nuclear power reactors, but on a much smaller scale. Typical designs contain only a few kilograms of fuel, compared to perhaps a hundred tonnes in a power reactor. However, there is a wider variety of fuel types compared to power reactors which can result in very diverse and sometimes difficult to handle waste streams. Some of the fuels can be in chemical or metallurgical forms that make them less chemically stable and more difficult to manage for disposal alongside other long-lived waste.

Many Member States using highly enriched uranium fuel in research reactors have entered agreements to send the SNF back to the United States of America or to the Russian Federation for final disposal [21]. However, those take-back programmes have ended, and some countries will need to find solutions for the disposal of relatively small amounts of SNF. Many research reactors have been converted to run on low enriched fuel, however this does not alleviate the need for disposal.

2.3.1. Examples of research reactor waste inventories

Australia chose to have the SNF from its HIFAR research reactor reprocessed abroad and returned as ILW. After about 25 years of operation the reactor had discharged 1.288 fuel assemblies, which were reprocessed in France to produce 20 CSD(U) canisters of ILW. These canisters were returned to Australia where they are stored pending a final disposal solution.

Norway has some 16 tonnes of SNF from the operation of 3 research reactors. There are approximately 12 tonnes of aluminium-clad fuel, of which 10 tonnes is metallic uranium fuel and the remainder oxide (UO_2) [22].

Portugal shut down its research reactor in 2017. The SNF was shipped to the United States in March 2019 as part of the “United States Foreign Research Reactor SNF Acceptance Program” [9] (see also Section 4.1). The waste from decommissioning the reactor will include irradiated graphite and activated beryllium.

Viet Nam operates the Dalat Research Reactor. The SNF has been sent to the Russian Federation in the framework of “Russian Research Reactor Fuel Return” [9] (see also Section

4.1). The operational waste in 2019 amounted to 237 200-litre containers with solid and liquid waste [23].

2.3.2. Examples of small nuclear power programme waste inventories

Lithuania operated the Ignalina NPP for more than 25 years. The plant consisted of two 1.500 MW graphite-moderated channel-type boiling nuclear power reactors. This resulted in 2.416 tHM SNF [24] and ca. 44.000 tonnes of LLW and ILW waste, including 3.820 tonnes of graphite [25].

Slovenia operates a single NPP, jointly owned with Croatia. The 696 MWe Krško PWR has been in operation since 1982. During approximately 32 years of operation the plant has discharged about 334 tHM SNF and about 2.700 tonnes of operating waste, along with around a further 1.000 tonnes of contaminated exchange parts and equipment [16].

3. FACTORS AFFECTING THE DISPOSAL STRATEGY

A radioactive waste disposal programme needs to be embedded in a wider national policy and strategy on waste management. Such a policy defines the goals and principles for waste management while the strategy describes the approach for implementing it. A well-defined policy and associated strategies can promote consistency between the actions and plans of all involved parties in waste management.

Guidance on developing a waste management policy and strategy is given in the IAEA report on “Policies and Strategy for Radioactive Waste Management” [26]. A concise summary of key issues related to the development of a sound radioactive waste and SNF management system for countries adopting nuclear power can be found in [20, 27, 28]. Countries planning to embark in nuclear power, or a research reactor project can find guidance in [29-30]. Those reports also address how the management of the radioactive waste resulting from nuclear power or research reactor can be planned for.

As mentioned in previous sections, a suitable or preferred disposal option depends on the characteristics and size of the inventory and the resources available. When developing a disposal solution, there are several other factors that also need to be considered, such as the legal and regulatory framework, national policies, available technical options and preferences of the major interested parties.

It is important that those factors are identified and understood. This section discusses some factors that may affect or bound the disposal strategy. The following factors are considered:

- National policy on waste management;
- Legal and regulatory framework;
- Waste inventories;
- Predisposal management;
- Human and financial resources;
- Available infrastructure;
- Stakeholder expectations.

In addition, the range of disposal strategies and disposal options that are feasible nationally depends on country-specific characteristics such as the available geologic, climatic environments, demography, land use, the presence of mineral resources, public acceptance, etc.

3.1. NATIONAL POLICY ON WASTE MANAGEMENT

National policy sets out the goals or requirements ensuring the safe management of waste. It represents the views of all organizations concerned with the management of radioactive waste and reflects national priorities, circumstances, infrastructure, human and financial resources, as well as the types and characteristics of the radioactive waste, its geographical distribution and demographics.

Some examples of issues for which a policy can provide guidance or direction:

- Establishing clearance levels or methods for determining a materials safe release from regulatory control [31];
- Allowing or prohibiting the import or export of radioactive waste or the definition of conditions on such import or export;
- Reprocessing and the status of SNF, i.e., is SNF considered a resource or possible resource, is it regarded as a waste, or is the definition of its status postponed to a later date;
- Setting policy on disused sealed radioactive sources; the policy may express a preference for repatriation or recycling;
- Establishing mechanisms to facilitate stakeholder involvement in waste management planning;
- Defining level of collaboration with other countries, e.g., joint research programmes up to pursuit of a multinational disposal facility;
- Providing direction on requirements for reversibility or retrievability of waste.

The policy needs to be consistent with existing legislation and other national policies. In turn, the policy will serve as a basis for further developing the legal framework for waste management and specifying the regulatory framework for implementation. The national policy for radioactive waste management needs to reflect the magnitude and scale of the hazard posed by the waste following a graded approach.

3.2. LEGAL AND REGULATORY FRAMEWORK

The legal and regulatory framework under which the waste management programme operates might either specify or eliminate certain waste management options. German regulations, for example, direct that all radioactive waste is to be disposed of in deep geological repositories [32]. It is essential for the agency charged with managing radioactive waste to take account of all legal and regulatory requirements on the disposal programme, including those arising from the international framework of treaties and conventions [33-35].

3.3. WASTE INVENTORIES

A pre-requisite for developing a disposal strategy for waste management is a sufficiently accurate inventory of the waste that needs to be disposed of. The types and quantities of waste will define the disposal options that can be considered and the size of the disposal facility that is needed. It is therefore required to determine and, in case of future waste arisings, to predict the volume, production rate, schedule and characteristics in order to develop a national waste inventory.

It is also important to have a good assessment of when the waste will arise, as this can affect the strategy. For example, the time schedule of waste arising might be crucial information to assess whether storage capacity is sufficient. Furthermore, where there is a significant time gap between different waste arisings, it might be most efficient to dispose of different groups of waste during different disposal campaigns and, perhaps, in different disposal facilities.

3.4. PREDISPOSAL MANAGEMENT

Predisposal waste management is defined in the IAEA Safety Glossary [1] as "any waste management steps carried out prior to disposal, such as pre-treatment, treatment, conditioning, storage and transport activities." Predisposal and disposal are tightly linked, and any consideration of disposal also needs to consider predisposal. It is therefore important to develop predisposal and disposal plans in a consistent manner.

For example, when considering options for waste conditioning in the absence of a disposal facility and associated waste acceptance criteria, it may be appropriate to consider the use of reversible methods or the production of conditioned waste in relatively small unit volumes that can be overpacked in standard containers. This provides for as much flexibility as possible, to both meet the current storage requirements and to be able to adjust to future disposal requirements.

Ref. [10] provides guidance on the processing and storage of radioactive waste in countries with small amounts of waste generation.

3.5. HUMAN AND FINANCIAL RESOURCES

A national radioactive waste programme requires the establishment of:

- An organization, or organizations, charged with coordinating or overseeing radioactive waste management;
- An independent regulatory body established to develop regulations and enforce the implementation of the regulations on SNF and radioactive waste management.

A disposal programme requires a wide range of disciplines and skills. It will be important to understand the human resource capacity that is required by a given disposal option. This might require support from other institutions such as technical support organizations.

It is also important to ensure that sufficient financial resources are available for implementing the waste management programme up to its completion. This requires reliable methods for estimating the cost for the disposal programme. Guidance on costing and funding methods for disposal can be found in Ref. [9].

3.6. AVAILABLE INFRASTRUCTURE

Some national waste management strategies can rely on the use of already available infrastructure (e.g. nuclear research facilities), while others might require investment in new facilities or the development of new technologies. Where a disposal facility is already in operation, co-disposal might be envisaged, assuming the facility offers a suitable and safe disposal option for other waste in the national inventory. Co-disposal can result in a cost-effective and simple waste management system because fewer common facilities need to be developed (e.g. transportation systems such as ports, roads, bridges), although inclusion of additional waste types might require different disposal concepts to be developed at the same location (e.g. using differing types of engineered emplacement).

3.7. STAKEHOLDER EXPECTATIONS

As with many infrastructure projects, effective stakeholder engagement is an important consideration in the development of radioactive waste management. A disposal strategy and solution can only be successfully implemented when it has political support and when it is largely accepted by the public. This requires engaging with the public and other stakeholders in decision making. Typical examples of stakeholders involved in waste management include, among others, governmental bodies and regulators, local communities, the public at large, non-governmental organizations, scientific research institutions, media and advisory and consultative bodies.

Stakeholder involvement comprises understanding the expectations and concerns of different stakeholders on the disposal strategy, which could affect the disposal options or the disposal facility design. Different disposal options might have different degrees of public acceptance and public sensitivity.

For example, OPG (Ontario Power Generation) in Canada consulted its stakeholders early in its disposal programme for LLW and ILW, enabling OPG to take their expectations and concerns into account in the design of the disposal facility. The choice for geological disposal instead of surface disposal was based on the preference of local communities [36]. In Belgium waste management organization ONDRAF/NIRAS organized a public consultation on geological disposal in 2009. Participants expressed a preference to keep open the possibility of retrieving the waste after repository closure [37].

Specific guidance on involving stakeholders in the development and implementation of a disposal programme can be found in Refs. [38-39].

4. STRATEGIC CONSIDERATIONS

Before selecting and developing a specific disposal solution, strategic choices might need to be made. In some Member States, certain strategic choices are already captured in policy, law or regulations by the factors described in the previous section. Examples include the import or export of radioactive waste, the possibility to reprocess SNF or the need to develop a retrievable disposal solution. However, where such issues are not already determined, they could be part of the disposal strategy.

Examples of strategic choices are:

- Time schedule of disposal: What is the timing for implementing the disposal facility? It might be decided to have a disposal facility as soon as possible, but taking due account of scientific, technological, societal and economic considerations. This might depend on the capacity of storage facilities. Similarly, once all waste is placed in the disposal facility, will it be closed as soon as possible, or left open for a certain period to enable waste retrieval, taking due account of the financial and economic, environmental and safety impact this might have?
- Number of disposal facilities: Will one disposal facility be developed for the complete waste inventory or will different disposal facilities be used for different waste streams? Use of a single facility can offer certain economic benefits by allowing optimization of workforce, infrastructure and security costs. On the other hand, more cost-effective disposal solution might be developed for certain waste streams potentially requiring multiple facilities;

- Range of disposal concepts: If a single disposal facility is planned, can different waste types be placed together, or would it be more efficient and cost effective to emplace them in separate sections of the repository, perhaps using different engineered isolation and containment solutions?
- Flexibility: Will the disposal facility allow for expansion of disposal space for expected future waste arisings or the flexibility to accommodate other waste streams potentially arising in the future?

The following additional strategic considerations might be of particular interest to Member States managing small inventories:

- Repatriation;
- SNF reprocessing;
- Keeping options open;
- Multinational disposal and international partnerships.

These are described further below.

Knowledge of waste management strategies in other countries can provide guidance. Specific examples, relevant to disposal of small inventories, are included in this report. It is however important to keep in mind that each country has its own specific situation. There is great diversity in the types and amounts of radioactive waste in different countries and, as a result, the strategies for implementing waste policies can vary accordingly.

4.1. REPATRIATION

Several States have returned SNF from research and other non-power reactors for reprocessing and/or disposal to their country of origin. Repatriation avoids the need for further management of the SNF at a national level.

Two examples of repatriation programmes for SNF from research reactors are the United States of America Foreign Research Reactor SNF (FRRSNF) acceptance programme and the Russian Research Reactor Fuel Return (RRRFR) programme [21]. Another example is the repatriation of spent fuel from research reactors in Ghana and Nigeria to China [40-41]. The major goal of these take-back programmes is to eliminate inventories of highly enriched uranium (HEU) by returning research reactor SNF to the country where it was originally enriched.

The US FRRSNF acceptance programme was launched in 1996. The programme was originally planned to run for 13 years until 2009, but it was twice extended until 2016 and 2019 [42]. At the end of 2007, the programme had safely and successfully completed 41 shipments and 27 countries have participated, returning a total of 8078 SNF elements to the United States, most comprising HEU [21].

Under the RRRFR programme, which originated in 1999, the Russian Federation takes back fresh or SNF enriched in the former Soviet Union or the Russian Federation. A total of 446 kg of fresh HEU fuel has been removed from Serbia, Romania, Bulgaria, Libya, Uzbekistan, the Czech Republic, Poland, Germany and Viet Nam.

One option for Member States with newly established nuclear power programmes could be to arrange take-back of the spent fuel by its supplier (sometimes called fuel leasing). The availability of this scheme is subjected to case-by-case assessment: conditions for such services have been negotiated between the Russian Federation and several countries (the Islamic

Republic of Iran, Turkey and Viet Nam) [20]. If the fuel is leased and there is an arrangement about taking back the spent fuel, it needs to be clarified if disposal of HLW and ILW is included [20].

Repatriation has also been implemented for DSRS. A number of states that supply sealed radioactive sources for use in medicine and industry also accept the return of DSRS. Examples are Canada, France, Germany, the Russian Federation, South Africa and the United States of America. This is typically conducted for Co-60, Cs-137 and Am–Be neutron sources [12].

Although the return of sources to their original suppliers or manufacturers is encouraged by regulators in many Member States, it is not always possible or easy because:

- The original supplier is unknown, no longer exists or is untraceable;
- Source certificates have expired;
- Adequate transport means, such as an appropriate transport container, are missing or the funds for source packaging and transportation are not available;
- The regulatory system imposes import or export restrictions.

Leasing sources instead of purchasing them becomes an increasingly common option [12]. Under such an arrangement, the source returns to the supplier after the term of the lease and the supplier is responsible for the further safe management of the source.

In the past, the IAEA has supported work with Member States to return fresh and spent HEU research reactor fuel and DSRS to their countries of origin. The IAEA works on a case-by-case basis with Members States in possession of HEU fuel or DSRS to ensure the safe and secure repatriation of such material by offering technical support for conditioning and transportation of fuel and sources, assistance with funding for repatriation projects and support in developing repatriation agreements with the countries of origin.

4.2. SPENT NUCLEAR FUEL REPROCESSING

Reprocessing of SNF enables the separation and reuse of fissile materials in new fuel. It can also be a solution to stabilising some types of research reactor fuels that would otherwise be difficult to dispose of along with other waste. Reprocessing generates vitrified HLW containing most of the fission products in the original SNF and ILW waste. This waste requires geological disposal as well, so SNF reprocessing does not avoid the need for an underground disposal facility.

Reprocessing facilities are currently operated on a significant scale in France, India and the Russian Federation (see Fig. 2 and Table 1) [43]. Other countries have utilized or are still utilizing these facilities including Belgium, Bulgaria, the Czech Republic, Germany, Italy, Japan, the Netherlands, Slovakia, Spain, Sweden and Switzerland. Research reactor fuel has also been reprocessed by Australia, Belgium, China, Sweden, among others.

SNF reprocessing abroad is strictly controlled and performed based on bilateral agreements. HLW from reprocessing is typically conditioned and, in most cases, the conditioned ILW and HLW is returned to the country where the fuel was used.

FIG. 2. Orano reprocessing plant, France (courtesy of Orano; Copyright: Larrayadieu Eric).

TABLE 1. COMMERCIAL SCALE REPROCESSING FACILITIES

	Facility	Status
France	UP2-400, La Hague	Under decommissioning
	UP2-800, La Hague	In operation
	UP3, La Hague	In operation
	UP1, Marcoule	Under decommissioning
India	Coral, Kalpakkam	In operation
Russian Federation	RT-1, Mayak	In operation
	RT-2, Zheleznogorsk	Under construction

Source: IAEA Integrated Nuclear Fuel Cycle Information System.

A decision for reprocessing depends largely on political and economic factors, including commercial arrangements with the suppliers of reactor technologies and fuel. For some potential users it can also provide a technical solution to management of small quantities of fuel, perhaps damaged, or in forms that are poorly suited (e.g. unstable) for geological disposal, by converting the material to stable waste forms for storage and disposal. The time frame for making a decision to reprocess or not needs to be clearly specified in a strategy with respect to long-term SNF management [43].

4.3. KEEPING OPTIONS OPEN

It can be a strategic choice is to keep options open with respect to waste management. This means a decision on disposal is deferred until a later date. This might be done to allow time for the necessary human and financial resources to be built up, for organizational systems to be established or for RD&D programmes to be executed. Any such decision needs to be taken cautiously because it could:

1) Transfer the responsibility for managing the waste to future generations, which is not consistent with the principle that the waste management should not impose an undue burden on future generations [44];
2) Increase uncertainty on the cost for managing the waste and make it more difficult to apply the "polluter pays" principle;
3) Jeopardise the continuity of knowledge on waste management.

A "keep options open" strategy is not the same as "doing nothing". Such a strategy still requires active management of the radioactive waste. It needs to be embedded in a wider waste management policy defining the responsibilities and national organizational structures for waste management. It also requires safe and adequate waste collection and storage provisions. It may lead to the extension of any temporary storage situations and is only possible for a limited time, determined by the state of the storage buildings, the storage capacity and possibly by the duration foreseen in the license for operating the storage facility.

Apart from very short-lived waste, for which decay storage can be the final step in waste management, radioactive waste will ultimately require disposal. Storage can thus only be an interim measure [1]. Reasons for keeping the waste in store for can be:

- A disposal policy is not yet in place;
- No decision has been taken on the ultimate disposal solution;
- No disposal facilities are available;
- The thermal output of the waste needs to decrease prior to its disposal;
- The funds for disposal have not yet been made available or collected;
- More waste needs to be accumulated to enhance the economic feasibility of disposal.

An extended period of waste storage can thus help to make a disposal solution affordable. Extending the storage period is not the same as keeping options open where no decision is taken. The option to extend the storage period is predicated on the decision that a disposal solution will follow the storage period.

However, keeping waste in storage longer also comes at a cost and available storage capacity needs to be considered. Extended storage might require constructing additional storage capacity. Furthermore, there are operational costs for a storage facility related to security, inspection and maintenance of the facility and the waste packages. Apart from maintaining the storage facilities themselves, it also necessary to ensure that expertise and know-how on managing the waste is maintained.

The Netherlands currently manages approximately 11.000 m^3 LLW and ILW, 17.000 m^3 of NORM waste and almost 86 m^3 HLW in its national storage facility (see Fig. 3). Ultimately this waste will be disposed of in a geological disposal facility, planned for around 2130. By then it is forecast that about 70.000 m^3 of radioactive waste will be in storage, of which 400 m^3 will be HLW. The long storage period will enable the Netherlands to gather the necessary resources for their disposal programme [45].

FIG. 3. Storage facility in the Netherlands (courtesy of COVRA).

4.4. MULTINATIONAL DISPOSAL AND INTERNATIONAL PARTNERSHIPS

Countries with small inventories of radioactive waste may consider sharing dedicated waste management facilities with other countries. This has the benefit of standardising approaches and technologies and decreasing the cost of waste management for all countries involved, owing to the economies of scale.

The ERDO working group is a multinational group whose members study the feasibility of setting up a Development Organisation (ERDO) that would implement one or more shared geological repositories in Europe [46]. Another example of possible way of multinational collaboration on radioactive waste management is the use of mobile and modular systems in different waste management predisposal steps (e.g. treatment and conditioning) [47].

Collaboration to develop a multinational disposal facility can take several forms [48]:

- "Add on" scenarios in which a large disposal programme accepts waste from smaller ones;
- "Supranational concepts" in which a facility is implemented with international management and control;
- "Partnering scenarios" in which countries collaborate in a multinational repository.

IAEA report Ref. [48] addresses a wide range of the legal and institutional aspects of multinational disposal, including the contractual obligations among partners, economic and financial arrangements, liabilities, nuclear security, regulatory and legislative aspects, waste transportation arrangements and social matters. The uncertainties and risks involved in the implementation of a multinational repository are also addressed.

The report emphasizes that it is not appropriate for a country to define involvement in a multinational repository as the sole strategy for disposing of its radioactive waste. The uncertainties and risks involved in the implementation of a multinational repository make this unacceptable as the only national strategy. Instead, countries need to have a coherent national disposal policy and strategy that is based upon national plans for disposal within their own territories. In addition, they can include involvement in a multinational repository project as part of their national strategy following a dual track strategy.

5. DISPOSAL CONCEPTS FOR SMALL WASTE INVENTORIES

Disposal facilities use a combination of natural and engineered barriers to isolate and contain radionuclides so that they do not cause unacceptable health and environmental impacts now or in the future. A disposal facility is sited to isolate the waste from natural or human disturbances and to ensure that the characteristics of the geological environment will function together with the engineered barriers to provide adequate containment. Different kinds of waste require longer periods of isolation from people and the environment and thus different disposal solutions.

Several near surface disposal facilities using trenches or above-ground structures are being operated worldwide. They represent safe and cost-effective means for disposing of large volumes of LLW and large nuclear power programmes have facilities for disposal of hundreds of thousands of cubic metres LLW. The cost for constructing and operating such facilities ranges from tens of millions of USD to over a billion USD [9].

As explained in Section 1.2, near surface disposal concepts are not considered in this report. This is because the costs for such facilities are typically more proportional to the waste inventory. The issue of affordability for small inventories therefore mainly manifests itself for underground disposal facilities.

ILW and HLW, along with SNF, cannot be sufficiently isolated and contained in near surface disposal facilities and need to be disposed of in underground facilities. Designs for mined deep geological repositories have been developed for a range of geological environments, predominantly in salt, crystalline rock or clay host rock formations. The WIPP facility (USA) is an example of a purpose-built geological disposal facility in a bedded salt formation at a depth of ca. 650 m (see Fig. 4).

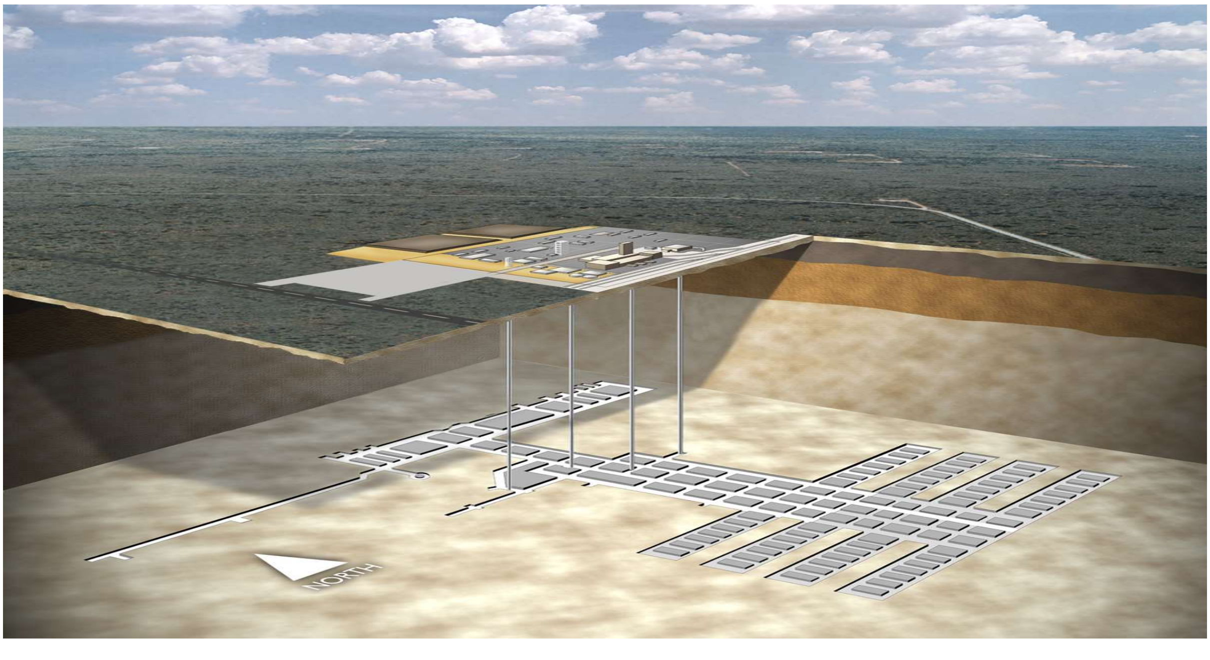

FIG. 4. Schematic picture of the WIPP facility at a depth of ca. 650 m in a salt formation in New Mexico (USA) (Courtesy of USA DOE).

The cost for implementing large geological disposal programmes, such as those in France, Germany, the UK and USA, reaches tens of billions of USD [9]. The cost for implementing small to middle-sized programmes, such as in Belgium, Finland, Sweden and Switzerland, is estimated to be in the order of billions of USD [9]. Because a part of the overall cost is "fixed", i.e. will not scale with the size of the inventory, constructing such a mined deep geological repository for the disposal of small inventories can pose an economic challenge.

Alternative disposal concepts to a mined deep geological repository may therefore be considered for small waste inventories requiring underground disposal. The concepts presented here are:

- Silo-type facilities (tens of metres deep);
- Underground caverns or silos (tens up to around one to two hundred metres deep);
- Converted mines (tens or hundreds of metres deep);
- Boreholes at intermediate depth (tens to a few hundreds of metres deep);
- Very deep boreholes (several kilometres deep).

The grouping of the concepts presented above and considered in this report is stylised. It is, for example, not possible to define meaningful depth constraints for any of the groupings, as this will depend on the siting environment and the details of the engineered barrier system developed. Similarly, there is no purpose in making a rigorous definition of the diameter at which a borehole becomes a silo. Depending on the inventory, waste volume and the siting environment, specific solutions might be found that overlap the stylised groupings discussed here. The intention is that these stylised groups can be used as examples of what is being considered and may be implemented, illustrating the factors that will need to be considered when developing any specific solution.

This particularly applies to the silo-type facilities, which depth in this report is considered to be in the order of tens of metres. Those depths place this concept in the category of near surface disposal facilities. Near surface disposal is defined to be "*located at or within a few tens of metres of the Earth's surface*" [1]. Nevertheless, there is no clear delineation between disposal at surface and at an intermediate depth, and for inventories with only a limited activity of long-lived radionuclides or for sites with exceptional isolating properties, such as remote and unhabitable sites for example, the concept could be considered.

Furthermore, it is also important to highlight that the first four concepts are either planned or being implemented. Very deep borehole disposal has not yet been implemented and has only been studied. It is within the technological capabilities of Member States, but it remains to be demonstrated that a safety case for deep borehole disposal can be developed and licensed.

These concepts are further discussed in the following Sections 6 to 10. Each section starts with a real case example, where available. Subsequently the following aspects of the concept are evaluated:

- Principal safety features;
- The waste types for which the concept could offer a safe disposal solution;
- Potentially suitable siting environments;
- Technological feasibility and constraints.

Finally, it is worth referring to [3] which provides examples of disposal concepts that have been designed, and in many cases implemented, for a wide range of existing radioactive waste inventories. The examples demonstrate how combinations of waste inventory, geological setting and concept of operations have been developed.

6. SILO-TYPE FACILITIES

Silo-type disposal facilities are constructed to depths of tens of metres and are excavated directly from the ground surface. Their diameter is typically in the order of metres to tens of metres. They can be lined or unlined but designs that penetrate the water table will typically incorporate a concrete base and liner to stabilise the opening and prevent ingress of water during operations. Upon closure the silo will be backfilled, to provide additional containment. The silo is covered during operations, with waste packages being lowered into place by crane. At closure, the upper sections are backfilled, sealed and isolated from the surface environment. Larger silos might also be accessed from below the ground during operations.

As mentioned in the previous section, the limited depth places those facilities rather in the category of near surface disposal facilities. This makes them unsuitable for inventories with significant activities of long-lived radionuclides in a silo. Nevertheless, for inventories with only a limited activity of long-lived radionuclides or for sites with exceptional isolating properties, such as remote and unhabitable sites for example, the concept could be considered.

Examples of such facilities are the Mount Walton facility [49], which is constructed in arid, unsaturated environments, and the disposal facility at Vrbina-Krško (Slovenia), which is in a saturated environment and is discussed in detail in Section 6.1. The facility in Mount Walton received LLW in 1992 and two additional consignments of LLW in 1994 [50]. The waste is emplaced in drums in a 2 m wide and 28 m deep borehole constructed in a clay formation. The borehole is backfilled with concrete and has a concrete plug. The top of the borehole is covered with compacted clay.

6.1. CASE STUDY: THE FACILITY AT VRBINA-KRŠKO (SLOVENIA)

The Republic of Slovenia has a small nuclear programme [16]:

- The Krško NPP, which is jointly owned and operated along with the Republic of Croatia;
- One research reactor, near the capital city Ljubljana;
- A storage facility for institutional waste;
- A former uranium mine at Žirovski vrh with two closed disposal sites for mining and milling waste.

It furthermore uses radioactive materials in various medical, industrial, research and agricultural applications.

In 2004, Slovenia started a new repository siting process for the disposal of LLW and ILW-SL, as defined by the Slovenian waste classification system. The siting process combined technical screening with a volunteer community approach. During this process different disposal concepts were proposed for each potential site. For the Vrbina-Krško site, the following three disposal concepts were considered for the LLW and ILW-SL:

- Engineered structures at the surface, similar to Centre de l'Aube or El Cabril [3];
- An approximately 60 m deep underground silo excavated from the surface;
- A 200 m deep underground repository.

All three proposed concepts were compared and assessed based on criteria related to the following features:

- Safety;
- Social acceptability;
- Economic efficiency;
- Environmental acceptability;
- Technical appropriateness.

In 2009, Vrbina-Krško was chosen as site for the disposal facility in conjunction with the silo-type repository concept. The site lies near the Krško NPP (see Fig. 5). This type of the facility, in combination with the Vrbina-Krško site properties was considered by ARAO as an optimal selection, combining both public acceptance with a geologically well-suited site.

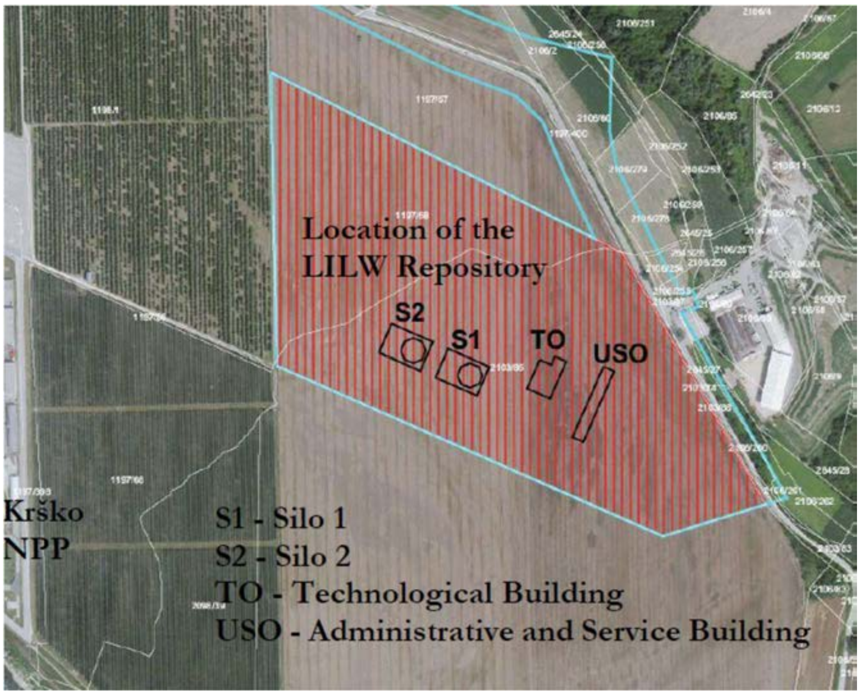

FIG. 5. Site for LILW disposal facility Vrbina-Krško in the municipality of Krško (Courtesy of ARAO).

A construction licence for the silo is expected in 2020. Two disposal campaigns are foreseen (see Fig. 6). During the first campaign all radioactive waste that is currently in storage in Slovenia and that meets the waste acceptance criteria for the repository will be disposed. The campaign is expected to last 4 years. The second campaign will start during the decommissioning of Krško NPP, which is expected to cease operations in 2043), and will include all remaining radioactive waste meeting the facility WAC, including waste from decommissioning. In between both campaigns an idle phase. The closure and decommissioning of the disposal facility are planned for 2061 and 2062.

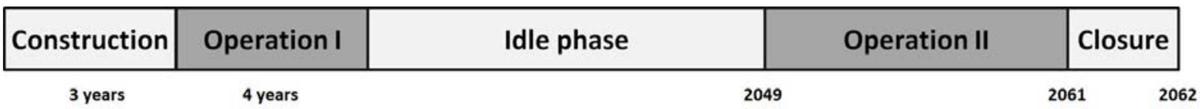

FIG. 6. Planning for the construction, operation and closure of the Vrbina-Krško disposal facility.

6.1.1. Waste inventory

The facility is designed for the disposal of LLW and ILW-SL, as defined by ARAO, from:

- The operation and decommissioning of the NPP;
- The decommissioning of the research reactor;
- Medical, industrial, research and agricultural applications;
- The operation and decommissioning of the disposal facility itself.

The activity of the total waste inventory is estimated to be around 238 PBq and the total disposed waste volume is expected to be around 22.500 m^3. The waste also contains a significant chemo-toxic load, including several hundred kilograms of arsenic, selenium, chromium and nickel.

6.1.2. Disposal site

The repository site lies about 300 m east of the Krško NPP and about 700 m northeast of the river Sava [51] (see Fig. 7).

FIG. 7. Location of the repository site in Vrbina (the Krško NPP lies 300 m to the west and the river Sava 700 m to southwest) (Courtesy of ARAO and Google Earth).

The silo will be excavated from the surface in a thick sequence of Miocene silts with a hydraulic conductivity lower than 10^{-7} m/s (see Fig. 8). The silt is overlain by a 3 to 15 m thick, sandy carbonate gravel deposit of the Sava River. The groundwater table lies about 4 m below the surface.

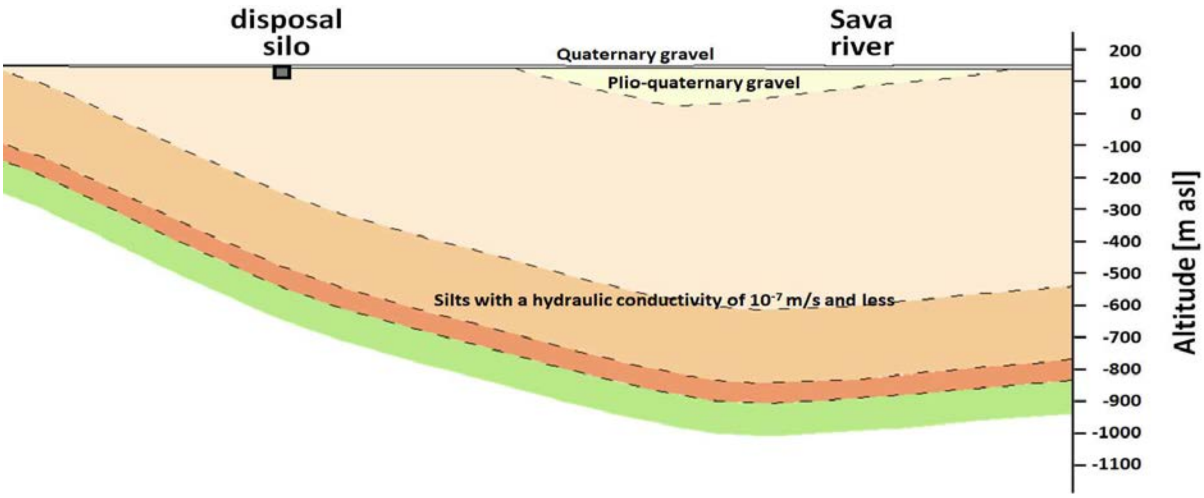

FIG. 8. Geological profile of the Vrbina-Krško site (modified from [51]).

6.1.3. Facility design

The waste will first be packaged in concrete containers. The waste packages have dimensions of 1.95 by 1.95 m wide and 3.25 m high with a maximum weight of 40 tonnes.

The concrete waste packages are emplaced in the silo (see Fig. 9). The silo is about 55 m deep with an inner diameter of 27 m (see Fig. 10). The top of the disposal zone is 15 m deep. The silo is excavated from the surface. An initial 1.2 m thick reinforced concrete diaphragm wall will provide stability and a second 1 m thick reinforced concrete liner will provide isolation. In addition to supporting the dual liner system prevents potential water inflow to the silo during the operational phase. To support operations a temporary hall is placed above the silo.

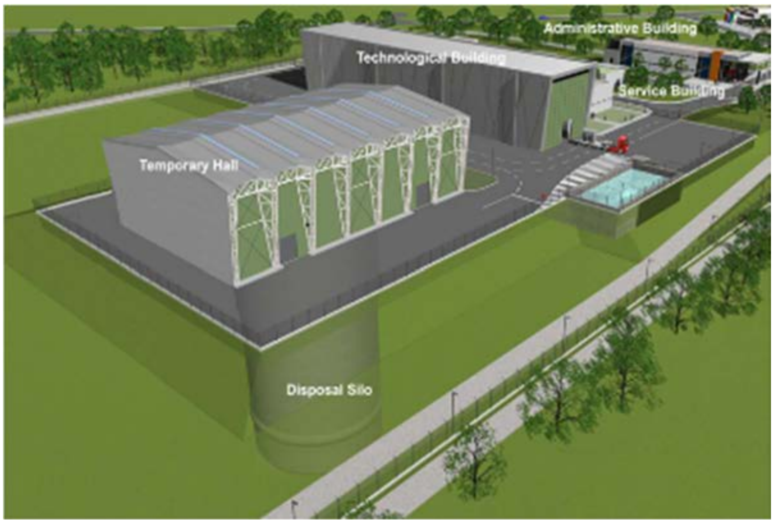

FIG. 9. Drawings of the concrete disposal container (left) and disposal silo during the operational phase (right) (Courtesy of ARAO).

The containers will be arranged in ten levels with 99 containers per level. The voids between the containers will be backfilled with concrete. When the silo is full, it will be closed by a 1 m thick concrete layer over which a clay layer will be placed almost to the surface. The space above the clay layer will be filled to the surface with native site gravel. The closure design is intended to limit water inflow to the silo.

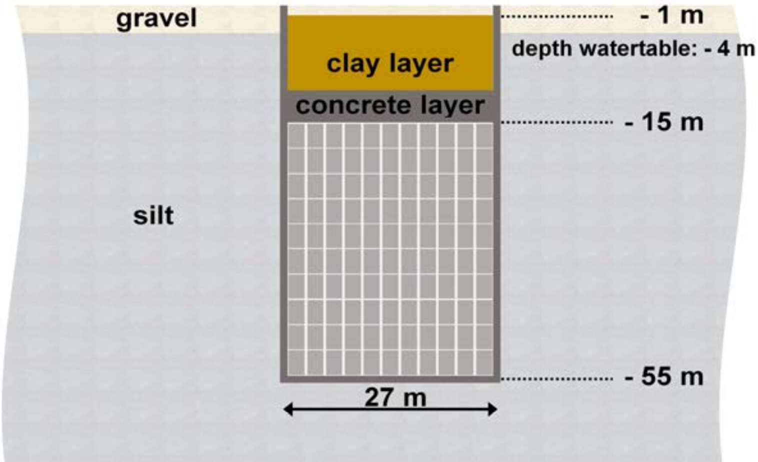

FIG. 10. Schematic view of the disposal silo.

After closure an institutional control period of 300 years is foreseen (50 years of active control and 250 years of passive control).

6.1.4. Safety concept and safety demonstration

The disposed radioactive waste will be embedded in a monolithic concrete structure which is made up of the concrete containers, the backfill and the concrete lining of the silo. As the water flow through this structure is limited due to the low permeability of the site, the degradation of the structure will occur slowly. This results in a waste containment period for the specifics of the Slovenian concept estimated on an order of 1000s of years.

After the containment period, the site characteristics and in particular its hydrogeology determine the radionuclide releases into the biosphere. These releases are evaluated by the safety assessment supporting licensing. Slovenian regulation requires that the dose rate considering the normal evolution of the repository to a potentially exposed individual remains below 0.3 mSv/year at all times. Safety assessments were performed to evaluate the dose rate under a normal and altered evolution scenarios. Several possible accident scenarios during the operational phase were also examined, which included fire, container drops, and airplane crash hazard (fire and explosion). After closure the following altered evolution scenarios were evaluated:

- Early failure of the engineering barriers;
- River meander and surface erosion;
- Inadvertent human intrusion;
- Changes in hydrological conditions.

The safety assessments found that for all evaluated scenarios the dose remained below regulatory limits.

Although the period of institutional control ends after 300 years, additional calculations up to a million years were performed to demonstrate long-term safety. For example, Fig. 11 shows the calculated dose rates based on a safety assessment up to 1 million years for a normal evolution scenario in which drinking water is pumped from a well. The dose rates remain below the regulatory limit. The dose rate is dominated by the following radionuclides: Ca-41, Ag-108m, Pb-210 and Po-210.

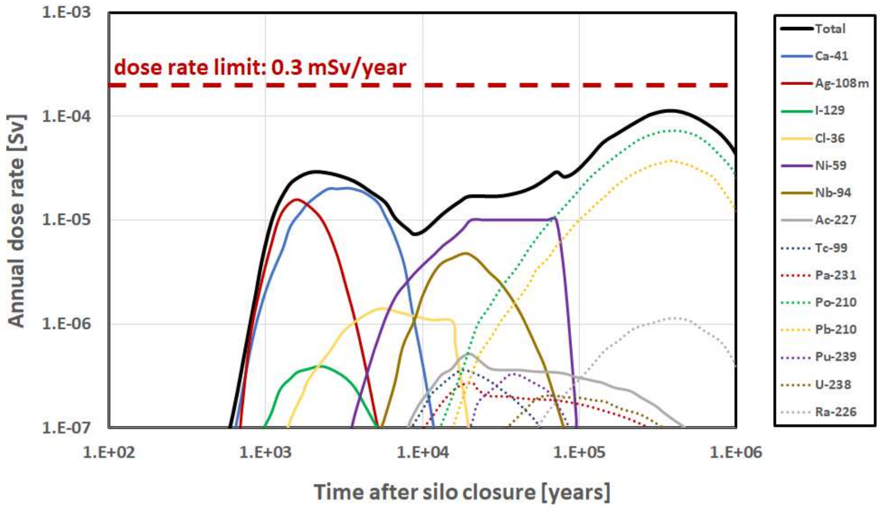

FIG. 11. Calculated dose rates based on a safety assessment for a normal evolution scenario.

6.1.5. Cost

The cost for constructing the silo facility was estimated at 43 MEUR (2013 values). The cost for acquiring the land was estimated at 8 MEUR. An additional 24 MEUR was estimated for documentation, engineering, operation procedures, and analysis. The operational cost was estimated at 320 MEur (2013 values) for 41 years of operation. These figures do not include contingencies, taxes or compensation for local communities.

6.2. APPLICABILITY OF THE DISPOSAL CONCEPT

6.2.1. Main safety features

In a silo-type facility, isolation may be provided by with concrete liners or grouts and robust waste packages and institutional control. This can provide adequate isolation from people and the environment for as long as the site is controlled. Isolation provided by the depth of the disposal zone, typically several tens of metres below the surface, is limited. This makes the concept vulnerable to long-term processes such as erosion, permafrost and glaciation and may not provide adequate isolation against human intrusion. This in turn limits the amount of long-lived waste that can be disposed in a silo-type facility.

For facilities constructed in arid environments, containment is assured by the lack of groundwater flow around the waste and the low water percolation flux through the thick unsaturated zone. In temperate or tropical environments, with a water table within metres of the surface, waste containment is provided by the performance of the engineered barriers, located in a suitable geological and hydrogeological environment. Typical designs will provide containment by a combination of:

- The engineered systems, i.e., the silo structure, the waste packages and the backfill material in which the waste is embedded, providing resistance to seismic and human intrusion impacts, and physical containment for at least several hundred years;

- The low permeability of the natural environment, resulting in limited water flow through the repository and favouring continued chemical containment for many hundreds of years.

Depending on the site characteristics, waste containment by the engineered systems can be achieved for periods of 100s to 1000s of years.

6.2.2. Possible waste inventories

A silo offers considerable flexibility to meet all likely volume requirements, from a few cubic metres up to thousands of cubic metres. The ability to construct large diameter silos enables the disposal of large waste packages and offers flexibility in designing the engineered barrier system.

The limited depth of those facilities — i.e. tens of metres — makes this concept a near surface disposal facility. This makes them unsuitable for inventories with significant activities of long-lived radionuclides in a silo. Nevertheless, the concept could be considered for inventories with only a limited activity of long-lived radionuclides. Evaluating its suitability for such inventories will require evaluating the site's stability to erosion and changes in hydrogeological conditions over a few tens of thousands of years. It will also require demonstrating that the sealing system remains effective over such long timescales.

The concept is unsuitable for HLW and/or SNF, which require isolation and containment for tens to hundreds of thousands of years, because:

- The typically shallow depth of a silo-type repository does not provide sufficient isolation from surface processes that could occur over the time periods during which concentrated long-lived waste remains hazardous;
- Dissipation of the heat from the waste may be problematic;
- There is a potential direct pathway for buoyant water movement between the waste and the biosphere, through the engineered barriers, that could bypass the geosphere.

6.2.3. Potentially suitable sites

This is a relatively flexible disposal concept with respect to siting. A wide variety of geological and geographical environments is feasible for silo-type disposal facilities.

Because the silos are located relatively close to the surface, the site needs to be stable with respect to erosion and flooding. Site mineralogical and hydro-chemical conditions need to be favourable for the long-term preservation of the concrete and cement engineered barriers used in the disposal system.

In arid conditions, with deep water tables that will not rise into the silo region, many geological formations can be considered, provided it is feasible to construct stable openings, with or without liners. In saturated conditions, the host formation needs to have low hydraulic conductivity, in environments with low lateral hydraulic gradients favouring containment.

6.2.4. Technical aspects

For practical engineering reasons and to control construction costs, this concept is limited to depths of tens of metres, especially for wider diameter silos (up to tens of metres). There are no significant technological hurdles for implementing a silo-type disposal facility at depths of tens of metres.

The construction technique will depend on diameter and any structural support systems required. Auguring can be used in softer sediments at small diameters. In saturated environments, silos will require lining to exclude water during operations. Conventional diaphragm or secant pile wall construction can be used.

Disposal sites will require a long period of institutional control: hundreds of years, as with trench or surface vault disposal facilities.

6.2.5. Conclusions

The limited depth makes the concept vulnerable to long-term processes such as erosion, permafrost and glaciation and may not provide adequate isolation against human intrusion. This limits the amount of long-lived waste that can be disposed in a silo-type facility. Because of the limited depth, the concept is unsuitable for HLW and/or SNF which require deep geological disposal.

For inventories with limited activity of long-lived waste, the concept could be considered. It offers large flexibility in terms of operational campaigns, assuming institutional control can be guaranteed during idle periods.

7. UNDERGROUND CAVERNS OR SILOS

Underground caverns or silos used for the disposal of radioactive waste are typically constructed at depths of tens up to around one to two hundred metres deep. These facilities are distinguished from the silos discussed in the previous section, which are excavated directly from the surface, by being entirely enclosed by the host geological formation and being accessed via a tunnel or shaft.

These facilities can be in a variety of topographic settings. Construction under hills allows access by gently inclined adit and can take advantage of the isolating thickness of overlying rock formations, although attention needs to be paid to potential high hydraulic gradients that could drive groundwater flow. Underground caverns are particularly suited for construction in hard, competent rock and can be lined or unlined, depending on the host rock formation. Shotcrete is often used to line cavern and access walls. Waste packages are emplaced by stacking in caverns, with or without backfill. Waste requiring a higher level of containment can be emplaced in underground silos with a more substantial engineered barrier system, typically comprising concrete silo walls with grouting between waste packages. On closure, access tunnels and shafts are backfilled and sealed.

Underground caverns or silos are operated in the Republic of Korea, Sweden, Hungary, Norway and Finland and have been considered in detail in Switzerland. Examples are described briefly below. A case study from Finland — the LLW and ILW waste disposal facility in Loviisa — is discussed in detail in Section 7.1.

The combined disposal and storage facility in Himdalen (Norway)

The Himdalen facility is used for the disposal and storage of LILW [52]. The radioactive waste is generated from the operation of two research reactors, research institutes, hospitals and the oil industry. The facility is expected to be in operation until the year 2030. It will enable the disposal of all Norwegian LILW, including waste from the decommissioning of two research reactors. The capacity of the facility is 10.000 drums (210 l each). The total radioactivity inventory will be about 570 TBq.

The facility is constructed into a hillside in crystalline bedrock, 50 m below the surface. It consists of four caverns (three for disposal and one for storage) that can be accessed by a 150 m long tunnel (see Fig. 12). After the facility closure in 2030 institutional controls will be implemented for a period of 300 to 500 years. Total construction costs were on the order of 7 to 8 MUSD.

FIG. 12. Himdalen disposal facility for LLW, Norway (Courtesy of IFE).

The National Radioactive Waste Repository at Bátaapáti (Hungary)

The National Radioactive Waste Repository in Bátaapáti accepts waste, classified under Hungarian regulation as LILW, originating from the operation and the future decommissioning of the Paks NPP [53]. Most of the solid waste is loaded, if possible, in compacted form, into 200 l drums. Liquid waste is first solidified in the NPP prior to transfer to the repository. The estimated amount of operational waste is about 18.000 m^3.

The facility consists of large disposal chambers excavated in granite rock at a depth of 250 m below a hillside (see Fig. 13). The facility is accessed by two 1700 m long ramps. A first disposal chamber — 90 m long and with a cross-section of 96 m^2 — was put into operation in 2012. It has a capacity of 4671 waste drums.

FIG. 13. The National Radioactive Waste Repository in Bátaapáti (Courtesy of PURAM): schematic view of the facility (top left), facility entrance (top right), access tunnel (bottom left) and emplaced waste containers (bottom right).

The Swedish Final Repository for Radioactive Waste SFR (Sweden)

The Swedish Final Repository for Radioactive Waste (SFR) is designed for the disposal of the LLW and ILW waste from the operation of Sweden's NPPs [54]. Waste from medical, research or industrial applications is also disposed in the SFR. SFR receives around 10 to 20 m^3/year of this kind of waste. In the future, it is intended that the facility will also accommodate decommissioning waste from NPPs.

The facility is excavated in granite rock and is situated 50 metres below the bed of the Baltic Sea (see Fig. 14). Two parallel access tunnels of ca. 1 km link the facility to the surface on land. SFR currently comprises four vaults and a single silo. The silo has a diameter of 30 m and is about 70 m high, of which about 50 m is intended for waste disposal. It is designed for disposal of ILW, comprising about 90% of the SFR's total activity content. This waste consists mostly of ion exchange resins solidified in cement or bitumen. Concrete-embedded trash and scrap metal are also disposed in the silo. Concrete or steel boxes (referred to as moulds) and steel drums placed on drum trays are used for waste packaging. The remaining 10% of the activity will be disposed of in four rock caverns. The caverns when filled will contain the bulk of the waste volume at the SFR. The caverns are about 160 m long, 19.5 m wide and have a height of 16.5 m. The waste is packaged in accordance with the requirements for the designated disposal vaults in either ISO containers (lowest activity waste) or more robust waste packaging, i.e., steel drums, large concrete containers (called tanks), or moulds for higher activity LLW. The waste is segregated and emplaced into designated vaults based on waste type and activity content. Three different vault designs are currently in use at the SFR.

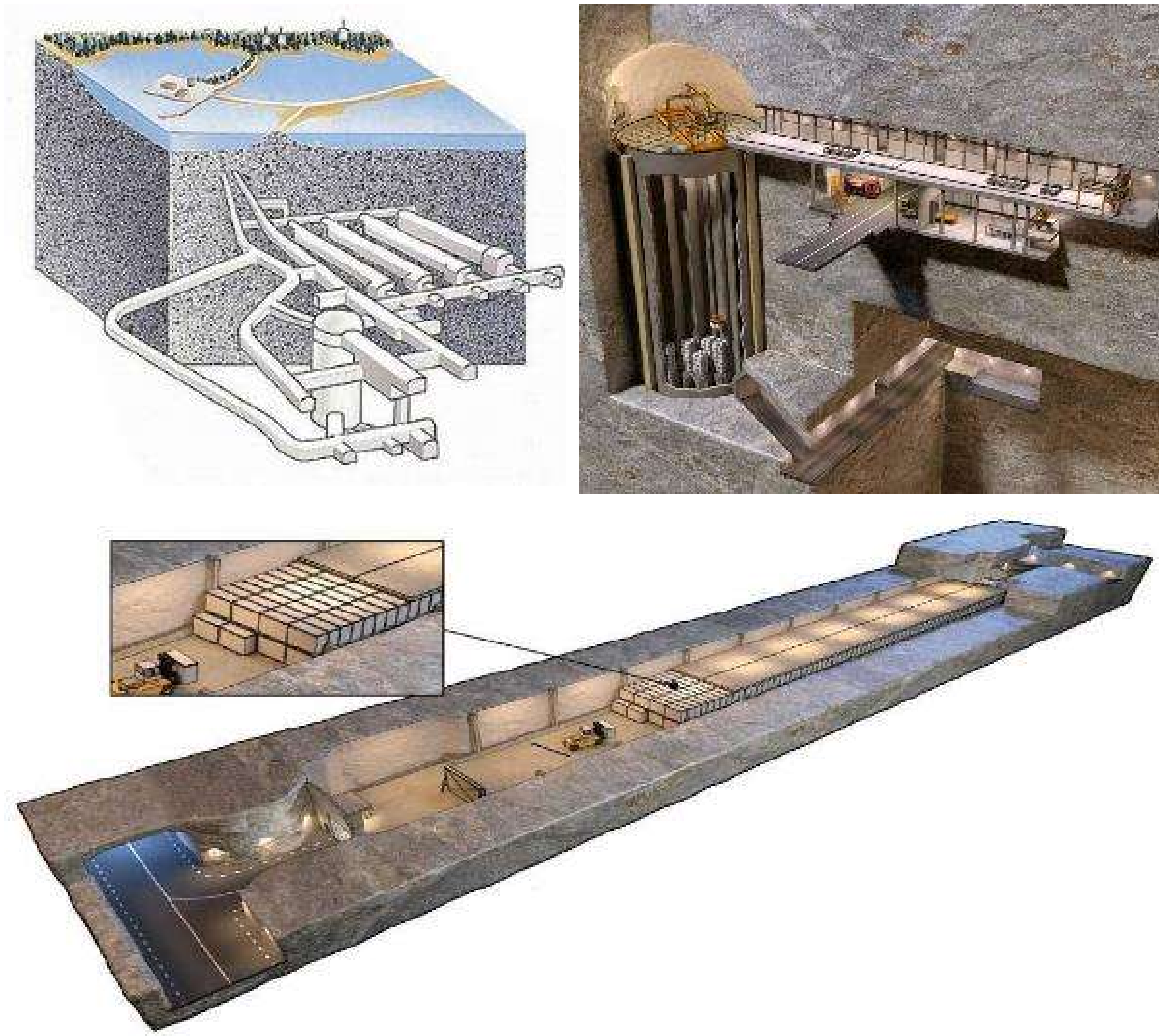

FIG. 14. Schematic picture of the current layout of the SFR disposal facility (top left), the disposal silo (top right) and a disposal cavern (bottom) [54] (Courtesy of SKB, Illustrator LAJ illustration).

The disposal operations started in 1988. Approximately 600 to 1,000 m^3 waste is disposed of every year and the total capacity of the current facility is about 63,000 m^3. The annual operating cost is around 4 million USD. An extension that will add 6 additional vaults is planned.

Wolsong LILW Disposal Centre (Republic of Korea)

The Wolsong LILW Disposal Centre in the Republic of Korea was established to dispose of both LLW and ILW. In the first phase six underground silos were constructed for the disposal of both LLW and ILW [55]. In the second phase near surface concrete vaults will be constructed for the disposal of LLW, including decommissioning waste. At this point the silos will be used primarily for ILW disposal. The disposed waste is generated from the operation of NPPs, research institutes, nuclear fuel and manufacturing facilities.

Waste drums are placed in circular or rectangular concrete containers, which are emplaced in underground silos (see Fig. 15). The first six silos at the facility are constructed approximately 80-130 meters below sea level and are 25 m in diameter and 50 m in height, with a total disposal capacity of 100.000 waste drums (approximately 16.700 waste drums per silo). The cost for constructing these silos amounts to about 1.5 billion USD.

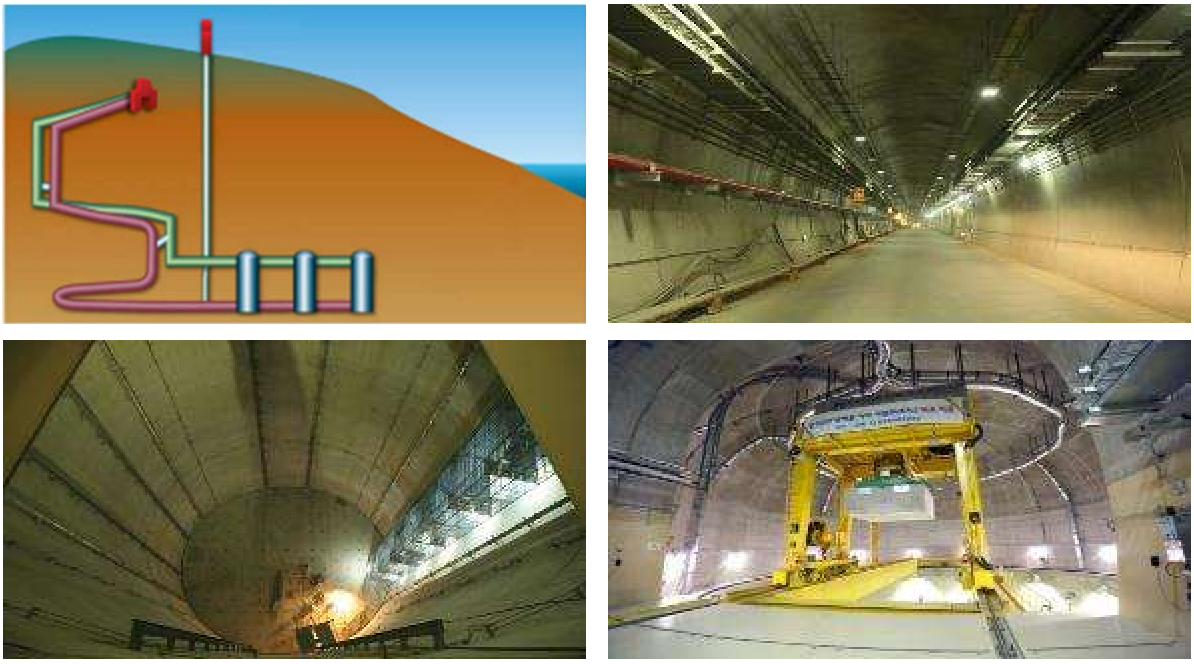

FIG. 15. The Wolsong LILW Disposal Centre (Courtesy of KORAD): schematic view (top left), operating tunnel (top right), disposal silo (bottom left) and waste container emplacement device (bottom right) (from [55]).

Ultimately, the underground facility will be used to dispose a total of 800,000 waste drums, with a total activity on the order of 10^3 TBq.

7.1. CASE STUDY: THE DISPOSAL FACILITY IN LOVIISA AND OLKILUOTO (FINLAND)

Finland has 4 nuclear power units in operation at 2 different sites: Olkiluoto and Loviisa. A fifth unit is under construction at Olkiluoto site. The Finnish waste management policy for LLW and ILW generated by the operation and later decommissioning of NPPs foresees disposal in dedicated repositories located at the NPP sites. The repository at Olkiluoto also accommodates small radioactive waste inventories generated by Finnish healthcare, research and through industrial uses. In the future a separate deep geologic repository for the disposal of SNF is planned at the Olkiluoto site.

The VLJ repository[4] at the Olkiluoto site is excavated in crystalline rock and has been in operation since 1992 [56]. It is situated about 0.8 km from the power plant and is connected to the surface by a transport tunnel and shaft. It currently consists of 2 silos, one for LLW and the other for ILW (see Fig. 16). Both silos are approximately 24 m in diameter and 34 m high and excavated at a depth of about 60 to 100 meters into the bedrock [57]. A planned extension to the facility will add additional silos for operational waste and later for decommissioning waste from all units.

[4] VLJ is an abbreviation of the Finnish word “voimalaitosjäte” which means “reactor operating waste”.

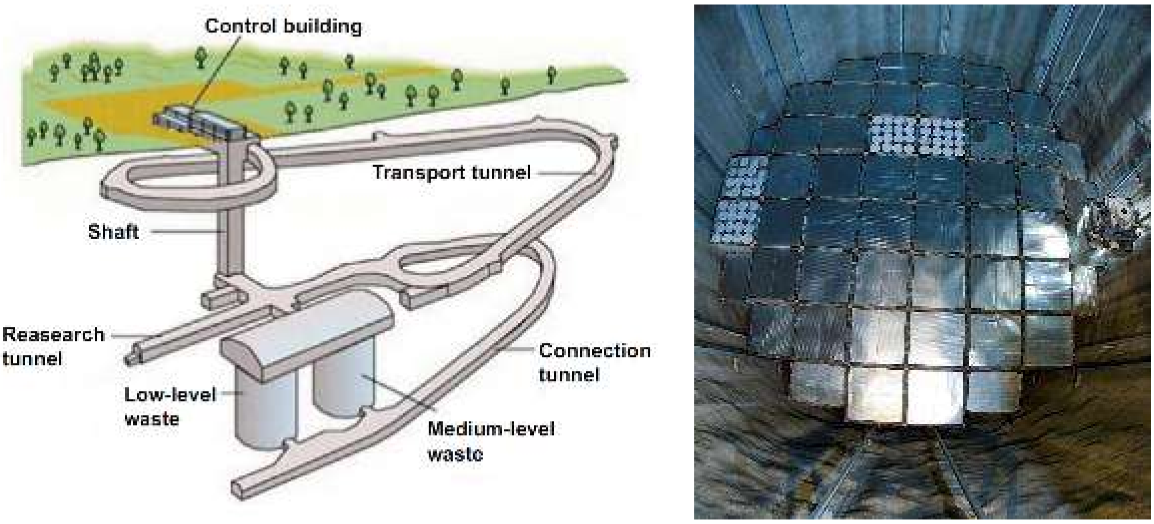

FIG. 16. Schematic drawing of the current layout of the VLJ repository for LLW and ILW (left) and top view of a silo (right) (modified from [56]) (Courtesy of POSIVA).

A similar facility following a different design concept has been in operation since 1998 to support waste disposal at Loviisa NPP [56, 58]. At Loviisa underground waste chambers were constructed as opposed to the silos used at Olkiluoto. The different approaches were selected to best match the local geologic conditions at the respective sites. This case study will focus on the Loviisa site.

7.1.1. Waste inventory

The facility is designed for the disposal of LILW from the operation and decommissioning of the Loviisa NPP. Low level operational waste includes, for example, various packaging, scaffolding, protecting, insulating and cleansing materials used in maintenance and repair work. The intermediate level operational waste includes ion-exchange resins used in the cleansing of process water.

The estimated total activity of the expected operational waste at the time of repository closure in 2068 is about 16 TBq, 80% of which can be attributed to the activity from ion exchange resins. Other waste includes evaporator concentrates, sludge and sediments, maintenance waste, filters and radiation sources. The radionuclides mostly contributing to the activity are Ni-63 and Cs-137. Currently, some 900 m^3 of liquid waste, mainly ion exchange resins and evaporator concentrates, have accumulated and are stored at the site. This waste will be solidified by cementation before disposal.

The total activity from decommissioning waste is estimated at 21.000 TBq and is almost completely due to activated metals, mainly reactor internals. The major components of the decommissioning waste, such as the reactor vessels and the steam generators, are planned to be disposed of in bulk form.

7.1.2. Disposal site

The disposal facility is located near Loviisa NPP, on Hästholmen Island, approximately 100 km east of Helsinki (see Fig. 17). Post-glacial rebound and associated sea level changes have shaped the surface environment to its present form and are expected to continue to do so for several millennia to come.

FIG. 17. Location of the disposal facility at the Loviisa NPP site at the Hästholmen Island. The power plant includes two VVER-440 units.

The facility is excavated in crystalline rock (Rapakivi granite which is 1,6 billion years old) with a thickness of roughly 10 km. The rock is fractured with fracture zones that divide the bedrock into blocks of variable shape and size. The facility is at a depth of 110 m below surface, which is well below the fresh water/salt water boundary between 30 m and 80 m below mean sea level (see Fig.18). Continued isostatic uplift will impact the hydrology at the site and the repository is expected to be completely within the fresh water zone in several millennia.

Groundwater flow takes place in large fracture zones and smaller fractures in the bedrock. Fresh groundwater mainly infiltrates through precipitation on the island with subsequent discharge to the sea.

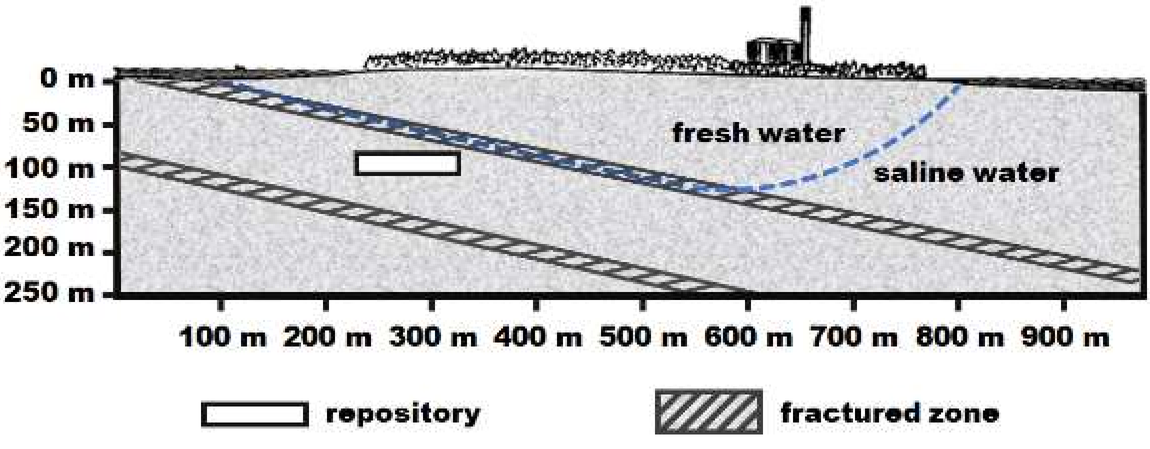

FIG. 18. Schematic drawing of the hydrogeological profile of the Loviisa site.

7.1.3. Facility design

The repository is located at a depth of 110 m below the current sea level. It is connected to the surface by a 1.170 m long access tunnel and two shafts (one for personnel and a second for ventilation). The subsurface layout is shown in Fig. 19 and consists of:

- 3 halls for operational waste;
- 1 hall for solidified liquid waste;
- 2 halls for decommissioning waste (future extension);
- 1 hall for primary circuit components beneath which 2 vertical silos for the reactor vessels are located (future extension).

The halls or caverns are located to avoid major fracture zones in the bedrock and to isolate the waste from the accessible biosphere.

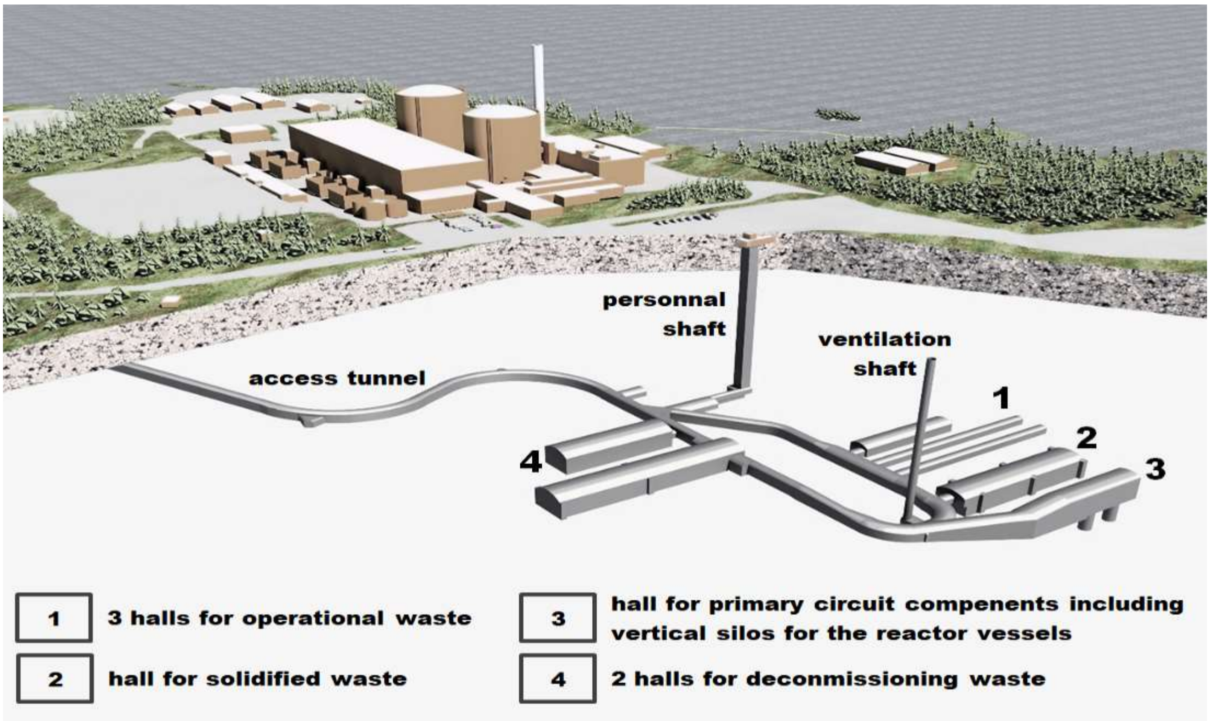

FIG. 19. Layout of the disposal facility consisting of several waste caverns (halls or silos) for different waste types. The caverns for the decommissioning waste will be excavated prior to decommissioning phase of the reactor unit; other parts of the facility have been already built (Courtesy of FORTUM).

Drums with LLW are placed in a hall equipped with a temporary cover to avoid contact with dripping ground water during the operational phase. ILW are solidified into cylindrical concrete containers (see Fig. 20). These containers are placed are placed inside concrete caverns (‘halls’ or silos) which are backfilled with concrete and sealed.

The repository will be extended to also accommodate decommissioning waste from the reactor units. The decommissioning waste halls will host miscellaneous activated and contaminated components and materials. Both halls will be equipped with concrete vaults similar to that in the solidified waste hall. The reactor pressure vessels (RPVs) will be lowered into two vertical silos with the reactor internals placed inside each RPV, after which the RPVs will be backfilled with cement. The RPVs thereby act as containers contributing to radionuclide containment. The hall above the RPV silos will be used for the disposal of large primary circuit components (e.g. steam generators and pressurisers).

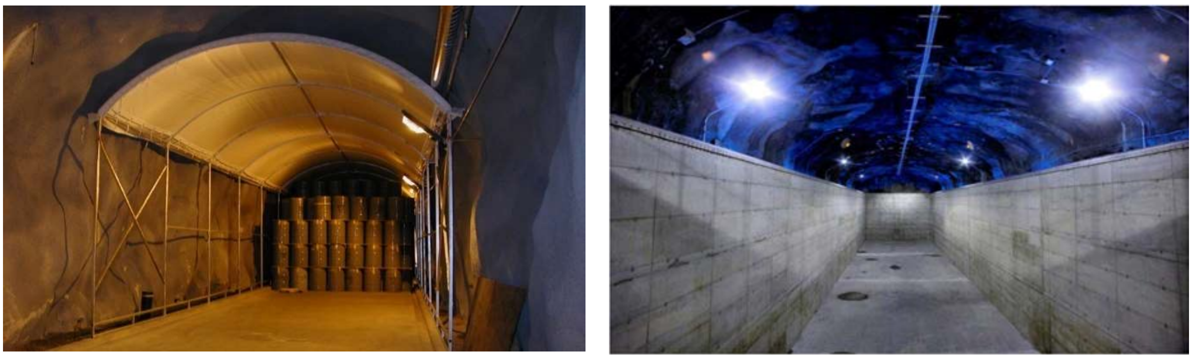

FIG. 20. Hall with LLW waste drums (left) and underground concrete vault for the disposal of ILW containers (right) (Courtesy of FORTUM).

According to current plans, the facility will be closed after disposal of the decommissioning waste in the 2060s. In the closure phase, most of the waste caverns will be filled with crushed rock and concrete plugs will be installed to seal off caverns, access tunnels and shafts in order to prevent inadvertent human intrusion and limit groundwater inflow.

The long-term safety assessment assumes that the closure of the facility is followed by a 200-year period of institutional control [59]. Institutional controls will be placed to ensure the integrity of the host rock they will not however be imposed to preclude human habitation at the surface.

7.1.4. Safety concept and safety demonstration

The safety concept for the Loviisa disposal facility is similar to that of the silo-type facility in Vrbina-Krško. The waste is embedded in concrete, which protects the waste packages by providing an alkaline environment and acts to limit and retard radionuclide releases by sorption, slow diffusion and limited water flow. Isolation from the surface environment is achieved by locating the waste caverns at sufficient depth and by closing the waste caverns, access tunnel and shafts with concrete plugs and backfill material as previously described.

Once the barrier function of the waste packages and concrete buffer no longer acts to ensure adequate containment radionuclide release to the biosphere will be determined by groundwater flow. Transport in the biosphere is governed by surface hydrology and radionuclide retention in the overburden. The dose assessment assumes a self-sustaining community living at the site utilising the natural resources and well water.

The regulatory constraint dose rate is 0.1 mSv/year for the first 10.000 years. After this period, constraints on radionuclide releases are specified in Finland by the Radiation and Nuclear Safety Authority (STUK) separately for each nuclide in Bq per year [59].

Figure 21 shows the calculated dose rates for a normal evolution scenario up to 10.000 years. The safety assessment calculations demonstrate that the dose release rates are below regulatory dose limits. The dose rate is dominated by radionuclides C-14 and Cl-36.

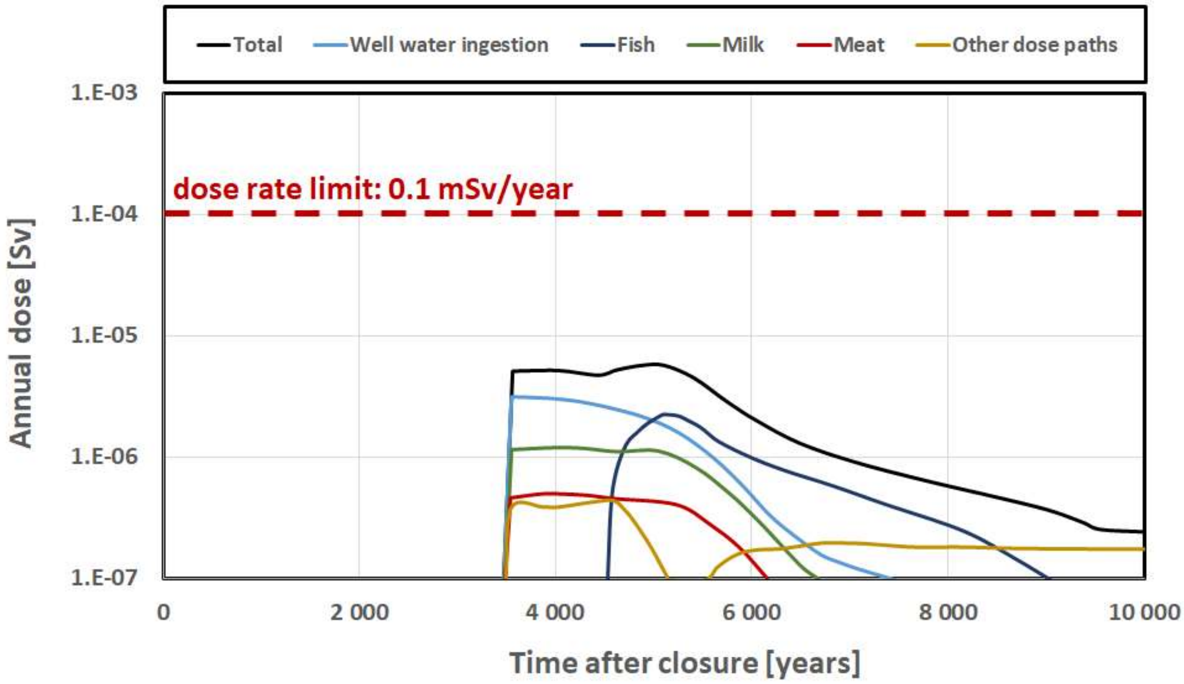

FIG. 21. Calculated dose rates for a normal evolution scenario [58].

In addition to the normal evolution scenario, the several scenarios were formulated to study the impacts of declined performance of barriers. The following altered evolution scenarios were evaluated [58]:

- Accelerated degradation of the concrete barriers and plugs in combination with microbiological corrosion of the reactor pressure vessels and steam generators;
- Initial defect in welds and microbiologically induced corrosion of the reactor pressure vessels and steam generators;
- Large earthquake damage to the concrete barriers and plugs.

The dose and release rates remained below the respective constraints in all evaluated scenarios.

7.1.5. Cost

The cost for construction, operating and closure of the Loviisa disposal facility is roughly estimated to be around 100 MEur. The estimated cost can be further broken down as follows:

- Construction of access tunnel, maintenance and solidified waste halls: 35 MEur;
- Construction of decommissioning waste halls: 35 MEur;
- Operation: 20 MEur;
- Closure: 15 MEur.

This estimate assumes the total waste volume that will be disposed of is approximately 35.000 m^3.

7.2. APPLICABILITY OF THE DISPOSAL CONCEPT

7.2.1. Main safety features

Underground caverns and silos provide isolation by the depth of the disposal zone, typically tens up to around one to two hundred metres below the surface, and the undisturbed rock overburden, which provides a natural barrier to disturbance of the waste. This barrier is the principal difference between this concept and silo-type facilities in Section 6. In a stable siting environment, this depth may provide sufficient isolation of the waste from exposure to people and the environment for tens of thousands of years. Additional isolation can be provided through the design of the concrete liners, composition of the backfill (e.g., grouting) and selection of robust waste packages. Compared to a trench facility or a near surface silo, the land control area needed to protect the sealed access is likely to be smaller.

The limited depth compared to deep geological repositories makes the concept vulnerable to long-term processes such as erosion, permafrost and glaciation. The impact of these processes and possible other processes specific to the site needs be evaluated if the disposal of long-lived waste is considered.

For facilities constructed in arid environments, containment is assured by the lack of groundwater flow around the waste and the extremely low rates of moisture permeation downwards through the thick unsaturated zone. In temperate or tropical environments, with a water table within metres of the surface, waste containment is provided by a combination of the selection of a host formation with adequately low groundwater flow rates and the performance of engineered barriers. The design of the engineered barriers will depend both on the site-specific conditions and the activity and characteristics of the waste. More than one system might be used in the same facility. Depending on the site characteristics and the repository design, waste containment by the engineered system can be achieved for periods of 100s to 1.000s of years.

7.2.2. Possible waste inventories

A wide range of waste types and forms could be safely disposed of in cavern- and underground silo-type facilities, including operational and decommissioning waste from reactors and waste from medical, industrial, research and agricultural applications. It has considerable flexibility to meet all likely volume requirements, from a few cubic metres up to thousands of cubic metres. The ability to construct caverns and silos with large dimensions enables the disposal of large waste packages and offers flexibility in designing the engineered barrier system.

In principle, this option could provide a suitable disposal solution for small volumes of ILW plus additional waste from medical, industrial, research and agricultural applications. Depending on the properties of the site and, in particular, its stability to erosion and changes in hydrogeological conditions over a few tens of thousands of years, it might not be feasible to guarantee sufficient isolation of long-lived waste. These might then need to be separated out for deeper disposal. Nevertheless, the concept is considered to provide a higher degree of isolation than silo-type facilities, making the disposal of such waste potentially feasible.

The limited depth makes the concept unsuitable for HLW or SNF which require disposal in a deep geological repository.

7.2.3. Potentially suitable sites

A variety of geological and geographical environments is feasible for underground cavern and silo facilities. Sites are preferred where mineralogical and hydrochemical conditions are favourable for the long-term preservation of the concrete and cement engineered barriers. Furthermore, a sufficiently strong and competent host rock will help to minimise rock support requirements and allow the facility to be easily maintained during the operational period. For a small inventory, it may prove to be less cost effective to construct a facility in weak rocks requiring substantial support. Under these circumstances a silo-type facility (constructed from the surface) might present more economical solutions.

Because the disposal depth is relatively close to the surface, the site needs to be stable with respect to erosion. Continued isolation needs to be ensured and the period over which there needs to be high confidence in stability could be in the order of several thousands to a few tens of thousands of years.

In arid areas with long-term stable deep-water tables and a thick unsaturated zone, such that ground water will not rise to the level of the cavern or silos, many geological formations can be suitable, provided it is feasible to construct stable openings, with or without liners. In saturated conditions, the host formation needs have low hydraulic conductivity, with environments with low lateral hydraulic gradients favouring containment: there needs be little or no potential for upward groundwater flow under current or likely future climate scenarios – again, over a period of several thousands to a few tens of thousands of years.

Access to a suitable volume of rock might be possible by tunnelling into a hillside or mountain, which can provide additional isolation depth, provided hydraulic conditions (groundwater gradients and fluxes) in the disposal zone are acceptable. Care is also required to ensure that such locations are stable with respect to erosion, landslips and flooding.

7.2.4. Technical aspects

Several cavern-silo disposal facilities are being operated, as is demonstrated from the examples at the beginning of this section. Their construction, operation and closure do not pose any particular technical challenges.

If a suitable siting environment is available, the construction of a cavern or silo facility into a hillside could be considered. The construction and access may be simplified and there may be the option to gain additional isolation by extending the access works deeper into the hill. Mining regulations might require that there is more than one access tunnel into the facility.

Experience in operating cavern-silo facilities suggests that larger caverns for LLW might not require backfilling at the time of closure, but this will need careful consideration with respect to safety case requirements and site-specific factors. In general, backfilling of a small disposal cavern would provide long-term physical and chemical stability that could be advantageous to the safety case. The access tunnels will, in any case, require at least partial backfilling to deter intrusion and will need to be sealed to prevent access after closure.

Except in highly arid environments, water management will be a central issue in both operational and post-closure safety. The hydrogeological environment, the location of the caverns and the access inclines need to avoid that tunnels could provide a preferential flow pathway out of the repository after closure. Consideration of the flow regime will also affect decisions on the most appropriate tunnel backfilling.

Protection of the sealed access areas will require institutional control arrangements, possibly extending for hundreds of years.

7.2.5. Conclusions

Large waste packages and a wide range of waste forms could be disposed of in an underground cavern-silo facility. In principle, the whole of a small national inventory might be disposable. Facilities constructed into the sides of hills or mountains could be of particular interest, provided the area is sufficiently stable. The limited depth compared to deep geological repositories makes the concept vulnerable to processes such as erosion and glaciation, which in turn could affect its suitability for the disposal of long-lived waste. Because of the limited depth, the concept is not suitable for the disposal of HLW or SNF.

8. CONVERTED MINES

Disused mines have been converted into disposal facilities for radioactive waste in several countries. They offer the advantages of existing underground space, access infrastructure and availability of geological data and operating experience. There might also be a locally skilled work force with extensive knowledge of working in the specific underground environment of interest.

There are also significant potential disadvantages that are specific to such disposal in a converted mine. The mineral resources that have been exploited often occur in complex geological structures, mining activities might have caused considerable damage to the rock and modified the hydrogeological regime, and there might be residual resources that have not been extracted and which might form a target for future exploitation. All of these factors can make it more difficult to construct a post-closure safety case.

A particular issue is that the space requirements for disposal are likely to be a minute fraction of the existing underground space, but the eventual safe closure of the disposal facility requires all or most of the other mine spaces to be addressed in the safety case managed. This could lead to both technical difficulties and increased costs. Consequently, although potentially attractive, options for disused mine disposal need to be approached with caution.

Examples of the use of converted mines are the Baita Bihor in Romania, the Richard and Bratrství repositories in the Czech Republic, and the Konrad and Morsleben (ERAM) repositories in Germany. The latter repository is presented as the case study in Section 8.1.

The Baita Bihor radioactive waste repository (Romania)

The Baita Bihor radioactive waste repository has accepted LLW and some ILW from industry, medical establishments and research activities since 1985 (see Fig. 22). The waste includes sludges, evaporates and ashes, solid waste (including shredded plastics and small components), activated materials, ion-exchange resins, spent sealed sources and components from the decommissioning of research reactors [60]. Most waste is conditioned in standard containers (mostly 220 litre drums).

The repository is located in a disused uranium mine in the Bihor Mountains, which are in the western part of the Carpathian Mountains. The repository was originally an exploration drift with several galleries in an open pit uranium mine. When the mine became exhausted in the early 1980s, the repository was converted into a disposal facility by excavating chambers transversally to the central gallery. Chamber volumes vary from 10 m^3 to 250 m^3. The disposal zone is situated in the unsaturated zone, several hundred metres above the water table.

FIG. 22. The Baita Bihor repository: access gallery (left) and stacked waste drums (right) (Courtesy of IFIN-HH).

The total capacity of the repository is around 21.000 standard waste drums (220 l). It is estimated that disposal activities will continue until 2040.

The Richard and Bratrství repositories (Czech Republic)

In the Czech Republic the old Richard and Bratrství mines are used for the disposal of radioactive waste (see Fig. 23).

The Richard repository was constructed in a former limestone mine. It has been used since 1964 for the disposal of institutional LLW and ILW, as defined by the Czech waste classification scheme. The repository is at a depth of about 30 to 70 m below ground surface. The repository field is accessible via a horizontal gallery. The disposed waste consists of solid material, low activity liquid waste and sludges. A significant inventory of organic material might be present (including paper, cotton wool, wood, rubber, gloves, textiles, plant waste, bedding, straw, animal excrement and animal carcasses) [61].

The original limestone mine was excavated into a hillside and was subsequently used for military production during World War II, leaving several well-developed underground chambers. The total available volume amounts to about 17.000 m^3, of which 10.250 m^3 is used for waste disposal. The remainder is used as service areas. The repository capacity enables further disposal until 2025. The waste disposal chambers are covered by approximately 30 to 70 m of marl. The repository is accessed from the surface through a horizontal tunnel. The distance from the entrance to the first disposal chamber is approximately 100 m.

The Bratrství repository was developed by converting a gallery in a former uranium mine into a disposal gallery for NORM waste and some radium sealed sources. The disposal facility was operated from 1974 through its planned shutdown in 2020. The repository itself makes up only a small part of the mining works, which comprise more than 80 km of tunnels. The disposal gallery has a capacity of around 360 m^3 of waste.

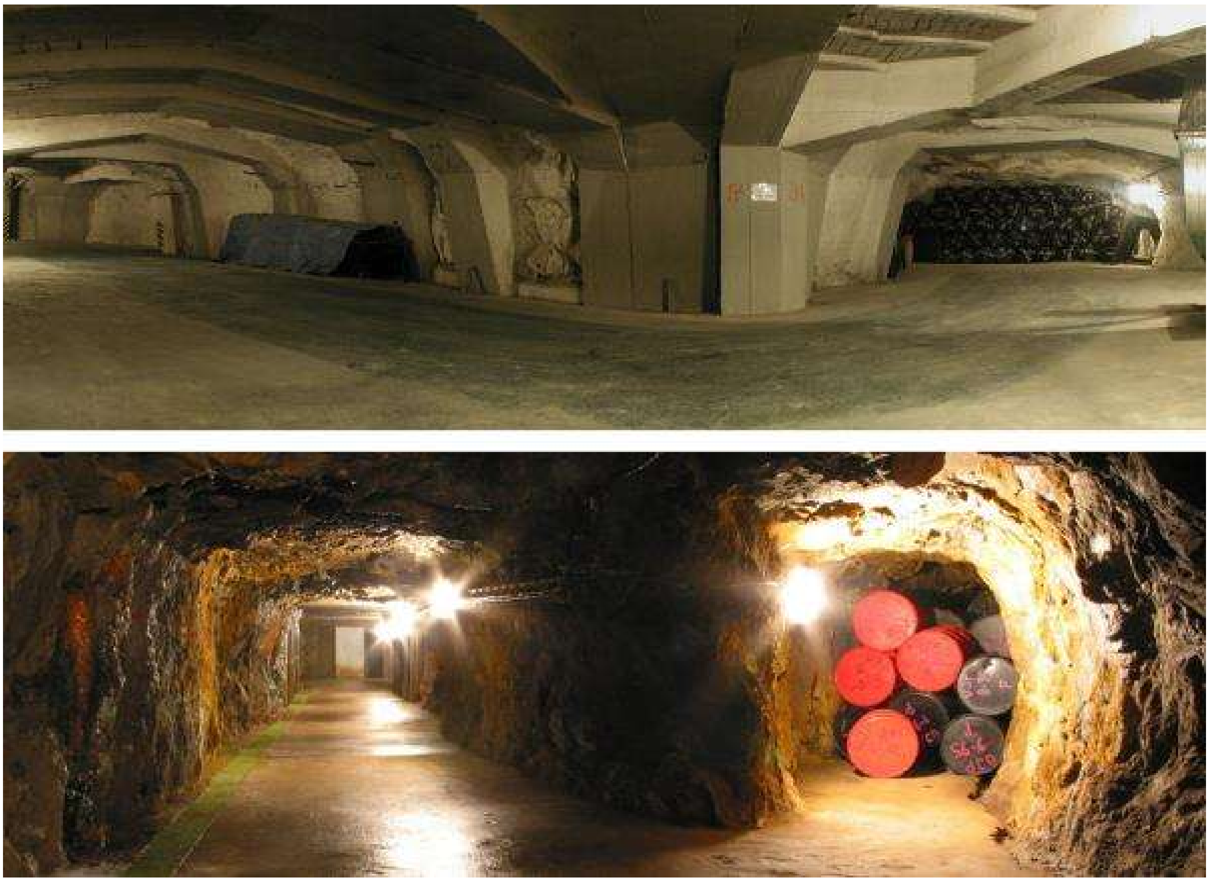

FIG. 23. The Richard repository for institutional waste (above) and the Bratrství repository for NORM waste (below), Czech Republic (Courtesy of SURAO).

An early repository that operated from 1959 to 1965 was installed in a former limestone mine near the village of Hostím. Operations ceased at Hostím once the Richard repository became operational. The Hostím repository was backfilled with concrete and sealed in 1997.

The Konrad repository (Germany)

The Konrad mine is a former iron ore mine located near the city of Salzgitter. It was operated from 1961 to 1976. Mining operations ceased in 1976 as continued mining was no longer economical. Currently the old shaft is being converted into an entrance shaft to a repository for radioactive waste with negligible heat generation (LLW and ILW) (see Fig. 24). The repository will not include the previous mining areas but will be newly excavated rooms.

FIG. 24. The Konrad repository for LLW and ILW: mine shaft (left) and construction of a permanent transport drift (right) (Courtesy of BGE).

Early after the mining operations ceased, the geologic condition at the mine were recognized as being potentially favourable to the siting of a repository for radioactive waste. The iron ore body was found to be located at a depth between 800 m and 1.300 metres. The deposit itself was found to be sandwiched between thick layers of low permeable clays and marls lying both above and below the formation. Confirmatory studies were conducted from 1976 to 1982 with positive results and a licensing process was initiated. After a long process a final license to construct was granted in 2002 and subsequently confirmed by the courts in 2009.

The licence allows for the disposal of maximum 303.000 cubic metres of radioactive waste (package volume) with negligible heat generation. Work is currently underway to complete the conversion activities including the excavation of new emplacement chambers. The waste emplacement chambers are located at a depth between about 800 m to 1100 m. The chambers are about 7 m wide and 6 m high. The longest chamber is approximately 1000 m long.

8.1. CASE STUDY: THE ERAM DISPOSAL FACILITY IN MORSLEBEN (GERMANY)

In 1970 the NPP operator of the former German Democratic Republic (East Germany) bought the Morsleben mine, a former rock salt and potash mine, to convert it into a radioactive waste disposal facility [62]. The disposal facility has two shafts which are approximately 1.7 km apart (see Fig. 25). Those provide access to a widespread system of cavities, drifts and blind shafts, between 380 m and 630 m deep. The mine extends over a length of ca. 5.6 km and crosswise over 1.7 km at maximum. The cavities have dimensions of up to 100 m in length and 30 m in width and height. The total volume of the cavities is about 8.9 million m³ of which approximately 5.34 million m^3 are still open.

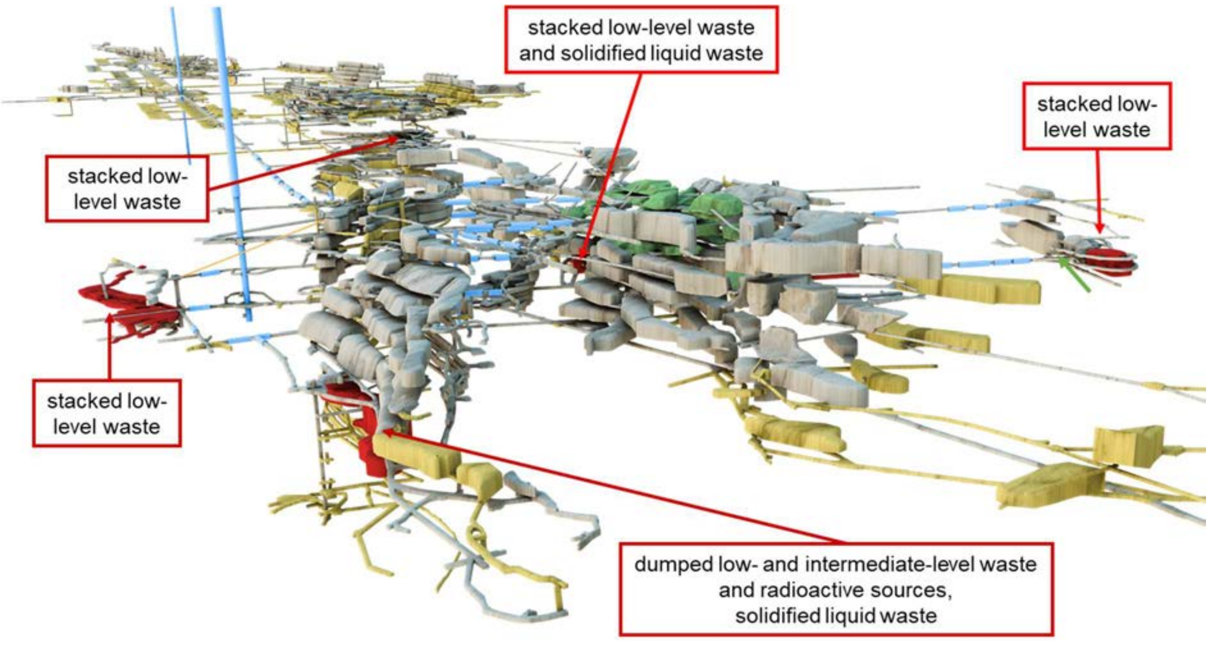

FIG. 25. Layout of the Morsleben repository (Courtesy of BGE).

Disposal operations started in 1971 in rock cavities some 500 m below the surface. The disposal operations have been stopped in 1998 and today the facility is being kept open to implement closure measures (extensive backfilling, grey colour in Fig. 25; drift and shaft seals, blue colour in Fig. 25) after getting a license to do this.

8.1.1. Waste inventory

The Morsleben disposal facility was used for the disposal of LLW and ILW, predominantly short-lived. This waste originated from the operation of NPPs, decommissioning and applications of radionuclides in research, industry and medicine.

In total ca. 36.800 m³ waste was disposed of which ca. 8.250 m³ was liquid waste. Also 6.600 disused sealed radioactive sources were placed in the facility. The total activity amounted ca. 360 TBq in 2015.

Important radionuclides in the radionuclide inventory and their activities in 2015 are presented in Table 2.

TABLE 2. MAIN RADIONUCLIDES IN THE RADIOACTIVE WASTE INVENTORY DISPOSED OF IN THE MORSLEBEN REPOSITORY

Radionuclide	Total activity [TBq]	Radionuclide	Total activity [TBq]
Cs-137	110	H-3	1
Co-60	66	Pu-241	0.6
Ni-63	14	Sm-151	0.3
C-14	3	Ni-59	0.2
Sr-90	2	Tc-99	0.1

Figure 26 shows how the radiotoxicity of the radionuclide inventory evolves over time.

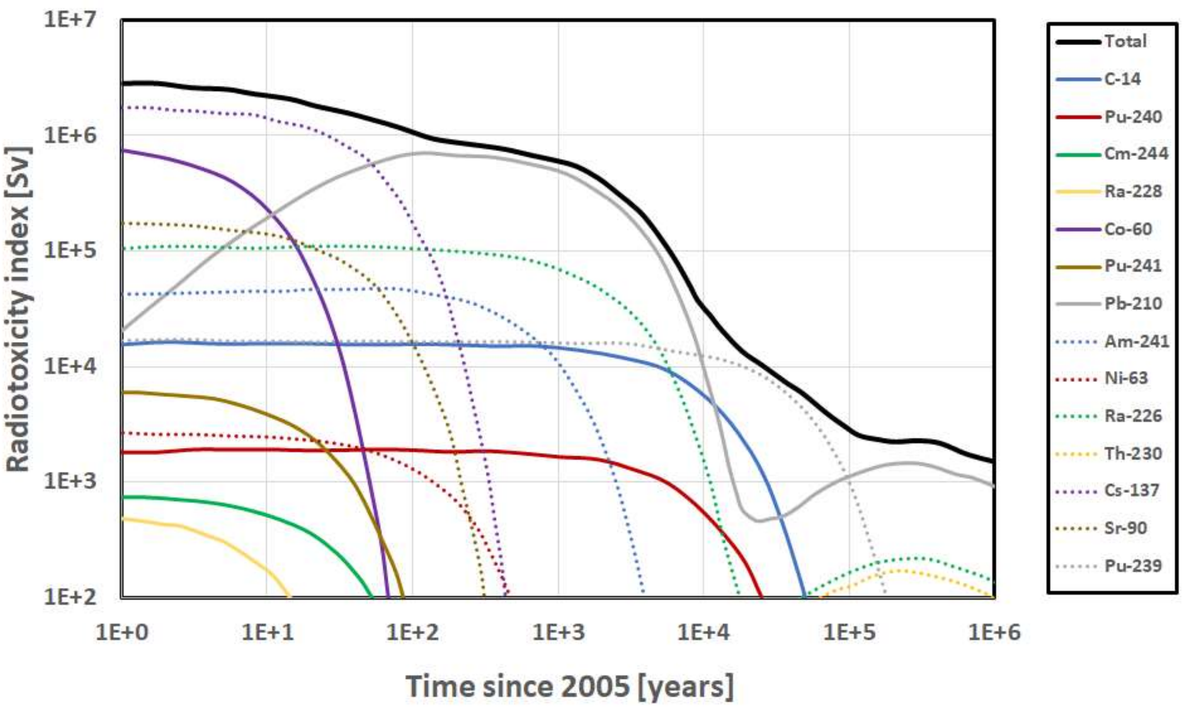

FIG. 26. Evolution of the radiotoxicity index.

8.1.2. Disposal site

The Morsleben disposal facility lies between the cities of Braunschweig and Magdeburg in Saxony-Anhalt. The two shafts Bartensleben and Marie of the mine are ca. 1.7 km apart from each other. Figure 27 shows the above ground infrastructure of the Bartensleben shaft where the radioactive waste has been delivered and transported underground.

FIG. 27. The Bartensleben shaft of the Morsleben repository (Courtesy of BGE).

The Morsleben disposal facility is located in the salt structure of the Aller valley. This salt structure extends over a distance of ca. 50 km, from the city of Wolfsburg in the northwest to the village of Seehausen in the southeast. The Aller valley is bordered by the Lappwald depression in the southwest and the Weferlingen Triassic plate in the northeast. The mine has been excavated at a depth extending from 380 m and 630 m below the ground surface. The Bartensleben shaft is located ca. 1 km to the west of the river Aller. The top of this salt structure is 140 m below sea level (ca. 275 m below ground surface) and its thickness varies between 330 m and 580 m. The disposal areas are at a depth between 480 m and 530 m below ground surface. The salt structure is isolated from the overlying strata by a up to 240 m thick gypsum cap rock with a very low hydraulic conductivity (see Fig. 28). This cap rock is overlain by permeable sediments of Cretaceous and Quaternary in the western part and by mainly low permeable consolidated rock in the eastern part.

Groundwater movement in the Lappwald depression and in the Weferlingen Triassic plate is directed predominately to the Aller valley. Groundwater exfiltrates via the permeable Cretaceous and Quaternary sediments of the Aller valley in the region of the river Aller. Groundwater travel times between the top of the salt structure and the biosphere amount to thousands to tens of thousands of years.

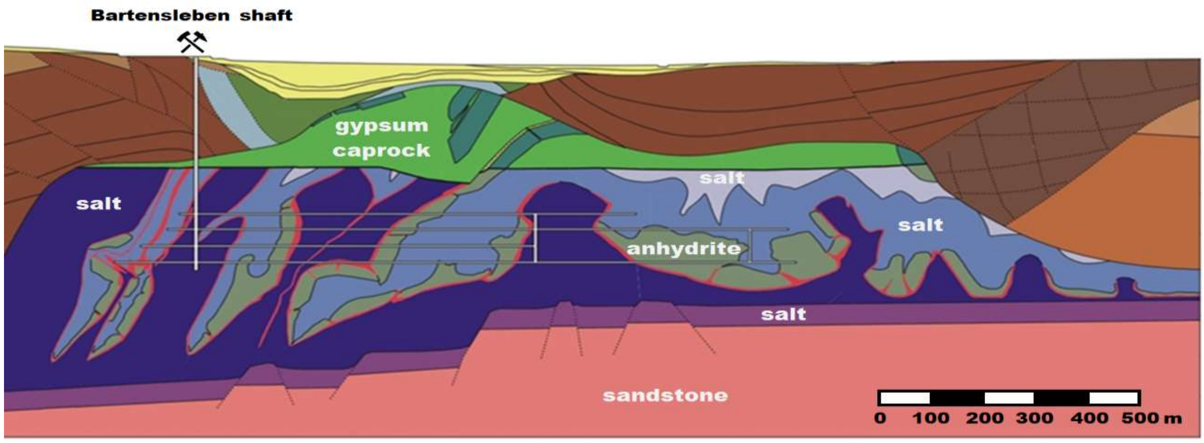

FIG. 28. Geological profile of the Morsleben mine (Courtesy of BGE).

8.1.3. Facility design

Different areas of the mine were used for the disposal of different waste types which have been disposed of in different ways. Most solid waste is contained in waste drums that are stacked, but in one area solid waste is dumped. Solid waste with a higher activity is lowered into closed chambers from a drift above through shielding lock systems. Liquid waste is disposed of by in-situ solidification using lignite fly ash as a hydraulic binder.

As can be seen in Fig. 25, the disposal areas are mainly in the border areas of the mine. Some disposal chambers are very large (see Fig. 29). One chamber has a capacity of about 20.000 m³, theoretically sufficient for LLW that is generated in Germany in 7 years [63].

FIG. 29. Disposal of solid waste by stacking waste drums (Courtesy of BGE).

The facility currently is being kept open to implement closure measures after getting a license to do this. These closure measures include backfilling the facility and installing seals in the shafts and between the major disposal areas. Backfilling is necessary to stabilize the cavities thereby limiting rock convergence and preventing the creation of new flow paths, a dipping or buckling of the ground surface and a potential brine intrusion into the remaining mine openings. It also functions as a physical and chemical barrier that contributes to the waste containment (see further below in Section 8.1.4). Salt concrete will be used as backfilling material. Due to the mining activities, there are large cavities with dimensions of up to 100 m in length, 30 m in width and in height. An estimated 4 million m^3 of salt concrete are needed to backfill the facility. Fig. 30 shows a backfilling operation.

FIG. 30. Picture of backfilling a mine opening as an advanced activity prior to final closure (Courtesy of BGE).

In total, 25 seals will be needed to separate the disposal areas from other parts of the mine. Those seals are long concrete structures (see Fig. 31). The shafts will be sealed by a system consisting of crushed rock, asphalt, gravel, sand and clay.

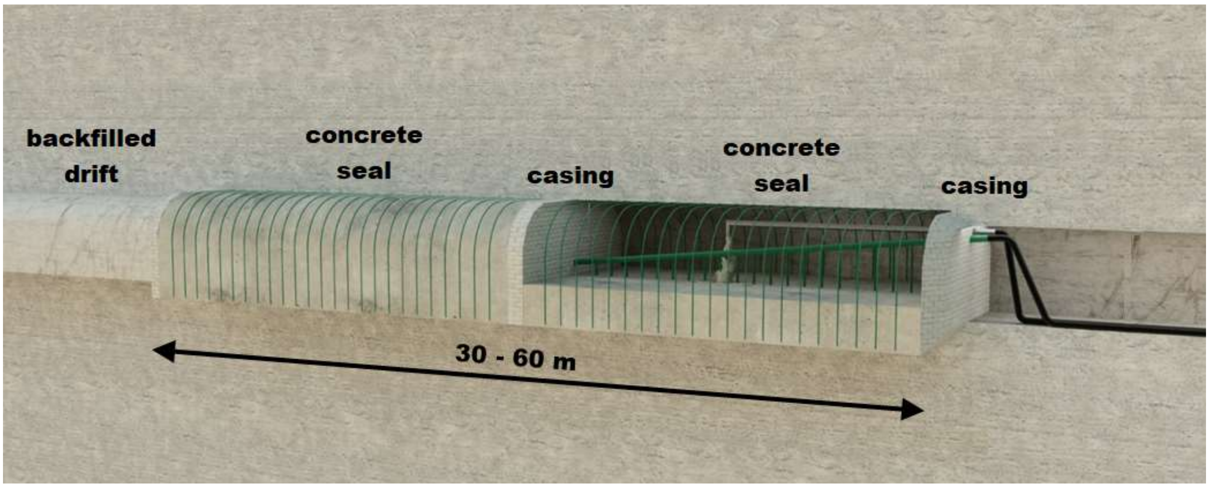

FIG. 31. Drift seals consisting of a long body of concrete (Courtesy of BGE).

8.1.4. Safety concept and safety demonstration

The safety concept primarily relies on the disposal depth and on the host rock formation which functions as a geological barrier. The engineered barrier system supporting the safety functions of the host rock formation consists of the backfill material and seals. The role of the backfill is to

- Protect the ground surface by limiting subsidence and inclination;
- Provide long-term integrity of the salt barriers around the waste emplacement areas and at the top of the salt structure;

- Limit the amount of open space in the mine to limit the convergence of the mine openings;
- Limit the amount of liquid intrusion into the salt structure to limit the amount of salt dissolution caused by liquid that is not satisfied by sodium chloride;
- Limit and delay liquid intrusion into the waste disposal chambers;
- Act as a physical barrier limiting water flow;
- Act as a physical and chemical barrier delaying and limiting radionuclide releases.

The role of the shaft seals is to re-establish an intact barrier between the salt structure and its overburden and to prevent liquid intrusion into the mine openings. The role of the drift seals is to prevent or at least to delay liquid movement into, and contaminant transport out of the waste disposal areas. No credit is taken from the containment capacity of the waste packages because this effect is considered negligible.

Three laws apply to the facility:

- The Mining Act prescribes that ground surface subsidence and inclination are limited;
- The Water Resources Act prescribes that the groundwater is protected from unacceptable contamination;
- The Atomic Energy Act is focused on radiological protection and prescribes a prevention against harm according to the state-of-the-art of science and technology.

The latter is further specified by following dose constraints:

- Dose constraint for normal evolution evolutions: 0.1 mSv/year;
- Dose constraint for less probable system evolutions: 1.0 mSv/year.

It is furthermore required to optimise the system focussing on probable system evolutions taking into account less probable and improbable system evolutions as well as human intrusion.

The post-closure safety assessment considers two main evolution scenarios, one where liquid intrusion into the mine openings is very limited, and the other where liquid intrusion takes place with considerable amount.

The first scenario leads to gas pressure increase in different parts of the mine due to rock convergence and the production of gas from the corrosion of metallic parts and the degradation of organic material. According to this pressure build-up the integrity of the salt barrier could be violated at later times and then gas could escape out of the salt structure. At that time radionuclides that could be transported via the gas phase have been decayed to negligible amounts. A transport of radionuclides via the liquid phase does not take place.

In the second scenario the mine openings are filled with liquid. Rock convergence and gas production in turn leads to liquid and gas that are squeezed out of the disposal areas into the remaining part of the mine and subsequently through the cap rock and overburden, into near surface groundwater. Radionuclide sorption by argillaceous facies in cap rock and overburden as well as dilution in the groundwater are taken into account.

Figure 32 shows the calculated dose rates for this scenario using two different safety assessment models. Both models assume that the part of the mine which is not sealed by the drift seals is filled with water after 7.500 years. Then the pressure in this area can start to build up and the drift seals will be penetrated slowly leading to liquid intrusion into the sealed disposal areas and finally to radionuclide transport.

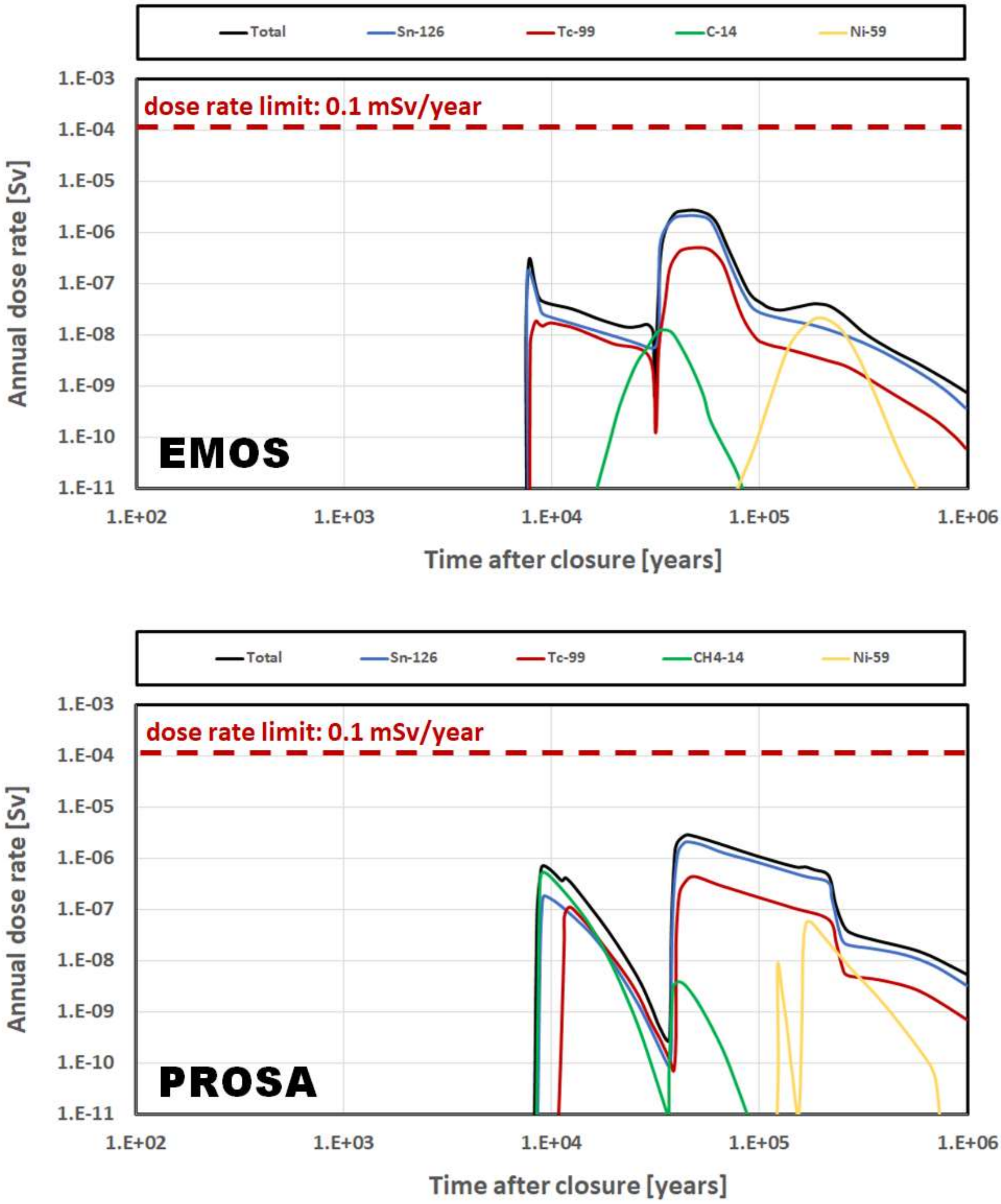

FIG. 32. Calculated dose rates from the Morsleben repository disposal facility using the EMOS model (top) and PROSA (bottom) models.

Both models produce similar results showing two peaks in radiation exposure. The first peak is caused by the waste in disposal areas that cannot be sealed. The second peak results from the waste in the sealed disposal areas. The delay of the second peak is caused by the resistance of the seals to corrosion by brine for more than 10.000 years.

The calculations based on the reference values of all parameters show that the dose maxima remain two orders of magnitude below dose constraint. The radionuclides dominated the radiation exposure are Sn-126, Tc-99 and C-14. The calculations also show that most part of the radiotoxicity remains in the disposal areas, due to the decay of the radionuclides.

Sensitivity analyses and several alternative scenarios — such as one where radionuclide sorption is not taken account of — and human intrusion scenarios were considered as well. In all those cases the calculated radiation exposure was below the applicable dose constraints.

The results of these safety assessments have been published in 2009 (e.g. [63-64]). A public hearing took place in 2011. According to a recommendation of the German Nuclear Waste Management Commission in 2013 — an advisory body to the responsible German ministry — the safety assessments have to be adjusted to the state-of-the-art, which developed significantly since 2009. Therefore, the safety demonstration presented here is preliminary and only indicative.

8.1.5. Cost

The overall cost for operating the Morsleben disposal facility until 2017 amounts ca. 1.4 billion euro. The annual cost for keeping the facility open is around 50 million euro. The cost for closing the facility — backfilling the cavities and installing seals — is estimated at 1.2 billion euro ± 30%.

8.2. APPLICABILITY OF THE DISPOSAL CONCEPT

8.2.1. Main safety features

For deeper mines, the safety concept for waste disposal does not a priori differ from that of purpose-built, mined geological disposal facilities. The level of isolation provided depends on the depth but can be of the same order as for a geological disposal facility. Indeed, in the case of the Konrad mine described above, the depth is considerably greater than the planned depth of several national geological disposal facilities for HLW or SNF. However, some converted mines are at similar depths to the cavern examples discussed in Section 7 — several tens to around a hundred metres — thus providing only a similar level of isolation to those concepts.

Again, for deeper mines, the level of containment provided can be similar to that of purpose-mined geological disposal facilities, provided the geological environment has suitable hydrogeological characteristics. Because mine locations were not chosen with respect to their containment properties, the implementer of a disposal facility needs to accept whatever conditions present themselves. In the case of the Konrad repository, the containment properties of the over and underlying formations are excellent. Converted mines at shallower depths or in less favourable geological environments might need to consider enhancing containment through the use of engineered barriers for some categories of ILW and HLW.

In all cases, the post-closure safety case will need to take account of the complexities specific to the environment of old mines, discussed at the beginning of this section, including:

- Possible disturbances to geological stability and the hydrogeological regime caused by the mining activities;
- Possibly complex geometrical structures and complex geology;
- The presence of unused openings or investigation boreholes (which may not always be documented);
- Impact of mineral resources on probability of human intrusion.

The extent to which such complexities will require evaluation and potential mitigation will depend largely on the waste inventory that is disposed of and the depth of the facility. The long-term safety provided by disposal of LLW in a deep mine is likely to be insensitive to even major perturbations or uncertainties caused by some of these factors.

8.2.2. Possible waste inventories

A wide range of waste types and forms could be safely disposed of and the potentially large cavities could accommodate large waste packages and volumes. The highest quality disused mines can provide high levels of isolation and containment and are in principle capable of accepting any type of radioactive waste. Deep mines with less suitable characteristics are also likely to prove suitable for disposal of all of the waste in the majority of Member States with small inventories. However, considerable care would be needed in evaluating the containment potential if such facilities were to be considered for the disposal of HLW or SNF.

Shallower mines can be categorised with underground caverns and silos in terms of the waste that they can suitably accommodate (see Section 7.2.3). Depending on the properties of the mine and, in particular, its structural stability and susceptibility to erosion and changes in hydrogeological conditions over a few tens of thousands of years, it might not be feasible to guarantee sufficient isolation of long-lived waste, which might then need to be separated out for deeper disposal.

8.2.3. Potentially suitable sites

The most suitable mine locations for conversion to disposal facilities would possess similar geological and environmental characteristics to those of a purpose-built, mined geological disposal facility. A low permeability host formation and/or low permeability overlying formations would provide great confidence in containment. However, for the reasons discussed above, implementers need to be prepared to work with the conditions available, which requires careful consideration of potentially adverse features.

A suitable disused mine preferably has a limited volume that needs to be backfilled. Both for safety reasons (ensuring the waste remains isolated and there is no remaining open access from other workings; having confidence that the groundwater system will not be perturbed after closure, etc.) and for cost reasons, smaller volumes would be preferable. For example, the estimated cost for backfilling the ERAM disposal facility in Morsleben (see Section 8.1 and Fig. 25) is significant.

8.2.4. Technical aspects

Converting a mine into a disposal facility can require significant refurbishment works or additional excavations to make the facility suitable for its new purpose. Bringing the access works and disposal areas up to the standards of an operational nuclear facility could require considerable work to stabilise openings and install water management systems. Backfilling a disused mine might also turn out to be a significant task and cost and its sealing could prove more challenging than, for example, a mined underground cavern or silo.

8.2.5. Conclusions

Although many disused mines might prove to be unsuitable for conversion, it is worth considering those that might be available as part of a national options study. A high-quality disused mine offers several advantages, especially if the waste inventory is diverse and contains significant volumes of materials. As the safety concept for waste disposal in disused mines does not a priori differ from that of purpose-built, mined geological disposal facilities, deeper mines can be considered for the disposal of all waste categories, including HLW and SNF. The potentially large cavities in old mines may enable the disposal of large waste packages and volumes.

The advantage of this concept is that parts of the underground infrastructure already exist, which can result in cost savings. However, converting a mine into a disposal facility can require significant investments, as can be seen from the example of the Konrad facility (Germany). Moreover, the closure of the facility may also become very costly, as is illustrated by the Morsleben ERAM repository (Germany). Those costs could outweigh the cost savings offered by using the mining infrastructure and make a purpose-built geological disposal facility more cost effective than a converted mine. Furthermore, developing a robust safety case for disposal in a converted mine could be challenging due to the possibly complex geology and disturbances from the mining activities. Also, the presence of mineral resources could increase the probability of human intrusion.

9. BOREHOLES AT INTERMEDIATE DEPTH

In the context of this report, the category of ‘boreholes at intermediate depth’ applies to cased drill holes up to a few tens of centimetres in diameter and tens to hundreds of metres deep, constructed using widely available drilling technology. The disposal of certain types of radioactive waste in boreholes can be a safe, cost effective and efficient solution for small volume waste inventories as the construction and closure of a borehole requires a limited area and infrastructure and can be established in a relatively a short time.

Depending on the isolation and containment that is required, the borehole depth may be in the order of tens of metres, up to hundreds of metres — the greater depths providing conditions approaching those of geological disposal facilities.

Borehole diameters in the range of tens of centimetres pose dimensional and volumetric constraints on the waste packages that can be emplaced in a borehole. They can be ideal for small packages of higher activity waste, such as DSRS.

The concept of borehole disposal can be combined with other disposal options. Assume, for example, that a cavern- or silo-type disposal facility offers a safe disposal solution for most waste in a national inventory, apart from some long-lived sources, for which it might not be able to provide sufficient isolation. It could then be considered to drill a separate disposal borehole for the sources, possibly at the same site, or even from within a cavern- or silo-type disposal facility.

A concept for borehole disposal of DSRS has been developed over the last two decades. This concept requires that the waste be first conditioned into suitable, specifically licensed, waste packages which in turn are lowered into a cased borehole that is subsequently sealed. The concept is explained further in the case study presented in Section 9.1. The concept should not be confused with the shallow ‘RADON’ boreholes used for the disposal of DSRS in the former Soviet Union, which are only a few meters deep [65].

A way of overcoming the dimensional constraints related to borehole disposal can be the disposal in a shaft. Shaft construction technology is widely available and there is considerable engineering experience in a wide variety of geological environments. The difference between a shaft and silo, as described in Chapter 6, is their depth: silos are tens of metres deep, shafts several hundreds of metres.

Shaft disposal has however never been done. A concept of shaft disposal would require evaluating:

- The potentially direct pathway from the disposal zone to the biosphere, formed by the shaft;
- In case of HLW or SNF disposal, the heat dissipation from this waste could result in water flow up the shaft;
- Criticality issues related to the disposal of SNF in a limited space.

Shaft seals would play a crucial role in a shaft disposal concept. Whether the concept would prove feasible would depend on specific site properties and the design of the engineered barriers.

9.1. CASE STUDY: THE DSRS BOREHOLE DISPOSAL PROJECT IN MALAYSIA

During an AFRA[5] course in 1995, the South African Nuclear Energy Corporation (NECSA) proposed developing a concept for borehole disposal of DSRS. Most participating countries did not have the possibility to co-dispose those sources with other radioactive waste and expressed a need for economically feasible disposal solutions for their DSRS inventories. Since, the idea of DSRS disposal in boreholes has evolved into a well-defined concept offering an internationally accepted solution for a wide spectrum of sources that can be implemented in different geological and climatic settings.

In 2019 the Malaysian Nuclear Agency (MNA) received a license for the implementation of this concept. The case study presented in this section is based upon this Malaysian project.

9.1.1. Waste inventory

The source inventory managed by MNA contains 12.928 category[6] 3-5 sources [66], comprising 15 different types of radionuclides, with a total activity of ca. 32 Ci or 1 TBq (Table 3).

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[5] AFRA is an IAEA technical cooperation regional agreement that started in 1990. It provides a framework for African Member States to collaborate in projects that aim to meet the shared needs of the members. In the field of radioactive waste management, projects have focussed on the safety and security of disused sealed sources through improvements in the regulatory and waste management infrastructures.

[6] The IAEA has established a categorization system for sealed radioactive sources [66]. The categorization aims to provide a simple and logical system for ranking radioactive sources based on their potential to cause harm to human health. Five categories are defined, with category 1 being the most dangerous and category 5 the least dangerous.

TABLE 3. DSRS INVENTORY OF THE MALAYSIAN BOREHOLE DISPOSAL PROJECT [67]

Radionuclides	Half-life	Number of sources	Total activity [GBq]
Ra-226	1600 years	629	105
Am-241	433 years[7]	10241	161
Cs-137	30 years	325	513
Sr-90	29 years	535	65
Co-60	5 years	419	43
Kr-85	10756 years	62	278
Fe-55	2.7 years	31	1.0
Cd-109	463 days	35	0.4
Ni-63	100 years	23	7.9
Pm-147	2.6 years	88	3.5
Tl-204	3.8 years	89	5.1E-04
Po-210	140 days	385	9.1E-03
Co-57	271 days	20	6.0E-02
Pb-210	22 years	45	3.4E-04
Ba-133	11 years	1	2.1E-04

9.1.2. Disposal site

The disposal site is located within the complex of MNA, some 32 km south from Kuala Lumpur [68]. This is a secured area with strict access control.

The host rock is dominated by phyllite and schist. The groundwater table is ca. 30 m deep. The main hydrogeological and geochemical characteristics are summarised in Table 4. It is a slightly acidic and reducing environment with a low salinity. Groundwater flow takes place in bedrock fractures and moves towards a river at 1.3 km from the borehole.

[7] The daughter product of Am-241, Np-237, has a half-life of over 2 million years.

TABLE 4. MAIN HYDROGEOLOGICAL AND GEOCHEMICAL CHARACTERISTICS [67]

Parameter	Value
Hydraulic conductivity	4 x 10^{-6} m/s
Hydraulic gradient	0.05 m/m
Water-filled porosity	9 %
Transmissivity	3.4 m^2/d
Ph	4.6 – 6.0
Eh	120 mV
Sulphate concentration	3.4 mg/l
Chloride concentration	7.9 mg/l
Calcium concentration	3.8 mg/l

9.1.3. Facility design

The sources are first conditioned into waste packages. Each waste package consists of a 3 mm thick stainless-steel capsule placed in a cementitious barrier that is in turn surrounded by a 6 mm thick stainless-steel container (Fig. 33). The lengths of the waste packages range from 250 mm to 600 mm. All containers have an outer diameter of 115 mm. The complete inventory is contained in 60 capsules. Each capsule in turn is placed into a single waste package.

FIG. 33. Design of the waste package: sources are placed in 3 mm thick stainless-steel capsules (left) which are placed in a 6 mm thick stainless steel disposal container which is backfilled with a cementitious material (middle). A set of disposal containers with different lengths is available (right).

The 60 waste packages are lowered into a cased borehole to their emplacement depth between 115 m and 175 m. The borehole has an external diameter of 26 cm, its casing has an internal diameter of 14 cm. The void space between the waste packages and casing in the disposal zone is then backfilled with a cementitious material. A borehole schematic of the disposal concept is shown in Fig. 34.

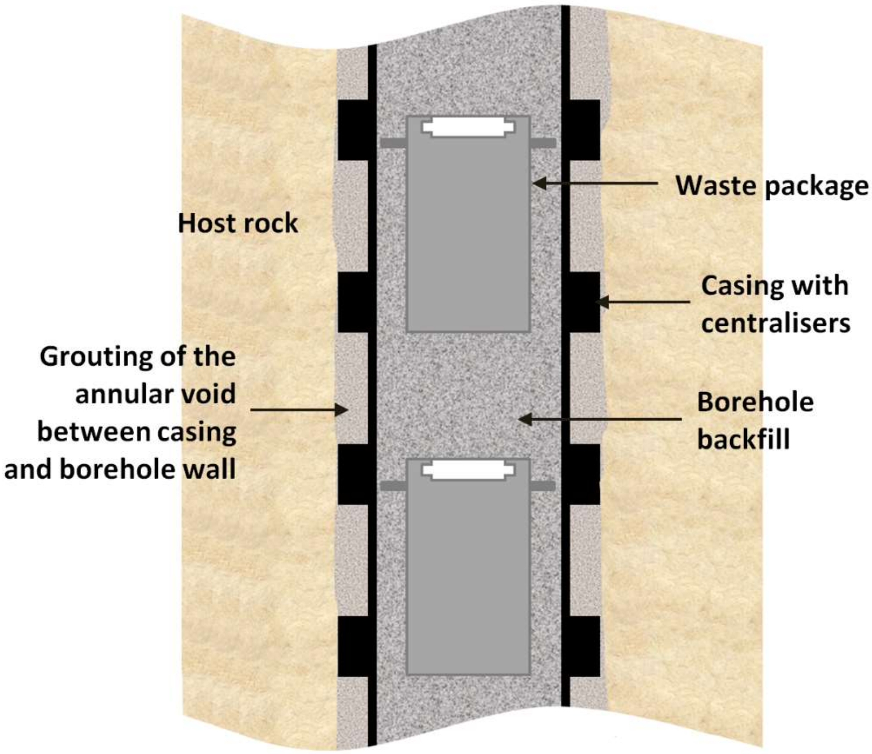


FIG. 34. Cross-section of the borehole in the disposal zone.

To preclude formation of preferential pathways, prior to backfilling the casing above the disposal zone is partially removed. With the casing removed, the borehole is backfilled using the same cementitious material as used to seal the disposal zone.

9.1.4. Safety concept and safety demonstration

The regulations applying to the disposal project specifies a public dose limit of 1 mSv/yr. No cut off time or explicit time limit is specified concerning the time frame considered in the safety assessment.

Waste containment is first provided by the waste package. Both the capsules and containers are made from corrosion resistant 316L stainless-steel. The high alkaline environment provided by the cement used in the waste packages and as backfill results in low corrosion rates and long capsule and container lifetimes.

The safety assessments assume that the disposal container and capsule fail completely once they are breached. Failure of external stainless-steel waste package container is estimated to occur after 6.800 years and subsequent capsule failure after 11.000 years. As most radionuclides in the inventory are short-lived, their activity will have already decayed to exemption levels by this time. The 7 radionuclides that will still be radioactive are:

- Ra-226 and its daughters, Pb-210 and Po-210;
- Np-237, resulting from the decay of Am-241 that itself has also decayed to exemption levels, and its daughters U-233, Pa-233 and Th-239.

Radionuclides are assumed to instantaneously dissolve into groundwater and radionuclide solubility limits are not considered in radionuclide release and migration assessments. In the assessments dissolved radionuclides migrate out of the near field.

The hydrogeological and geochemical parameter used in the safety assessment are those presented in Table 5. The site was specifically selected for its favourable geosphere characteristics, i.e., the low permeability and advantageous geochemical conditions. As a result, potential radionuclide releases after waste package failure are expected to be sufficiently delayed by the natural barriers so that they will not pose a hazard to humans or the environment. During transport through the geosphere, radionuclide migration is retarded through sorption. The assessments take radionuclide solubility limits into account during transport through the geosphere.

The normal evolution scenario for the site considers a water release scenario in dose assessments. However, because naturally occurring groundwater at the site is slightly acidic and not fit for human consumption or agricultural use, a water well scenario could be discounted. Alternatively, since surface water is abundant at the site, a scenario where contaminated water discharges to a nearby river, located 1.3 km from the disposal borehole (see Fig. 35), is considered in the dose assessments. A gas release scenario could be screened out because gases are assumed to dissolve completely in the groundwater. A solid release case where disposal containers are exposed through erosion was also screened out as unrealistic given the erosion rates at the site and the depth of disposal.

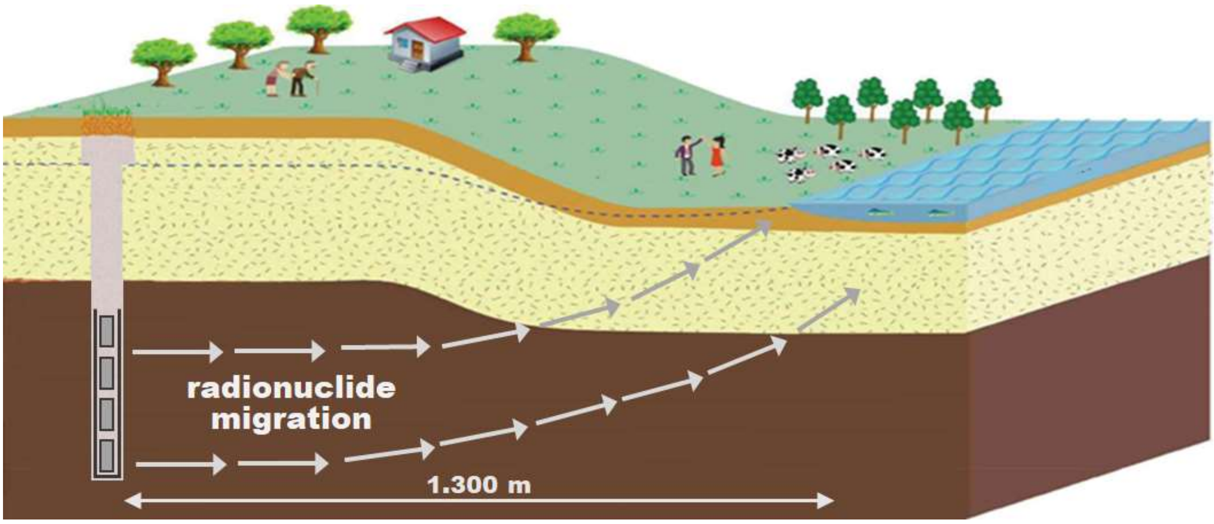


FIG. 35. Conceptual model of the normal evolution scenario: liquid radionuclide release in the saturated zone with the river as the geosphere-biosphere interface (figure is not to scale) (modified from [67]).

The dose rate calculations assume a self-sufficient family of 4 adults residing onsite for 6 hours each day. River water is used for drinking, domestic and agricultural purposes like paddy planting and crop cultivation, chicken and cattle farming, as well as fishing from the river. Human activities also involve bathing in the river.

The calculated annual dose rate resulting from each radionuclide and the cumulated annual dose rate are shown in Fig. 36. Two peaks are observed. The first peak, 9 x 10^{-15} Sv/year after ca. 20,000 years, is attributed to Ra-226 and its daughters Po-210 and Pb-210, which have fully decayed within 60.000 years. A second peak of 1.4 x 10^{-12} Sv/year occurs after approximately 395.000 years resulting from Np-237, a daughter of Am-241, and its daughters Th-229, U-233 and Pa-233. These values are well below the limit of 10^{-3} Sv/yr.

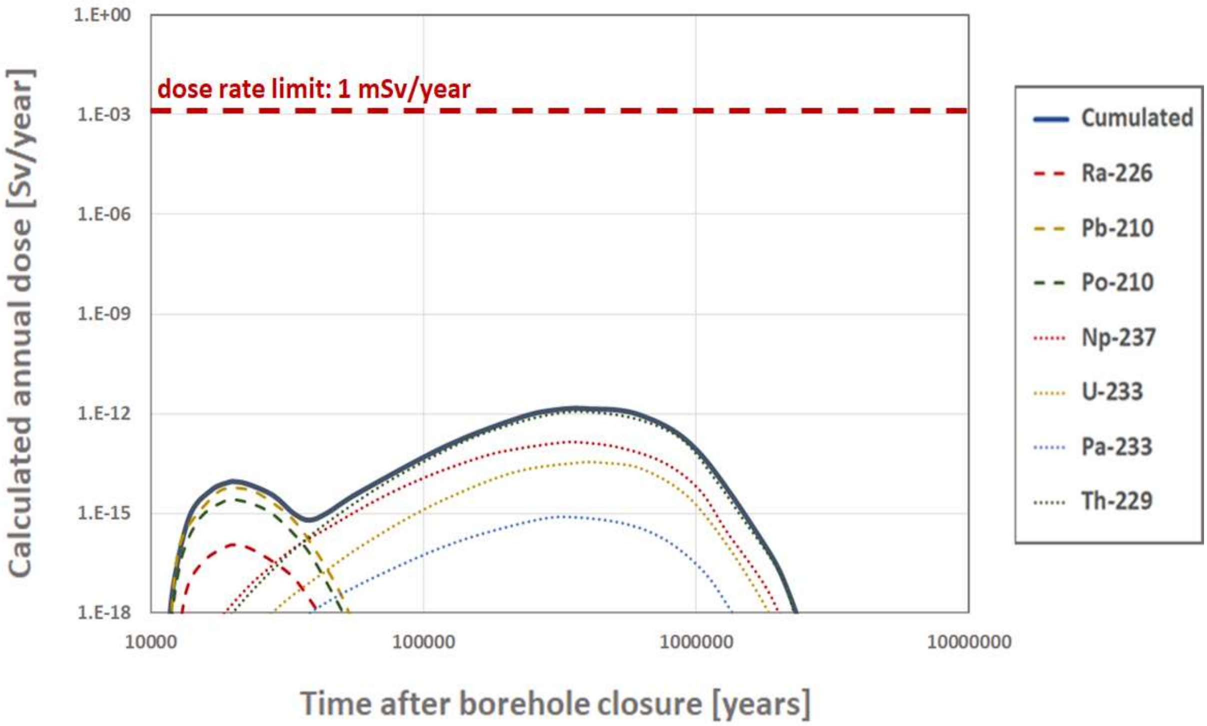


FIG. 36. Annual dose from each radionuclide and the cumulated annual dose received by a farmer in the design scenario.

Alternative scenarios are also considered in the assessment, including separate scenarios for a waste package manufacturing defect resulting in an early release and installation of a groundwater extraction well near the disposal borehole. Sensitivity studies, varying hydraulic conductivity, Eh, and pH, are also evaluated for the scenarios. The assessment results indicate that geosphere performance was the driving consideration in the system. The system was found to be sensitive to path length and the hydraulic conductivity. The degradation rate of waste packages has little effect on dose. Even under early failure scenarios, the calculated impact falls orders of magnitude below the regulatory limit.

9.1.5. Cost

The DSRS borehole disposal concept is developed to provide a safe, technically sound and cost-effective disposal solution for DSRS inventories. Its design uses readily available materials and technology. Concrete and stainless steel, for instance, are materials that are in everyday use throughout the world and boreholes are widely drilled for the exploitation and exploration of natural resources. The total engineering cost (transport, conditioning, site investigation and disposal) for a DSRS inventory that can be disposed of in one borehole is estimated to be a few hundred thousand US dollars. This does not include costs for preparing a licence application or any other country-specific costs for regulation and approval.

9.2. APPLICABILITY OF THE DISPOSAL CONCEPT

9.2.1. Main safety features

A high level of isolation can be achieved by locating the disposal zone at depths of tens to hundreds of metres in an appropriately selected, geologically stable location. The small footprint of the borehole also makes inadvertent drilling into the borehole very unlikely.

Containment is provided by both the engineered barriers of the waste package and the characteristics of the geological formations in which the borehole is constructed, such as a low permeability and/or high radionuclide sorption potential. Depending on the geochemical environment and resulting corrosion rates, waste containment by the waste packages can be ensured for hundreds to thousands of years. Sources containing radionuclides with half-lives ranging between 100 days and 30 years (e.g. Sr-90, Cs-137 and Co-60) will take between 200 and 1200 years to decay to insignificant levels (see Section 5). As the intended lifetime of the waste package is longer, such short-lived radionuclides (i.e. radionuclides with a half-life lower than 30 years) will have decayed to exemption levels before they can be released into the geosphere.

Radionuclides with longer half-lives, like Ra-226 or Am-241, might eventually be released into the geosphere as the packages degrade. The selection of sites with suitable geosphere characteristics will ensure that any radionuclide releases into the biosphere do not pose a hazard to humans or the environment now or in the future.

A generic post-closure safety assessment of the borehole disposal system for DSRS is documented in [69]. The assessment demonstrates that the concept can be implemented safely in a wide range of sites. It concludes that even if early failure of a disposal package is assumed and the hydrogeological conditions of the site are relatively unfavourable, quantities of radionuclides greater than 1 TBq can be disposed of without posing a safety problem.

9.2.2. Possible waste inventories

The concept can be used for the disposal of DSRS and other LLW and ILW following an appropriate site selection process. The borehole diameter however constrains the size of the waste packages (order of 10s of centimetres) that can be emplaced in the borehole. In addition, the volume of a single borehole is restricted. For example, a 200 m deep, 20 cm diameter borehole, with the bottom 100 m used for waste emplacement, has a useful volume of only about 3 m^3. Boreholes, then, are effectively limited to disposing sources contained in small diameter packages.

No studies have been carried out on the disposal of HLW and SNF in a borehole at depths of hundreds of metres. Disposal at a similar disposal depth to that of mined geological repositories (hundreds of metres) would require developing a similar safety case including a comprehensive understanding of the host rock in both the near and far fields. An equivalent borehole concept might thus be expected to require similarly robust engineered barriers, which would require large borehole diameters.

Exploring the suitability of the borehole concept for such waste would require, in particular, evaluation of the combination of the potentially direct pathway from the disposal zone to the biosphere, formed by the borehole, and the heat dissipation from HLW or SNF, which can result in water flow up the borehole. It can therefore be expected that borehole seals would play a crucial role in a borehole disposal concept for HLW or SNF. Consequently, boreholes do not appear to be a feasible solution for such waste.

9.2.3. Potentially suitable sites

Although the concept can be implemented in a wide range of geological settings, geological environments with a low permeability and good radionuclide sorption properties are favoured. It is suitable for disposal in the saturated zone below the water table and in the unsaturated zone present in arid regions. A generic safety assessment evaluating the concept for disposal of sources in different hydrogeological and climatic environments concluded that it can be safely implemented in a wide range of hydrogeological and climatic environments [69].

Several of the widely applied constraints used for locating other types of disposal facilities apply to borehole disposal. Locations with unstable geological conditions (seismicity, thermal waters, upward groundwater flow potential, karstic terrane etc.) or that are sensitive to hydrogeological regime changes or significant climate change are to be avoided. Other potential exclusion factors are less relevant; it might prove acceptable to locate a borehole disposal facility in areas susceptible to future urbanisation, provided the disposal depth is a few hundred metres. Similarly, the existence of a good transport infrastructure is less relevant in siting, owing the simplicity of the equipment needed for borehole construction, operation and closure.

9.2.4. Technical aspects

The drilling and casing of boreholes to depths of several hundreds of metres has been done worldwide for the exploitation and exploration of natural resources or to drill water supply wells. Also, the emplacement of materials in a borehole and its closure by backfilling and sealing has been accomplished on a routine basis. The disposal of radioactive waste in a borehole up to depths of hundreds of metres is therefore not expected to pose a technological challenge. It is however to be noted that this technology has only been considered for DSRS. If the concept is to be considered for other radioactive waste further RD&D would be required

9.2.5. Conclusions

Disposal in boreholes is effectively limited to small items or packages. The concept provides a high level of isolation and containment and has some specific advantages. It requires a limited land area and infrastructure and can be constructed, operated and closed in a short time, making it a cost-effective disposal solution. The small footprint also contributes waste isolation, as it results in a lower probability of human intrusion.

For larger volumes of waste and larger items, the borehole diameter constrains the size of waste packages and limits the engineered barriers system that can be implemented. Borehole disposal at depths of hundreds of metres has not been considered for the disposal of HLW and SNF and its feasibility is questionable. HLW and SNF emit heat for some hundreds to possibly some thousands of years. The higher temperature around the borehole may create an upward driving force for water flow. As the borehole itself may form a direct pathway from the disposal zone to the biosphere, it will be important that it is properly sealed to avoid upward movement of fluids along the borehole during this phase. For HLW and SNF, the sealing of the borehole therefore plays a crucial role in the safety concept.

10. VERY DEEP BOREHOLES

The concept of very deep borehole disposal consists of disposing of the waste at depths of some kilometres in an environment where any groundwater present is likely to be effectively stagnant and unlikely to communicate with the biosphere (i.e., isolated from advective flux with shallow aquifers). Such conditions can result from the density stratification of groundwaters and deep fluids caused by the increasing salinity with depth. In addition, topographically driven hydraulic gradients are considerably reduced at depth. These conditions would only be expected to be encountered at depths of several kilometres. This is much deeper than what is technically implemented for a mined geological repository. The technology exists and is widely used in the hydrocarbons and geothermal industries to construct boreholes with relatively large diameters to such depths.

However, application of the concept for radioactive waste disposal remains untested and considerable RD&D is still needed. Sandia National Laboratories developed a generic safety assessment has been performed (see Section 10.1), but no safety case has yet been developed for a specific deep borehole disposal project. The development, and approval, of such a safety case is necessary to test the concept.

The possible advantages of very deep borehole disposal are exceptional levels of isolation from aquifers and the biosphere and with good containment relying primarily on natural barriers. The volumes and sizes of material that can fit in a borehole are however limited by the borehole diameter. This means it is both technically and economically unsuited to disposal of large volumes of LLW, which have less expensive near surface disposal options. However, the primary potential for very deep borehole is for the disposal of HLW and SNF in packages with appropriate dimensions.

For countries whose small inventories do not contain such materials, the concept would not be an appropriate solution, as a shallower borehole to about 1 km would likely be sufficient for ILW of lower activity. The concept could also be of interest to programmes with large inventories, wishing to manage certain specific materials independently of their mined geological disposal programmes (e.g. for reasons of flexibility to address safeguards, or to provide a local solution for a particular waste stream).

A conceptual design for disposal in very deep boreholes is shown in Fig. 37. Waste canisters are placed in a section of a cased borehole, the waste emplacement zone, which is located at a depth of several kilometres. Buffer material fills the annular space around the canisters and can be used to space heat-emitting waste containers or to provide bridging so that the stack load is distributed to the borehole walls. Sealing materials are placed above the waste emplacement zone to close and seal the borehole. The upper kilometres of the borehole are backfilled and sealed at intervals.

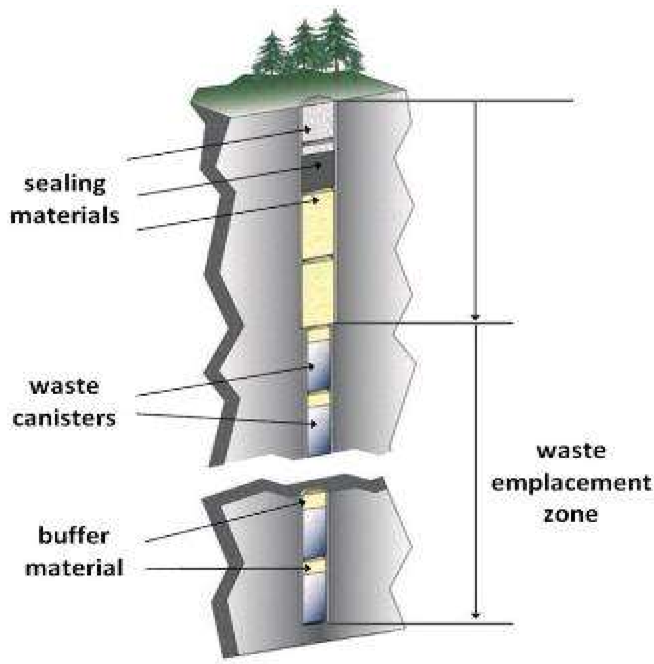


FIG. 37. Very deep borehole disposal concept (modified from [70]) (Courtesy of SKB).

This concept has not yet been implemented, but several countries have studied very deep borehole disposal or are currently interested in this concept, mainly as an alternative to disposal in a mined repository. The majority of the work in this area has been carried out on behalf of the United States Department of Energy (USA DOE) [71-73] and the Swedish Nuclear Fuel and Waste Management Company (SKB) [74-75]. The most recent initiative for the very deep borehole disposal were plans for a deep borehole field test in the USA, used as the case study, described in the section below.

10.1. CASE STUDY: THE DEEP BOREHOLE FIELD TEST (USA)

In 2002, the United States Congress approved the development of a deep geological repository for SNF and other HLW at Yucca Mountain. In 2009, the project was deemed unworkable by the Administration such that no further funding was appropriated in Congress. This decision was followed by the instalment of a Blue Ribbon Commission on America's Nuclear Future in 2010. The Commission was tasked with conducting a comprehensive review of policies for managing the back end of the nuclear fuel cycle and to recommend a new plan.

The Commission published its recommendations in 2012. It concluded that geologic disposal in a mined repository is the most promising and technically accepted option available for safely isolating HLW for very long periods of time. The Commission however also acknowledged several possible advantages of the deep borehole disposal concept, stating:

"These [advantages] include the potential to achieve (compared to mined geologic repositories) reduced mobility of radionuclides and greater isolation of waste, greater tolerance for waste heat generation, modularity and flexibility in terms of expanding disposal capacity, and compatibility with a larger number and variety of possible sites. On the other hand, deep boreholes may also have some disadvantages in terms of the difficulty and cost of retrieving waste (if retrievability is desired) after a borehole is sealed, relatively high costs per volume of waste capacity, and constraints on the form or packaging of the waste to be emplaced." [76]

Therefore, the Commission recommended to do further RD&D to fully assess the potential of deep borehole disposal. This led the USA DOE to develop an RD&D plan for deep borehole disposal [77] and support the Sandia to re-evaluate of the option of deep borehole disposal [78-84]. In 2014, the USA DOE initiated R&D for a Deep Borehole Field Test (DBFT), and in 2015 released a request for proposals to implement this full-scale field demonstration test [84] with a detailed set of associated R&D activities that were to be directed and analysed by Sandia National Laboratories [82-84]. The DBFT was planned to demonstrate, evaluate and further develop the feasibility of a generic deep borehole disposal facility, as well as to advance the generic safety case for such [85].

The design and objectives of the test are described in Refs. [83-84] (see Fig. 38). The goal was to site and drill 2 5.000 m deep boreholes into crystalline basement rock. The first borehole was planned to be 0.22 m wide at the bottom and used primarily for characterization of the deep crystalline basement system. The second one was to be 0.43 m wide and represented a full-scale disposal borehole. The proposed testing in the larger hole included the emplacement demonstration testing of surrogate waste packages not containing any radioactive waste. The test was cancelled in 2017 because of changes in Administration priorities.

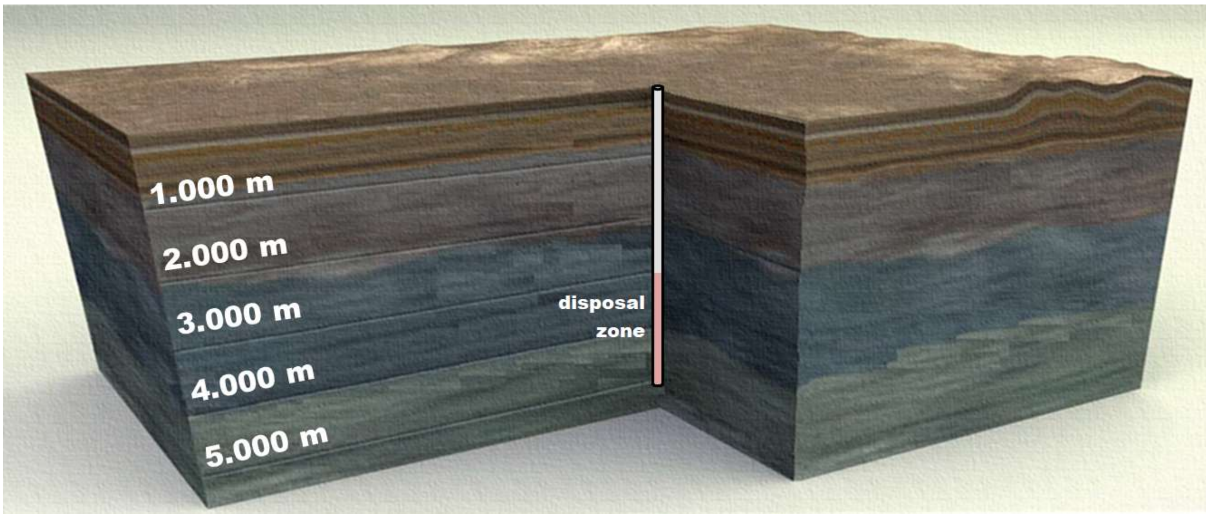


FIG. 38. The deep borehole disposal concept considered in the Deep Borehole Field Test studies (modified from [83]) (Courtesy of SANDIA NL).

Nevertheless, the planned test resulted in some technical reports and publications, including guidelines for siting the field test [84], a description of the conceptual design [82, 85] and a safety case and assessment for deep borehole disposal [86-87]. The safety case and assessment are performed for a hypothetical generic reference case. This reference case is described in the sections below.

10.1.1. Waste inventory

The reference generic safety case [87] considers the disposal 1.335 CsCl capsules (Cs-135 and Cs-137) and 601 SrF_2 capsules (Sr-90) currently stored on the Hanford Site. Those radionuclides were extracted to generate thermal sources (the capsules) from liquid waste, which in turn was generated from the processing of defence SNF.

The Cs was poured as molten CsCl to form a glass-like solid in 3 mm thick stainless-steel capsules (see Fig. 39). The Sr was also put into similar capsules in the form of SrF2, a granular material that was mechanically compacted in the capsule. The filled capsules are capped, welded, leak tested and decontaminated. They were then placed in outer capsules, which were also welded closed. The double-wall capsules outer dimensions are generally between 50 and 55 cm long and 7 to 8 cm wide.

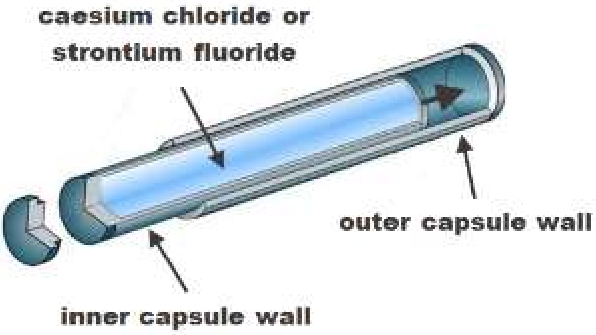


FIG. 39. Schematic drawing of the Cs and Sr capsules (modified from [83]) (Courtesy of SANDIA NL).

In 2007, the average activity of the Cs and Sr capsules was around 1.100 TBq. The activity of the whole inventory of Cs and Sr was around $2 \cdot 10^6$ TBq. This represents approximately one third of the total radioactivity on the Hanford Site [88]. The thermal output of the Cs and Sr capsules in 2007 was around 144 W/capsule and around 193 W/capsule, respectively. The reference case assumes the disposal of these capsules in 2050. By then the thermal output of the Cs capsules and Sr capsules will be around 54 W and 70 W per capsule, respectively.

While there is no technical limitation to deep borehole disposal of SNF, it has not been considered in the US DOE program for deep borehole disposal since 2014 [86].

10.1.2. Disposal site

The safety assessment of the reference case included some assumptions about the generic crystalline basement host rock and the overlying sediments. The crystalline basement rock was assumed to extend from a depth of 2.000 m to a depth beyond 5.000 m below land surface and overlain by a 2.000 m thick (generally sedimentary) overburden. The permeability of the crystalline basement host rock at depth is about 10^{-19} m^2 and is assumed to be scarcely fractured at depth.

The basement rock pore fluid is taken to be hydrologically isolated from shallow groundwater (low permeability and long groundwater residence time) and to exhibit density stratification (saline brines underlying less saline water) that opposes upward flow. Furthermore, there are reducing conditions at depth limiting the solubility and enhancing the sorption of many radionuclides. Within such older and colder crystalline basement systems, the temperature the disposal zone is taken to range between 125°C at a depth of 3 km to ~140°C at the 5 km total depth for this particular generic safety case [86].

Key parametric values for materials utilized in the safety case are summarized in Ref. [86], for a deterministic case and probabilistic performance assessment cases, respectively. In the deterministic case, the permeability of the crystalline host rock was set to $1 \cdot 10^{-18}$ m^2 (similar to the initial permeability of seals in the seal zone) and that for the disturbed rock zone (DRZ) around the borehole was set to $1 \cdot 10^{-16}$ m^2. Note that because the DRZ exists (along the length of the borehole in the crystalline basement) and has a 2 order-of-magnitude higher permeability than the host rock, the DRZ is the likely transport path in the crystalline basement.

In addition, within the disposal/emplacement zone there is an annular space between the waste packages (~22 cm outer diameter) and the emplacement zone wall (~32 cm diameter), which is modelled as a brine-filled EZ annulus (i.e., the EZ Liner is not modelled explicitly). Beyond the borehole wall (diameter is ~32 cm), the DRZ is modelled as a concentric zone (of 62 cm diameter, corresponding to a 15 cm thick zone) around the entire length of crystalline basement borehole wall. The host rock and the DRZ are assigned the same transport properties with K_d values for Cs and Sr of 22.5 L/kg and 1.7 L/kg, respectively, and with an effective diffusion coefficient of $1 \cdot 10^{-12}$ m^2/s.

In the probabilistic analyses of the generic safety case for Cs/Sr capsules, the physical properties of the DRZ were varied with permeability ranging from $1 \cdot 10^{-18}$ m^2 to $1 \cdot 10^{-15}$ m^2, and porosity ranging from 0.005 to 0.01. Additionally, the K_d values for Cs and Sr are varied from 5 to 40 L/kg and 0.4 to 3 L/kg, respectively, for both the DRZ and host rock. These physical and transport properties are also evaluated over ranges of values for the engineered materials.

10.1.3. Facility design

All Cs/Sr capsules are placed in waste packages which need to ensure radionuclide containment during the operational phase. The packages are 24 mm thick carbon steel cylinders with an outer diameter of 22 cm and an outer length of 4.76 m (see Fig. 40). Each package is planned to contain 18 capsules in an internal basket that groups them into 6 layers of 3 capsules. This results in a total of 74 packages for the Cs capsules and 34 packages for Sr capsules (totalling 108 waste packages). The waste packages have a shield or plug for radiation protection installed on the upper end. The packages would also be fitted with an impact limiter on their lower end and a fishing neck on their top end. For the reference case, the waste packages are assumed to be disposed of in 2050 when the thermal output of the Cs packages and Sr packages will be around 978 W and 1.229 watts per package, respectively.

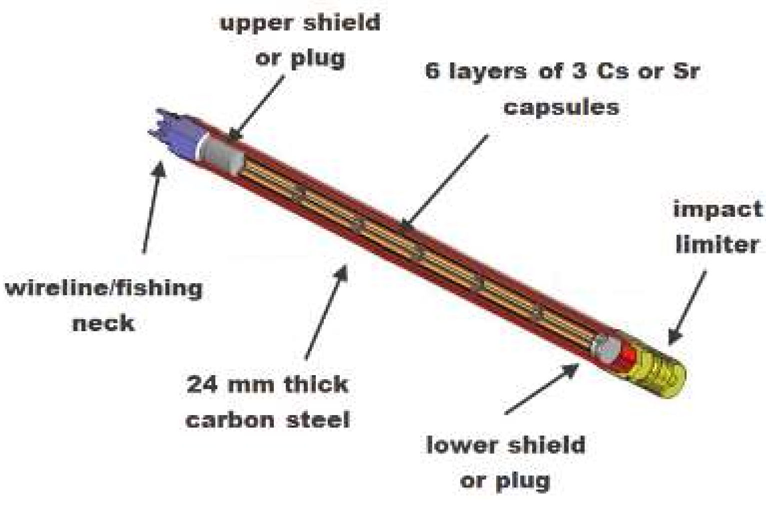


FIG. 40. Schematic drawing of the Cs and Sr capsules (modified from [83]) (Courtesy of SANDIA NL).

The 108 waste packages, which have a cumulated length of 514 m, would be disposed of in a borehole at a depth between ~4.465 m and 5.000 m.

The borehole guide tube and the emplacement zone (EZ) liner have internal diameters of ~25 cm at the bottom, leaving an average radial gap of 1.25 cm between the waste package (~22 cm diameter) and the EZ liner. This liner is perforated for fluid dynamics purposes during emplacement and to allow backfilling the emplacement zone. The EZ liner would remain in the borehole after sealing.

After every stack of 40 waste packages, a cement bridge plug would be installed for structural support above the top waste package and a packer would be set 10 m above the bridge plug. These cement plugs are emplaced to prevent waste packages at the base of the EZ from being crushed by the weight of overlying waste packages and may also serve to partially isolate lengths of the borehole. The emplacement disposal zone is then 534 m total length: the total length of the packages, 514 m, plus the 20 m from the 2 cement plugs.

The conceptual reference design of the borehole is shown in Fig. 41. A telescoping set of casing and liners is placed from the top to the bottom of the borehole. In general, the casing provides for stability of the borehole, especially down to the level of the crystalline basement rock. The guidance casing and emplacement zone (EZ) liner are smaller diameter casing used to guide the packages for emplacement and are interior to the casing for borehole support (including the upper basement liner). The guidance casing would be removed as would the upper basement liner to provide access to emplacing seals against the host rock throughout the seal zone. As noted above, the EZ liner would be perforated but left in place. The rest of the casing would be left in the borehole to just above the level of the crystalline basement. The casing and liner materials are standard steel casing pipes from industry, just having various diameters and wall thicknesses (see Ref. [86]). The EZ liner is partially cemented and has perforations spaced along its length for fluid dynamics purposes. The perforations allow the relief of pressure resulting from fluids heated by the waste and the dissipation of hydrogen resulting from corrosion of the steel waste packages.

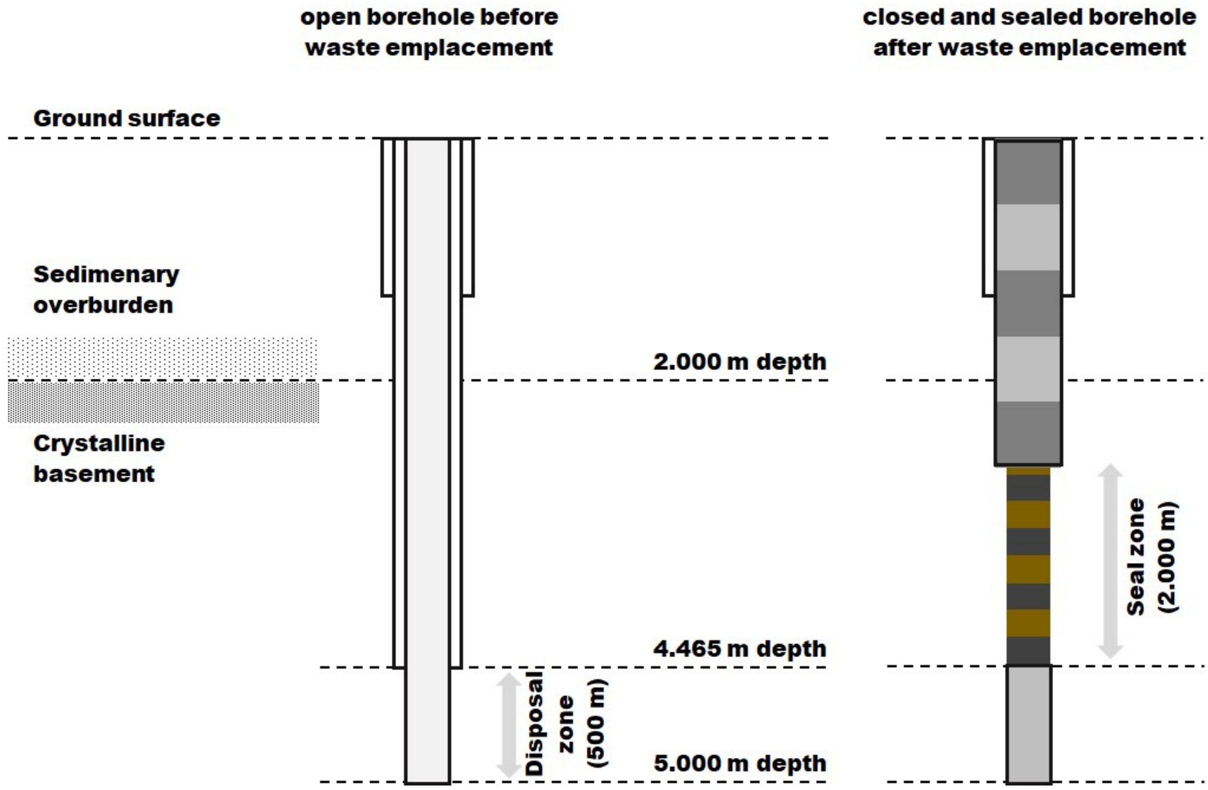


FIG. 41. Conceptual design of the disposal borehole: open borehole before waste emplacement (left) and closed borehole with the sealed zone consisting of an alternating sequence of bentonite and cement plugs and the part above this zone with alternating concrete and cement plugs (right) (modified from [82]) (Courtesy of SANDIA NL).

During borehole construction, the borehole is filled with fluid that helps lubricate the drill string and wireline operations and flush drill cuttings. Before starting the waste emplacement, the borehole will be flushed and refilled by a so-called waste emplacement fluid. This fluid provides buoyancy supporting waste emplacement operations. A brine with a composition similar to that of the host rock formation (a high-density Na-Cl or Na-Ca-Cl brine) is assumed. Contrary to the drilling fluid, the waste emplacement fluid would contain no organic additives [89].

After waste emplacement, the disposal zone is backfilled with a grout and the casing is removed from the seal zone above the disposal zone, (i.e., the upper basement liner casing and the guidance casing, which is fully removed from the borehole). The reference case assumes that the seal zone is approximately 2.000 m high. This portion of the borehole is sealed using an alternating sequence of bentonite and cement plugs which are, as the casing is removed, emplaced directly against the host rock. The seal zone needs to provide a low-permeability barrier against upward flow during the period of thermal perturbation (less than a few hundred years). The elevated temperatures during that period may create a driving force for upward water movement. Some portions of the borehole would be backfilled with geomaterials that serve to fill voids and maintain support to mitigate full scale collapse of the hole. Those materials also augment the diffusive transport seals represented by the multiple layers of bentonite and cement.

In the part of the borehole above the seal zone, which lies predominantly in the overlying sediments, the casing that was cemented in place during drilling is left in place. This part is filled with concrete and cement plugs and geomaterials. These plugs are meant to prevent fluid flow into the borehole, including downward fluxes of surface water, and contribute to the stability of engineered components of the seal zone and isolation from shallow aquifers.

10.1.4. Safety concept and post-closure safety assessment

The waste is emplaced at a depth well below the extent of naturally circulating groundwater, and up to about 10 times the depth of some mined geologic disposal systems. The transport of radionuclides that are released from the waste packages into this very deep environment is limited to the mechanism of aqueous diffusion, which is a very slow process. In addition, the geochemically reducing conditions in the deep subsurface limit the solubility and enhance the sorption of many radionuclides, leading to limited mobility in groundwater. The low permeability of the seal zone and the high sorption capacity of the bentonite in this zone prevent vertical fluid flux and radionuclide transport up the borehole.

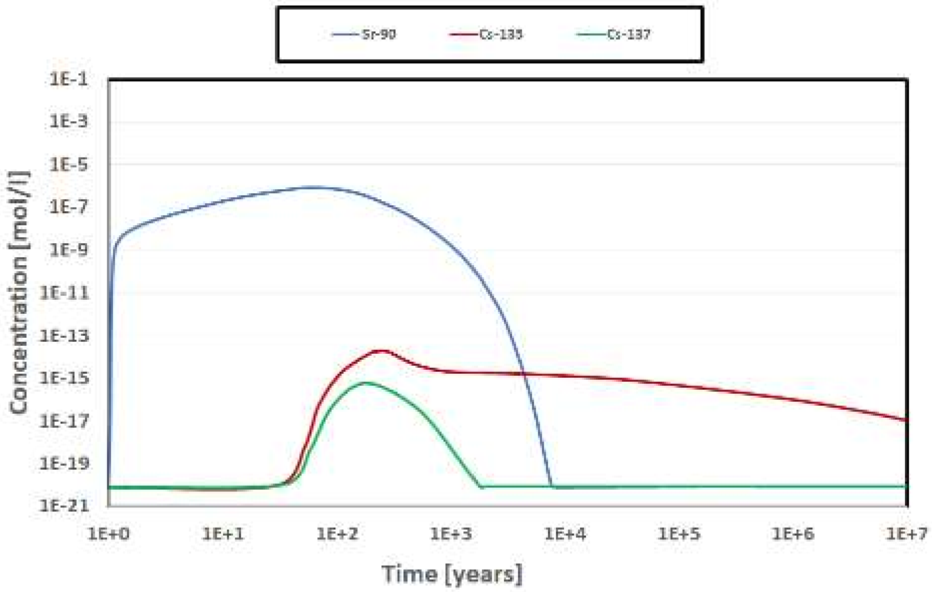
Performance assessment analyses were done for the reference case of the disposal of Cs and Sr capsules at a depth between ~4.500 and 5.000 m, as described in previous sections [86]. The assessments did not include a biosphere model and did not assess dose rates. Instead radionuclide concentrations were modelled. Fractures in the crystalline basement are not explicitly modelled in the nominal scenario. Instead the homogenous permeability of the crystalline rock is increased by one order of magnitude, up to 10^{-18} m^2 in the deterministic case, whereas the DRZ permeability is varied over a range of 10^{-18} m^2 to 10^{-15} m^2 in the probabilistic case.

The assessments do not take credit for the containment provided by the waste packages and assumes instantaneous dissolution of the waste forms in the waste packages. It is furthermore conservatively assumed that there are no solubility limiting phases formed for either the Cs (reasonably conservative) or Sr (very conservative). The heat generated by the radioactive waste results in fluid thermal expansion (short duration ~< year) and buoyant advection, i.e., a thermally driven upward groundwater flow in and immediately around the borehole. This period of elevated temperatures is calculated to last approximately 200 years with peak temperature and buoyant advection at about 3 years with a maximum temperature increase of around 100°C near the uppermost Sr-capsule waste package.

Two release paths are considered:

- Up the borehole through the seal zone;
- Through the crystalline basement.

The concentrations of Cs-135, Cs-137 and Sr-90 in the first and second cement plug above the disposal zone (counted from below), which are respectively 2.5 m and 27.5 m above the top of the disposal zone, are shown in Fig. 42. Figure 43 shows the calculated Cs-135 concentrations around the disposal zone after 10 million years.



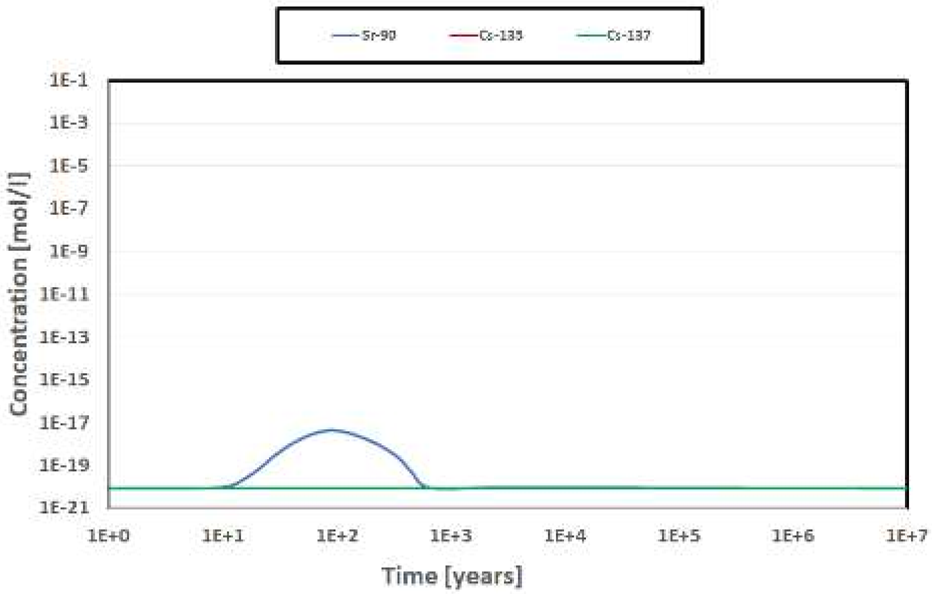


FIG. 42. Calculated dissolved radionuclide concentrations (in mol/l) through time in the first/closest cement plug 2.5 m above the disposal zone (top plot) and second cement plug 27.5 m above (bottom plot) the disposal zone (modified from [86]) (Courtesy of SANDIA NL).

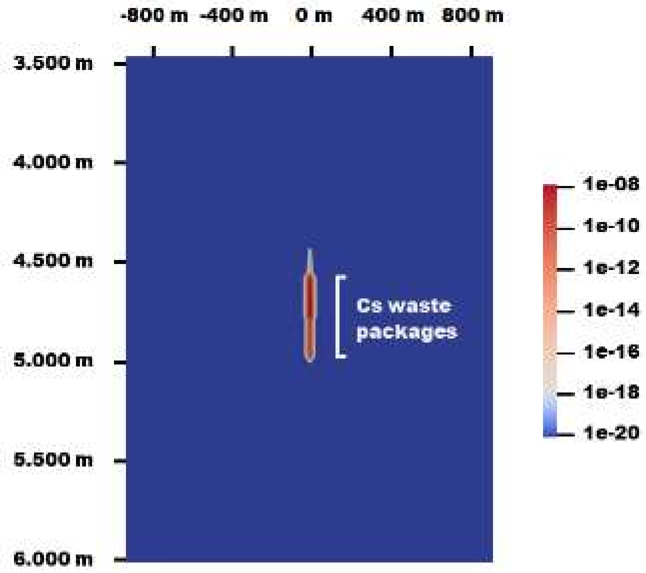


FIG. 43. Calculated dissolved Cs-135 concentrations around the disposal zone after 10 million years (modified from [86]) (Courtesy of SANDIA NL).

The assessments indicate that dissolved radionuclide of 10^{-15} mol/L from the Cs/Sr capsules travel only about 25 m up the seal zone and 20 m out in the host rock [86] in a period of 10 million years. In this period the Cs-135 will almost completely decay away.

An alternative scenario was analysed [87] in which a Cs-capsule waste package is assumed to get stuck in the borehole at the location of an intersecting fracture at a depth of 2.500 m, within the crystalline basement (see Fig. 44). The 74^{th} Cs capsule package is taken to be the one that gets stuck, with the other 73 successfully emplaced. The scenario has 74th package remaining stuck, then cemented in place, and the seals are emplaced in the seal zone before the hole is abandoned. In the performance assessment of this scenario, one case includes a regional head gradient of 0.1 mm/m, which can drive advective flus along the fracture. The fracture permeability of 10^{-14} m^2 is based on a discrete fracture network representation. After 10 million years, the calculated dissolved Cs-135 concentrations (above background) show up around the fracture for approximately 200 m upwards due to advective transport resulting from the regional flow gradient [87]. This extent of migration is small and still more than several hundred meters below the sedimentary overburden.

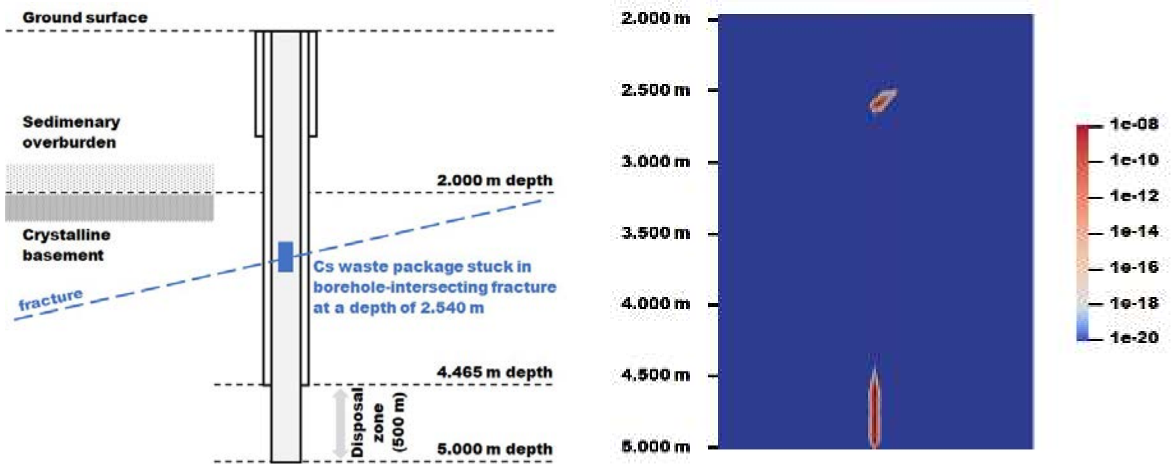


FIG. 44. Alternative scenario of a Cs-containing waste package that got stuck at a borehole-intersecting fracture at a depth of 2.500 m (left) and the calculated Cs-135 concentrations along this fracture after 10 million years (right) assuming a regional flow gradient of 0.1 mm/m (modified from modified from [86]) (Courtesy of SANDIA NL).

10.1.5. Cost

The cost for constructing and completing a reference design borehole for disposal to a depth of 5.000 m with a bottom-hole diameter of 43 cm was estimated to range from ~27 to ~41 MUSD (2011 dollars) [80] over a period of about 140 to 210 days, respectively. The primary difference of the higher expense and time was the inclusion of coring and characterization studies during drilling. That 2011 study also estimated an additional ~13 MUSD representing the cost of loading the waste into canisters, emplacing the canisters in the borehole, and sealing/closing the borehole to complete disposal over an additional ~50 days.

An alternative large diameter very deep borehole that would be shallower (3.000 m deep) and wider (0.91 m bottom-hole depth) evaluated for disposal of glass HLW canisters (~61 cm diameter) also had cost estimated [90]. For construction/completion cost and schedule, the estimate used a straightforward cost ratio based on the excavated volume of their larger shallower borehole versus the reference design hole (~27 MUSD) resulting in ~49 MUSD over a comparable time. Additionally, a total cost for completing disposal in the 3.000-meter borehole was estimated at ~74 MUSD by applying the same scaling ratio to the waste emplacement and sealing/closure costs as well. However, if those emplacement/sealing/closure costs are more comparable to those for the reference design, the total cost may only be on the order of ~62 MUSD. These values provide a rough order of magnitude estimate on costs and schedules, but each specific instance for a particular disposal case would have its own constraints that may lead to variation in these.

10.2. APPLICABILITY OF THE DISPOSAL CONCEPT

10.2.1. Main safety features

Very deep borehole disposal has the potential to provide exceptional isolation of waste because of the great depth of the disposal zone and the isolated nature of the fluid system. In a stable basement geological environment, the waste is unlikely to be affected by natural disturbances for tens or hundreds of millions of years and is also outside regions of the crust that are targets of present-day human intrusion, other than for highly uncommon scientific drilling. The great depth and the very limited footprint of the borehole result in an extremely low probability of human intrusion.

Containment is provided primarily by the massive natural geological barrier surrounding the disposal zone, with little or no natural movement of fluids around the waste. In a properly sited facility, there are no natural driving forces likely to move radionuclides to the surface. The safety concept is based on the disposal of the waste in an environment where the groundwater is highly unlikely to communicate with the hydrosphere. At great depths (several kilometres) increasing groundwater salinity helps to provide such conditions, together with, and reinforced by, decreasing permeability with depth. There is ample evidence that at depths of several kilometres, such conditions exist and can prevail for very long periods of time, up to more than one billion years [91-92]. The transport of radionuclides that might be released from the waste packages into this environment is limited to exceptionally slow aqueous diffusion over a very long transport pathway. The great depth also makes it unlikely that climate-driven changes in erosion, precipitation or glaciation could affect the hydraulic properties or flow at depth.

Due to the robust containment provided by the host rock, the only significant release pathway to consider is directly up the borehole. Therefore, the seals play a central role in assuring containment, particularly for heat-emitting waste, during the short period when the host rock temperature is elevated. An alternating combination of sealing materials, emplaced over a scale of at least ca. 1 km, has been proposed to manage this period, including bentonite and cement. The waste packages mainly play an operational safety role, providing containment during waste emplacement and preventing radioactive contamination of the borehole fluid, but are not relied on to provide any substantial post-closure safety function.

10.2.2. Possible waste inventories

Because of the potentially high degree of containment and isolation, very deep borehole could offer a disposal solution for any waste categories including the most problematic waste streams. It would be particularly suitable for disposal of fissile materials where nuclear safeguards considerations could be easily met, as the waste can be made practically irretrievable.

Depending on the volumes of waste involved, other additional waste forms of LLW may also be placed into the shallower portions of such very deep boreholes, subject to the dimensional constraints.

From an economical point of view, the concept may be considered for small packages and volumes of HLW for which no more cost-effective solution is available or where there are specific (e.g. safeguards) motivations to seek such high isolation. The main constraint on the use of very deep boreholes is the size of the packages, as the borehole diameter at depth is limited by current technologies to the order of tens of centimetres (up to about 60 cm at 5 km in crystalline basement) [93]). After casing the borehole, waste packages with a diameter up to about 300 mm could be readily disposed of in such a very deep borehole. The Cs- and Sr-capsules considered in the case study presented above in Section 10.1 have a diameter between approximately 60 and 80 mm and are accommodated by even smaller boreholes at 5 km depth.

Consideration of very deep borehole disposal for HLW or SNF would require ensuring that this waste can be packaged in sufficiently small waste packages for the above concept. This means that the size of the waste packages is a factor that is taken account of in the designing of the vitrification process. Some existing vitrified HLW packages might be too large to fit into currently feasible very deep boreholes. For small inventories of such waste forms, however, boreholes of a somewhat shallower nature and larger bottom hole diameter may suffice. An example is given by Ref. [92] for a very deep borehole to 3 km (with bottom hole diameter of 0.91 m) with the deepest 500 m being the disposal zone that would accommodate canisters up to 66 cm (660 mm) in diameter.

Waste that can lead to volatile releases if mechanically damaged (e.g. SNF) can be a matter of concern for the operational safety by potentially contaminating the borehole. For such operations the disposal package design may need to be more robust and pre-closure/operational risk analyses need to consider the number of canisters being emplaced, as well as the likelihood of canister failure during operations [82, 85].

10.2.3. Potentially suitable sites

In principle, very deep borehole disposal could be implemented in many locations and in a range of geological formations, but the safety case concept example above is specifically intended to utilise crystalline basement rocks in stable tectonic environments. Crystalline basement rocks at depths of 2 to 5 km have been commonly found in geologically stable regions [82]. In many locations, drilling to depths of several kilometres will encounter such geologically ancient basement rocks, below younger sedimentary formations.

Because the deep basement environment is hydrologically isolated, compared to the geological environment of conventional geological repositories located a few hundred metres below the surface, the safety concept requires less detailed characterization information on the host rock surrounding the waste. Consequently, the site characterisation work needed for a very deep borehole disposal concept will be of considerably smaller extent than is required for a mined repository disposal concept at depths of hundreds of metres.

Sites are in tectonically stable regions and have an absence of natural resources. For example, deep sedimentary basins with hydrocarbon or geothermal energy potential are to be avoided. Sites with low differential stresses are preferred. Large differential stresses may indicate potential difficulties in drilling a vertical hole and keeping the borehole stable during operations. Overlying geological formations can contribute to waste containment by providing additional, low permeability sealing of the basement formations. Generally, if there were any potential for deep fluids to seep upwards, the presence of overlying sediments would result in extensive dispersion in more active nearer surface (but still deep geologic of 100's of meters) groundwater flow systems.

10.2.4. Technical aspects

The very deep borehole conceptually designed in the case study discussed above in Section 10.1.3, is assumed to be feasible using currently available borehole construction technologies [93]. The cost for such a borehole was estimated to be around 50 MUSD for a single hole. The borehole construction will need to meet certain specifications in terms of maximum deviation and straightness to reduce the likelihood of a waste package becoming stuck, but this is unlikely to be a problem with existing technology. Other current proposals are to utilise deviated boreholes, where the disposal zone at great depth is near horizontal for which pre-closure risk assessment would need to be considered.

Although it is believed that the very deep borehole design can be constructed, operated and closed, a demonstration of construction and waste package emplacement has not yet been carried out. Some technical issues with characterization at depth are still to be further examined or demonstrated. The risks associated with dropping a waste package in the borehole or managing a package that is stuck or breached in the borehole need to be assessed in each specific case [82, 85]. This includes limiting the probability of such an event by concept and design measures and/or operational procedures, evaluating the radiological consequences of such an event, and developing processes to mitigate the event and/or the consequences of a breached package above the disposal zone. Additional topics to be addressed are the emplacement and performance of the seals and the thermal impact of heat-generating waste on the borehole casing for operational conditions.

10.2.5. Conclusions

Given the potentially high degree of containment and isolation it can offer, very deep borehole disposal can provide a disposal solution for any waste categories including the most problematic waste streams. For countries whose small inventories do not contain such materials, the concept is not likely a needed solution. The main limitation of the concept concerns the dimensional constraints imposed on the waste package diameter. The currently feasible borehole diameter at disposal depths beyond 3 km is in the order of decimetres. The waste therefore needs to fit into sufficiently small waste packages.

The scope of the site characterization work needed for the very deep borehole disposal concept may be of more limited extent than for concepts at shallower depths. On the other hand, no such disposal facility is being operated or planned and less experience and expertise are available. Full development of a safety case is necessary to test the concept.

11. CONCLUSIONS

Many near surface disposal facilities for radioactive waste are in operation worldwide and several examples of the underground disposal of LLW and ILW exist as well. No such facilities are being operated today for the disposal of HLW and/or SNF. Several member States, such as Finland, Sweden, France and Switzerland, are however making progress in developing and planning mined repositories for the geological disposal of these higher activity waste.

These repositories are being developed for significant waste inventories. For countries with smaller inventories of ILW and HLW/SNF disposal in a mined deep geological repository can pose a serious challenge. This is due to the relatively large fixed costs required for a deep geological repository associated with the construction and closure of access shafts and/or ramps.

This publication therefore explored a portfolio of underground disposal concepts that could provide alternatives to a deep mined repository and which could be an economically feasible solution for certain small waste inventories. It is important to emphasize that, although those concepts could offer a disposal solution with lower fixed — i.e. costs independent of the size of the inventory — any disposal project will require the site characterisation, engineering developments and assessments needed to provide for a robust safety case. This requires developing a disposal programme as part of an overall waste management programme and strategy. The related costs and time for those activities needs to be acknowledged.

The concepts presented in this report are:

- Silo-type facilities;
- Underground caverns;
- Converted mines;

- Boreholes at intermediate depth;
- Very deep boreholes.

The first four concepts are either planned or being implemented. Very deep borehole disposal has not yet been implemented and has only been studied. It therefore remains to be demonstrated that a safety case for deep borehole disposal can be developed and licensed.

Silo-type facilities are typically at depths associated with near-surface disposal facilities. This makes them unsuitable for inventories with significant activities of long-lived radionuclides in a silo. Nevertheless, for inventories with only a limited activity of long-lived radionuclides, the concept could be considered.

Inventories of HLW/SF will require deep geological disposal. Therefore, only converted mines at sufficient depths and very deep boreholes could be considered as a possible alternative for a mined deep geological repository.

The concepts identified and presented are stylised ones, in that they can overlap in terms of depths, dimensions and engineering application. A Member State will need to tailor those concepts to its specific needs, siting possibilities, inventory concerned, etc. It may also be that the preferred disposal solution lies in a combination of one or more of those disposal concepts. The portfolio presented here can provide a useful starting point and a source of inspiration for Member States.

Finally, it is important to emphasize that what is a suitable or preferred disposal concept generally depends on many factors. Examples of such factors are the predisposal management, the legal and regulatory framework and preferences of stakeholders. An evaluation of the disposal concepts therefore cannot be done in isolation from the wider waste management strategy.

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CONTRIBUTORS TO DRAFTING AND REVIEW

Ahmad, Z.	Pakistan Atomic Energy Commission, Pakistan
Akhmedov, M.	Nuclear and Radiation Safety Agency, Tajikistan
Al Sabbagh, A.	Jordan Atomic Energy Commission, Jordan
Asaduzzaman, K.	Bangladesh Atomic Energy Commission, Bangladesh
Bennett, P.	Institute for Energy Technology, Norway
Bracke, G.	Gesellschaft für Anlagen- und Reaktorsicherheit, Germany
Chapman, N.	Consultant, Switzerland
De Paiva, I.	Instituto Superior Tecnico, Portugal
Degnan, P.	Catalystra, Australia
Feinhals, J.	DMT, Germany
Frazier, T.	Deep Isolation, USA
Gangadharan, A.	Bhabha Atomic Research Centre, India
Gheorghe-Sorescu, A.	Nuclear Agency and for Radioactive Waste, Romania
Gordon, I.	International Atomic Energy Agency
Griffiths, H.	ANSTO, Australia
Herzog, H.	Federal Ministry of Sustainability and Tourism, Austria
Klevinskas, G.	State Enterprise Ignalina Nuclear Power Plant, Lithuania
Kristiansen, H.	Norsk Dekommisjonering, Norway
Kunene, N.	The National Radioactive Waste Disposal Institute, South Africa
Langegger, E.	Nuclear Engineering Seibersdorf, Austria
Liu, J.	Beijing Research Institute of Uranium Geology, China
Malekifarsani, A.	Atomic Energy Organization of Iran, Islamic Republic of Iran
Mallants, D.	CSIRO, Australia
Mayer, S.	International Atomic Energy Agency
Mechora, S.	Agency for Radwaste Management, Slovenia
Muller, R.	Deep Isolation, USA

Neckel, W.	Nuclear Engineering Seibersdorf, Austria
Nieder-Westermann, G.-H.	International Atomic Energy Agency
Norasalwa Binti Zakaria	Malaysian Nuclear Agency, Malaysia
Nummi, O.	Fortum, Finland
Pham, X.L.	Inspectorate of Viet Nam Agency for Radiation and Nuclear Safety, Viet Nam
Prasertchiewchan, N.	Radioactive Waste Management Centre, Thailand
Radonjic, S.	Environmental Protection Agency of Montenegro, Montenegro
Sassani, D.	Sandia National Laboratories, USA
Savvidou, A.	INRASTES NCSR 'Demokritos', Greece
Shin, K.	Korea Atomic Energy Research Institute, Republic of Korea
Sriwahyuni, H.	Centre for Radioactive Waste Technology, Indonesia
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