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Geological Disposal of Radioactive Waste: Technological Implications for Retrievability

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GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE: TECHNOLOGICAL IMPLICATIONS FOR RETRIEVABILITY

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GEOLOGICAL DISPOSAL OF RADIOACTIVE WASTE: TECHNOLOGICAL IMPLICATIONS FOR RETRIEVABILITY

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FOREWORD

The possibility of retrieving spent nuclear fuel or high level waste placed in geological repositories is an issue that has attracted increased attention during the last decade, not only among technical experts but also among politicians at different levels, environmental organizations and other interested representatives of the public. As an argument for retrievability, it is often stated that a repository programme will need to respond flexibly to:

— New technical information regarding the site and design;
— New technological developments relevant to nuclear waste management;
— Changes in social and political conditions and acceptance;
— Changes in regulatory guidance and its interpretation, or in basic safety standards.

The IAEA, therefore, cooperated with the Swedish National Council for Nuclear Waste (KASAM) in organizing an international seminar on the issue of retrievability in Saltsjöbaden, a town near Stockholm, Sweden, in October 1999. Also around this time, the OECD Nuclear Energy Agency (OECD/NEA) Radioactive Waste Management Committee identified “the reversibility of decisions in waste disposal programmes and the potential for retrieval of disposed waste from a geological repository” as a key topic within the area of overall waste management approaches. As an outcome of an ad hoc meeting exploring this topic, in 2001, the OECD/NEA published an overview of the relevant issues based on the current understanding and views of experts from the waste management community in OECD/NEA member countries. The European Commission carried out a study on “the retrievability of long lived radioactive waste in deep underground repositories” during the period 1998–1999 with the objective of comparing approaches in nine European countries and to establish a clear interpretation and working definition of the concept of retrievability; a report was published in 2000.

Consequently, in a number of IAEA Member States, requirements for the reversibility of waste management decisions and actions, including provisions for the retrievability of waste packages after their disposal, have been introduced in the national legislation or regulations regarding long term radioactive waste management.

Complementing the discussions and work performed in international forums and the reports on reversibility and retrievability that have already been published, this report assesses the technological implications of retrievability in geological disposal concepts. Scenarios for retrieving emplaced waste packages are considered, and the publication aims to identify and describe any related technological provisions that should be incorporated into the design, construction, operational and closure phases of a repository.

The IAEA wishes to thank all those involved in the preparation and review of this report and its reviews.

The IAEA staff members responsible for this publication were B. Neerdael and S. Hossain of the Division of Nuclear Fuel Cycle and Waste Technology.

EDITORIAL NOTE

CONTENTS

SUMMARY

Various IAEA Member States are discussing whether and to what degree reversibility (including retrievability) might be built into management strategies for radioactive waste. This is particularly the case in relation to the disposal of long lived and/or high level waste and spent nuclear fuel (SNF) in geological repositories. It is generally accepted that such repositories should be designed to be passively safe with no intention of retrieving the waste. Nevertheless, various reasons have been advanced for including the concept of reversibility and the ability to retrieve the emplaced wastes in the disposal strategy. The intention is to increase the level of flexibility and to provide the ability to cope with, or to benefit from, new technical advances in waste management and materials technologies, and to respond to changing social, economic and political opinion.

The technological implications of retrievability in geological disposal concepts are explored in this report. Scenarios for retrieving emplaced waste packages are considered and the report aims to identify and describe any related technological provisions that should be incorporated into the design, construction, operational and closure phases of the repository. This is based on a number of reference concepts for the geological disposal of radioactive waste (including SNF) which are currently being developed in Member States with advanced development programmes.

The report begins with a brief overview of various repository concepts, starting with a summary of the types of radioactive waste that are typically considered for deep geological disposal. The main host rocks considered are igneous crystalline and volcanic rocks, argillaceous clay rocks and salts. The typical design features of repositories are provided with a description of repository layouts, an overview of the key features of the major repository components, comprising the waste package, the emplacement cells and repository access facilities, paying special attention to the buffer, backfill and/or closure of these openings.

In a number of countries, it is becoming increasingly important to include provisions for waste retrieval, and retrievability is a legal and/or regulatory requirement in certain cases. Accordingly, the potential benefits and detriments that retrievability may provide are discussed, possible retrievability strategies are outlined and a summary of some of the non-technical considerations and implications is provided, which also includes discussions on IAEA safeguards and safety implications, the cost factors involved and the management of repository information and expertise.

The requirement to be able to retrieve waste from a geological repository has technological implications in terms of the design of the disposal system and the associated repository infrastructure. Certain common repository design features (e.g. the use of long lived waste containers) are inherently beneficial in terms of the ability to retrieve waste. However, certain provisions are required to facilitate waste retrieval and the effort involved in any retrieval operations will depend on several factors, which have been outlined by reference to example repository design concepts. In the context of retrievability, the environmental conditions within the repository have potential implications in terms of the timescales of waste container integrity and the operational safety of personnel. During a potentially long period of repository implementation and operation, some critical decisions need to be made about how, when and whether various implementation steps should be taken. This may include decisions as to whether the emplaced waste has to be retrieved. Monitoring information can assist the repository operator (and society) in taking these decisions. More detailed information supporting the analysis (programme, waste inventory, repository design and retrieval concept) is provided in the country annexes.

The main conclusions of the study are that:

— Several Member States are incorporating reversibility and/or retrievability provisions in their development plans for geological repositories, largely in response to public concerns.
— The timescales for when retrieval is likely to be practicable on technical grounds is of the order of hundreds of years.
— Retrieval of waste from a repository may be feasible during repository operations or following closure. Depending on the concept, however, waste retrieval is likely to become progressively more difficult during the operating life of the facility and beyond.

— Waste retrieval may have a negative impact on both conventional and radiological safety. Any potential deleterious effects could be reduced by appropriate provisions, especially by incorporating the provision for retrievability as early as possible into the design process.
— Any retrievability provision must not have a negative impact on the long term safety of the disposal system.
— There may be significant additional costs associated with retrieval provisions.
— Many disposal concepts have inherent provisions for retrievability (e.g. long lived containers, removable backfill) and some concepts include specific design provisions (e.g. waste package handling facilities that are designed for both emplacement and retrieval). Retrieval of waste from repositories without specific provisions is also possible, but may be more difficult and costly.
— Suitable monitoring would be required to ensure that waste package retrieval remains possible.

Additional work may be useful in confirming the results of studies to date on retrievable concepts and waste retrieval processes. In particular, it would be useful to gain further practical experience of the removal of engineered barriers and the retrieval of waste packages in different types of geological repositories.

1. INTRODUCTION

1.1. BACKGROUND

Various IAEA Member States are discussing whether and to what degree reversibility (including retrievability) might be built into management strategies for radioactive waste. This is particularly the case in relation to the disposal of long lived and/or high level waste (HLW) and spent nuclear fuel (SNF) in repositories located hundreds of meters below the surface in stable geological media. It is generally accepted that such repositories should be designed to be passively safe with no intention to retrieve the waste [1]. Nevertheless, various reasons have been discussed for including the concept of reversibility and the ability to retrieve the emplaced wastes in the disposal strategy. There is also general consensus that any provisions should be compatible with the safety objectives of the disposal system, both before and after repository closure.

In some Member States, requirements for reversibility of waste management decisions and actions, including provisions for the retrievability of waste packages after their disposal, have been introduced in national legislation or regulations regarding long term radioactive waste management. In some other Member States, where such requirements have not been formally adopted, radioactive waste management organizations have chosen to introduce reversibility and/or retrievability provisions in their disposal concept. The intention is to increase the level of flexibility and to provide the ability to cope with, or to benefit from, new technical advances in waste management and materials technologies, and to respond to changing social, economic and political opinion.

Reversibility and retrievability have been discussed from different perspectives in various forums and reports at the international level [1–4]. Changes in repository design, such as modification for the disposal cell design to allow easy access to the waste packages, or to ensure the stability of the underground structures, are generally considered to enhance retrievability for a prescribed period of time.

Nevertheless, there is little or no practical experience from operating geological repositories to draw upon when considering the implications of implementing waste retrieval. The emplacement of engineered barriers in ways designed to allow relatively easy removal may have an impact on safety, particularly during the operational phase. In addition, retrievability will have an impact on costs and this is especially the case when this requirement is not introduced at an early stage in the repository design process. The technical feasibility of provisions envisaged for waste retrieval has been established in demonstration projects and in situ tests (see the ESDRED and SKB web sites: http://www.esdred.info, http://www.skb.se). As a result of the current level of progress, the technical implications discussed in this document need to be considered as tentative in nature, requiring future confirmation and development. Therefore, retrievability is identified as a subject potentially requiring further demonstration.

1.2. OBJECTIVE

This document explores the technological implications of retrievability in geological disposal concepts. A basic assumption is that the technological implications of any provision to retrieve emplaced waste must not jeopardize the safety of the disposal system both before and after repository closure. Scenarios for retrieving emplaced waste packages are considered and the document aims to identify and describe any related technological provisions that should be incorporated into the design, construction, operational and closure phases of the repository. The assessment of such technical provisions is based around a number of repository concepts currently under development in several Member States, thus reflecting considerations relevant to a variety of geological settings and repository designs. The aim is to identify and highlight the technical provisions and related considerations in relation to retrievability that are relevant in the various stages of the repository life cycle.

1.3. SCOPE

This report presents an assessment of the potential technological implications of retrievability on the geological disposal of radioactive waste. This is based on a number of reference concepts for the geological disposal of radioactive waste (including SNF) which are currently being developed in Member States with advanced development programmes. The intended audience is those who are responsible for deep geological disposal programmes, including repository designers and decision makers.

This publication encompasses a consideration of the relevant aspects associated with the properties of the different types of waste, different potential host rocks and different repository designs. Those components of the disposal system, such as the waste package, the emplacement cell and associated engineered barrier system (EBS), are considered in relation to their influence on the ability to retrieve the waste. Timescales over which waste retrieval might need to be considered are also addressed in relation to the various stages of repository development and evolution. Consequently, scenarios relevant to the operational, closure and post-closure phases are discussed.

The scope of this document includes all types of waste that may be destined for deep geological disposal in engineered repository systems. However, it does not consider disposal concepts based on the emplacement of waste in deep boreholes drilled from the surface.

1.4. KEY DEFINITIONS

For the purposes of this report, it is important to clearly define a number of specific terms. These definitions are provided below.

Closure is the administrative and technical actions directed at a repository at the end of its operating lifetime — for example, for a geological repository, the backfilling and/or sealing emplacement and the access points leading into it, and the termination and completion of activities in any associated structures [5].

Reversibility is the ability to reverse one or a series of steps in repository development at any stage of the programme. This implies the review and, if necessary, re-evaluation of earlier decisions, as well as the technical means to reverse previous steps. A disposal programme planned to facilitate reversibility needs to include provisions for review of the programme at discrete steps, as well as measures to facilitate reversal of actions taken at each step of implementation. In the early stages of a programme, reversal of a decision regarding site selection, or the adoption of a particular design option, may be considered. At later stages, during construction and operation, or following emplacement of the wastes, reversal may involve measures, such as modifications of one or more components of the disposal system, or retrieval of waste packages [1].

Retrievability is a special case of reversibility, being the ability to reverse the action of waste emplacement [1].

Retrieval is the action of recovery of the waste or waste packages, which may need to be considered at various stages after emplacement, including after final sealing and closure [1]. Retrieval must always be linked to an alternative strategy for dealing with the waste.

1.5. STRUCTURE

A brief summary of repository concepts is provided in Section 2 so as to provide a basis for subsequent discussions of the technological implications of retrievability. Section 3 outlines some of the major considerations in relation to retrievability and illustrates some of the strategies and provisions for waste retrieval by reference to current repository concepts. The technological implications of retrievability are then identified in Section 4. Finally, the conclusions of the study are discussed in Section 5 and some recommendations are provided. More detailed information supporting the analysis made in Section 4 (programme, waste inventory, repository design and retrieval concept) is provided in the country annexes.

2. REPOSITORY CONCEPTS

This section provides a brief overview of repository concepts, starting with a summary of the types of radioactive waste that are typically considered for deep geological disposal. It is included to provide some context for the subsequent discussion of retrievability.

2.1. RADIOACTIVE WASTE TYPES

The operation of nuclear power plants and the reprocessing of spent fuel generate radioactive wastes. Radioactive wastes are also produced by a variety of activities in industrial sectors, in research, medicine and in military programmes.

Different categories of radioactive waste may be defined and categorization is normally based on the radionuclide content, the longevity of the radiological hazard presented and the activity level. Typically, several waste classes are defined, namely exempt waste, low and intermediate level wastes (both short and long lived) and HLWs. The classification of radioactive waste is discussed in Ref. [6]. A new classification of radioactive waste is currently under development by the IAEA, but it is not likely to change the scope of this report.

This study is concerned with those wastes that may be destined for disposal in deep geological repositories and three types of waste are identified for the purposes of this report, as described below.

2.1.1. Spent nuclear fuel

SNF contains fissile material and, depending on future strategies and programmes, it may be inappropriate to classify such material as waste. The ability to retrieve SNF, and to extract and utilize the fissile component, where this is technically and economically feasible, is one of the potential drivers for retrievability.

Different types of nuclear reactor utilize various types of fuel. Nuclear fuels differ in terms of the fuel dimensions, composition and type of cladding. Fuel is typically oxide based (e.g. uranium oxide (UOX) and mixed uranium and plutonium oxide (MOX)), although some reactors utilize metallic fuel elements (e.g. Magnox reactors). Depending on the reactor, fuel type and fuel burnup, the properties of SNF can vary considerably, particularly in relation to the radionuclide inventory and heat generation properties.

A key consideration in SNF disposal, which impacts on the disposal strategy, is the level of heat generation (i.e. the thermal output). Depending on the nature of the spent fuel and its history, the package design and spent fuel loading, the magnitude of the thermal output can vary widely, e.g. from some kilowatts up to 12 kW per package (see Annex V). Certain types of SNFs (e.g. spent Magnox fuel) have considerably lower thermal output.

2.1.2. Wastes from spent nuclear fuel reprocessing

During the reprocessing of SNF, uranium and plutonium are separated from the other actinides and fission products. The extracted uranium and plutonium are separated, and can be used to produce new fuel. The remainder, consisting of other actinides, fission products and certain activation products, form a high level, long lived liquid waste that is generally vitrified to make it passively safe and easier to handle. The cladding removed from SNF and any additional secondary wastes arising from reprocessing operations (e.g. ILW and LLW arising from the treatment of effluent streams and residues) may also be destined for geological disposal.

The three main types of waste produced by reprocessing are:

- Heat-generating HLW, which is generally vitrified (thermal output higher than a few Watts per litre);
- Hulls and end-pieces that are slightly heat generating (thermal output at least one order of magnitude lower than HLW);
- Wastes generating no significant heat (ILW and LLW).

2.1.3. Other radioactive wastes

These may include various decommissioning wastes, such as reactor internals (e.g. core components) and certain radioactive wastes produced by a variety of activities in other sectors. Such wastes may be packaged in a variety of ways, often using specialized containers (e.g. to accommodate large items). The use of specialized containers can lead to specific constraints in terms of disposability and retrievability.

2.2. POTENTIAL HOST ROCKS

Geological disposal is based on the isolation of waste within the geosphere in locations where it is expected to be stable over a very long time. Repository concepts and potential host rocks differ between Member States. The main host rocks considered are igneous crystalline and volcanic rocks, argillaceous clay rocks and salts (see Section 3). The choice of host rock is mainly governed by the availability of suitable geological formations of convenient thickness and geological setting. Underground laboratories for testing and building confidence in disposal technologies have been built in all types of potential host rocks.

2.3. REPOSITORY DESIGN

The long term safety of a geological repository is based on the concepts of defence in depth and isolation that is provided by the combined effects of multiple, man-made and natural barriers. The definition of an EBS refers to the container, backfill and buffer sealing materials, and any man-made component that is designed to isolate radioactive waste and limit its release and transport over long periods of time.

This section begins with a description of repository layouts, which is followed by an overview of the key features of the major repository components, comprising the waste package, the emplacement cells (with or without buffer) and repository access facilities, paying special attention to the buffer, backfill and/or closure of these openings.

The design features of some disposal concepts are illustrated by the country annexes for countries with advanced programmes and in particular those concepts which have been the subject of specific studies on retrievability.

2.3.1. Repository layout

When dealing with heat-generating radioactive waste, a major consideration is managing the thermal loading of emplacement cells or drifts so as to stay within defined temperature criteria. This is a key determinant of the layout configuration and repository design. The thermal load resulting from the design depends mainly on the thermal power of the waste package, the thermal features of the host rock, the spacing of the waste packages, and the quality of the thermal coupling between the waste package and the host rock.

There are clear advantages in cooling the waste to a temperature below 100°C before emplacement. However, in the case of the Yucca Mountain project (USA/YMP), the aim is first to limit the spatial extent of temperature increase and to avoid temperatures that exceed stated goals for the waste package or disposal container surface and the surrounding host rock.

Some designs are characterized by host rocks with good thermal conductivity or disposal cells with good thermal coupling (rock salt with temperatures up to 200°C) or by an active cooling system during the pre-closure phase and during retrieval, if necessary (e.g. USA/YMP). Other countries are considering extended storage durations prior to waste emplacement, which result in lower thermal output in the repository (e.g. Belgium, France).

For waste with low or insignificant thermal output (LILW), the cells may be large and contain a large number of waste packages, thus providing a more compact disposal area. In such cases, the cell size (diameter and length) and spacing depends mainly on the stability of the host rock.

2.3.2. Waste packages

The emplaced waste package is an integrated element of the repository. The waste package comprises the waste container and the waste form. The waste package, as an engineered barrier, is designed to ensure operational safety during interim storage, transport and waste package handling operations, and may provide a long term containment function. The design configuration of the waste package varies according to the repository concept and reflects the steps and processes that are required to safely handle the waste and transport it from the reactor or storage site to the repository.

Physical features of waste packages vary according to different waste package configurations. The major parameters are as follows:

— Physical properties/size/mass: The shape of the package is typically cylindrical for spent fuel and vitrified waste, and may be cubical or cylindrical for LILW. The mass and size of waste packages may vary significantly, ranging from less than 1 t and 1.3 m in length and 0.4 m in diameter for vitrified waste to more than 70 t and about 6 m in length and 2.1 m in diameter for the spent fuel packages. In some recent concepts, larger and heavier waste packages are considered, e.g. “supercontainers” (Belgium) which include in-built concrete cylinders as EBS;
— Container materials: The disposal containers can be made out of a variety of materials. Canisters for SNF and/or HLW may contain copper (Canada, Sweden, Hungary and Finland), nickel alloy (USA) or steel (Belgium, Canada, France, Japan, Hungary and United Kingdom). For other types of waste, containers are made of carbon/stainless steel or concrete (Germany, France, Switzerland, Japan and United Kingdom). The use of other materials, such as titanium, is also proposed;
— Radiological protection: Integral radiation shielding is usually not included in the design of a waste package. However, in some designs, this may be included (e.g. the German POLLUX design (using thick steel) and certain shielded containers designed by Nirex [7]);
— Thermal output: The thermal output of the waste package at the time of disposal depends on the type of waste. The thermal output of SNF and HLW may vary considerably and in the USA, for example, this may be as high as 11.8 kW per package. Thermal output depends on several factors such as the kind of fuel, the number of fuel assemblies contained in the package, fuel burnup, extent of fission product incorporation (in the case of vitrified HLW) and the time since reactor discharge (i.e. the cooling time) before emplacement.

2.3.3. Emplacement cells and related infrastructure

That part of the repository where the waste packages are emplaced is referred to here as the emplacement cell, noting that depending on the repository design this could be a chamber, cavern, vault, drift or vertical/horizontal cylindrical hole. The main features of the emplacement cells, boreholes, chambers, tunnels, liners and EBS vary according to the different repository designs as follows:

— Number of waste packages and size of the cell: Some cells are designed for a single package (e.g. Sweden, Japan), while others are planned to accommodate a large number of packages (e.g. USA/YMP, Germany). Typically, larger package numbers are associated with LILW emplacement cells;
— Presence or absence of a buffer between the package and the sidewall or lining: In most concepts, a buffer is placed between the waste package and the sidewall or lining of the emplacement cells. Bentonite or a bentonite–sand mixture is used as a buffer in saturated host rock within spent fuel emplacement cells (Sweden, Spain, Switzerland and Canada). In some countries, there is a functional clearance between the waste package and the sidewall or lining (USA/YMP, French HLW option and Japanese ILW option). In Germany, the gap between the package and the sidewall is backfilled. Due to the specific unsaturated environment at Yucca Mountain (USA), backfill will not be placed in the emplacement drifts;
— Nature of the lining/rock support: Depending on the nature and characteristics of the host rock, a rock support/lining may be necessary (e.g. USA, Belgium, Switzerland and France);
— Access: Access from the surface to the disposal level can be achieved by shafts (Germany, Belgium, Japan, Canada), by a combination of shafts and ramps (Sweden, France, Japan, Canada) or by a horizontal set of

ramps (USA/YMP). The various designs reflect differences in the layout, waste inventory, host rock and the proposed emplacement process;
— Orientation: The orientation of the waste packages and associated repository components is either vertical (KBS-3V in Sweden, H12 in Japan) or horizontal (Belgium, France, Germany, USA/YMP).

2.3.4. Sealing and backfilling

Backfilling is typically used to stabilize the access openings, to limit associated rock damage and to restrict inadvertent intrusion. It may also provide a degree of chemical buffering. In most cases, backfill and seals made of buffer are used to seal the disposal cells and to facilitate waste isolation and repository closure. In the USA/YMP, backfilling and closing of access drifts and ventilation shafts would be with crushed host rock, concrete plugs and other materials. The selection of backfilling materials further depends on the host rock. Backfill can include the excavated rock (Germany, France), mixed rock spoils with bentonite (Sweden, Canada), chemical buffering materials (USA/WIPP), or cementitious backfilling (United Kingdom Nirex concept and German concept).

Sealing materials, which are referred to here as buffer, typically comprise swelling clay, such as bentonite, and/or a mixture of clay and a suitable aggregate such as sand. The objective is to produce a seal with a permeability as low as technically achievable, with a good mechanical stability. Seals are placed where necessary, and this is typically at the entrance of emplacement cells and at fractures or highly conductive areas of the host rock that are intersected by the access openings (access drifts, galleries, dams, shafts and ramps).

3. CONSIDERATIONS IN RELATION TO RETRIEVABILITY

Disposal in a deep geological repository aims to provide a permanent, long term radioactive waste management solution. However, in a number of countries, it is becoming increasingly important to include provisions for waste retrieval and retrievability is a legal and/or regulatory requirement in certain cases (Table 1, Annexes I–VI).

Prior to the development and implementation of a disposal concept, it is difficult to anticipate all of the reasons why radioactive waste might be retrieved from a geological repository. Indeed, the related ethical considerations [8] and socio-political imperatives may differ both regionally and over time. Various stakeholder surveys have shown that a major factor in gaining public acceptance is the ability to retrieve the waste [9]. This factor became one of the key drivers for developing the retrievability of the French concept (Annex II). In the case of spent fuel, an additional technical driver for retrievability is the potential to recover fissile material that may become useful as a future resource (e.g. USA, Annex V).

This section begins with a consideration of the potential benefits and detriments that retrievability may provide. Possible retrievability strategies are outlined and a summary of some of the non-technical considerations and implications is provided.

3.1. BENEFITS AND DETRIMENTS OF RETRIEVABILITY

It is worthwhile considering some of the reasons why retrievability may be included in a disposal strategy and evaluating both the potential positive and negative implications. This section summarizes some of the potential benefits and detriments of retrievability in the context of the deep geological disposal of radioactive waste. Benefits and detriments are defined here as the potential advantages and disadvantages, respectively, of including retrievability in a disposal strategy and these may be of an economic, technical, ethical or socio-political nature. The technological implications of retrievability are discussed further in Section 4.

The following lists may not be comprehensive and the applicability of each benefit or detriment may vary between concepts. Some aspects may represent site specific issues. There is a need to ensure that the associated

TABLE 1. RETRIEVABILITY REQUIREMENTS OR RECOMMENDATIONS

Country	Legal requirements	Under consideration	Host rocks
Belgium	—	+	Clay
Canada	+		Crystalline and sedimentary
China	—	—	Crystalline
Finland	+[a]		Crystalline
France	+		Clay
Germany	—	—[b]	Salt, iron ore under clay
Hungary	+		Crystalline and claystone
Japan	—	+	Clay, crystalline
Netherlands	+		Clay, salt
Russian Federation	—	+[c]	Clay, crystalline
Sweden	—	+	Crystalline
Switzerland	+		Clay, crystalline
United Kingdom	—	+	Not defined
Ukraine	—	+[d]	Crystalline
United States of America	+		Volcanic, (YMP); salt (WIPP)

[a] Based on container integrity.
[b] Concept considered inherently retrievable.
[c] Law under consideration requires retrievability of SNF.
[d] Draft regulations include retrievability.

benefits and detriments are assessed and that a balanced approach is adopted during the development of a disposal strategy.

The potential benefits provided by retrievability include the following:

- May facilitate confidence building and may engender public acceptance. People are generally reluctant to accept any irreversible waste management solution and this is particularly the case when dealing with radioactive waste;
- Enables the potential future utilization of perceived resources, such as uranium and/or plutonium in spent fuel. This advantage does not apply to LILW and HLW, unless it is economically viable and technically feasible to obtain useful materials from them;
- Recognizes the possibility that future technologies may offer improved methods for dealing with the waste;
- Provides the ability to take corrective action in cases where there are shortfalls in performance;
- Helps to ensure that future generations have the opportunity to make their own decisions. Provision of a retrievability strategy allows technological flexibility in a stepwise decision making process, which is particularly important when taking decisions for large and complex actions;
- Helps to enable a precautionary approach. However, this only applies during the time period when retrieval is practical and this may be short in comparison to the timescales typically considered in post-closure performance assessments.

The potential detriments of retrievability include the following:

- Provisions for waste retrieval may have a negative impact on both conventional and radiological safety. Relative to early closure scenarios, the risks to workers are increased during any period of extended operations in situations where a repository is to remain open to facilitate the potential retrieval of waste. The worker risk burden of maintaining the facility to retrieve waste and the risks associated with waste retrieval operations may exceed the conditional, long term risks to the public and the environment following facility closure;

— Long term safety may be reduced should the engineered barriers degrade significantly during any period prior to repository closure and in cases where any specific infrastructure to facilitate waste retrieval prevents or hinders optimized closure of the disposal system;
— Unstable socioeconomic and political situations may lead to the abandonment of a facility prior to closure with negative implications in terms of long term safety;
— Uncertainties regarding the timing of closure may complicate the development of an acceptable safety case;
— The ability to retrieve waste may complicate safeguards measures;
— Additional costs are associated with the provision of retrievability and may include costs related to repository infrastructure, continuing operations, maintenance and refurbishment.

The process of deciding whether, and to what extent, retrievability features in a waste management strategy should be based upon detailed assessments, which appropriately evaluate the potential advantages and disadvantages associated with waste retrieval and/or any other alternative actions that may be appropriate. Such assessments should consider any additional facilities that may be required for the handling, storage, processing or reworking of retrieved waste packages. An evaluation of the alternative waste management options that may be adopted following retrieval would also be required, although this aspect is not discussed any further in this report.

3.2. RETRIEVAL STRATEGIES

Several countries have performed studies to evaluate the feasibility of waste retrieval [10–12]. The ease of facilitating waste retrieval depends on the repository concept, the timescales during which waste retrieval may be required and the stage of repository evolution under consideration. Some countries have integrated retrievability into the concept design and management arrangements (e.g. France). In other countries, no special measures are designed to facilitate waste retrieval but the repository concepts have been evaluated to be inherently retrievable.

Waste retrieval could be facilitated in a number of ways depending on a variety of factors. Besides the properties of the host rock, the specific aspects of repository design and the degree of backfilling and sealing of repository openings and connections with the surface are highly relevant. In addition, the time of the action, the delay between waste emplacement and its retrieval may also affect the feasibility and practicability of retrieval. Certain common design features, such as long lived waste containers, are clearly beneficial in terms of the retrieval of the waste over timescales where package integrity remains (see Section 4.1.1).

Studies have been performed to evaluate the feasibility of waste retrieval in various disposal concepts. Typically, retrievability is integrated as an input to repository design studies and the intention is that waste packages will remain easily retrievable as long as the repository remains open. The repository closure strategy and any specific provisions for retrieval have a major impact on the feasibility of retrieving waste. In the context of retrievability, three general categories of repository concept are identified:

— Repositories where the intention is for early closure following waste emplacement: Here, waste retrieval may be possible, even though the repository may not be specifically designed to facilitate waste retrieval (e.g. Swedish and Swiss concepts (see Section 4.2.2), also Germany (Annex VI));
— Repositories that are based around a stepwise approach to implementation: Such concepts may include specific design provisions to facilitate waste retrieval. At the end of each implementation step, a decision is made to further close part of the repository or to reverse the previous steps. It is anticipated that efforts to retrieve the waste would increase progressively as repository closure progresses in a stepwise manner (e.g. French concept and the United Kingdom Nirex concept (Section 4.2.2);
— "Open repository" systems: Here, the emplacement and closure operations take place at different times (e.g. Yucca Mountain in the USA, see Annex V). This allows the waste to be easily retrieved up to the time that the repository is closed and sealed. When the repository is closed, the emplacement drifts are not backfilled and access tunnels and ventilation shafts are backfilled and sealed.

Even without special provisions and design enhancements to facilitate waste retrieval, it would be possible, at least in principle, to recover waste from closed geological repositories (e.g. using specific mining techniques). However, the practicability of such actions would need to be considered in relation to the associated expense, technical effort and worker risk burden.

3.2.1. Repository closure strategies

The stages of repository development during which retrieval may be required could include the following:

- Waste emplacement;
- A period of monitoring in a cell prior to and possibly after sealing and backfilling;
- Closure of the emplacement cell, which may include sealing and backfilling, and continuous monitoring of the repository;
- Closure of the facility, which may include sealing and backfilling, and post-closure monitoring;
- The early post-closure phase assuming package integrity remains.

The strategies that are proposed for repository closure in the various repository concepts will clearly have implications in terms of the period over which waste retrievability is practicable and the ease of accomplishing it. Typically, the main phases of the repository life cycle that have a bearing on the retrieval strategy are:

- *Phase 1*: Emplacement of the waste packages in disposal cells or vaults. Cells and vaults essentially remain open while waste is being emplaced. In certain concepts, this phase may be extended to encompass a period of care and maintenance prior to progressing to Phase 2;
- *Phase 2*: Sealing of emplacement cells. These remain accessible, however, because tunnels and/or handling drifts have not been backfilled and sealed;
- *Phase 3*: Backfilling and sealing of the underground openings and access tunnels in one step, or in several progressive steps, leading to repository closure.

In all of the disposal strategies, there is a period of time during which the repository remains open (i.e. in Phases 1 and 2) and accessible for operational reasons (i.e. the shafts, access drifts or ramps are still open, and the ventilation and transport equipment are operational). Retrievability would be straightforward during Phase 1 (reversal of the waste emplacement operation), should be possible during Phase 2 and would become significantly more difficult following repository closure (Phase 3). Following Phase 3, some form of mining operation would be required to retrieve waste packages. It should be noted that postponing closure may ultimately delay a favourable situation where the repository is passively safe.

The effort associated with package retrieval could be evaluated by assessing the likely evolution of the repository during each phase and by estimating the quantity of backfill/seal material that would need to be removed to enable access to the waste packages. This latter aspect has an impact on the technology that would be required for retrieval.

For some concepts, the facility could remain open (Phase 1) for a period of time that could be longer than is necessary for operational reasons, e.g. from decades (USA/YMP) to centuries (France). In the USA/YMP concept, this postponed closure strategy is essential for a number of reasons, namely regulatory compliance, thermal management of the waste output and to enable a monitoring programme to confirm the performance of the disposal system to be completed. It may also provide the opportunity to build public confidence in the chosen disposal solution.

It is important to recognize that the period during which it is technically practicable to postpone repository closure, without compromising long term safety, may vary for different host rocks. For example, in salt, leaving a repository open for a long period may be inappropriate as this might not allow full use to be made of the plastic nature of the rocks in achieving repository sealing. In plastic clay, there may be a risk of introducing an extended engineered disturbed zone (EDZ) [13].

A stepwise approach includes discrete and explicit steps in the disposal process with appropriate societal inputs at each stage. This approach is particularly suitable when the operational period necessary for waste disposal has an estimated duration of several decades, based on the amount of waste that is to be disposed and a suitable repository design and emplacement process. In such cases, it may not be appropriate to prescribe the detailed process at this stage, because a significant part of the operational period will be controlled by future generations. Indeed, the stepwise approach is intended to provide the opportunity for future generations to make the decisions regarding appropriate actions and the repository is managed step by step with decision points between each step. It is important to avoid situations where a series of relatively small decisions, each of which may be made on narrow criteria, could lead the programme onto an unsound path [14]. At each decision point, three main choices are possible:

— Reverse previous steps by removing some or all seals or backfilling or by retrieving some or all waste packages;
— Wait before deciding to close some of the underground facilities in order to obtain more monitoring data;
— Progress the closure process by deciding to close some or all of the remaining open underground facilities.

The closure strategy may differ for different types of waste (e.g. Type C versus Type B waste in the French concept, Annex II) and so the number of possible choices may be much larger. Such a closure strategy would be reliant on data acquired in underground and surface studies conducted during repository construction and operation. In such a stepwise approach, monitoring systems are required to provide the decision makers with appropriate information, as discussed further in Section 4.4.

3.2.2. Retrievability timescales

The timescales over which it is practicable to retrieve waste packages may vary between the various disposal concepts. This section summarizes current thinking with regards to the timescales, as exemplified by the Canadian, French and United Kingdom Nirex concepts.

It is generally recognized that retrievability will become progressively more complicated with time, and this is particularly the case following sealing, backfilling and closure. For example, should disposal cells or vaults remain open for extensive periods, there is a possibility of progressive degradation of the waste packages and the repository infrastructure, and this may adversely impact retrievability. Typically, the timescales of monitored, retrievable storage prior to facility closure are of the order of hundreds of years (e.g. up to 500 years).

In Canada, the Adaptive Phased Management (APM) approach (Annex I) enables used fuel to be retrievable at all times, both during above and below ground interim storage and during emplacement in a deep geological repository, which may not commence for another 60 years. APM ensures that the used fuel is accessible should monitoring activities indicate that there are problems with the management system, or if there is a clearly justifiable reuse of the material, or should future technologies emerge to better manage the used fuel over the long term.

In the French concept (Annex II), the following timescales are currently being considered for the retrieval of vitrified HLW [12]:

— The whole repository area for vitrified waste may be constructed and operated (with waste emplacement during approximately 40 years, requiring a new module every two years);
— No timing for retrievability was defined in the 1991 French Radioactive Waste French Act. ANDRA's (National Radiactive Waste Management Agency) studies show that the repository, as designed in 2005, enables reversible management of the waste packages for at least 200 to 300 years. During this time period, no schedule for the step by step closure process is imposed by the physical evolution of the repository;
— According to the results of the public debate (see Section 3.2), the 2006 French Act asks for a reversibility duration of at least 100 years;
— The thermal output of vitrified waste lasts for approximately 1000 years, but it could have an impact on the temperature inside the rock layer for some tens of thousands of years. However, the timing is very dependent on the cell concepts and on the repository layout;
— The French regulatory rules (RFSIII-2.f) require that the repository is designed to provide human protection even when there is no more institutional control, that is estimated to be maintained for 500 years. It is, therefore, considered to be possible to keep records for this duration;

— The safety case simulations are performed on a duration of around 1 000 000 years according to the half-life of the radionuclides present in the waste, and their travel time through the geological environment to the biosphere.

In the United Kingdom Nirex concept (see also Section 4.2.2), technical studies indicate that the repository could be designed to operate as a monitored, retrievable storage facility for up to about 100 years by initial design measures and routine maintenance activities [15]. If a longer period of monitored, retrievable storage is required, then this could be achieved by the construction of additional vaults and a rolling programme of waste transfer between vaults and refurbishment of the emptied vaults. On this basis, it is argued that the repository could be kept open for hundreds of years. When and if there is sufficient confidence in the system, the repository vaults could be backfilled (using a specially designed cement-based material in this case). Not all of the vaults need to be backfilled at the same time. Monitoring of a backfilled vault can continue while other vaults remain unbackfilled. Waste packages could still be retrieved at the end of this phase, albeit with increased difficulty [16].

3.3. NON-TECHNICAL ASPECTS

This section discusses some of the non-technical aspects which have a bearing on retrievability and is based largely on relevant considerations in a number of Member States. If there is an insistence on retrievability throughout the operating life of the repository, there is a potential prospect of an uneasy compromise between the technical requirements of the safety case and any prevailing socio-political pressures. The solution may involve an acceptance that retrievability is limited in time, and that retrieval will become progressively more difficult during the operating life of the facility and beyond, as discussed further in Section 4.

The public may favour a particular waste management strategy if there is an effective and transparent possibility for control and corrective intervention in the event of unsatisfactory performance. The retrieval of waste from a geological repository may be considered to be the ultimate remedial action in cases where control measures indicate shortcomings in compliance with performance expectations or may allow the future retrieval of a perceived resource.

Transparency is generally considered to be an important aspect relating to public acceptance of disposal. It is essential to provide all requested information and to openly demonstrate radioactive waste emplacement methodology and repository operations to foster public confidence in the safety of geological disposal. Providing public access to surface or underground facilities and demonstrating the transport and handling of waste canisters (including their retrieval) may be an essential feature in this regard. Stakeholder dialogue is an important aspect. It is important to ensure that the safety case is openly available and communicated in such a way as to be understandable to stakeholders.

Long term protection of human health and the environment is central to repository development. The precautionary principle, arising from the 1992 United Nations Rio Conference on the Environment, states:

> "…in order to protect the environment, the precautionary approach shall be widely applied by States according to their capability. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing cost effective measures to prevent environmental degradation".

Retrievability is considered as a possible means of implementing the precautionary principle in certain countries. It could be the expression of a cautious attitude for dealing with the uncertainties related to the very long lifetime of the waste. However, the timescales over which provisions for retrieval are maintained are likely to be short in relation to the timeframes that are considered in post-closure performance assessment (see Section 3.2.2).

In the context of retrievability, the precautionary principle also raises issues in relation to intergenerational equity. For example, leaving the repository or emplacement areas open may impose an undue burden on future generations (e.g. through associated negative impacts on short and long term safety, cost implications, etc.).

A balance is required to ensure that adopting a precautionary approach does not compromise intergenerational equity.

Ethical arguments for and against retrievability may be concept and site-specific issues. The following paragraphs present a summary of some of the ethical considerations in Canada, Sweden and France.

In Canada, the Nuclear Fuel Waste Management Organization (NWMO) carried out public consultations to establish an acceptable management approach for the long term care of used nuclear fuel. The approach has to be socially acceptable, technically sound, environmentally responsible and economically feasible. In 2005, the NWMO recommended that Canada proceed in a deliberate and collaborative way to isolate the spent fuel in a deep underground repository where the waste would be safely and securely contained by engineered barriers and the geosphere. It would be monitored and remain retrievable over time until a future generation decides to close the repository. The NWMO considered the technical implementation method to be crucial. An informed and willing host community would be identified and the process would be phased and transparent with explicit decision points where citizens are provided with genuine opportunities to influence the progress and outcomes. The recommendation presented by the NWMO in their report to the Federal Government is called APM by the NWMO [17].

The Swedish National Council for Nuclear Waste (KASAM) looked extensively at the question of responsibility to future generations. Two lines of reasoning were developed [8]:

— Our generation, which has had the benefit of nuclear power, must also take full responsibility for the radioactive waste (nuclear waste and spent fuel), and not leave an undue burden on future generations. This also means that the long term safety of a repository shall not be dependent on continued monitoring or maintenance by future generations;
— In a world where knowledge is increasing with time, and where value judgements are changing, future generations shall be given the freedom to make their own decisions with regard to the utilization of resources for safety and long term protection. Furthermore, a repository should not be designed so that it unnecessarily impairs future attempts to retrieve the waste, monitor or repair the repository.

In France, the 1991 Radioactive Waste Act prescribed three fields of research, namely partitioning and transmutation, deep geological disposal and long term storage. The Act also set a 2006 target for review and decision. To prepare for the decision, the Government required a National Commission (Commission Nationale du Débat Public) to organize a public debate on radioactive waste management. This public debate was based on several meetings and a web forum (www.debatpublic-dechets-radioactifs.org) dedicated to public feedback and inquiry, public information and dialogue in several locations in France, and particularly in the regions directly/potentially concerned by the radioactive waste. The main output of this public debate [18] is to state that the next Act should:

— Deal with all radioactive waste and not only HLW and ILW-LLW;
— Regularly update the waste inventory and the National Plan for radioactive waste management;
— Underline the importance of timeframes: delay for research, for the decision making process and a lack of public confidence with regard to very long term assessments. As a result, possible deadlines could be one to several decades in the short term, and possibly 100–150 years for the medium term;
— Maintain a choice between various solutions, i.e. an underground repository as the reference solution and/or durable storage facilities to await another long term solution;
— Develop information and dialogue with the public at the local and national scale, and for having a broader independent review by experts in order to increase confidence;
— Request justice, equity and balance between generations, and also between territories (from the very local communities to the whole country).

The Government's conclusions of this public debate, and the main options outlined in the draft version of the new Act were published only one month after the end of the public dialogue [19]. This Act was debated by the French parliament during the second quarter of 2006 and was voted on 28 June 2006. It confirms the underground repository as the reference solution, states that the minimum period for which reversibility must be guaranteed shall not be less than 100 years, and describes the procedure to be followed before licensing the construction of a deep geological repository. This procedure will comprise, among others, a public debate before the licence application, and a new Act, to be debated and voted by the parliament after the licence application, which will prescribe the relevant reversibility conditions. Once the Act is promulgated, the licence to build such a facility may be granted by State Council decree after holding a public debate on the issue.

3.4. SAFEGUARDS

Safeguards measures are applied to all fissile material and are a legally binding requirement for signatories of the Treaty on the Non-Proliferation of Nuclear Weapons. This also applies to any spent fuel disposed of in a repository as long as a safeguard regime remains in place for that facility. Specifically, the agreements on non-proliferation between the signatory States and the IAEA specify that nuclear safeguards can only be abandoned if the nuclear material is practicably irretrievable [20]. It could, therefore, be argued that any provision to enhance retrievability is in conflict with the objective of preventing inadvertent diversion of fissile nuclear material. Providing a retrievability period after emplacement operations will, therefore, require that safeguards measures are maintained continuously for the surface and the underground facilities during that period.

The required safeguards provisions will depend upon the ease of access to the nuclear material and the ease of retrieval. For example, the level of safeguards required during any extended period where the disposal cells (or only the access routes to the repository) remain open will be much higher than those that are required following final closure. The safeguards effort, if the disposal cells remain open, will be comparable to that of an interim disposal facility at or near the surface. Spent fuel could be diverted from such an open repository within days, while it will take years to remove fuel out of a closed repository [2]. Moreover, a repository designed to facilitate waste retrieval after closure may require more careful post-closure surveillance.

With regard to safeguards considerations, the following aspects need careful consideration if the disposal facility allows for the retrieval of waste:

— Diversion potential: While the repository is open, there may be greater potential for diversion of nuclear material if institutional controls are not maintained. Hence, from the safeguards point of view, the extended time for retrieval may be less effective than if closure occurs immediately after completion of the waste emplacement;
— Prolonged inspection: A repository that remains open to facilitate retrieval will prolong underground safeguards inspections. Maintaining an underground inspection regime, and maintaining safeguards inspections as well as underground monitoring systems may result in a significant effort. A prolonged period of repository operations may lead to longer underground occupancy times for safeguards inspectors, and this in turn may result in additional radiation exposure.

3.5. COST FACTORS

It is important to consider and evaluate the financial implications of any specific provisions relating to retrievability and the costs associated with any waste retrieval activities that may be undertaken. This section discusses some of the cost factors that would require consideration, but does not provide any detailed cost analyses based on developed repository concepts.

The cost of a retrievability option will depend on the repository concept, the amount of waste to be disposed (and potentially retrieved) and the timescales over which the ability to retrieve waste is required. In particular, the implementation of a retrievability option could substantially increase the repository life cycle costs if an extended period of repository operations is required beyond the timescales needed for waste emplacement. The following cost factors would need to be considered in any economic analysis:

— Costs associated with any upgraded disposal system components as may be required to facilitate waste retrieval. Specifically, additional costs may be associated with the following, where necessary:
  • The use of enhanced waste containers and emplacement cell/vault designs to facilitate waste retrieval;
  • Reinforcement of the underground chambers/cells for long term stability during any retrievable phase.
— Costs associated with any period of extended repository operations, including the costs of ensuring that the repository remains in a safe condition during any monitoring period. Specifically, additional costs may be associated with the following, where necessary:
  • Staffing of the facility as required to maintain safe conditions, including facility security and monitoring;
  • Accident prevention and provisions for recovery from abnormal conditions (emergency preparedness);
  • Maintenance and repeated, periodical replacement of the repository equipment and vehicles at the end of their operational lifetime;
  • Groundwater management activities and equipment;
  • Safeguards provisions (as discussed in Section 3.4).
— Costs associated with retrieving the waste if such a decision is taken. Depending on the stage at which waste retrieval is initiated, this may need to include the cost of dewatering the repository and the management of any secondary wastes (e.g. if backfilling and sealing materials have been saturated with water or contaminated by radionuclides from breached waste packages);
— Costs associated with any management provisions (e.g. storage facilities) and remedial actions (e.g. processing plant) for the retrieved waste and any secondary wastes that might arise.

3.6. SAFETY IMPLICATIONS

A safety case is a collection of arguments and evidence to demonstrate the safety of a facility or activity [21]. The aim should be to develop a robust concept and an accepted safety case before waste emplacement begins, so that new technical information about the site and repository components that arise later do not lead to major revisions to the case.

The IAEA Safety Standards Series publication on the geological disposal of radioactive waste [21] does not deal with the issue of retrievability extensively, and in its introduction only states that:

> "No relaxation of safety standards or requirements could be allowed on the grounds that waste retrieval may be possible or facilitated by a particular provision. It would have to be ensured that any such provision would not have an unacceptable adverse effect on safety or performance."

Potentially negative conditions may be introduced by measures adopted to extend the operational period of a repository or any associated monitoring and maintenance (e.g. degradation of repository materials (e.g. container corrosion) or near-field rock conditions (e.g. aeration of the surrounding host rock)). Any such effects would need to be assessed and assurance reached that any detrimental influences will not significantly degrade long term safety.

For the purposes of this study, we are concerned largely with radiological safety (e.g. doses to workers and members of the public as a result of handling and disposal of radioactive waste and material). However, it is also prudent to consider the conventional safety aspects (e.g. the use of heavy plant equipment and mining activities). Operational safety relates to the safety of activities in the repository, which includes the period when the facility is open (e.g. when waste is being emplaced or monitored) and may include any operations to retrieve waste at a later date (e.g. following repository closure). By post-closure safety, we refer specifically to the radiological hazards associated with the repository (e.g. doses to members of the public as a result of the presence of the repository, which could relate to hazards arising in the very long term as a result of disposed radionuclides entering the biosphere).

Generically, the safety implications of retrievability can be summarized as follows:

— Retrieval of waste effectively constitutes an extended period of operations and would be accompanied by conventional and radiological risks to workers that are additional to those associated with waste

emplacement. Clearly, there would be a need to ensure that suitable radiological protection practices and conventional mining safety guidelines are adhered to, so as to ensure that these risks are minimized;
- Provisions for retrieval in waste repository concepts may ultimately enhance or degrade safety overall, both in the short and long term. Depending on the retrieval strategy and the approach, retrievability requirements may encourage the development of innovative concepts or new technical solutions without diminishing the high level of safety.

3.6.1. Design measures

Implementation of design measures to facilitate retrievability could have implications in terms of both operational and long term safety (e.g. following repository closure) for fundamental reasons. For example, design features to facilitate retrieval may require a specific repository layout. In addition, in cases where a facility is to be operated for an extensive period following waste emplacement, there is a need to ensure a suitable design lifetime for all repository components. Consideration should also be given to how design options for retrievability might affect conventional safety, although this is not the focus of this publication.

In addressing operational safety, the following should be taken into account, noting that such considerations are not exclusively pertinent to retrievability:

- Ambient temperature: Heat-generating waste will cause the temperature to rise in the disposal cells, connecting tunnels and the host rock. The temperature in the repository must be maintained at a level that allows people to work under regular environmental conditions and the mechanical equipment to function properly (e.g. during waste retrieval). An elevated temperature may require adequate ventilation and cooling;
- Radiation protection: Maintenance work and surveillance activities in the vicinity of the emplacement cells could lead to additional radiation exposures for the operating personnel. Appropriate design measures may include utilization of robust equipment with reduced maintenance needs, integration of sensors in support structures during construction, remote data acquisition and centralized data handling facilities. Additional radiation shielding may be introduced into the disposal cell after waste emplacement to reduce subsequent worker radiation exposures;
- Geomechanical stability: Underground openings must be maintained for extended periods during a prolonged operational phase (relative to early closure). Additional structural components (e.g. rock bolts, thick liners) may be needed to ensure the stability of tunnels, emplacement cells, drifts and shafts. Other design measures could involve the use of long lived materials such as stainless steel rather than carbon steel, or the inclusion of provisions to limit lining degradation (e.g. control measures to minimize groundwater and air access). The possibility of failure (e.g. due to rock falls, flooding and other geohazards) depends broadly on the timescale over which the repository remains accessible. Should such events occur, post-accident recovery may prove difficult and may ultimately complicate the optimized closure of the facility;
- Maintenance and preservation of infrastructure for retrieval: A large network of surface and underground infrastructure (e.g. reception area, encapsulation plant, ventilation, monitoring and water handling systems, package emplacement and retrieval equipment, etc.) may need to be kept in service, be readily replaceable or be refurbished during the required retrieval period. These systems must be periodically inspected, maintained and refurbished. Such activities may have associated worker dose and conventional safety implications. Extended maintenance, replacement and refurbishment of repository infrastructure may increase radiological and conventional risks to operators;
- Monitoring (see Section 4.4): There may be conventional and radiological safety implications associated with any prolonged period of monitoring in support of retrievability;
- Fault situations and recovery: In any period of operations, there are risks associated with fault situations (e.g. loss of electrical power, flooding, rock fall, dropped packages) and there will be conventional and radiological hazards associated with fault recovery.

Retrievability provisions could have both positive and negative impacts in terms of operational and post-closure safety. For example, provisions for retrieval could encourage the use of remote handling equipment (reducing worker doses), increased waste container thickness and the use of long lived liners (which may provide containment over extended periods, thus potentially improving post-closure safety). However, there may be negative impacts in terms of an increased time at risk, multiple package handling operations and degradation of engineered barriers during any extended, open period of repository operations.

In addressing post-closure safety, the following should be taken into account:

— Safety functions of disposal system: It is fundamentally important that any design measures and operational conditions implemented to assure retrievability do not have any significant detrimental effects upon the safe performance of the disposal system;
— Uncertainties: Retrievability should not introduce additional materials other than those necessary for the emplacement operations. If additional materials are introduced to facilitate retrieval, they might increase the complexity of the disposal system and in turn introduce additional uncertainties relating to the long term performance of the repository.

3.6.2. Safety implications of performing retrieval actions

Each waste package handling operation entails worker radiation exposure and has implications in terms of conventional safety (e.g. the risks associated with operating heavy plant equipment). Retrieval of a waste package entails an additional package handling operation, which may be more or less hazardous than the original emplacement operation. Where invasive mining approaches are required (e.g. during waste package retrieval following repository closure), the hazards associated with conventional mining activities are relevant.

When new equipment is required for retrieval (i.e. different equipment to that which was used for emplacement), the associated risk for operators and the public needs to be carefully evaluated and balanced against the applied work safety standards. In some cases, the option of opening new access routes by re-mining should be considered carefully.

After retrieval, provisions have to be made for a safe interim storage of the waste packages before these are subjected to any other (long term) management option.

3.7. REPOSITORY INFORMATION AND EXPERTISE MANAGEMENT

To ensure continued safety (and retrievability), it is necessary to retain and store information relating to the repository (e.g. numbers and types of packages, package locations within the disposal system, etc.). Most waste management organizations are in the process of establishing long term information management systems. This is to ensure that the relevant information is retained in a readable format and that it is understandable for future generations [22].

Additionally, there is a need to ensure that trained personnel with the appropriate skills and expertise to retrieve the waste are available. Specifically, it is important to maintain the level of expertise to:

— Support the safe operation of the repository and to assist those who may want to retrieve the waste for legitimate purposes;
— To avoid any unintentional human intrusion and to permit future generations to conduct their own safety evaluations.

4. TECHNOLOGICAL IMPLICATIONS

The requirement to be able to retrieve waste from a geological repository has technological implications in terms of the design of the disposal system and the associated repository infrastructure. Certain common repository design features (e.g. the use of long lived waste containers) are inherently beneficial in terms of the ability to retrieve waste. However, certain provisions are required to facilitate waste retrieval and the effort involved in any retrieval operations will depend on several factors, as outlined below by reference to example repository design concepts.

4.1. DISPOSAL SYSTEM COMPONENTS

4.1.1. Waste container

Waste containers isolate the waste to enable safe handling and protection in the event of accidents or malfunction (Section 2.3.2). Where the intention is to be able to safely retrieve waste, it is important that the safety functions of the container are ensured during any period when retrieval may be required. Continued waste package integrity is, therefore, a primary requirement for waste retrieval and the timescales over which waste package integrity can be assured is an important factor.

Depending on the concepts, the long term safety requirement leads to a very long design life for the waste container (e.g. from 1000 to 100 000 years). Container longevity is typically provided in the various concepts by the choice of materials, a specific thickness of material (e.g. mild steel) and control of the storage environment (depending on the associated degradation process) so as to ensure the specified lifetime. In addition to container integrity, any external handling features of the package must be designed to survive the retrievability period. In this regard, materials that resist corrosion over a long period of time are favourable. The robustness of the waste package will need to be sufficient so as to ensure continued integrity during any preparation processes for retrieval (e.g. during removal of buffer or debris, cleaning or otherwise preparing the disposal cell).

In the case of long lived ILW, waste containers are mainly designed to meet operational requirements, although it is generally recognized that such containers will also contribute to long term safety. The materials proposed for these containers are generally concrete (and reinforced concrete) and iron-based metals (cast iron, mild steel and stainless steel). In certain cases, the containers are vented to prevent gas pressurization [7]. The possible implications of package vents should be considered. For example, in a backfilled cell, there is a possibility that material could migrate through the vent leading to contamination of the backfill, which could have implications in relation to any subsequent retrieval operations.

In some concepts, the waste package design for ILW of lower activity may include integral radiation shielding. This could prove to be a favourable aspect for retrievability, in that it could enable contact handling and may remove reliance on the use of remote handling equipment.

Waste package size and weight are important factors when emplacing and retrieving waste. When considering a unit volume of waste to be disposed of, there are implications in terms of package numbers that relate directly to package size. Large packages could prove more difficult to handle but would accommodate more waste per package, meaning that the number of package handling operations would be reduced. Small packages would imply more packages to be retrieved, but handling of the smaller packages may be easier considering mass and shielding requirements. The use of smaller packages implies more packages and handling operations (both during emplacement and any subsequent retrieval operations). Multiple handling operations have implications in terms of conventional and radiological safety and there may be an increased probability of equipment failure as the number of such operations increases.

4.1.2. Host rock

The host rock has implications in terms of retrievability. Key to this is the ability to excavate and maintain suitable openings for waste retrieval, noting that in many instances, and for practicality, these are likely to comprise the original waste emplacement cells and access openings.

Hard rocks (e.g. crystalline gneiss, granites, welded volcanic tuffs) are effectively self-supporting and minimal engineered support and maintenance is required to prevent failure of the rock walls in the emplacement cells and access drifts. Therefore, waste packages may be expected to remain accessible for retrieval. Maintenance of rock support, if necessary at all, is not expected to be required over extended periods.

Argillaceous rock formations in France (Callovo-Oxfordian), Canada (Ordovician argilites) and Switzerland (Opalinus Clay) are highly consolidated sediments. Such rock formations possess relatively high mechanical strength, depending on the particular structure (fracturing) and mineralogy of the rock. However, these may exhibit some plastic behaviour, which progressively reduces fracturing but these may also lead to excavation damage zones (EDZs) around excavations in the repository, depending on the support and rock characteristics. Appropriate support would be required for operational safety, although it is considered that excavations could be kept open with suitable maintenance to facilitate waste retrieval over extended periods. In argillaceous rock, short term support (from a few months to some years) is often provided by means of rock bolts with metallic arches, metallic meshes and/or shotcrete. Concrete linings can subsequently be deployed to provide mechanical stability for a longer period.

In the case of the Boom Clay in Belgium, mechanical support by liner systems is required. Regular maintenance of the excavation lining may be necessary should the access excavation remain open to enable easy access to the waste emplacement cell. The frequency and scale of any maintenance work will depend on the deformation rate of the rock at the proposed depth and on the design and properties of the lining.

A liner is usually not required in salt formations. Here, rock creep is a continuous process leading to rock deformation in response to lithostatic pressure. The creep rate depends on in situ stress (increasing with depth) and temperature. Salt creep will rapidly close the void space around waste packages in the emplacement cells, leading to complete encapsulation. The encapsulation process is enhanced by using crushed salt as backfill material. Given that salt encapsulation is one of the main safety elements of a disposal concept in salt, it is advantageous to backfill the emplacement cells rapidly after waste emplacement and keeping the disposal cells open has never been considered in the German salt based repository concept. Therefore, waste retrieval will require re-excavation work and studies have shown that this is possible with current state of the art mining technology [23]. In contrast, the Dutch repository concept in salt intends to keep the galleries open to allow for retrievability [24].

Access shafts or ramps may need to be excavated through aquifers or fracture zones. In such cases, it is important to ensure that any lining acts as an appropriate barrier (e.g. preventing or minimizing groundwater ingress) and that an appropriate level of maintenance is carried out. Any rock support, access drift and shaft linings will need to be designed to remain integral during the period when waste retrieval may be required, or to be readily maintained during such periods. Selecting support and lining systems that are mechanically and chemically robust would be beneficial in this regard (e.g. use of stainless steel or fibreglass rock bolts, stainless steel reinforced concrete linings).

4.1.3. Emplacement cell

Waste retrieval requires access to the disposal cells and the length scale of any access pathways has implications for retrievability. Shorter cells may require less complex machinery for waste package emplacement and retrieval. However, this provision needs to be balanced against the capacity and extent (footprint) of the repository. Ideally, any additional materials that are incorporated into the design of the disposal cell for retrievability purposes (e.g. a sleeve or collar) should be designed to be chemically compatible with the package container materials and should not induce any supplementary disturbance of the buffer or host rock.

4.1.3.1. High level waste and spent nuclear fuel

Several emplacement cell concepts exist for HLW and SNF. These differ in that buffer material may be inserted before or after waste emplacement, or not at all. The orientation of the cells may be horizontal or vertical, with various lengths ranging from very long horizontal drifts (e.g. Switzerland) to short vertical boreholes drilled from the disposal tunnels (e.g. Sweden, Finland, Canada). There may only be one access (e.g. dead-end cells in the French concept).

Depending on the concepts, various provisions contribute to retrievability, either inherently or explicitly:

- The handling equipment for emplacement could be used in reverse to facilitate waste retrieval;
- Controlling the re-saturation, and hence swelling, of the buffer placed around the waste package. For example, this may be accomplished by temporarily introducing a tight plastic membrane in the cell between the rock and the buffer, as evaluated in Sweden;

— Maintaining clearance between the waste package and the lining or the sidewall so that the package may be freely retrieved. This gap may be maintained during the retrieval period (e.g. by a metallic sleeve or collar as proposed in the French concept);
— Ventilation of the emplacement drifts maintains the temperature at an acceptable level for the operation of retrieval machinery (e.g. USA/YMP);
— Where the requirement is for the disposal cell to remain open for a longer period of time than would be necessary for waste emplacement, it will need to be designed so as to ensure mechanical stability over this period (e.g. French concept).

For wastes that are sufficiently heat generating (spent fuel and vitrified waste), the length of the repository zones is dependent on the distribution of the cells in the repository, which is designed so as to limit the temperature inside the host rock and the emplacement cells. Any measures to reduce the length scales over which retrieval operations would need to operate would offer potential benefits (e.g. retrievability could be enhanced by extended decay storage of heat-generating wastes, thus facilitating smaller repository zones or by an appropriate optimization of the disposal layout).

The choice of buffer material has implications in terms of retrievability. Ideally, the buffer material surrounding the waste packages or overpacks should be removable by a method that would not damage container or overpack during waste package retrieval. For example, the use of easily removable seal and buffer materials facilitates ease of retrieval (e.g. use of pre-compacted bentonite blocks or pellets). In contrast, it may prove more challenging to remove rigid materials (e.g. cementitious seals and backfills).

4.1.3.2. ILW

Given that ILW does not generate significant heat, the emplacement cells for such wastes are characteristically larger than those designed to accommodate HLW and SNF, and are designed to accommodate a larger number of ILW packages. The size of the emplacement cell is largely governed by the mechanical stability of the host rock or the ability to provide adequate engineered support, as discussed in Section 4.1.2.

The following design provisions contribute to retrievability:

— Sufficient clearance between the waste packages and the lining or sidewall of the cell; the clearance should be designed to be minimal but sufficient to enable retrieval;
— A remote handling system capable of accurate positioning of the waste packages, with the possibility of use in reverse for retrieval operations;
— Ventilation of the cell to evacuate hazardous gas (if present);
— Mechanical stability of the disposal cell over a long period;
— Use of backfills and seals that are easily removable;
— A suitable groundwater management system to ensure that the repository remains dry (e.g. to prevent waste package degradation by chloride induced corrosion of stainless steel containers before the repository is backfilled) [15].

4.2. WASTE PACKAGE RETRIEVAL

This section considers some of the approaches to the waste package retrieval that may be adopted. These approaches, and the related technical implications, are illustrated by reference to various developed repository concepts and related pilot studies.

4.2.1. Retrieval equipment and machinery

Two categories of equipment can be defined for recovering and transporting waste packages during retrieval operations, namely mobile equipment that may be deployed at various locations in the disposal system and fixed equipment within the emplacement cells and access tunnels [11].

The retrieval process and associated equipment is likely to be based essentially on the same facilities and designs used for emplacement, with potential modifications as may be required. Special considerations may be required in the case of retrieval operations, for example:

— Remote controlled machinery would generally be preferred, since it may be necessary to adapt the retrieval process to the changing conditions of the system;
— There may be a need to operate in adverse conditions (e.g. at high temperature and/or a wet environment).

The details of the retrieval process could differ based on the phase of repository development (as outlined in Section 3.2.1).

During the first phase, the disposal cells are in an open condition, i.e. the cell is not sealed and the packages can be freely accessed. The equipment and machinery used for waste package emplacement would be suitable for waste package retrieval (i.e. operating in reverse mode). If the same procedure is used for emplacement and retrieval, inspection and maintenance would be necessary before any retrieval operations and replacement may be required where any fault cannot be repaired. This is especially the case in situations where a significant amount of time has elapsed between emplacement and retrieval (e.g. several decades to centuries).

When designing waste package handling equipment, it may be useful to consider and attempt to accommodate potential changes in the system, e.g. corrosion of the waste packages, presence of debris, etc. Additional equipment (e.g. for cleaning or removal of debris, etc.) may be required to restore the conditions of the cell prior to any retrieval operations.

It is preferable to avoid use of fixed equipment (rails, liners, utilities, electrical and mechanical services, etc.) in inaccessible areas. Any such fixed equipment should be designed for minimal and easy maintenance.

During later stages of repository operations, revised retrieval equipment may be necessary to retrieve waste packages should a significant evolution have occurred inside the emplacement cells (e.g. if there has been significant waste package degradation). Facilities to transport waste packages to the surface for re-packaging and/or removal may be required. A decontamination facility to remove surface radioactive particles from the waste packages, EBS and transporting equipment could also be requested. Research and development with demonstration in underground laboratories may be required to verify and validate performance.

At each following phase, after cell sealing and later after gallery backfilling and sealing, specific equipment and retrieval methods are necessary to restore the access to the waste packages. The type of equipment required depends on the concept and material selected for the repository. Some examples of such methods are illustrated below.

4.2.2. Illustrative examples of approaches to waste package retrieval

4.2.2.1. Retrieval process for KBS-3 concept

The KBS-3 concept is designed for the disposal of SNF in long lived containers (Fig. 1). The disposal cell is a vertical borehole. SNF is contained within highly engineered canisters, which are emplaced within vertical boreholes that are subsequently in-filled with swelling clay.

In principle, retrieval from the disposal cell can take place in the following situations:

— Retrieval before the disposal cell hole is closed;
— Retrieval after the tunnel has been closed.

In the first case, the canister will be surrounded by bentonite that is not yet expanded (i.e. the bentonite buffer has not swelled in response to water ingress). This means that the canister can be lifted from the disposal cell using the canister installation vehicle in a reverse operation.

In the second case, where retrieval will be conducted after the disposal tunnel has been closed, the increase in the tunnel temperature due to heat generation of SNF has to be considered. The tunnel temperature will be at its highest (almost 65ºC) some 100 years after the tunnel has been closed.

The conditions in the tunnel can be restored to safe working conditions by means of normal ventilation. The retrieval of spent fuel requires opening of the tunnel, opening of the cell and removal of the canister. The

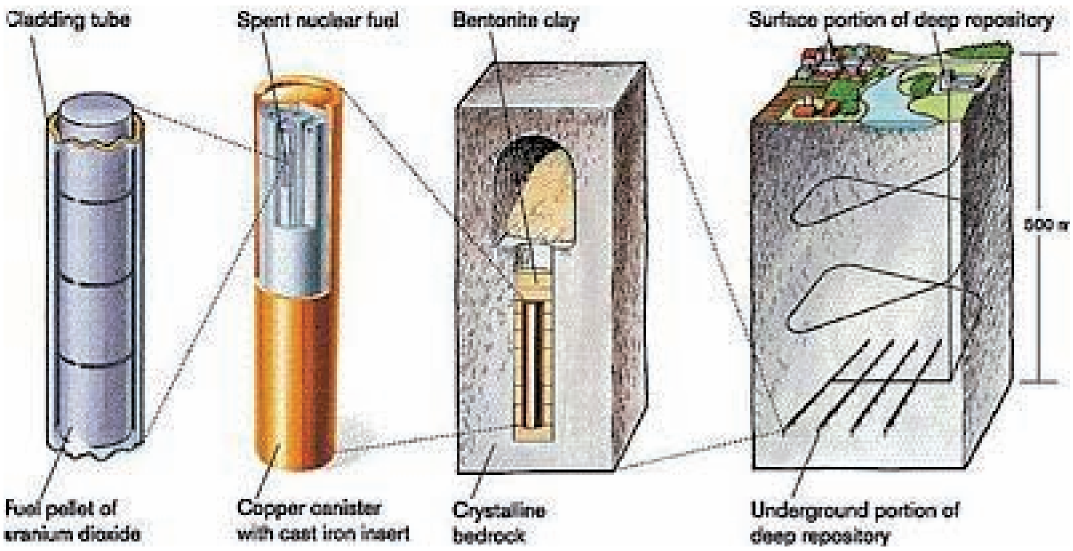

FIG. 1. Representation of the KBS-3 concept.

reinforced concrete barrier structure at the entrance of the tunnel has to be demolished and the backfill material removed from the tunnel, one hole at a time. At this point, the bentonite clay surrounding the canister will have absorbed water and tightly compressed around the canister. The retrieval process is simplified, because the host igneous rocks are effectively self-supporting and the excavated openings are quite stable. In addition, the seal and backfill materials exert pressure on the rock walls providing further support.

The emplaced canisters cannot be retrieved until the bentonite clay has been removed from the top and sides of the canister, otherwise the canister could be damaged during lifting. Bentonite removal would be accomplished using salt water (salt content of 5–10 wt%). The salt water is sprayed with pressure onto the surface of the bentonite, turning the bentonite into a sludge that can be pumped out. The bentonite sludge is pumped out of the hole, layer by layer, until the canister can be retrieved using the installation vehicle. The tunnel backfill is removed and the next disposal cell is reached and the operation repeated sequentially.

When removing the bentonite sludge from the disposal cell, the system will need to contain sufficient radiation protection shielding, so as to reduce the radiation exposure of the personnel.

If the decision was made to retrieve spent fuel after repository closure, and if the facilities above ground had been demolished, certain parts would need to be re-constructed. Access routes would need to be re-opened. Backfilling materials and plugs, consisting of bentonite or concrete, would have to be removed from tunnels and shafts. Rock supports would be used, if and when necessary. In addition, normal supporting systems such as lifts, ventilation and water pumping would be needed. After the necessary surface access points and tunnels have been opened and the construction work completed, the canister retrieval process would continue in the same way as described above.

4.2.2.2. Retrieval process for Swiss concept

The technological effort associated with the retrieval operation depends on the accessibility of the disposal tunnels and is related to the particular implementation phase: while waste emplacement is in progress, the retrieval of HLW/SF canisters is technically feasible (with little effort) by reversal of the emplacement procedure. After closure and sealing of the main facility (i.e. operational tunnels and ventilation shafts are backfilled and sealed, access to pilot facility is open — see country annex), excavation of the operational tunnel and the removal of the seals is necessary prior to waste retrieval. If the whole repository has been closed and sealed, the re-excavation of the access tunnel (or alternatively a new tunnel) would be required as a first step.

Preliminary conceptual studies for the retrieval procedure (methodology, equipment and machinery) have already been performed and the applied technologies are available. All mobile systems move on rails, are electricity-powered and operate under remote control.

Backfill material (granular bentonite) and canister support (bentonite blocks) are removed from the disposal tunnels using the excavation module (Fig. 2(a)). The drilling module (Fig. 2(b)) will create the necessary empty space in the tunnel ceiling for loosening the waste canisters. The retrieval module (Fig. 2(c)) will place a hydraulic jack under the free end of the waste canister and lifts the canister. Consequently, the backfill material above the canister will be loosened, and the canister can now be pulled back into the recovery module using a hydraulic gripper. Finally, the module will be removed from the disposal tunnel with the aid of a mechanical winch. If necessary, the rock securing module (Fig. 2(d)) will stabilize the tunnel by applying rock bolts and meshes.

The procedure for the retrieval of the containers for long lived ILW from the corresponding disposal tunnels will be done in a similar way as conceptually developed earlier for the retrieval of short lived L/ILW [25].

4.2.2.3. Retrieval process for the French concepts

The French concepts are outlined in Annex II. The feasibility of waste retrieval has been assessed and studied for the following three key stages [12]:

— After the packages are emplaced (cell not sealed);
— After cell sealing (access drift accessible);
— After backfilling of the module drifts (connecting drifts accessible).

At each stage, a restoration operation is required, both to provide access to the cell head and to restore the cell to its workable condition.

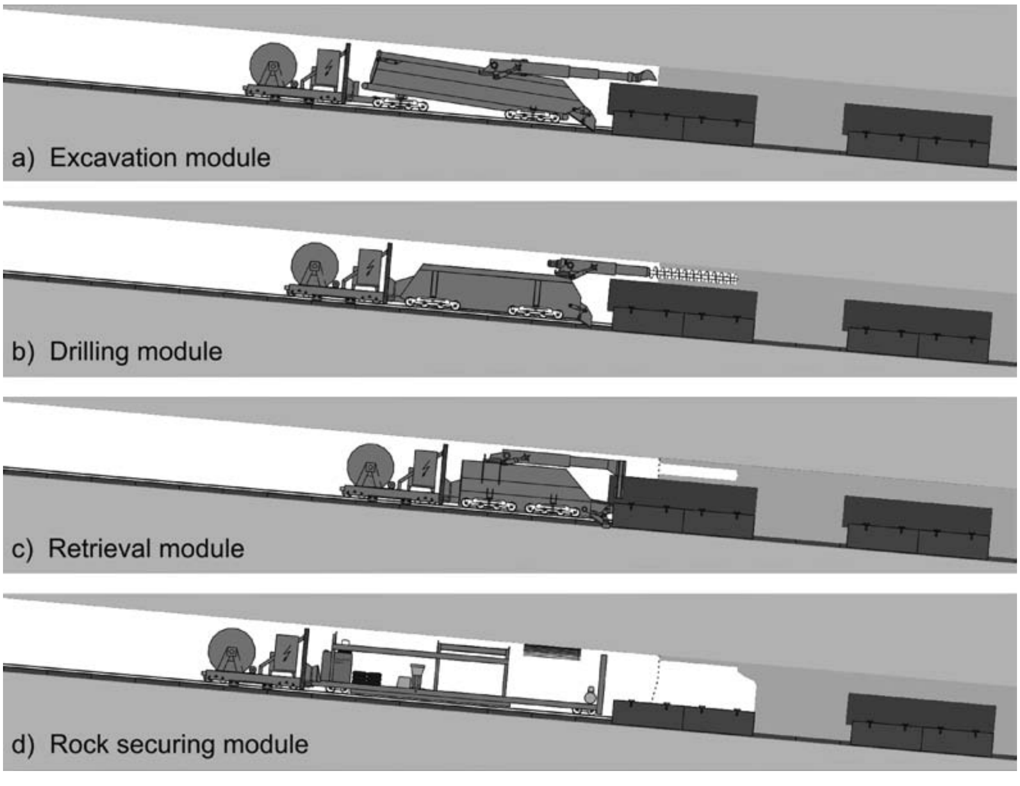

FIG. 2. Swiss concept: Recovery of HLW/SF canisters from backfilled emplacement tunnels; procedure and equipment.

During the first stage, the restoration phase prior to the retrieval operations is limited to routinely checking the chamber equipment if the packages are to be retrieved a few years after emplacement. Alternatively, this could involve replacing the equipment in situations where the operation is performed several decades after waste emplacement (e.g. if the equipment is non-functioning and beyond repair). Radiation protection is provided in the ILW disposal cell by the airlock doors or by a shielding wall made of concrete blocks if these doors have been removed. Shielding in front of the HLW and SF disposal cells is provided by a metal plug emplaced permanently in the cell. The equipment and process used to retrieve the packages from the cell are essentially identical to the ones used for package emplacement but operating in reverse mode. Management of the disposed packages at this stage is essentially storage and this may extend over 100 years to multi-century timescales.

Demonstration tests have been performed in the framework of the European Commission integrated project ESDRED (Engineering Studies and Demonstrations of Repository Design, web site: http://www.esdred.info). Emplacement machines for vitrified waste (pushing robot) (Fig. 3) and spent fuel (industrial air cushion machine for heavy loads) have been designed, fabricated and tested. These tests, performed with dummy packages at full scale, have demonstrated the feasibility of emplacement and retrieval of vitrified waste or spent fuel packages in horizontal cells, with small clearances around the packages, as designed in the French concept.

After cell sealing, a borehole is drilled through the seal. This enables checks to be performed on the atmosphere in the cell, characterization of the ambient conditions (temperature, gas, clearance) and the state of the packages contained therein using standard equipment. The characterization results are then used to determine any prior work that would need to be undertaken to restore the cell to its workable condition. For ILW cells, a ventilation system could be necessary to evacuate accumulated gas. Several solutions may be considered to restore ventilation. One solution is to drill an air drift built specifically for package retrieval, thus removing the air through the bottom of the cells (Fig. 4).

Restoring the cell entrance to its operating condition consists of clearing the seal, then re-installing the same equipment as was used for waste package emplacement.

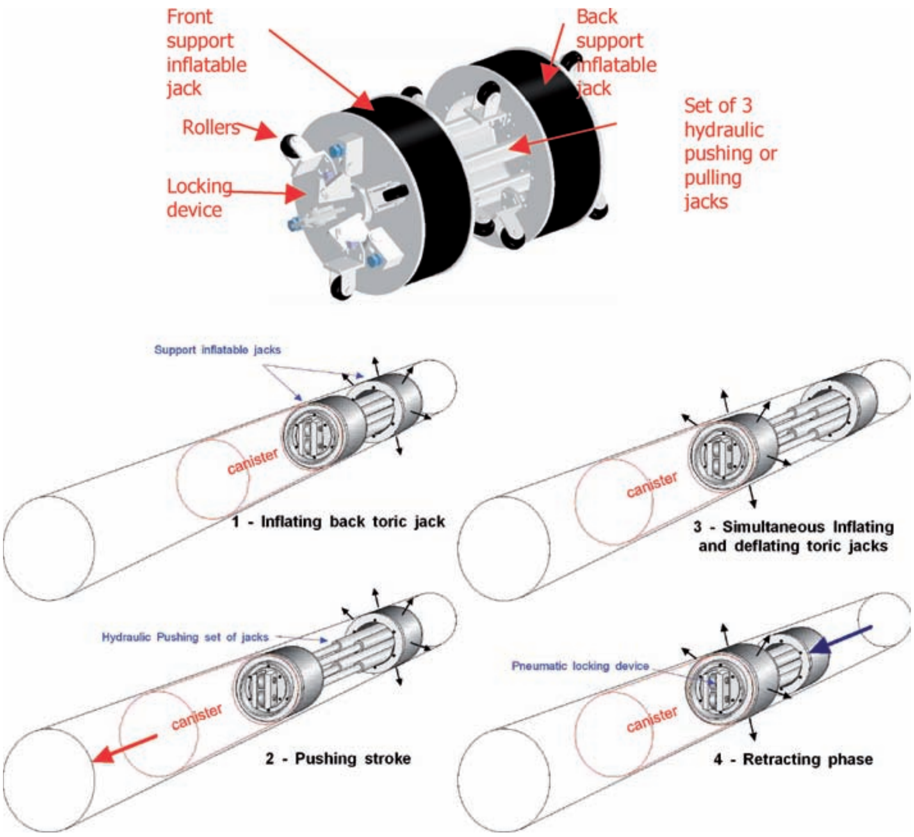

FIG. 3. French concept: Prototype robot for vitrified waste package emplacement and retrieval.

For ILW cells, a road-header type machine is suitable for removing the materials from the seal (compacted clay and concrete), without adversely affecting the liner of the drift. Some reparation of the liner using standard civil engineering techniques could be necessary after the boring operation. Deconstruction work is complete when the radiation protection wall made of concrete blocks is reached (Fig. 4).

Once the equipment is reinstalled and the chamber is operational, the concrete blocks are removed by the same process used to install them and the packages are retrieved following the same process as indicated in the previous stage.

For vitrified HLW or spent fuel cells, deconstructing the cell seal consists of removing the seal and installing a support casing (Fig. 5). The support casing, whose diameter is slightly larger than that of the

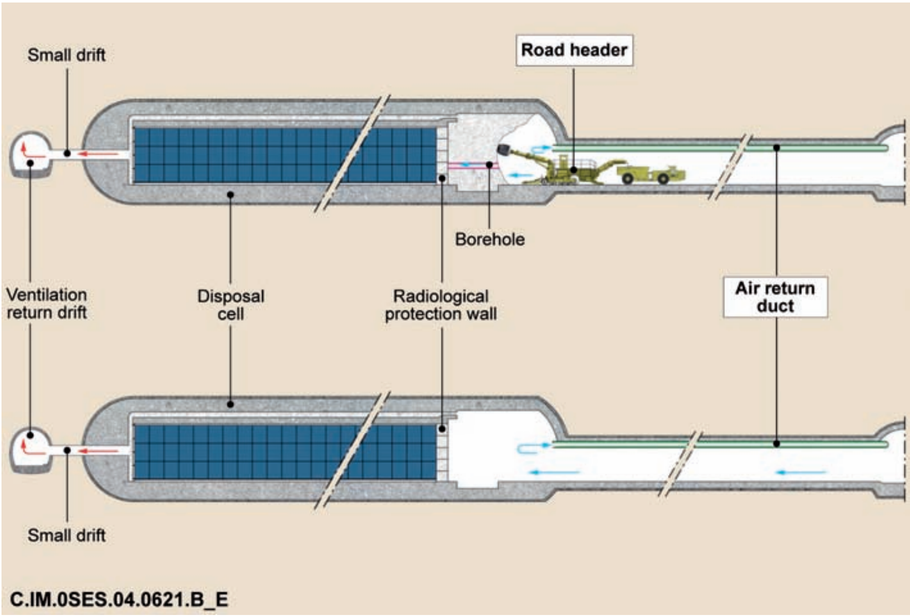

FIG. 4. French concept: Ventilation and seal deconstruction process before ILW retrieval.

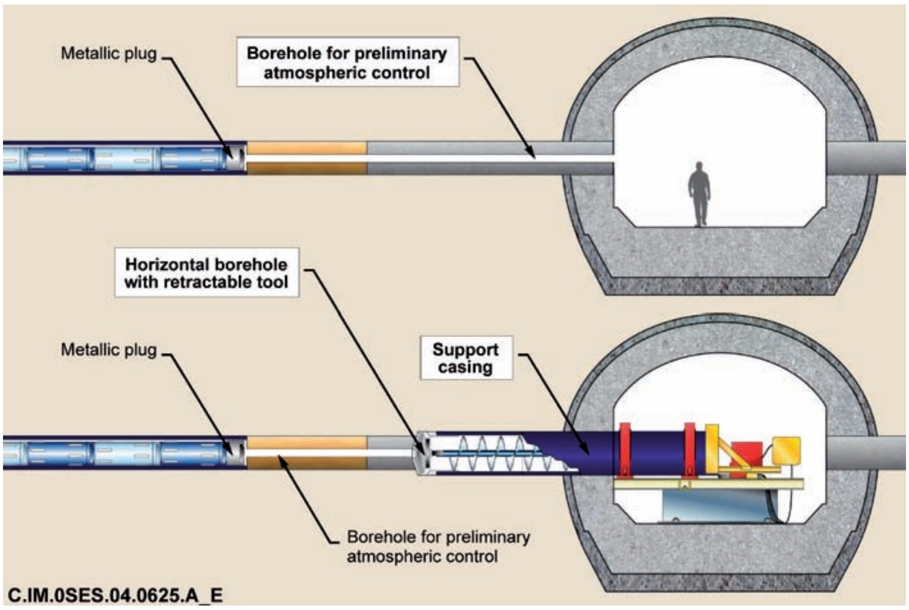

FIG. 5. French concept: Cell seal boring before vitrified HLW retrieval.

permanent sleeve, is intended to facilitate later installation of the temporary sleeve. The excavation work may be performed using a horizontal boring machine (external motor micro tunnel borer and retractable tool) with simultaneous support casing installation.

This operation is completed when a boring tool on the micro tunnel borer comes into contact with the head of the cell's permanent sleeve. The boring head may then be retracted to finish pushing the support casing and withdrawing the micro tunnel borer.

Once the support casing is installed, the temporary sleeve may be connected to the permanent sleeve. The inside diameters of both sleeves shall be identical in order to minimize junction discontinuity. The temporary sleeve is brought into contact by the tube pusher of the equipment used previously. It is then properly aligned with the permanent sleeve and welded onto the support casing at the entrance to the cell head section.

Once the cell has been re-equipped with the shielded trap door, the retrieval process is the same as the one described before cell sealing.

After drift backfilling, additional work would be necessary to remove the backfill material. The backfills are deconstructed by using traditional mining techniques (of the 'road-header' type). These processes can be used for backfills whose temperature reaches 55°C, provided that machinery with air-conditioned cabs is used and the air in the drift is cooled down as backfill removal progresses. The use of air-conditioning systems is common practice in deep, high-temperature mines (e.g. in South Africa). The condition of the drift liner should be inspected as backfill removal progresses and, if applicable, reinforced with rock-bolts or arches according to proven techniques used in the civil engineering or mining field.

4.2.2.4. Retrieval process for United Kingdom Nirex concept

Nirex's Phased Geological Repository Concept (PGRC) is a multi-barrier, phased and reversible approach, based on storing waste deep underground (Fig. 6), where it is much less vulnerable to disruption by man-made or natural events. It is designed for intermediate and some long lived LLWs. The incorporation of monitoring (Section 4.4) and retrievability means that the choices on how, and when to proceed towards closure of the facility are offered to future generations without placing an undue burden on them.

Wastes are typically immobilized in a cement-based grouting material within a standardized, highly engineered stainless steel or concrete container. The typical stainless steel thicknesses used for waste containers are expected to resist penetration by corrosion under controlled repository conditions for many thousands of years.

The strategy behind this is that retrievability should be achievable at all stages during the development of the PGRC [15]. Emphasis is, however, placed on the period during and after completion of waste emplacement and before vault backfilling. During this period, the waste is fully accessible and can be easily retrieved by reversal of emplacement operations, using the same installed equipment. The waste is monitorable and the

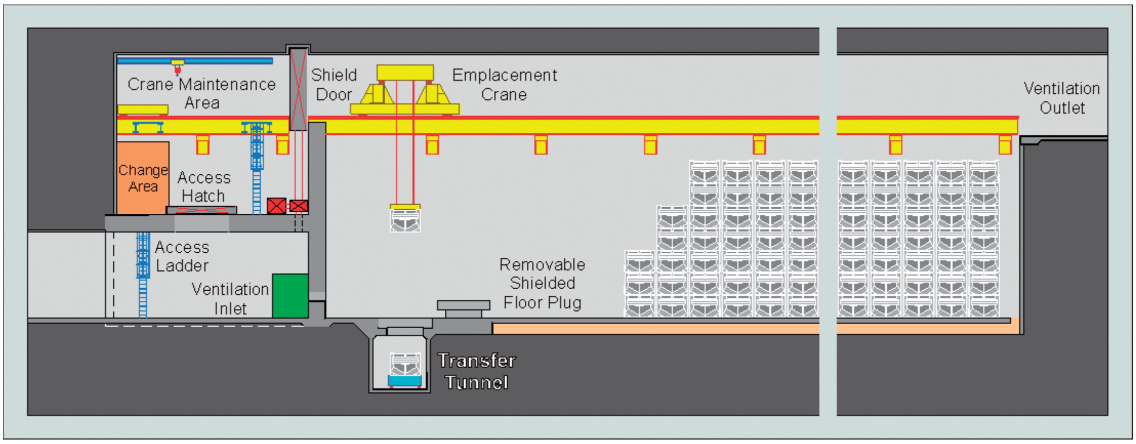

FIG. 6. United Kingdom Nirex concept: Retrievable underground storage facility.

concept demands monitoring to ensure that the condition of the waste, vaults and installed equipment remains satisfactory.

Nirex envisaged that the repository may be held at this step in its implementation until such time as society is ready to take the decision to move towards closure, or to define some other course to manage the waste safely. Nirex's technical studies indicate that a repository can be designed to be held in such condition for up to about 100 years by initial design measures and routine maintenance activities similar to those required during the operational period. If a longer period of monitored, retrievable storage is required, then this could be achieved by the construction of additional vaults and a rolling programme of waste transfer between vaults and refurbishment of the emptied vaults. The repository could be kept open for hundreds of years.

The key technical requirements to ensure satisfactory underground storage conditions and the capability to retrieve the waste are:

— The emplacement vaults must retain sufficient structural stability for storage and waste retrieval operations;
— Waste packages and stillages must retain sufficient integrity to be lifted and removed from the vaults;
— The emplacement/retrieval equipment and other in-vault systems, must remain operable, or be maintainable and/or renewable;
— The groundwater management system must prevent direct contact of groundwater with waste packages and also minimize degradation of vault rock stabilization systems;
— The vault environment must be controlled, e.g. with adequate ventilation, to provide suitable conditions for extended storage and, if necessary, waste retrieval operations.

To assess and maintain the condition and effectiveness of the above, and also to ensure the safety of underground facilities, services and workers, a comprehensive programme of monitoring and maintenance would be needed, as well as the capability to recover from accidents and fault conditions. This, in turn, requires continued commitment to maintaining the operating organization and regulatory functions, and corresponding financial commitments. In particular, the technical capability to proceed towards final closure must be maintained to give assurance that a state of passive long term safety can be reached.

Maintaining the emplacement vaults in an open condition for an extended period has some influence on waste package and local geological conditions that could potentially influence the backfilling operations and post-closure performance. Nirex has made exploratory studies of the relevant issues [26, 27] and concluded that, for its reference conceptual design, potential impacts are manageable and need not have any significant impact on long term safety. These issues will have to be assessed on a site- and design-specific basis.

After vault backfilling, retrieval of the waste packages would still be possible [16], but additional equipment would be required and the retrieval would be more costly. Even after the repository is closed and sealed, the waste could be retrieved by conventional mining techniques. However, this is considered unlikely because the decision to finally close the repository would not be taken unless long term safety was assured and all reasons for keeping the waste accessible for longer had been assessed and dismissed.

4.3. REPOSITORY CONDITIONS

In the context of retrievability, the environmental conditions within the repository have potential implications in terms of the timescales of waste container integrity and the safety of operational personnel.

4.3.1. Container integrity

Environmental factors within the repository will influence the corrosion rate of the waste containers, any package handling features and surrounding materials (e.g. metal sleeve or collar depending on the concepts). Such factors may have implications in relation to the timescales over which packages remain integral and retrieval is possible. Key factors for metallic waste containers are the ambient temperature and humidity, the redox state of the system, and the concentration and composition of any salt solutions that may contact the surfaces and induce corrosion (e.g. pitting corrosion of stainless steel can be induced by contact with chloride-rich ground waters). In the case of heat-generating wastes, the temperature inside the emplacement cell will be controlled largely by the spacing between the waste packages (e.g. French concept) or by specific design features which facilitate ventilation (e.g. USA/YMP concept). The humidity of the air will depend largely on the hydrogeological properties of the rock and the local, ambient temperature.

As discussed above (e.g. Section 4.2.2.4), and depending on the repository concept, it may be necessary to include specific provisions to control the conditions within the repository so as to ensure that waste package integrity remains over extended timescales. Early backfilling of the repository may be beneficial in terms of ensuring extended container lifetimes (e.g. by embedding the containers in a protective medium that minimizes corrosion rates), but this may have a negative impact overall in terms of retrievability.

4.3.2. Operating environment during retrieval

The safety of personnel must be assured during any waste retrieval operations and this may require specific controls on the environmental conditions with the repository. Key parameters in this regard include the quality of the air supply, an acceptable working temperature and acceptable radiation levels to ensure that any worker doses are as low as reasonably achievable. As discussed in Section 4.4, monitoring should provide data on ambient conditions in the disposal cell and access gallery (temperature, air hygrometry, air quality and radiation levels).

In an HLW or SBF repository, the ambient temperature in the disposal cell and in the access drift (close to the cell) would increase, after a certain period of operation, due to the heat generated by the waste packages. In USA/YMP, the ventilation of the cells for cooling the waste maintains the temperature at an acceptable level for retrieving the waste during the ‘reversible period’ (i.e. before closure).

In most concepts, there is no ventilation in the cells but the design temperature is generally limited to approximately 100°C. In some concepts, however, higher temperatures are allowed. In the German concept, for example, there is a temperature limit of 200°C at the waste package/salt rock interface.

In order to maintain operational conditions in the repository, some ventilation (and possibly cooling systems) may be required and this would extend to any periods of surveillance and monitoring (e.g. during a period of retrievable storage). After backfilling of the access drifts, the maximum wall temperature must not be higher than any limits specified in the relevant regulatory recommendations (e.g. approximately 60°C in French regulations). However, during and after removal of backfill during waste retrieval, some form of ventilation and cooling systems would be required to lower ambient air temperature (down to approximately 30°C). Here, access drifts would need to be designed to accommodate the ventilation system, which would be required to cool the working environment for retrieval operations. Part of the infrastructure required to accommodate the cooling system could be designed and constructed at the time of waste emplacement.

Mechanical equipment used to retrieve the waste may be operational up to temperatures approaching 100°C. If the temperature of waste packages and surrounding air is higher, cooling measures could be applied. To avoid a high temperature in the cells, a larger spacing between waste packages and also between the disposal cells could be adopted; however, this solution induces longer drifts and cells to be excavated, and could make the emplacement process and also the retrieval process more time consuming and costly.

Where appropriate, ventilation would be required to enable the evacuation of hazardous gases, such as in situations where there is a possibility that explosive gases (e.g. hydrogen or methane) or toxic gases (e.g. hydrogen sulphide) may have accumulated. Appropriate design features may be required (e.g. ventilation doors, airlocks and crosscuts) to ensure that activities in one emplacement cell do not impact on surrounding cells.

Appropriate radiation protection measures will be required to minimize radiation doses to workers. As with waste emplacement, it will be necessary to minimize radiation exposure to personnel operating the package retrieval equipment. The timing of any waste retrieval operations may have implications in terms of operator dose uptake (e.g. intuitively, retrieval at longer times following waste emplacement would be associated with lower dose uptakes as a result of radioactive decay in the disposal cell). Depending on the package dose rates, a shielded cabin may suffice or remotely operated equipment may be required. In addition, a passive radiation shield can be kept between the seal of the cell and the waste in order to facilitate seal removal.

For ILW, the ambient conditions depend on the waste type but the temperature is much lower than for heat-generating wastes. In the case of ILW, the operational conditions may not be far removed from those encountered in operational surface stores.

4.4. MONITORING ASPECTS

During a potentially long period of repository implementation and operation (e.g. spanning decades or several centuries), some critical decisions need to be made about how, when and whether various implementation steps should be taken. This may include decisions as to whether to retrieve the emplaced waste. The primary objective of monitoring is to provide information to assist the repository operator (and society) in taking these decisions.

4.4.1. Repository system monitoring

A range of characterization and monitoring activities are likely to be performed in support of the development and operation of a disposal facility [28]. Baseline monitoring would be carried out from the surface before underground excavation begins to specify undisturbed site conditions. During construction, emplacement operations and possibly also during the period before closure of the facility, monitoring will continue from both the surface and underground to confirm or refine site-specific information and to validate performance assessment models. After closure, post-closure monitoring of the repository can take place from the surface.

Any monitoring during the phase before closure of the facility (i.e. when waste retrieval is most feasible) is likely to be carried out from underground. The purpose of this monitoring would be largely to confirm that the key components of the repository system are performing as expected. Much of the monitoring for an extended waste retrieval period would be similar to the monitoring during normal repository operations. Monitoring may be installed in a small part of the repository (e.g. in a pilot facility or distributed at specific locations ('test cells') throughout the repository).

In addition to monitoring for operational and long term safety, a complementary monitoring programme may be required to provide information on the status of retrieval systems and waste packages. Retrieval would require knowledge of:

- The physical conditions of the waste packages (related to container integrity);
- The mechanical and hydrogeological conditions of seals (including bulkheads) and backfilling material (where applicable);
- Ambient conditions in the emplacement cells (e.g. temperature, pressure, presence of hazardous gases);
- The status of mechanical and electrical installations and machinery for waste retrieval;
- A detailed analysis of the rock and material deformations in order to evaluate the clearance necessary to retrieve the waste packages from the emplacement cells, which may be required in some concepts.

Monitoring programmes in support of retrievability would need to provide sufficient information to enable assessment of these aspects before waste retrieval could begin. In reality, normal monitoring may provide most of the relevant information, but a key difference may be the required monitoring timescales.

4.4.2. Illustrative examples of approaches to monitoring

Repository monitoring is considered in most Member States in different ways. The following sections illustrate the various monitoring approaches adopted in the USA (YMP), Finland and France.

4.4.2.1. Monitoring approach for YMP

USA/YMP will monitor the geological repository for the purpose of performance confirmation. In 10 Code of Federal Regulations (CFR) 63, the US Nuclear Regulatory Commission requires that the performance confirmation programme for the repository confirm that the actual subsurface conditions encountered, and changes in these conditions during construction and waste emplacement operations, are within the limits assumed in the licensing review.

The performance confirmation programme is also required to indicate, where practicable, whether the natural and engineered systems and components designed or assumed to operate as barriers after permanent closure are functioning as intended and anticipated. The performance confirmation programme is designed to increase confidence that performance objectives designed to protect public health and safety are satisfied and confirm that the waste retrieval option is preserved.

In situ testing has been, and is being, performed to observe subsurface performance. The monitoring of the repository during and after the emplacement period will be used to verify that the actual performance of the repository conforms to the predicted performance established by computer modelling. Activities in the programme were selected using a risk informed, performance-based decision analysis process. Direct observations and measurements as well as lab testing during the pre-closure period are planned to achieve these goals.

4.4.2.2. Monitoring approach in Finland

The Finnish Government has decided that “spent fuel disposal shall be planned so that no monitoring of the disposal site is required for ensuring long-term safety and so that retrievability of the waste canister is maintained to provide for such development”.

However, there will be monitoring of the biosphere and bedrock conditions. A baseline monitoring programme is already in operation at Olkiluoto. During the stepwise repository construction project, monitoring activities will be developed from cored boreholes drilled from the ground surface or from tunnels (access tunnels to vertical disposal cells). In addition, there will be continuous monitoring activities related to nuclear safeguards and operational radiation protection. Some specific monitoring activities may still be envisaged in connection to retrievability.

4.4.2.3. Monitoring approach in France

In France, the monitoring system is part of the repository design with the intention of limiting any disturbance that monitoring devices may cause to an insignificant level (i.e. ‘discretion’ of the sensors). However, the monitoring system may also be progressively adapted during the stepwise closure process.

Monitoring would provide the implementer with knowledge of the physical condition of the various components of the repository system. The monitoring system for retrievability, and more generally for reversibility, is part of or in addition to the monitoring system used for operational safety and for confirming the existence of conditions conducive to the long term safety of the repository.

The nature of the parameters monitored should be specific to each step of the closure process for the following reasons:

- The duration of the closure process could be longer than the lifetime of the monitoring sensors or transmission systems;
- The parameters monitored may change or could be different when passing from one step to the next.

Monitoring while disposal cells are open or temporarily plugged

Representative test cells could be used to comprehensively monitor the physical evolution, rather than performing systematic monitoring of all of the emplacement cells. The parameters to be monitored, for retrievability, are mainly stress/strain changes in the cell lining (or sleeve) and the air composition (humidity, oxygen concentration or hydrogen evolution rate, etc.) in the cell. In order to correctly analyse these measures, it is also necessary to monitor the temperature and the stress/strain and pore pressure in the host rock and in the buffer (if present). The sensor distribution and acquisition frequency should also provide sufficient measurement data to evaluate the temporal and spatial variations of the monitored parameters.

In addition, robust and simple instrumentation could be considered in the vicinity of all emplacement cells to confirm the findings of the test cell (e.g. temperature measurement with optical fibres).

As the disposal cells are not accessible after waste emplacement, the sensors placed inside the cell have to be long lived, robust and resistant to ambient conditions (e.g. such as vibrating wire extensometers that have been operated for decades in civil engineering). In the ILW cells, the sensors can be incorporated inside the concrete lining by insertion before cementing. In the HLW and SF cells, the sensors could be placed on the outer face of the metallic sleeve or in boreholes in the surrounding rock. Installing additional (initially redundant) sensors has been identified as one way of mitigating sensor failure.

4.4.2.3.1. Monitoring after sealing of the disposal cells

The instrumentation system of the test units could be kept for longer term monitoring. The transmission system with cables may be changed and replaced by a wireless system. Such systems adapted to the repository context are under development.

4.4.2.3.2. Monitoring after backfilling of the access

With the progressive closure of the repository, it is envisaged that the requirements for monitoring in the repository will decrease as confidence in the performance of the system increases. Any further monitoring would rely on remote or wireless monitoring systems. It could be reduced in the vicinity of the cells and placed in the rock or in the lining of the accessible openings at larger distances from the disposal cells. The parameters to be measured are mainly rock temperature and stress or strain in the drift lining. The presence of gas in the vicinity of the sealed and backfilled galleries would also be monitored.

The monitoring during these steps is designed in order to be compatible with the performance of the various barriers of the system.

5. CONCLUSIONS

This study has considered the technological implications of retrievability on the geological disposal of radioactive waste. The major conclusions are as follows:

— Several Member States are incorporating reversibility and/or retrievability provisions in their development plans for geological repositories, largely in response to public concerns. Retrievability is intended to respond to social drivers for reversibility and may provide a level of confidence that potential resources, such as the fissile material in SNF, may be available for future utilization;
— The timescales when retrieval is likely to be practicable on technical grounds is of the order of hundreds of years (e.g. up to 500 years), based on the repository concepts considered here. Such timescales are short in comparison to the timescales over which the waste remains hazardous (e.g. the long timescales considered in post-closure performance assessments);
— Retrieval of waste from a repository may be feasible, regardless of the stage of development reached, e.g. during waste emplacement, during repository operations or following closure. Depending on the concept, however, waste retrieval is likely to become progressively more difficult during the operating life of the facility and beyond. In addition, there may be significant implications, particularly in terms of cost and safety. If there is an insistence on retrievability throughout the operating life of the facility, there is the prospect of an uneasy compromise between the technical requirements of the long term safety case and prevailing socio-political pressures. The solution may involve the acceptance that retrievability is limited in time and that retrieval will become progressively more difficult, and essentially impracticable, in the long term;
— Any retrievability provision must not negatively impact upon the long term safety of the disposal system. It is advisable to consider the benefits and detriments that are associated with retrievability, and to plan for any related technical provisions that may be required to facilitate waste retrieval at the conceptual repository design stage. If this is not the case, any complementary provisions should be included at the earliest possible stage in the repository development process;
— Many disposal concepts have inherent provisions for retrievability (e.g. long lived containers, removable backfill) and some concepts include specific design provisions (e.g. waste package handling facilities that are designed for both emplacement and retrieval). Retrieval of waste from repositories without specific provisions is also possible, but may be more difficult. Removable barriers facilitate relatively easy retrieval of the waste and may not detract from the performance of the disposal system. In any case, the multiple

barrier concept is unlikely to be challenged by any specific provisions for retrievability, if these are suitably designed;

- Waste retrieval may have a negative impact on both conventional and radiological safety. Any potential deleterious effects could be reduced by appropriate provisions, especially by incorporating the provision for retrievability as early as possible in the design process. The worker risk burden of maintaining the facility to retrieve waste, and the risks associated with waste retrieval operations, may exceed the conditional, long term risks to the public and the environment following facility closure. There is a need to ensure that the associated risks are assessed and that a balanced approach is adopted. It is noted, however, that long term and operational safety assessments have been performed with acceptable outcomes for some concepts which integrate specific provisions for retrievability;
- There may be significant additional costs associated with retrieval provisions (e.g. use of enhanced containers and cell infrastructure) and with extended operations (monitoring, security, radiation protection, maintenance) where required. Cost estimates for specific repository systems, including the cost of retrieval and any related extended operations, would be required to fully evaluate the cost implications;
- Suitable monitoring would be required to ensure that waste package retrieval remains possible. Monitoring equipment could be installed throughout the facility (e.g. all disposal cells), applied only to specific test cells or placed in pilot installations. Prior to establishing a monitoring regime, it is important to identify what system parameters require measurement and to identify criteria that would be used to evaluate whether retrieval is required and achievable. Monitoring activities in support of retrievability (e.g. monitoring of the status and operability of retrieval equipment) may be additional to any monitoring in support of repository development where there is no intention to retrieve the waste;
- Additional work may be useful in confirming the results of studies to date on retrievable concepts and waste retrieval processes. In particular, it would be useful to gain further practical experience of the removal of engineered barriers and the retrieval of waste packages in different types of geological repositories, including different host rocks. Further understanding may be obtained using scaled and full-size demonstration equipment (e.g. tests in underground laboratories) and modelling approaches.

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Annex I

CANADA

I–1. BACKGROUND

The Canadian Federal Government established its official policy for the management of radioactive wastes through its 1996 Policy Framework for Radioactive Waste. The Policy Framework consisted of a set of principles that held waste producers and owners responsible, in accordance with the principle of the ‘polluter pays’, for the funding, organization, management and operation of disposal and other facilities for their wastes.

Under the 1997 Nuclear Safety and Control Act (NSCA), the Federal Government has legislative authority for the development and control of nuclear energy, which it regulates through the Canadian Nuclear Safety Commission (CNSC). The Federal Government is responsible for the development of policy for radioactive waste disposal. The CNSC ensures that the use of nuclear energy does not pose undue risk to health, safety, security and the environment. They license nuclear facilities, which will include nuclear waste disposal sites and facilities.

I–2. NUCLEAR FUEL WASTE

There are 22 CANDU® power reactors in Canada owned by three provincial electrical utilities. Ontario Power Generation Inc. (OPG) owns 20 reactors while Hydro-Québec and New Brunswick Power each own one reactor. Bruce Power Inc. leases and operates the Bruce nuclear generating station from OPG where there are eight reactors. In 2005, the installed generating capacity of these 22 reactors was 16 000 MW of electricity [I-1].

Currently, 18 of these reactors are operating, producing about 15% of Canada’s electricity. In the province of Ontario, the 16 reactors owned by OPG provide 50% of the province’s total electricity production. Almost two million used fuel bundles (36 000 t U or 8000 m^3) have been produced to date in Canada, a number that is projected to double if the existing 22 reactors continue to operate for an average of a total of 40 years each. The used fuel bundles are initially stored in water-filled bays located at each nuclear generating station. Once a fuel bundle has spent ten years in a bay, its rate of heat generation has decreased sufficiently that it can be stored in dry storage facilities also located at the reactor sites. In addition to these, AECL, the developer of CANDU® reactor technology, has responsibility for a small amount of spent fuel from its research and radioisotope production reactors at its nuclear sites and research reactors at universities.

I–2.1. Canadian Nuclear Fuel Waste Management Programme

In 1978, the Governments of Canada and Ontario announced the Canadian Nuclear Fuel Waste Management Programme of research with the intention of verifying “that permanent disposal in a deep geologic repository is a safe, secure and desirable method of disposing of radioactive waste” [I-2]. AECL was given the role of developing the technology for immobilization and disposal, and OPG’s predecessor, Ontario Hydro, was given the responsibility for storage and transportation. In 1981, the two Governments issued a second joint statement in which they announced the process by which acceptance of the disposal concept would be undertaken and that “no disposal site selection will be undertaken until after the concept has been approved” [I-3].

In 1988, a formal review of the disposal concept was initiated in accordance with the Federal Environmental Assessment and Review Process, and AECL was charged with preparing the Environmental Impact Statement (EIS) on the concept for disposal of Canada’s nuclear fuel waste, which, together with nine reference documents, was issued to an environmental assessment (EA) panel in 1994 [I-4]. The EA panel completed a process of review, including public hearings held in five provinces across Canada.

The research and development work conducted at the Canadian Underground Research Laboratory (URL), located near Lac du Bonnet, Manitoba, played an important role throughout this process. Construction of the URL and characterization of the site, followed by an initial phase of large scale in situ geotechnical testing provided an R&D framework for the EIS. Public tours of the URL were an integral element of the process of public acceptance.

The EA panel conclusions in 1998 were that there must be broad public support to ensure acceptability of any concept for managing nuclear fuel wastes; that safety is only one part of acceptability and must be viewed from both technical and social perspectives; that from a technical perspective safety of the concept was, on balance, adequately demonstrated but from a social perspective it was not; and that the concept as described in the EIS was not demonstrated to have broad public support, and therefore, in its current form did not have the required level of acceptability. The EA panel report included recommendations for establishing a process to address these issues and recommended that Canada not move towards siting a repository until they were addressed and alternate options studied [I-5].

I–3. NUCLEAR FUEL WASTE ACT

The Government of Canada accepted the recommendations of the EA panel [I-6]. The Nuclear Fuel Waste Act (NFWA) was passed by the Federal Government and came into force in November 2002. The Act required the nuclear energy corporations (OPG, Hydro-Québec and New Brunswick Power) to form a waste management organization, which they did — called the Nuclear Waste Management Organization (NWMO). Within three years, the NWMO was required to complete a study of options for the long term management of nuclear fuel waste and recommend a preferred approach to the Federal Government. The options to be studied included deep geologic disposal, long term storage at reactor sites and long term centralized storage above or below ground. When the Federal Government takes a decision on the final approach, the NWMO will be responsible for its implementation.

The Act also required the establishment of a segregated fund for nuclear fuel waste management in Canada, with funding coming from all the nuclear fuel waste producers, including the nuclear utilities and AECL. The Government of Canada will exercise oversight throughout the decision making process via the Nuclear Fuel Waste Bureau, established within the Ministry of Natural Resources Canada.

I–3.1. Nuclear Waste Management Organization

In November 2005, the NWMO issued a report on their study of approaches for the long term management of Canada's used nuclear fuel to the Federal Government [I-1]. The examination of the options presented led the NWMO to develop another approach referred to as adaptive phased management (APM) that incorporates the most significant advantages of the options assessed. APM is a staged approach that has three phases of implementation:

— *Phase 1*: Preparing for central used fuel management (approximately 30 years);
— *Phase 2*: Central storage and technology demonstration (approximately the next 30 years);
— *Phase 3*: Long term containment, isolation and monitoring (beyond approximately 60 years).

The main characteristics of APM include:

— Central containment and isolation of used nuclear fuel in a deep geological repository in a suitable rock formation, such as the crystalline rock of the Canadian Shield or Ordovician sedimentary rock;
— Flexibility in the pace and manner of implementation through a phased decision making process, supported by a programme of continuous learning, research and development;
— Provision for an optional step in the implementation process in the form of shallow underground storage of used nuclear fuel at a central site, prior to final placement in a deep repository;
— Continuous monitoring of the used fuel to support data collection (e.g. data for repository engineering design) and confirmation of the safety and performance of the repository;
— Potential for retrieval of the used fuel for an extended period, until such time as a future society makes a determination on the final closure and the appropriate form and duration of post-closure monitoring.

I–4. PROPOSED DISPOSAL CONCEPT FOR USED NUCLEAR FUEL WASTE

OPG, being the principal owner of nuclear reactors in Canada and used nuclear fuel, has taken the lead in managing the programme for interim storage and long term management of used nuclear fuel.

The concept being considered is to excavate a deep geologic repository (DGR) in a suitable rock formation, such as crystalline rock of the Canadian Precambrian Shield or Ordovician sedimentary rock. The waste would be placed in long lasting used-fuel containers (UFCs), the UFC would be placed in the DGR, each container would be surrounded by a buffer material, and the repository would eventually be backfilled and sealed such that the repository would be passively safe, i.e. without requiring further societal attention. The optional step of implementing a shallow underground central storage facility (CSF) at the repository site could extend the timeframe for emplacement substantially, e.g. by as much as 100 years.

Some of the key design features for the proposed DGR for used nuclear fuel are identified below:

- The waste form would be bundles of used CANDU® fuel. There are no plans to dispose of reprocessing waste, since used fuel is not currently reprocessed in Canada;
- The containers could be made of copper or possibly carbon steel;
- The repository would include access shafts or ramps, access tunnels and disposal rooms. The disposal rooms would be nominally 500 to 1000 m deep;
- The containers could be placed directly in rooms or in boreholes drilled from the rooms;
- The buffer, backfill and other repository sealing materials could be clay-based, cement-based or a mixture of these materials;
- The size and capacity of the repository would depend on several factors, including the amount and decay power of the waste.

I–5. NEED FOR RETRIEVABILITY IN THE LONG TERM ISOLATION OF NUCLEAR FUEL WASTE

The need for retrievability of nuclear fuel waste in a repository is considered a necessary feature from the following perspectives:

- *Regulatory perspective*: The CNSC, formally the Atomic Energy Control Board (AECB), regulatory guideline R-71 (AECB 1985) requires that containers of used fuel be retrievable during the operating phase of a repository.
- *Operating perspective*: During the period that a repository is in operation, left open for an extended monitoring phase or in the process of being closed:
  - There may be a need for inspection or closeout tests and demonstrations involving the containers;
  - There may be a need to replace or repair one or more containers or the sealing materials because of some form of malfunction that has developed as a consequence of the emplacement operations or host rock stability.
- *Public confidence perspective*: Canadian public and special interest groups have expressed concerns about the permanency of disposal and a desire to have nuclear fuel waste in a situation where it can be monitored and is retrievable both before and after closure. Also, the possibility exists that alternative methods for treating nuclear fuel waste may be developed and future generations may consider them to be preferable to permanent disposal.
- *Adaptive phased management*: An important component of the APM approach adopted by the NWMO is a provision for ongoing monitoring after the used fuel is placed in the repository, to assess the performance of the repository system, and to allow for the retrieval of the used fuel, if desired.
- *Future resource perspective*: The fissile material contained in nuclear fuel waste may be a potential resource, depending upon future economic, societal or political factors. Therefore, the future retrieval of this material from the repository may be beneficial.

I–6. RETRIEVAL CONCEPT

The state of a repository at the time of retrieval could vary from an operating facility with some sealed rooms to a completely backfilled, sealed and decommissioned facility. The effort required to retrieving any given container increases as the state of the repository progresses towards closure. The least effort would be required during the operating phase when container emplacement operations are in progress. Retrieval from a sealed emplacement room would be more onerous, followed by retrieval from sealed rooms in a repository during the monitoring phase. The greatest effort would be required during the post-closure phase after the repository is sealed. In the case of the sealed repository, the time of retrieval could vary from a few years to many decades after re-entry.

Retrieval was considered in both the in-room and in-borehole repository design options identified above. Based on this work, it is concluded that it is feasible to retrieve containers from the repository [I-7–I-9]. However, efforts have not been undertaken to optimize the retrieval process. Certain design related issues have been identified, many of which could be addressed effectively in the initial planning of the repository if retrievability of the containers at some future time is taken into consideration.

I–7. SUMMARY

Significant progress has been made towards establishing safe, secure and environmentally acceptable practice for the management of nuclear fuel wastes in Canada. A comprehensive programme of research concerning permanent disposal in a deep geological repository has been carried out. An EIS describing a concept of a deep geological repository has been prepared and reviewed by an EA panel established in accordance with a Federal Environmental Assessment and Review Process. The Government of Canada acted upon the recommendations of the EA panel, passing legislation that requires the nuclear energy corporations to establish an NWMO, complete a study of options and recommend a preferred approach for the long term management of nuclear fuel waste. The NWMO completed its study and recommended APM, which incorporates the most significant advantage of deep geological disposal, long term storage at reactor sites and long term centralized storage above or below ground. One of the main characteristics of APM is the potential for retrieval of the used fuel for an extended period, until such time as a future society makes a determination on the final closure and the appropriate form and duration of post-closure monitoring.

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Annex II

FRANCE

II–1. BACKGROUND

The 1991 French Radioactive Waste Act requested the feasibility study of a deep geologic repository to include consideration of a reversible approach. In 1998, the Government re-emphasized the need for such a study, by stating that:

— "…the government clearly adopts the reversibility paradigm…";
— "…the reversibility paradigm has to be taken into account in the design of the repository…";
— "…appropriate provisions have to be adopted in compliance with the reversibility requirement…".

The reversible approach — while comparable to other management options in its need to make a safety case before applying for a construction and operation licence — acknowledges current limits of scientific knowledge and preserves the right for future generations to choose, and possibly to re-direct waste management options. It requires that a repository programme be managed in a flexible and modular manner, thus allowing future generations of stakeholders to decide upon its progress. It reflects a prudent approach, especially in light of the very large timescale to be considered.

Modularity is achieved by splitting the waste inventory into reasonable fractions and assigning each to dedicated modules. Flexibility is achieved by managing each module independently from others, and by following a stepwise approach leading from waste emplacement to post-closure of the repository. Each step is subjected to a prior decision, based on available technical arguments, including an updated long term safety assessment and taking into account negotiations with the stakeholders. At each decision, several options are given, including sealing or re-opening specific areas, delaying further activity or retrieving waste packages.

Based on these considerations, ANDRA (National Radiactive Waste Management Agency) defines the following attributes of reversibility [II-1]:

— Waste package retrievability;
— Ability to act on the disposal process: stepwise approach, flexible timeframe at each step, potentially supported by maintenance and monitoring;
— Ability to modify the design during the successive construction of disposal modules.

In December 2005, ANDRA provided the French Government with the "Dossier 2005" [II-2] that presents the research work done over the last 15 years and concerning the deep geological waste disposal in clay or granite rocks. After a public debate on 28 June 2006, the French parliament voted on a new law about the durable management of radioactive substances and waste. This law states that reversibility should be possible for at least 100 years.

The following sections present the French concept as it is described in the "Dossier 2005" [II-2] for clay rock.

II–2. FRENCH WASTE INVENTORY

A sensible approach to assessing geologic disposal feasibility must take into account the waste inventory. The studies have been based on four potential scenarios of future spent fuel reprocessing strategies, and have taken into account some variation in overall waste volume [II-2]. All scenarios include intermediate level, long lived waste (ILW-LL or B-type waste) and vitrified, high level, long lived waste (HLW-LL or C-type waste). Some include spent fuel. The inventory considered varies with the reprocessing strategies, between the following bounds:

— B-type waste: ILW-LL waste (notably bitumen and hulls and end pieces) (70 000 to 80 000 m^3, 160 000 to 195 000 waste packages);
— C-type waste: vitrified waste from reprocessing (Cogema's CSD-V canister) (2500 to 8000 m^3, 15 000 to 42 000 waste packages);
— Spent fuel: UOX/MOX (not considered as waste at the present stage, but under study) (UOX: 0 to 13 500 assemblies, MOX: 0 to 5400 assemblies).

II–3. DESCRIPTION OF THE REPOSITORY DESIGN

The repository is split into different areas, each dedicated to either B-type or C-type waste or to spent fuel. This approach minimizes potential interactions between the different categories and allows for independent, category-specific management of construction and operation, including decisions affecting the level of reversibility of each area. Within each area, the repository is split into distinct modules, built successively at a rate adapted to the anticipated container reception rate. The disposal concept and module design proposed by ANDRA [I-2] allows for a stepwise implementation, the separation of different categories of wastes and, if decided, the possibility of waste retrieval.

II–3.1. Module for B-type waste

The disposal concept for B-type waste is based on parallelepiped disposal packages placed in dead-end large horizontal disposal tunnels (excavation diameter: approximately 10 m, length: approximately 250 m). The package is a concrete box containing one or several primary B-type waste containers. These disposal packages are stacked on several levels in the rectangular waste disposal room. At the opening of each disposal tunnel, a radiological airlock is used to extract the disposal package from its transfer cask. The overall design emphasizes longevity and simple operations for waste emplacement and potential retrieval.

II–3.2. Module for vitrified HLW or spent fuel

The disposal concepts for vitrified HLW and spent fuel are similar. They include cylindrical carbon steel disposal canisters, horizontal, small diameter waste disposal cells and a grouping of 100 to 200 such disposal cells around dedicated access drifts. The disposal canisters are designed to have a lifetime of around 1000 years for vitrified HLW and 10 000 years for spent fuel. Each disposal cell (excavation diameter: approximately 0.7 to 2.5 m and length: approximately 30 to 40 m) is equipped with a steel liner in which the disposal packages are disposed of, thus assuring simple package emplacement and potential retrieval operations.

As shown in Fig. II–1, two alternatives of this concept are presently being considered: with or without interposition of a swelling clay-based buffer material between the steel liner and rock.

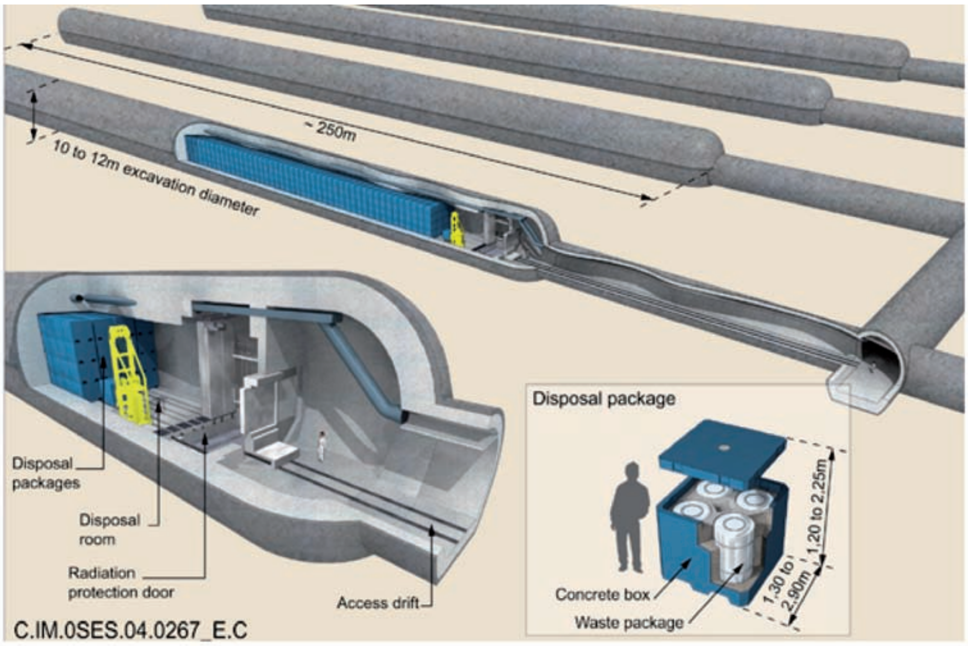
A stepwise, flexible approach provides for the option of delaying sealing of the disposal cell after waste packages have been emplaced. However, to avoid air renewal and to limit potential corrosion inside the drift, it may be temporarily closed with an operating plug.

Upon deciding to seal the cell, this plug is removed and a cylinder of swelling clay-based material is placed at the cell head and a concrete plug is placed to confine the clay material.

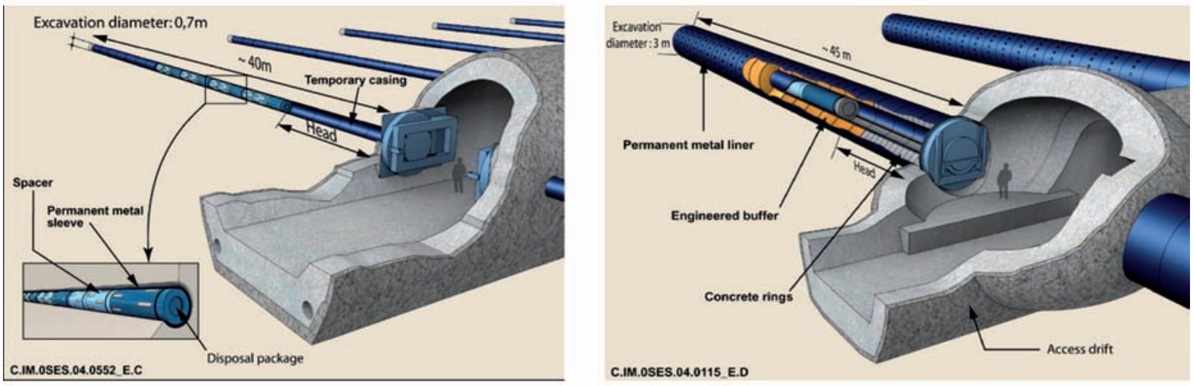
Upon sealing all disposal cells in a given module, it may be decided to close the module, by backfilling the corresponding access drifts.

II–4. REVERSIBILITY ANALYSIS

According to the stepwise approach considered in the framework of reversibility, each step is limited by milestones. At these points, the following main choices have to be made:



Module for B-type waste



Cell for vitrified HLW or spent fuel

without a swelling clay-based buffer material *with a swelling clay-based buffer material*

FIG. II–1. Illustration of repository designs for different waste types.

— Maintain the repository at its current stage;
— Go to the next step;
— Reverse the process and go back to the previous step.

It has to be noted that there are actually many more choices as the decision may be different for each type of waste and for each zone of the repository.

The analysis of the reversibility of the repository concept [II-1] consists of the following tasks:

— Identification of the successive steps of the disposal process;
— Phenomenological analysis of each step of the process, taking into account thermal, hydraulic, mechanical, chemical and radiological processes, in order to control the evolution of the repository and to identify any possible time constraint in the stepwise process;
— Definition of monitoring strategy, capable of providing the decision maker with suitable phenomenological data;

— Identification of the design and operational features favourable for the reversibility as defined above (retrievability, ability to act on the process and to modify the design).

II–4.1. Main steps of the disposal process

The analysis is based on successive steps corresponding to a progressive filling in of the underground works. These steps are (i) after placement of the packages — the cell is closed by an operating plug, (ii) after sealing of the cell(s) — drifts serving the cells remain accessible, (iii) after backfilling and sealing of the drifts serving the cells, (iv) after backfilling and sealing of the access drifts to the disposal modules, (v) after backfilling and sealing of the drifts and access shafts to the disposal zones.

II–4.2. Phenomenological analysis

The phenomenological analysis pointed out that the evolution of underground works and waste packages is very slow (except the temperature increase for the C-wastes and spent fuel) at a centennial timescale and has no significant impact on retrievability. Especially the ambient conditions inside the cells (dry air in B-waste cells and no replacement of air in C-waste or spent fuel cells) before sealing and the durability of the lining (for all types of cell) contribute to a slowing down or to a delay in the evolution process of the waste packages.

II–4.3. Reversibility and monitoring

The objectives of the monitoring, defined in accordance with the definition of reversibility, are to:

— Know the conditions of the retrievability of the waste packages;
— Know the state and evolution of the disposal system for management choices (and especially the possible stand-by duration) and operation follow-up of the repository in connection with the operational and long term safety;
— Increase technical and scientific knowledge to improve design (by comparing the acquired data with existing knowledge of the evolution of the repository and with modelling results).

The monitoring may provide the decision maker with complementary knowledge on the major phenomena controlling the state and evolution of the disposal system for repository management choices, with regard to maintenance, increasing the confidence in the understanding of the repository and retrievability.

II–5. RETRIEVABILITY AND DESIGN

Preliminary studies have been performed to evaluate the feasibility of retrieval of waste packages before and after cell sealing [II-1]. They concluded that the disposal packages can be retrieved with:

— The same equipment used for emplacement as long as the cell is not sealed and regardless of the duration of this step;
— Similar equipment as that used for emplacement after the sealing of the cell.

In both cases, this is mainly achieved by the very long lifetime of the cell lining. In this regard, favourable design factors for retrievability have to be taken into account in the design.

As far as the B-wastes are concerned, favourable design factors are:

— The residual voids between the concrete of the lining and the disposal packages are not backfilled, thereby allowing retrieval of the waste; but for long term safety they are minimized.
— The resistant part of the concrete lining of the disposal tunnels is designed to be always in compression; i.e. it does not need reinforcement with metallic devices; this contributes to its durability.

— The waste disposal package does not have any handling metallic devices, thereby allowing the retrieval even after a long period during which corrosion may occur.

As far as the vitrified wastes or spent fuel are concerned, favourable design factors are:

— The thickness of the steel liner is calculated in order to keep a sufficient mechanical resistance for more than one century, thereby allowing the retrieval of the waste with similar equipment as that used for emplacement;
— The cell may be closed by an airtight cover after placement of the packages in order to limit oxidizing corrosion by avoiding oxygen exchange at the cell entrance;
— The disposal packages are equipped with non-corrodible materials at the contact surface (ceramic), thereby avoiding any corrosion bond between the package and the steel liner.

In the framework of the ESDRED Integrated European Project [II-3], emplacement and retrieval tests were performed for dummy vitrified waste canisters and a 45 t dummy spent fuel canister in 2005 and 2006. These tests demonstrate the feasibility of canister emplacement and retrieval in horizontal cells as described above with remote controlled equipment (pushing robot or air cushion emplacement machine).

II–6. CONCLUSION

The French repository programme provides for the flexibility required by a reversible approach by:

— Favouring design choices providing for adequate lifetime of underground structures;
— Allowing for simple waste emplacement and retrieval operations;
— Adopting a modular and stepwise approach to managing the disposal process.

In practical terms, reversibility can be considered for a transient period, up to at least one century. During this period, the level of flexibility it provides for waste management is similar to that of a storage facility. This flexibility is gradually reduced as a series of stepwise management decisions lead to closure, by backfilling access drifts and emplacing a series of seals, thus ensuring the passive long term safety of the repository. Reversibility during the pre-closure phase does not prejudice long term safety, as was verified and stated by the international review team that reviewed the “Dossier 2005”.

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Annex III

SWEDEN

III–1. BACKGROUND

The Swedish Nuclear Fuel and Waste Management Co, SKB, is currently pursuing site investigations for a deep repository in the municipalities of Oskarshamn (350 km south of Stockholm) and Östhammar (150 km north of Stockholm). Both sites are situated in the vicinity of nuclear power plants. The site investigations should be completed in 2008. The aim is to build a deep repository at one of the candidate sites. An application to build the repository will be made at the end of 2009, according to the current time schedule. Trial operation will begin in 2017.

The planning for the deep repository is based on a reference scenario with an operating time of 40 years for the ten nuclear reactors currently in operation [III-1]. Spent fuel from the 11th and 12th reactors, which have been shut down prematurely, is also included. This will give rise to around 4500 canisters, equivalent to 9300 t of uranium. Canisters with both PWR fuel and BWR fuel will be disposed of. According to this plan, deposition in the deep repository will be concluded in 2050. The different repository parts can then be sealed and the buildings decommissioned prior to 2060.

Between 5 and 10% of the total quantity of nuclear fuel will be deposited in the repository during the test operation phase. This is equivalent to about 200–400 canisters. During and after the test operation phase, SKB and the authorities will conduct a thorough evaluation of repository performance.

III–2. REPOSITORY CONCEPTS

The Swedish principal alternative for disposing of SNF is called KBS-3. The method involves encapsulating the fuel in copper canisters and embedding each canister in bentonite clay at a depth of 400–700 m in crystalline bedrock. The principle is based on the use of multiple protective barriers to isolate the fuel.

The spent fuel is enclosed in canisters consisting of a cast iron insert for mechanical stability and a copper shell for corrosion protection. Each canister has a length of approximately 4.8 m and a diameter of 1.05 m. The weight of a filled canister varies between 25 and 27 t, depending on the type of fuel.

The deposited canisters are surrounded by a buffer that will protect the canister from flowing groundwater, hold the canister in place and greatly retard the transport of radionuclides. The buffer consists of blocks and rings of sodium bentonite clay (MX-80). The height of the blocks and rings amounts to 0.50 m. The thickness of the rings after water saturation will be 0.35 m.

At present, two variants of the KBS-3 concept are being developed. In the preferred variant, KBS-3V [III-2], the canisters are emplaced in vertical deposition holes. The second variant, KBS-3H [III-3], is characterized by horizontal drift disposal. In both variants, the canisters and the buffer are the same. The access tunnels and the parts of the repository located above ground are not affected either.

III–2.1. Vertical disposal

Between 5 and 10% of the total quantity of nuclear fuel will be deposited in the repository during the test operation phase. This is equivalent to about 200–400 canisters of a total of 4500. After the test operation phase, SKB and the authorities will conduct a thorough evaluation of the repository.

In the KBS-3V concept, the deep repository consists of an access tunnel, main tunnels, shafts and a system of deposition tunnels (Fig. III–1). The deposition tunnels are 265 m long. The length can, however, vary depending on local rock conditions. Each deposition tunnel has a cross-sectional area of approximately 30 m^2, and contains a number of vertical holes in which the canisters with spent fuel will be deposited. The diameter of each deposition hole amounts to 1.75 m and the depth to 8 m. After the canisters have been placed in the holes, surrounded by tightly compacted bentonite, the tunnel is filled with a mixture of clay and crushed rock.

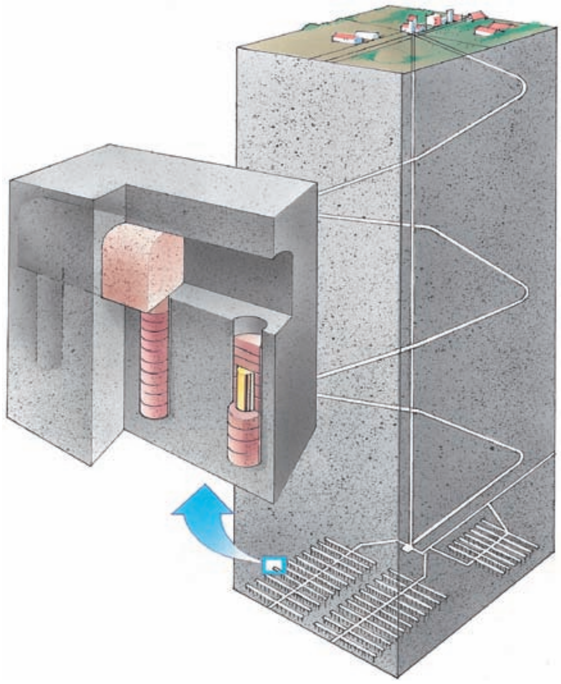

FIG. III–1. Illustration of the KBS-3V concept for the storage of SNF.

SKB has developed a full-scale prototype of a radiation shielded and remote controlled deposition machine for vertical disposal (Fig. III–2). Emplacement of the copper canisters and the surrounding bentonite in the deposition holes has been demonstrated at the Äspö HRL. The deposition process has also been reversed. During the deposition process, blocks and rings of compressed bentonite clay are first emplaced in the deposition hole in a vertical stack before the canister is lowered. At present, the space between the inside wall of the bentonite rings and the canisters is only 1 cm. This requires great precision on the part of the deposition machine.

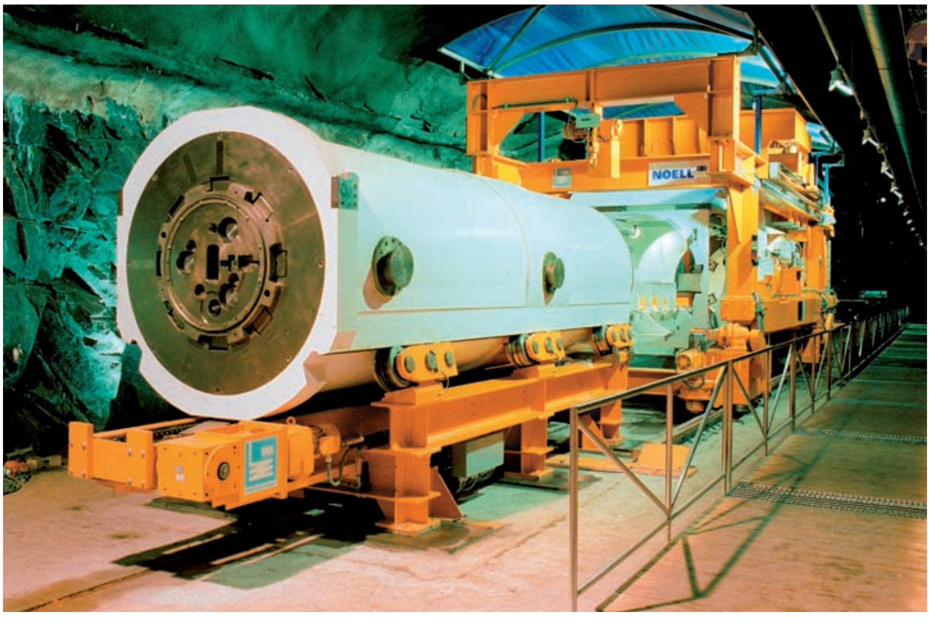

FIG. III–2. Prototype deposition machine for vertical disposal (the machine tilts the canister into the deposition hole).

III–2.2. Horizontal disposal

The deposition tunnels are not needed in the KBS-3H concept, since the 200–300 m long deposition holes are bored directly from the main tunnels. The diameter of the deposition holes is approximately 2 m; thereby, the excavation volume is reduced from 1 800 000 m^3 to about 900 000 m^3 compared to vertical disposal. Horizontal disposal differs from vertical disposal in one important way: deposition takes place in parcels (supercontainers). Around the canister and the bentonite is a perforated steel deposition cylinder. The cylinder is perforated so that water can get into the bentonite clay and make it swell. The steel cylinder will eventually corrode away.

An advanced remote controlled deposition machine that utilizes water-driven cushions to reduce friction is required to move the nearly 50 t parcel with canister and buffer. A distance block of bentonite is placed between each deposition parcel. When all positions in a deposition hole have been filled, the hole is sealed with a concrete plug.

A full-scale test of boring and deposition in Äspö HRL began in late 2004. A total of two deposition holes will be bored. The deposition tests start in 2005 and last at least until the end of 2006.

III–3. RETRIEVAL

It will take at least 40–50 years to carry out all the measures needed to dispose of all long lived and high level nuclear waste in a safe manner. It is, therefore, appropriate to proceed in steps and keep the door open for technological development, changes and possibilities for retrieving the canisters that have already been disposed of. This will ensure freedom of choice for the future while at the same time demonstrating the deep disposal method on a full scale and under actual conditions.

If the evaluation of the test operation phase shows that the method has deficiencies or that better methods exist, the deposited 200–400 canisters will be retrieved. SKB must, therefore, show that it is technically feasible to retrieve the canisters before starting deposition. If the evaluation gives a positive result, SKB will apply for an operating licence to begin regular operation. The remaining 4100–4300 canisters will then also be disposed of. If the results of the evaluation are not positive, it may be decided to free and retrieve the canisters. Like deposition, canister retrieval requires the permission of the regulatory authorities.

There are, however, no legal requirements for retrievability in Sweden. The impact of the safety of such measures that are adopted to facilitate the monitoring or retrieval of disposed nuclear material or nuclear waste from the repository, or to make access to the repository difficult, shall be analysed and reported to the Swedish Nuclear Power Inspectorate.

In the KBS-3 concept, there are no special measures to facilitate retrieval of the canisters. The concept itself is considered to be reversible enough. All tunnels will be backfilled and/or plugged as soon as all available deposition positions are occupied.

III–3.1. The Canister Retrieval Test

In 1998, SKB started the Canister Retrieval Test in order to develop methods for freeing and retrieving vertically disposed canisters in a safe way. Most of the practical tests are being performed at Äspö HRL [III-4, III-5]. A full-size canister with electrical heaters has been placed in a deposition hole lined with blocks and rings of bentonite clay. The hole was then plugged. When the bentonite has become saturated with water, the canisters will be freed. SKB believes that the best method for freeing canisters is to slurry the bentonite using a saline solution. In May 2006, the canister from the test was freed.

Retrieval tests of horizontally deposited canisters have not been performed. It is assumed that a retrieval of the deposition parcels will take place before the steel cylinders have corroded away. Hence, there will be no bentonite removal involved. Another assumption is that all the deposited parcels in one deposition hole are retrieved at the same time. Retrieval of one specific deposition parcel is considered to be too complicated from a technological point of view.

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Annex IV

SWITZERLAND

IV–1. BACKGROUND

In Switzerland, the revised Nuclear Energy Law [IV-1] has adopted the concept of monitored geological disposal, as proposed by the Swiss expert group on disposal concepts for radioactive waste [IV-2]. The disposal of radioactive wastes is envisaged in a facility where, after the emplacement, a period of monitoring is foreseen before the facility is closed. The concept combines the need for passive safety, as ensured by disposal at depth in a stable geological environment, with a cautious, stepwise approach to implementation, which is intended to address not only scientific and technical issues but also societal concerns. The approach involves an extended period of monitoring, during which retrieval of the waste is relatively easy, and the emplacement of a representative fraction of the waste in a pilot facility to test predictive models and to facilitate the early detection of any undesirable behaviour of the system, if this should occur. Opportunities are, thereby, provided for the review and possible reversal of decisions, including the retrieval of the emplaced waste.

IV–2. SITING OPTIONS

For the siting of the SF/HLW/ILW repository, sediments — where Opalinus Clay is the primary option and the Lower Freshwater Molasse a reserve option — and the crystalline basement in Northern Switzerland are under consideration. In December 2002, the Opalinus Clay Project (which represents the final step in the demonstration of the feasibility of final disposal in Switzerland — “Entsorgungsnachweis” in German) was submitted to the federal authorities for review [IV-3–IV-5]. Based on the highly promising results, Nagra proposed to the federal authorities that future investigations relating to deep geological disposal should focus on Opalinus Clay and on a potential siting area in the Zürcher Weinland. The repository for HLW and SF will be required around the middle of this century.

IV–3. WASTE INVENTORY

Swiss electric power utilities operate five nuclear power plants with a total electricity capacity of 3220 MW(e), corresponding to ca. 40% of the electric energy produced in Switzerland. The current position of the Swiss utilities is that the power plants should be in operation as long as the regulatory safety requirements are fulfilled and commercial aspects are in favour of a prolonged operation of the power plants. This may result in an operation period of up to 60 years for some plants.

Radioactive waste in Switzerland arises from the operation and decommissioning of nuclear power plants, from the fuel cycle of the power plants and from medicine, industry and research. Some of the spent fuel from nuclear power production is being reprocessed. The wastes arising from reprocessing (HLW and ILW-LL, as defined below) are being returned to Switzerland. The main categories of long lived radioactive waste are:

- Spent fuel, in the form of fuel assemblies containing UO_2 or mixed oxide (MOX) fuel;
- Vitrified HLW from the reprocessing of spent fuel;
- Long lived intermediate level waste (ILW-LL); this waste is broadly similar to the waste category sometimes referred to as TRU (transuranic-containing waste) even though the transuranics may not be the most safety-relevant radionuclides in such waste.

As a basis for planning of future licensing processes, preliminary safety assessments and studies related to the construction and operation of future repositories, information is required for all types of radioactive waste. Therefore, Nagra has developed a national model inventory for all waste types (SF, HLW, ILW, LILW). The model inventory contains information regarding waste volumes and arisings, and relevant waste features such as a radionuclide inventory, material composition, conditioning, packaging, etc.

For the current programme planning, arisings for SF, HLW and ILW-LL were evaluated [IV-6] under the assumption that the five existing power reactors in Switzerland will operate for 60 years each (equivalent to 192 GW·a(e)). The total SF arisings over this period are expected to be 4412 t IHM[1], of which about 1195 t IHM will have been reprocessed. This results in the production of about 292 t of HLW glass encapsulated in 730 stainless steel canisters. The remaining 1443 t IHM of PWR UO_2 fuel, 1629 t IHM of BWR UO_2 fuel and 145 t IHM of MOX fuel (all in the form of complete fuel assemblies) are assumed to be encapsulated in 2065 canisters for disposal in an unreprocessed form.

Additional wastes to be returned from reprocessing of SF are produced in the form of solidified ILW residues containing metals, organics and inorganic materials. The formally specified quantities and type of waste from reprocessing is presently referred to as the ‘high force compacted waste’ option where full compaction of fuel structural materials (hulls and ends) and technological wastes takes place and the resulting compacts (‘pucks’) are placed in standard ‘flasks’ [IV-6]. The corresponding waste volume is about 500 m^3. The ILW drums will eventually be incorporated into concrete emplacement containers, with cementitious mortar used to fill the void spaces around the drums.

In addition to these wastes, small quantities of ILW-LL are produced in research and, eventually, will arise from operation of the fuel encapsulation facility required for packaging the spent fuel for disposal. In the current repository design study [IV-3], some additional reserves (2900 m^3) are foreseen for wastes that may not be suitable for the low and intermediate level waste repository.

IV–4. REPOSITORY CONCEPT

The concept of monitored long term geological disposal is illustrated in Fig. IV–1 for the proposed repository for SF, vitrified HLW and ILW-LL in Opalinus Clay. The system elements include:

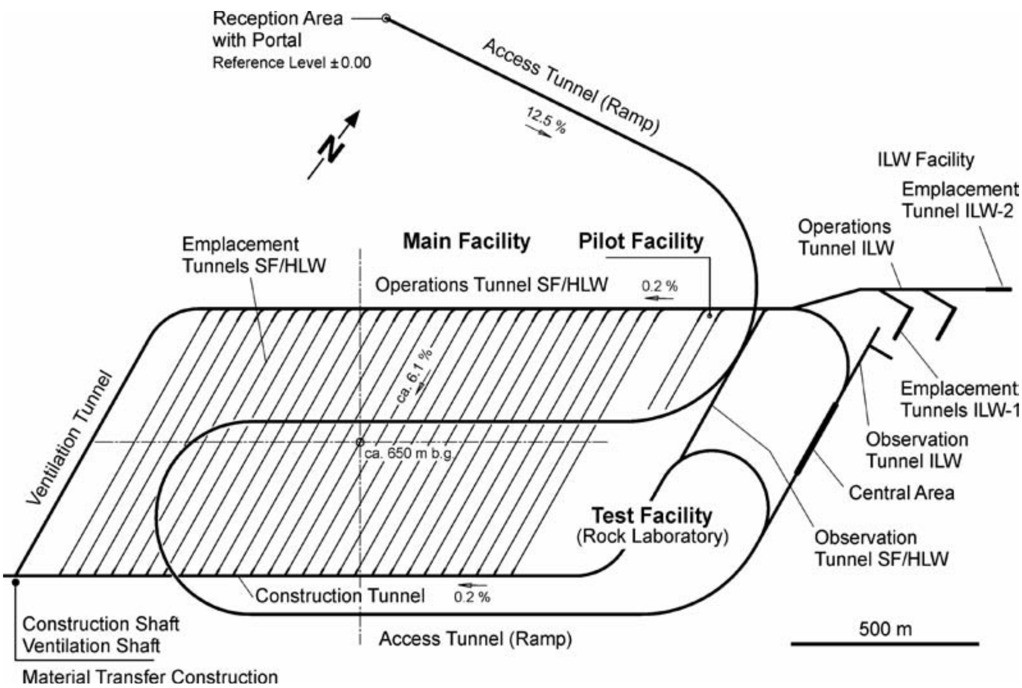

FIG. IV–1. Plan view of the repository for SNF, vitrified HLW and ILW-LL in Opalinus Clay.

[1] The unit t IHM refers to tonnes of initial heavy metal and relates to the original mass of U or U+Pu in the fuel assemblies.

— The main facility where the majority of the waste will be emplaced;
— The test facility to provide the information required before the main facility can start operation;
— The pilot facility containing a small but representative fraction of the waste, to provide information on the behaviour of the barrier system and to check predictive models;
— A tunnel system providing access and connecting the different system components, including tunnels for the near-field and environmental monitoring programmes.

IV–5. CONSTRUCTION AND OPERATION

Implementation and closure of a geological repository proceeds in a stepwise manner. Once investigations from the surface are complete, a test facility (rock laboratory) is constructed at the planned disposal level to obtain additional information for the construction of the main facility and for confirming the parameters that are important for long term safety assessment.

Construction of the repository involves the completion and installation of all components of the disposal facility that are required for the emplacement of radioactive waste. This is followed by the emplacement of SF and HLW in the pilot facility and of ILW in the corresponding emplacement tunnels. The disposal operation also includes backfilling and successive sealing of the disposal units. At the same time, the first emplacement tunnels are constructed in the main facility. This work is carried out using the construction and ventilation shaft. Further emplacement tunnels are constructed in parallel with emplacement operations in the main facility. Once emplacement has been completed, all tunnels are sealed and monitoring is concentrated on the pilot facility.

Special seals are installed when the main facility is closed. Access still remains possible to the test facility and by means of the observation tunnels to the pilot facility. After an extended monitoring phase, a decision is made to close the entire facility and the remaining open access routes are backfilled and sealed.

IV–6. MONITORING

Monitoring activities will change with regard to objectives and location during the stepwise implementation of the geological repository: Monitoring during site investigations from the surface and later from underground will primarily be done for establishing baseline conditions and later to detect any unexpected changes above ground and in the geological media during the construction of the exploratory/access tunnel; it may also contribute to confirming geological and hydrogeological information from previous investigation steps.

During the design and construction phase (and continued also during waste emplacement), monitoring will be focused around activities in the test facility in order to optimize the design, construction, operation and closure of the repository.

Monitoring of the pilot facility, after the waste has been emplaced and the emplacement tunnels are backfilled and sealed, supports the decision making process leading to closure of the repository. This facility provides ample possibilities for a broad instrumentation of basically all components of the disposal system which will allow for a comprehensive long term monitoring of the hydraulic, chemical and mechanical conditions of the waste, the engineered barriers and the surrounding host rock. Measurements will also be possible in boreholes drilled from the observation tunnels of the pilot facility and from the access tunnel (ramp) above the main facility.

After the repository has been closed, any monitoring will most probably be done from the surface, in order not to impair long term safety, and will be continued as long as it is thought to be necessary by society. Any direct radiological evidence for the validation of predictive modelling results is very questionable; due to the high efficiency of the engineered (and natural) barrier system, the potential impact of activity released into the biosphere will be very small and will only occur a very long time after waste has been emplaced. Such measurements may, however, provide a good basis for public reassurance and may, indeed, be a societal requirement.

IV–7. RETRIEVABILITY CONCEPT

The provisions for the surveillance (monitoring) of a deep geological repository and the retrieval of radioactive waste are stipulated in the Swiss Nuclear Energy Law [IV-1]. The law specifically defines an observation phase as a prolonged surveillance period of a repository before its closure during which radioactive waste can be easily recovered. The corresponding Nuclear Energy Ordinance [IV-7] requires that the proposed technology for the removal of the backfill material and the retrieval of the waste containers from the disposal tunnels are verified prior to the operation of the repository. Apparent reasons for waste retrieval could possibly be the re-use of fissile material (in the case of spent fuel disposal), innovative (new) waste management strategies, or an undesirable behaviour of the disposal system with adverse consequences for human health and the environment.

The overall objective for the final disposal of radioactive waste is (i) to protect human health and the environment in the long term against the ionizing radiation from the waste, and (ii) not to impose any undue burden on future generations. This objective is achieved by a set of safety principles [IV-8], which state, among others, that “any measure which could facilitate surveillance and repair of a repository or retrieval of the waste shall not impair the functioning of the passive safety system”. For this reason, individual disposal tunnels of the main facility are backfilled and sealed immediately after the waste canisters are emplaced.

IV–7.1. Retrieval strategy and procedure

The technological effort of a retrieval operation depends on the accessibility of the disposal tunnels related to the particular implementation phase: while waste emplacement is in progress, retrieval of HLW/SF canisters is technically feasible (with low effort) by reversing the emplacement procedure. After the closure and sealing of the main facility (i.e. operation tunnel and ventilation shaft are backfilled and sealed, access to pilot facility is open), a re-excavation of the operation tunnel and the removal of the seals of the emplacement tunnels is necessary prior to waste retrieval. If the whole repository has been closed and sealed, the re-excavation of the access tunnel (or alternatively a new tunnel) is first required.

Preliminary conceptual studies for the retrieval procedure (methodology, technical devices and machinery) have already been done and the applied technologies are available. All mobile systems move on rails, are electricity-powered and operate remote controlled. A full description of this system is given in Section 4.2.2.2.

The procedure for the retrieval of the containers for ILW-LL from the corresponding disposal tunnels will be done in a similar way as conceptually developed earlier for the retrieval of short lived L/ILW [IV-9].

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Annex V

UNITED STATES OF AMERICA

V–1. BACKGROUND

In the USA, the Nuclear Waste Policy Act of 1982 (NWPA) established a comprehensive federal policy to resolve the national problem of accumulated nuclear waste, by focusing on deep geologic disposal. In 1987, the NWPA was amended to characterize and evaluate only Yucca Mountain as a potential repository site. In 2002, the legally specified process was completed for finding the site suitable and designating Yucca Mountain as the site for the first permanent geologic repository for high level radioactive waste (HLW) and spent nuclear fuel (SNF). The governing regulation is 10 Code of Federal Regulations (CFR) 63 and the Nuclear Regulatory Agency provides independent oversight of the programme.

V–2. WASTE INVENTORY

Waste forms to be received and packaged for disposal include SNF from commercial power reactors, SNF owned by the Department of Energy (DOE) (including naval fuel), and canisters of solidified high level radioactive waste from prior commercial and defence fuel reprocessing operations, some of which will contain immobilized plutonium.

Section 114(d) of the NWPA limits the capacity of the first repository to no more than 70 000 t HM "...until such time as a second repository is in operation." The types of waste that will be accepted at the proposed repository have been allocated as follows:

— 64 693 t HM of SNF;
— 5307 t HM of vitrified high level radioactive waste.

The waste forms received at the repository will be in solid form. Materials that could ignite or react chemically at a level that will compromise containment or isolation will not be accepted by the repository. Neither the waste forms nor the waste packages will contain free liquids that could compromise waste containment. Materials that are regulated as hazardous waste under the Resource Conservation and Recovery Act of 1976 will not be accepted.

V–3. REPOSITORY CONCEPT

The proposed repository is located at Yucca Mountain, Nevada. Yucca Mountain is located on federal land in a remote area of Nye County in southern Nevada, approximately 160 km (100 miles) northwest of the city of Las Vegas, Nevada. Yucca Mountain provides an environment in which hydrogeological conditions important to waste isolation (e.g. a thick unsaturated zone with low rates of water movement) have changed little, if at all, for millions of years.

The area surrounding the site is sparsely populated and receives an average of about 170 mm (7 in) of precipitation per year. Little of this precipitation percolates into the mountain; nearly all of it (about 95%) runs off, is picked up by the root systems of vegetation or is lost to evaporation. This significantly limits the amount of water available to infiltrate the surface, move down through the thousand feet of unsaturated rock and seep into emplacement tunnels.

The repository is unique among sites being considered worldwide, in that the repository will be developed in unsaturated rock, well above the groundwater table (which is, on average, 305 m (1000 ft) below the repository), in an oxidizing environment. Yucca Mountain consists of alternating layers of welded and non-welded volcanic tuff: welded tuff at the surface, welded tuff at the level of the repository, and layers of non-welded tuffs above and below the level of the repository. These non-welded units contain few fractures; thus, they delay the downward flow of moisture into the welded tuff layer below, where the repository would be located. At the repository level, water in small fractures has a tendency to remain in the fractures rather than flow into larger openings, such as tunnels.

The repository will consist of 7.62 m (25 ft) diameter access and exhaust mains, and 5.5 m (18 ft) diameter horizontal emplacement drifts. The emplacement drifts will be the disposal area for the waste packages and are located at an average depth of 305 m (1000 ft) below the ground's surface. The emplacement drifts extend up to 800 m (2600 ft) in length. The waste packages are unshielded, and are placed on a waste package pallet and then emplaced in the emplacement drifts in a horizontal orientation. The emplacement drifts will receive forced-air ventilation of 15 m^3/s (32 000 ft^3/min) until the repository is permanently closed. This ventilation will remove approximately 90% of the heat generated by the waste packages during the period before repository closure from the emplacement drifts.

Waste packages will be placed within a 10 cm (4 in) end to end spacing in the emplacement drifts. The waste packages are constructed out of a 316 stainless steel inner structural cylinder placed inside an Alloy 22 nickel-based corrosion resistant barrier. Just prior to permanent closure of the repository, interlocking titanium drip shields will be placed over the waste packages. The drip shields provide the function of limiting the possibility of advective flow onto the waste packages as well as providing rock-fall protection for the waste packages. The drip shields and Alloy 22 outer barrier of the waste package would be expected to have long lifetimes in the repository environment. Alloy 22, the outer barrier material of the waste package, is very corrosion-resistant, with general corrosion expected to penetrate only about 0.03 in of this outer layer of material in 10 000 years. The Titanium Grade 7 is also corrosion-resistant, with general corrosion expected to penetrate only about 0.2 cm (0.08 in) of the 1.5 cm (0.6 in) in 10 000 years. Only about 1% the waste packages are projected to lose their integrity during the first 80 000 years.

Even though the waste packages and drip shields are expected to be long lived in the repository environment, the advanced computer simulations predict some eventual loss of waste package integrity. Even if water were to penetrate a waste package, several characteristics of the waste forms and the natural character of the repository rocks and water would limit radionuclide releases. In the early periods after closure, because of the warm temperatures, much of the water that penetrates the waste package will evaporate. The solid waste forms will not dissolve rapidly in the water expected in the repository environment. In addition, crushed tuff, which would be placed under the waste package and support pallet, would also delay the movement of radionuclides.

Eventually, the engineered barrier systems will suffer some loss of integrity, and small amounts of water could contact waste, dissolve it, and carry some radionuclides out of the repository and into the rock below. The repository level is in the unsaturated zone, where the microscopic holes in the rock are only partially filled with water. The water table lies, on average, 305 m (1000 ft) below the repository level. At the proposed repository level, the host rock is fractured, and these fractures provide the main pathways for water and radionuclide transport through this zone. As water flows through fractures, dissolved radionuclides would diffuse into and out of the pores in the rock, increasing both the time it takes for radionuclides to move from the repository and the likelihood that they will be exposed to sorbing minerals (minerals that attract and hold them).

Flow paths from beneath the repository are generally southerly toward the Amargosa Desert. Radionuclide migration through the saturated zone results in dilution and reduced radionuclide concentrations in groundwater. Additionally, the water in the Amargosa Desert is in an isolated hydrologic basin that does not connect to any lakes or rivers that discharge into the ocean, nor does it provide water for any sizeable population centres.

V–4. OPERATIONS

SNF and vitrified high level radioactive waste will be transported to the repository in Nuclear Regulatory Commission (NRC)-certified transportation casks, using US Department of Transportation licensed cask transportation contractors. The waste will mostly be transported by rail to the site. Surface facilities will be constructed to receive waste shipments and unload, handle and package waste containers into waste packages for underground emplacement. Some waste containers may need to be cut open, the waste removed and repackaged into a new waste container prior to placing the waste container into a waste package.

Waste packages will be moved from the surface to the emplacement drifts using a shielded waste package transporter. Once the waste package transporter arrives at the assigned emplacement drift and the drift isolation doors are opened, the waste package transporter doors will be opened and the waste package will be moved out of the transporter. An in-drift gantry will lift the waste packages by their supporting pallets and deposit them in their designated position inside the drift. Before the repository is permanently closed, drip shields will be placed over the waste packages to divert any water that might drip from the top of the emplacement drifts and to act as a rock-fall shield.

The design of a waste package is based on the characteristics of the waste forms that it will hold. The waste package is being designed, in conjunction with the natural and other engineered barriers, to ensure compliance with applicable NRC regulations, to contribute to safe operations during the pre-closure phase, to make efficient use of the proposed repository area and to preserve the option of retrieving the waste. To perform its containment and isolation functions, the waste package has been designed to take advantage of its location in the unsaturated zone of the repository.

Emplacement operations will take place in finished emplacement drifts at the same time as future emplacement drifts are being constructed. During construction, physical barriers and separate ventilation systems will be provided between the development side (i.e. panel construction) and the waste emplacement side (i.e. panel where waste is being emplaced) to minimize the risk of worker exposure to radiation from the waste. During emplacement, ventilation will maintain temperatures within the range for equipment operation.

After the operations in the repository and the performance confirmation programme have been completed, the DOE would file an application with the NRC for an amendment to the licence to permit closure of the repository. Once the licence amendment has been received from the NRC, the DOE will be able to permanently close the repository. US Environmental Protection Agency (EPA) and NRC regulations require the DOE to undertake measures to regulate or prevent activities that could impair long term waste isolation and to institute a monitoring programme after permanent closure. Permanently closing the repository will require the backfilling and sealing of the ventilation shafts, access ramps, exploratory boreholes and other openings to the repository. Closure seals will be designed to discourage human intrusion and prevent water from entering through these openings. In concert with 10 CFR Part 63, a network of permanent monuments and markers will be erected around the site to warn future generations of the presence and nature of the buried waste, and detailed public records will identify the location and layout of the repository and the nature and hazard of the waste it contains.

V–5. RETRIEVAL PROVISIONS

The capability to retrieve the waste is a requirement of the laws and regulations governing Yucca Mountain. The capability to retrieve waste is required to be maintained for a minimum of 50 years from the start of waste emplacement and until the end of the performance confirmation period; essentially, until permanent closure.

The primary purpose of retrieval would be to protect public health and safety. Retrieval might be considered if the results of the performance confirmation testing programme determine that the behaviour of the repository does not conform to predicted behaviour. Retrieval might also be considered during repository operations if new technologies are developed, or if a future decision is made to reprocess or otherwise utilize the SNF as a resource. Once the repository is closed, retrieval is neither planned for nor required by law or regulation.

The normal process of retrieval is the reversal of emplacement. The same equipment that emplaced the waste packages would be used to retrieve the waste packages. If conditions have deteriorated such that normal retrieval is not possible, special equipment and materials will be developed to retrieve the waste packages. All emplacement and retrieval operations will be done via remote control due to the high thermal (up to approximately 70°C) and radiation fields (up to approximately 10 Sv/h (1000 rem/h)) near the unshielded waste packages.

Regulations state that a reasonable schedule for retrieval is about the same time that it took to construct the repository and emplace the waste. Planning for retrieval operations is expected to take several years, and would require regulatory review and approval.

After closure, the Federal Government will maintain institutional control of the site. Active and passive security systems and monitoring will prevent deliberate or inadvertent human intrusion and any other human activity that could adversely affect the repository.

Annex VI

OTHER COUNTRIES

VI–1. BACKGROUND ON WASTE MANAGEMENT

Country	Background
Finland	The Finnish Parliament ratified in May 2001 the Government's positive Decision in Principle to locate the repository for spent fuel at Olkiluoto. At present, the Underground Rock Characterization Facility ONKALO is under construction. A construction permit application for the repository will be submitted in 2012 and operation is planned to begin in 2020. The Finnish Government decision 478/1999 states that spent fuel disposal shall be planned so that no monitoring of the disposal site is required for ensuring long term safety and so that retrievability of the waste canister is maintained to provide for such development in technology that makes it the preferred option.
Germany	German Atomic Energy Act. No further exploration work at the Gorleben site since 2000; No regulation concerning retrievability of radioactive waste from a repository; Regulatory decision on retrievability under review.
	Konrad repository licensed in 2002.
Hungary	There are nine Acts, 30 Governmental Decrees, 19 Ministerial Decrees relevant to radioactive waste management. The final disposal of LILW of nuclear power plant origin — also including waste originating from the decommissioning of a nuclear power plant — shall take place in a deep geological repository. In July 2005, a local referendum expressed the opinion that 90.7% of those who filled ballot-papers (75%) voted "yes". In November 2005, it was approved by parliament. At present, the licensing process is being established. A new URL siting process is in progress in Boda Claystone Formation
Japan	MITI's notification No. 591: Reprocessing of spent fuel, storage for 30–50 years (cooling period), final disposal in a stable geological environment. "Specified radioactive waste final disposal Act" (June 2000): Phase of selection of a disposal site for HLW. MITI's notification No. 592: Start-up of repository operation around 2033–2037.
Lithuania	Nuclear energy Act and Radioactive waste management Act. Strategy for RWM in Lithuania: Government document.
Netherlands	The 1993 policy directive of the Dutch Government decreed that deep underground disposal of highly toxic waste, including radioactive waste, will only be permitted if that waste remains retrievable in the long term. A phased disposal concept is being considered — long term storage above ground (at least 100 years) followed by retrievable underground disposal.
Russian Federation	Russian Atomic Energy Law. No regulation concerning the retrievability of radioactive waste from a repository regulatory decision is under consideration.
United Kingdom	The current Government policy on radioactive waste management is set out in a White Paper of July 1995 "Review of radioactive waste management policy — final conclusions". It is currently the subject of a major review and further policy statements are likely once the Government appointed independent committee (CoRWM) provides its advice in July 2006. It will be for ministers to decide further policy for the long term management of the United Kingdom's solid radioactive waste and to make arrangements for its implementation. Currently, there are no policy requirements relating to the retrievability of waste from geological repositories. The current Government policy on vitrified HLW is that it should be stored for 50 years, allowing decay of heat and facilitating less complex long term management.

VI–2. SITING OPTIONS/HOST ROCK AND WASTE INVENTORY

Country	Sitting options/Host rock	Waste inventory
Finland	Crystalline rock at Olkiluoto	SNF: around 2900 canisters (5640 tU)
Germany	Salt dome (Gorleben)	HLW vitrified: 4800 canisters SNF: 9000 t HM
	Iron ore mine with clay overburden (Konrad)	LILW: licensed for 303 000 m^3
Hungary	LILW: granite, depth 250 m. HLW, W-LL, SNF: claystone (Boda), depth 800 m	Non-vitrified waste SNF (30 years of operation): 13 500 assemblies or 1570 tU HLW/W-LL: 500 m^3 LILW: 40 000 m^3
Lithuania	Clay, granite	2500 t SNF in 2010 (= 22 000 assemblies)
Netherlands	All waste in a single repository. Both clay and salt formations are considered	LILW: 188 000 m^3 HLW: 3040 m^3 (vitrified reprocessing waste: 70 m^3, SNF: 40 m^3, non-heat processing waste 2930 m^3)
Japan	Under selection, either sedimentary or crystalline rock; depth 500 m. Long term stable geological environment	HLW glass: 40 000 canisters (in 2020)
Russian Federation	Clay: North-West region Crystalline rock: Ural region and Siberian region (Krasnoyarsk), Nizne-Kansky region, far east region near Vladivostok	HLW: 58 300 t SNF: 22 941 500 t
United Kingdom	No sites have been selected for deep geological repositories. A range of geological environments are potentially available in the United Kingdom	ILW: 220 000 m^3 HLW: 1300 m^3 SNF: 4100 t HM

[a] HLW: high level waste.
[b] ILW: intermediate level waste.
[c] LILW: low and intermediate level waste.
[d] W-LL: long lived waste.
[e] SNF: spent nuclear fuel.

VI–3. SPECIFIC ASPECTS OF THE COUNTRY REPOSITORY CONCEPTS FAVOURABLE FOR RETRIEVAL

Country	Repository concept: Specific aspects favourable to retrieval
Finland	KBS-3 cast iron insert copper shell for the canister embedded in bentonite clay at 400–700 m. Vertical or horizontal disposal of canister. No special measure to facilitate retrieval
Germany	Gorleben: Depth: 860–1200 m; SNF in self shielding casks in horizontal blind long drifts (up to 300 m); HLW in deep vertical boreholes; Backfilled with crushed salt for SNF drifts and sealing with a plug of salt concrete/crushed salt; Shaft sealing
	Konrad: Depth: 800–1300 m; Steel, concrete and cast iron containers, backfilled with concrete material, emplacement cells sealed by concrete dams; Shaft sealing
Hungary	LILW: Conditioned ion exchange resins, evaporator concentrate, sludge and compacted solid waste; Horizontal tunnels; Over pack: concrete container; Primary package: carbon steel drums; Bentonite sealing material is foreseen around the waste packages and inside the containers. HLW, W-LL, SNF: The surface and underground constructions are interconnected by two central and one diagonally positioned vertical shafts, which provide the construction, exploration and operation conditions in accordance with the safety requirements. The facility (single floor) will be approximately 700 m × 700 m. The most important design assumptions: — The development of the underground spaces is performed by conventional drilling and the cautious blasting method; — Similarly to the Swedish method, the SNF canisters (with cast iron basket and copper overpack) are stored one by one in large diameter boreholes; — The engineering barrier (buffer) around the canisters is pure pre-cast bentonite compacted at high pressure; — HLW/W-LL are packaged into sealed stainless steel containers, and disposed in various arrangements in the disposal drifts. For all waste types, the backfilling of the disposal drifts is performed successively after the completion of the loading operations in each drift, with the use of the appropriate mixture of bentonite and the excavated rock granulated to the appropriate grain size
Japan	Generic concept using overpack. Overpack longevity is enhanced by environmental conditions provided by buffer materials
Lithuania	KBS-3 concept (see Sweden)
Netherlands	Retrievability concepts for clay and salt essentially the same: with adequate maintenance and concrete support (clay), access tunnels and galleries can be kept open for more than 100 years, cells are backfilled (crushed salt) and sealed (salt blocks) in a salt host rock, or backfilled and sealed with clay/bentonite (in a clay host)
United Kingdom	Former national waste management agency, Nirex, developed the Phased Geological Repository Concept (PGRC) for ILW and certain types of LLW. Typically, the wastes are immobilized in a cement-based grouting material within a standardized, highly engineered stainless steel or concrete container. The concept is a multi-barrier, phased approach, based on storing waste deep underground prior to repository closure. The concept includes a period of monitored retrievable storage for periods of up to several hundred years. Retrieval may be possible following backfilling (with a cementitious grout) and sealing, although with increased difficulty. Nirex also investigated the applicability of the KBS-3 concept for United Kingdom HLW and spent nuclear fuel. However, at the end of 2006, the Government had yet to identify the national policy for the long term management of the United Kingdom’s higher activity wastes. If deep geological disposal is preferred, retrievability provisions would be required

VI–4. MONITORING AND RETRIEVAL STRATEGIES

Country	Monitoring	Retrieval strategy
Finland	Disposal shall be planned so that no monitoring of the disposal site is required for ensuring long term safety	In the KBS-3 concept, there are no special measures to facilitate retrieval of the canister. The concept is considered to be reversible enough. In addition, the design of the disposal panels is such that they can be constructed stepwise and be closed independently, which will ensure freedom for retrieving, if desired
Germany	Gorleben: Monitoring during operation	Closure after operation phase (i.e. after approximately 70 years). No retrieval intention. Retrieval of SF disposed of in the Gorleben repository would be technically possible at any time after repository closure
	Konrad: Monitoring during operation	Retrievability not foreseen
Hungary	Monitoring: 47/2003 Decree of the Minister of Health, Social and Family Affairs: “the behaviour of the barriers of the waste disposal system and their appropriateness shall be continuously evaluated/ qualified during facility’s lifetime”, “Measuring programme for controlling the radiation conditions of the site and for monitoring the environment shall be elaborated, which are approved by the inspecting authority. The licensing plans shall contain recommendation for the scope and frequency of the environmental control subsequent to facility closure.”	Retrievability: 47/2003 Decree of the Minister of Health, Social and Family Affairs: “The technology of the waste disposal shall be designed in such way that the waste remains retrievable under the operating time, if the retrieving is proved by further operating experience, or it is requested by the regulatory procedure.” Planning in progress
Japan	Appropriate monitoring and inspection is planned during each phase	Stepwise safety confirmation; Ability to reverse one or a series of steps during operational phase (before completely backfilling the repository)
Lithuania	As for Sweden	As for Sweden
Netherlands	Monitoring in pre-closure period	Stepwise, incremental decisions
United Kingdom	Current regulatory guidance requires monitoring to identify any changes caused by construction of the facility and the emplacement of waste. The philosophy and provisions, if any, with regard to monitoring and retrieval of waste should be stated and justified in facility related information	As of the end of 2006, there were no regulatory requirements for retrievability

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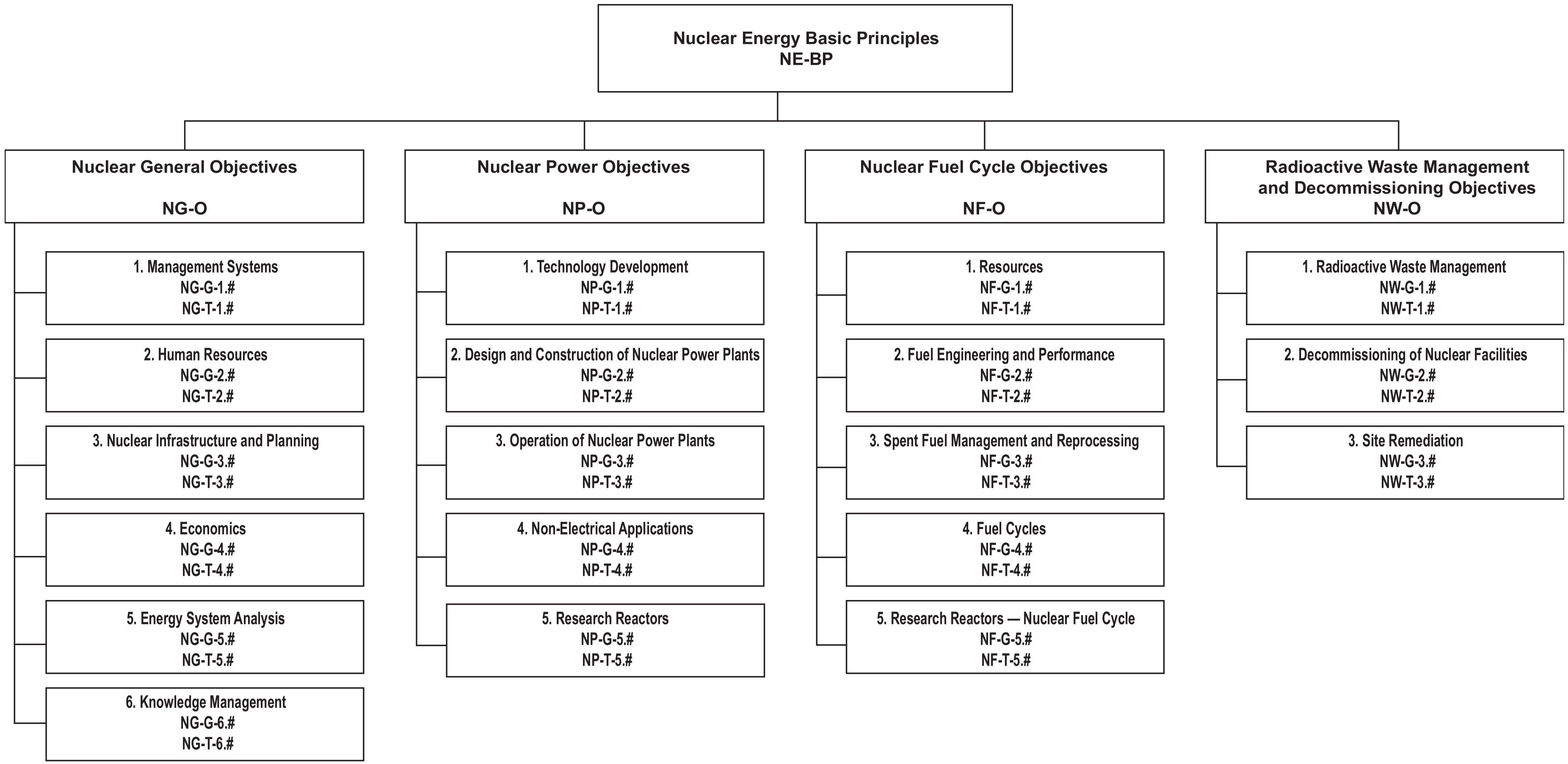

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