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# International perspective on repositories for low level waste

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*Keywords:* Low level radioactive waste, Repository, Criteria, Safety assessment, Design, Barriers, Location.

# Abstract

Nuclear energy production gives rise to different types of radioactive waste. The use of nuclear isotopes within the research, industry and medical sectors also generates radioactive waste. To protect man and the environment from radiation the waste is isolated and contained by deposition in repositories. These repositories may have various designs regarding location, barriers etc depending on the potential danger of the waste. In Sweden, low- and intermediate level waste (LILW) is disposed of in the SFR repository in Forsmark. The repository is located 60 metres down into the bedrock under the bottom of the sea and covered by 6 metres of water.

It is planned to extend SFR to accommodate decommissioning waste from the dismantling of the Swedish nuclear power facilities and also for the additional operation waste caused by the planned prolonged operation time. When planning the extension consultations will be carried out with the host municipality, authorities, organisations and general public. In planning the extension, SKB has performed a worldwide compilation of how other countries have, or plan to, handle the final disposal of similar wastes.

The aim of this report is to give a brief description of LILW repositories worldwide; including general brief descriptions of many facilities, descriptions of the waste and the barriers as well as safety assessments for a few chosen repositories which represent different designs. The latter is performed, where possible, to compare certain features against the Swedish SFR.

To provide a background and context to this study, international organisations and conventions are also presented along with internationally accepted principles regarding the management of radioactive waste.

Similar to SFR, suitable locations for the repositories have, in many countries, been found at sites that already have, or used to have nuclear activities, such as reactor sites. Abandoned and disused mines, such as the salt mines in Germany, also represent a common type of locality for a repository, given that siting criteria are fulfilled. There is also a site that was selected without any association to existing nuclear sites or mines. This is the case for the French L'Aube repository.

National repositories for disposal of all waste arising in that country are common, e.g. El Cabril in Spain and Low Level Repository close to Drigg in United Kingdom. The depth of the repositories varies from being on the surface to down to 650 metres below ground.

The geological conditions of the different repositories are described as well as engineered barriers, geographical location and, if available, information on safety analysis. It can be noted that in the safety analysis of repositories located close to the coast (such as in Sweden, Finland and the United Kingdom), the effect of post-glacial land rise or coastal erosion is taken into special consideration.

In general, the size of the repository reflects the size of the nuclear programmes in the respective country. The activity content of the facility, both the total and normalised figures against the volume capacities, are compared for groups of radionuclides.

# Sammanfattning

Produktion av energi från kärnkraft genererar olika typer av radioaktivt avfall. Det gör även användande av nukleära isotoper inom forskning, industri och för medicinska ändamäl. För att skydda människan och miljön från strålningen från avfallet isoleras och innesluts det genom att det deponeras i ett förvar. Ett sådant förvar kan utformas på olika sätt med avseende på läge och barriärer beroende på avfallets potentiella farlighet. I Sverige slutdeponeras det kortlivade låg- och medelaktiva avfallet i ett förvar, SFR i Forsmark. Förvaret är beläget 60 meter ner i berggrunden, vilken är täckt med 6 meter av Östersjövatten.

SFR behöver nu byggas ut för att rymma det rivningsavfall som genereras vid den kommande avvecklingen av de svenska kärnkraftsanläggningarna samt ytterligare driftavfall som kommer av förlängda planerade drifttider av kärnkraftverken. Samråd ska genomföras med kommunen, myndigheter, organisationer och allmänhet.

Vid planeringen av utbyggnaden av SFR har SKB, för att tillvarata internationella erfarenheter och fördjupa kunskapen om de tekniska barriärerna och deras konstruktion, gjort en omvärldsanalys/utblick och tittat på hur andra länder har löst eller kommer att lösa sina slutförvarsbehov. Syftet med denna rapport är att presentera en sammanställning av förvar i omvärlden och beskriva dessa kortfattat men också att beskriva avfall och barriärer samt säkerhetsanalyserna för några utvalda förvar, vilka kan ses som exempel på de olika förvarsutformningar som förekommer. Det senare underlaget används för att kunna göra vissa jämförelser med det svenska SFR och dess barriärer.

För att ge en bakgrund presenterar rapporten också de internationella organisationer samt konventioner och internationella principer som finns avseende hantering av radioaktivt avfall.

I likhet med SFR har för flera förvar i andra länder lämpliga lokaliseringsförhållanden funnits vid platser där kärnteknisk verksamhet såsom företrädesvis drift av kärnreaktorer har pågått eller pågår. Övergivna gruvor, såsom till exempel saltgruvor i Tyskland, utgör också en förekommande typ av lokalisering. Det finns också exempel på förvar som har lokaliserats till platser där varken kärnteknik verksamhet eller gruvor förekommer.. Ett exempel på detta är L´Aube i Frankrike.

Nationella förvar är helt dominerande, till exempel El Cabril i Spanien och Low Level Waste Repository i närheten av Drigg i England. Den horisontella lokaliseringen av förvaren varierar från förläggning på ytan ner till 650 meter under markytan.

I denna rapport beskrivs de geologiska förhållandena för förvaren, likväl som deras tekniska barriärer, geografiska lokalisering och beroende på om information finns tillgänglig även de säkerhetsanalyser som genomförts. I säkerhetsanalyserna för de kustbelägna förvaren beaktas de stora förändringar som erosionen i England och det motsatta förloppet strandlinjeförskjutning i Finland och Sverige orsakar.

Storleken på förvaren avspeglar delvis storleken på ländernas nukleära program Totala aktivitetsinnehållet samt normaliserat mot förvarens volym för de olika förvaren jämförs för grupper av radionuklider.

# Contents

# Abbreviations

| | |
|---|---|
| BMA | SFR's vault for intermediate-level waste |
| BNFL | British Nuclear Fuel Limited |
| BWR | Boiling Water Reactor |
| CEA | Atomic Energy Commission, France |
| CSFMA | French repository for short-lived low- and intermediate level waste |
| DGR | Deep Geologic Repository |
| DOE | The United States Department of Energy |
| EPA | United States Environmental Protection Agency |
| ESC | Environmental Safety Case |
| FEP | Features, Events and Processes |
| GRM | Generalised Repository Model |
| IAEA | International Atomic Energy Agency |
| ICRP | International Commission on Radiological Protection |
| IFE | Norwegian Institute for Energy Technology |
| ILW | Intermediate Level Waste |
| IWDF | Integrated Waste Disposal Facility |
| IX | Ion Exchange |
| JNFL | Japan Nuclear Fuel Limited |
| LILW | Low- and Intermediate Level Waste |
| LILW-SL | Short-lived Low- and Intermediate Level Waste |
| LLW | Low Level waste |
| LLWR | Low Level Waste Repository, UK |
| MLLW | Mixed Low Level Waste |
| MWe | Megawatt electric energy |
| NDA | Nuclear Decommissioning Authority, United Kingdom |
| NEA | OECD Nuclear Energy Agency |
| NORM | Naturally Occurring Radioactive Material |
| NPP | Nuclear Power Plant |
| NRC | The United States Nuclear Regulatory Commission |
| NSDF | Near Surface Disposal Facility |
| OECD | Organisation for Economic Cooperation and Development |
| OPG | Ontario Power Generation, Canada |
| PWR | Pressurised Water Reactor |
| RW, RAW | Radioactive Waste |
| SFR | Swedish repository for short-lived low- and intermediate level waste |
| SISP | State Interregional Special Plant |
| SKB | Swedish Nuclear Fuel and Waste Management Company |
| SLC | Site Licence Company |
| SNF | Spent Nuclear Fuel |
| UK | United Kingdom |
| VLJ | Finnish repository for short-lived low- and intermediate level waste |
| VLLW | Very Low Level Waste |
| WAC | Waste Acceptance Criteria |

# 1 Introduction

Radioactive waste is generated due to the operation of nuclear power plants (NPPs), research, and application of nuclear techniques in industry and medical use. All countries having such activities consequently generate radioactive waste.

The future decommissioning of nuclear facilities will also give rise to radioactive waste, with varying activity levels depending on the degree of contamination.

The radionuclides in the waste may be harmful to man and the environment both either directly (external) or through intake (internal) if released to the environment. A fundamental principle with the management of radioactive waste is to protect man and the environment from radiation exposure. This can be achieved by isolating the radioactive waste from man and the environment by disposing of it in repositories. Designs for such repositories are directly related to, the level of activity in the waste, the waste volumes, and the amount of long-lived radionuclides etc.

Until recently, for most of the repositories encountered in this study, radioactive waste was classified based on the following characteristics, heat generation, surface dose rates and inventories of long-lived radionuclides. The following categorisation was applied in most countries:

- *High level waste,* (i) The highly radioactive liquid, containing mainly fission products, as well as some actinides, which is separated during chemical reprocessing of irradiated fuel (aqueous waste from the first solvent extraction cycle and those waste streams combined with it), (ii) Any other waste with radioactivity levels intense enough to generate significant quantities of heat by the radioactive decay process, (iii) Spent reactor fuel, if it is declared a waste.
- *Intermediate level waste (medium level waste).* Waste which, because of its radionuclide content requires shielding but needs little or no provision for heat dissipation during its handling and transportation.
- *Low level waste.* Waste which, because of its low radionuclide content, does not require shielding during normal handling and transportation.

The international organisation International Atomic Energy Agency (IAEA) has recently made a new classification system of radioactive waste directly related to the safety of final disposal (IAEA 2009). The basic principle is that, the higher the activity of the waste the longer distance from surface ecosystem (see figure below) and more engineered barriers are required. The acronyms for the waste categories are:

| | |
|---|---|
| VSLW | Very short-lived low-level waste |
| VLLW | Very low-level waste |
| LLW | Low-level waste |
| ILW | Intermediate-level waste |
| HLW | High-level waste. |

It is not possible to give exact limits that differentiate between classes; there is a gradual transition between them. It is up to the national authorities to set the limits based on the specific national situation. The limits will depend on the specific repository design and geological conditions. As an example, our Swedish repository SFR is located at about 60 meters depth but contains waste that could be deposited at or on surface.

VLLW and LLW are dominant from the volume point of view. VLLW is mostly disposed of in shallow landfills while LLW is disposed of in near surface repositories. These near surface repositories have various barriers; some are engineered why others depend on site conditions. Most experience of final disposal has been gained from near surface located repositories, pointing out characterisation of the site and waste, and performance of engineered barriers as important factors for safe disposal.

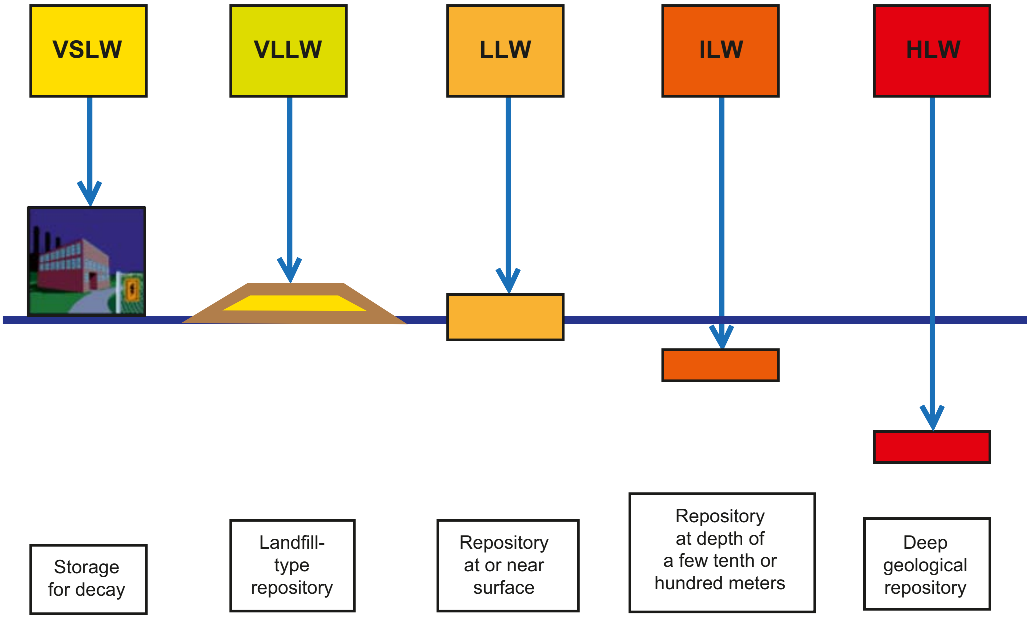

***Figure 1-1.*** *Relation between IAEA:s waste classification and final disposal.*

The Waste Isolation Plant in the USA is the only repository in operation for ILW. For HLW no repository has been commissioned but in Finland one repository is under construction and one application for construction of a HLW repository in Sweden was submitted to the authorities in March 2011.

There is an international consensus of the major principles for the safe final disposal of radioactive waste which combined with national regulations lead to various solutions and designs of repositories. The selection of a disposal option depends on many factors, both technical and administrative, such as radioactive waste management policy; national legislative and regulatory requirements; waste origin, characteristics and inventory; climatic conditions and site characteristics; public opinion; etc.

The safety for man and the environment from a repository is achieved through the combined effect of the above factors. How this has been or will be solved for the countries having LLW is of specific interest when analysing the safety of the existing and planned extension of our Swedish repository (SFR). SFR is planned to be extended to accommodate decommissioning waste from the future dismantling of the Swedish nuclear power facilities, see Figure 1-1. When planning the extension consultations will be carried out with the host municipality, authorities, organisations and general public. In the planning of the extension, SKB has commissioned this worldwide compilation of how other countries have, or plan to handle, the final disposal of similar types of waste. This is of interest to the planning of the SFR extension as gaining a knowledge of engineered barriers and the factors influencing their construction.

This report will focus on an overarching description of some selected national solutions for the final disposal of LLW. The report gives also a broad summary of repositories, planned and in existence worldwide.

## 1.1 Objectives

The purpose of this report is to:

- describe some existing and planned repositories for disposal of LLW,
- understand why certain options and solutions were selected,
- compare various solutions, where possible, against SFR, the Swedish repository for LLW.

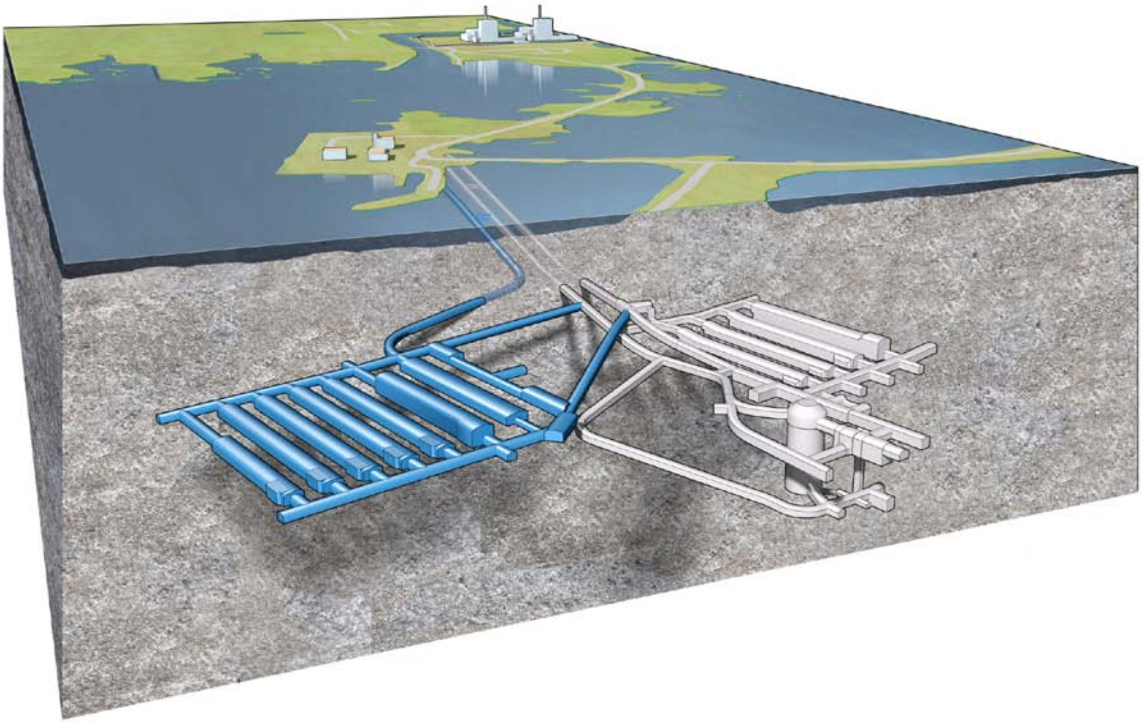

***Figure 1-2.*** *Swedish repository for low and intermediate radioactive waste (SFR ) with an example of the planned extension shown as the blue section.*

This international experience will be summarised and, where possible, specific features of the descriptions will be compared with the Swedish repository for LLW which has been in operation since 1988 at Forsmark on the Baltic east coast.

The descriptions will focus on locations and geological conditions at the respective sites and the design of the repository, considering specifically the barriers, both natural and engineered. The origin of the waste to be disposed of, waste forms, nuclide and activity content are also described.

The framework for the safety assessments is of interest, e.g. time periods to be considered, constant or varying conditions in geosphere and biosphere and the long term properties of the barriers. Exposure situations and dose criteria are other parameters to be described. Finally the plans for sealing of respective repository will be described.

# 2 International organisations, principles and conventions

## 2.1 International organisations

The issues associated with management of radioactive waste are in principle the same for all waste generators all over the world. Exchange of information and international co-operation have therefore been recognised as important for solving such problems. There have been international organisations in operation since the start of using nuclear power for energy production and these have evolved to also include radioactive waste management organisations. Below is a summary of three international organisations of most relevance for the safe disposal of radioactive waste.

### 2.1.1 International Commission on Radiological Protection (ICRP)

ICRP was founded in 1928 by the International Society of Radiology. At that time called "International X-ray and Radium Protection Committee" it has since changed its name to ICRP in 1950. It is an independent "non-profitable" organisation established to advance the public benefit of the science of radiological protection, in particular by providing recommendations and guidance on all aspects of protection against ionising radiation. ICRP is composed of a Main Commission, five standing Committees and a small Scientific Secretariat. Like other scientific academies, the Commission elects its own members, under strict rules. Renewal is assured in that 3 to 5 members must be changed every fourth year. Committees typically comprise 15–20 members. The activities of ICRP are financed mainly by voluntary contributions from national and international bodies with an interest in radiological protection. ICRP has, since 1977, its own Series of Publications, Annals of the ICRP, in which all its recommendations are published. The composition of ICRP is a guarantee that its recommendations have a solid scientific background and its recommendations are regularly used as a basis for national legislation of radiological protection. The latest general recommendation was published in 2007.

### 2.1.2 International Atomic Energy Agency (IAEA)

IAEA is an independent international organisation within the United Nation family. It was established in 1957, with headquarters in Vienna, following the Atoms for Peace Speech by President Eisenhower in 1953. Although the objective of the IAEA is to "seek to accelerate and enlarge the contribution of atomic energy to peace, health and prosperity throughout the world" it has focus on safeguarding and control of fissile material and ensuring safe use of nuclear techniques and safe management including disposal of spent nuclear fuel and radioactive waste. There are 145 Member States of the IAEA and its staff is 2 300 representing 90 countries. IAEA develops Safety Standards which also includes standards for waste management. The recommendations on radiological protection from ICRP are fully considered in the IAEA Safety Standards. Although the process at the IAEA to adopt a new Safety Standard is complicated and time consuming, the worldwide acceptance of the Safety Standard is large, thanks to the large number of Member States of the IAEA. This is especially valid for the standards for transport of radioactive material where the IAEA Safety Standard is used as a base for national legislation on the transport of radioactive material all over the world. The IAEA has also an important role in developing International Conventions on issues related to radiation and nuclear safety. Engineering solutions of technical issues, status and trends for different areas including all aspects of radioactive waste disposal are covered in IAEA Technical Reports.

### 2.1.3 OECD Nuclear Energy Agency (NEA)

European Nuclear Energy Agency was established in 1958 within the Organisation for Economic Cooperation and Development (OECD) with the objective to contribute to the development of nuclear energy through co-operation among its members. In 1972, it changed its name to Nuclear Energy Agency when non-European countries became members of the organisation. At present there are 28 countries from Europe, North America and the Asia-Pacific region in the NEA. The NEA members account for approximately 85% of the world's installed nuclear capacity and thus also existing experience. Its programme includes all aspects of the nuclear fuel cycle. NEA has a close co-operation with IAEA. The smaller and more homogeneous group of members of NEA as compared with IAEA makes it often easier to process a document through the NEA system, but the documents may on the other hand not have equally worldwide acceptance as IAEA documents.

### 2.1.4 Principal radiation protection and nuclear safety requirements for disposal

The basic radiation protection requirements developed by ICRP and elaborated by IAEA are presented in the Basis Safety Standards (BSS), some of which also apply to waste management. The well known principles for justification, optimisation and dose limitations can be found in ICRP and IAEA publications.

The IAEA has Safety Standards documents on three levels; Safety Fundamentals, Safety Requirements and Safety Guides. Examples of those related to waste management are summarised below.

**Table 2-1. Controlling documents for the performance of the activity.**

| IAEA Safety Standards<br>R: Waste Safety – Requirements<br>G: Waste Safety – Guidance | Safety Standards in Preparation<br>DS: Draft Safety Standard |
|---|---|
| **111-G-3.1** Siting of Near Surface Disposal Facilities (1994) | **DS355** The Safety Case and Safety Assessment for Radioactive Waste Disposal Facilities |
| **WS-G-1.1** Safety Assessment for Near Surface Disposal of Radioactive Waste (1999) | **DS356** Near Surface Disposal Facilities of Radioactive Waste |
| **SF-1** Fundamental Safety Principles (2006) | |
| **SSR-5** Disposal of Radioactive Waste Specific Safety Requirements (2011) | |
| **SSG-14** Geological Disposal Facilities for Radioactive Waste (2011) | |

## 2.2 Principles for radioactive waste management

There are two main principles for waste disposal i) dilute and disperse and ii) confine and contain. In the first option the radioactive material as aerosol, gaseous or in liquid form is discharged into the environment where the concentration of the radionuclide's activity is diluted to levels below concern. There is a general trend in the world to reduce the use of this concept but it cannot be entirely excluded. Discharges are made in connection with operation of a facility under strict rules and control by the authorities.

The second option implies that the radionuclide activity is concentrated and confined in a waste package which is disposed of in a way that ensures adequate protection of man and the environment now and in the future. Since the content of the waste in terms of the concentration of radionuclides and total activity directly relate to the associated hazards, and this can vary considerably, it is necessary to establish different types of repositories.

The importance of safe management of the radioactive waste generated with the objective to adequately protect man and the environment from the harmful effects of ionising radiation has long been recognised. There has been intensive international co-operation to establish a scientific and technical basis for safe waste management. The basic radiation protection criteria developed by the International Commission on Radiological Protection, ICRP, are fully applicable to waste management. The ICRP recommendations are further elaborated by the International Atomic Energy Agency.

IAEA has, in the Principles for Radioactive Waste Management (IAEA 1995), established nine fundamental principles that should be considered when developing and establishing a national waste management system. They cover principles which are also referred to in the Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management. The principles are:

1. Protection of human health
   Radioactive waste shall be managed in such a way as to secure an acceptable level of protection for human health.
2. Protection of the environment
   Radioactive waste shall be managed in such a way as to provide an acceptable level of protection of the environment.
3. Protection beyond national borders
   Radioactive waste shall be managed in such a way as to assure that possible effects on human health and the environment beyond national borders will be taken into account.
4. Protection of future generations
   Radioactive waste shall be managed in such a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.
5. Burdens on future generations
   Radioactive waste shall be managed in such a way that will not impose undue burdens on future generations.
6. National legal framework
   Radioactive waste shall be managed within an appropriate national legal framework including clear allocation of responsibilities and provision for independent regulatory functions.
7. Control of radioactive waste generation
   Generation of radioactive waste shall be kept to the minimum practicable.
8. Radioactive waste generation and management interdependencies
   Interdependencies among all steps in radioactive waste generation and management shall be appropriately taken into account.
9. Safety of facilities
   The safety of facilities for radioactive waste management shall be appropriately assured during their lifetime.

These principles although still valid have been superseded by SF-1, Fundamental principles (IAEA 2006), which addresses all activities within the nuclear field.

## 2.3 International conventions

There are a large number of international conventions and agreements that have an impact on the disposal of radioactive waste both directly and indirectly. Those related to transport of radioactive waste across international borders are examples of conventions and agreements that have an indirect affect on disposal and they are therefore not further discussed.

Of those which have a direct impact on waste disposal the following are of most importance:

Joint Convention on the Safety of Spent Fuel Management and on the Safety of Radioactive Waste Management.

The Convention, often referred to as the Joint Convention was developed under the auspice of the IAEA. It was opened for signature in 1997 and entered into force in 2001. In 2008 there were 42 Contracting Parties to the Convention including Russia that ratified its signature in 2006.

The Joint Convention applies to spent nuclear fuel (SNF) and radioactive waste (RW) resulting from civilian nuclear reactors and applications and to SNF and RW from military or defence programmes. It applies if and when such materials are transferred permanently to and managed within exclusively civilian programmes, or when declared as SNF or RW for the purpose of the Convention by the Contracting Party. The Convention also applies to planned and controlled releases into the environment of liquid or gaseous radioactive materials from regulated nuclear facilities.

The main objectives of the convention are:

- “to achieve and maintain a high level of safety worldwide in spent fuel and radioactive waste management, through the enhancement of national measures and international co-operation, including where appropriate, safety-related technical co-operation;
- to ensure that during all stages of spent fuel and radioactive waste management there are effective defences against potential hazards so that individuals, society and the environment are protected from harmful effects of ionizing radiation, now and in the future, in such a way that the needs and aspirations of the present generation are met without compromising the ability of future generations to meet their needs and aspirations;
- to prevent accidents with radiological consequences and to mitigate their consequences should they occur during any stage of spent fuel or radioactive waste management”.

The Convention calls for review meetings of Contracting Parties. To each such meeting the Contracting Party is required to submit a national report that addresses measures taken to implement each of the obligations of the Convention. The reports are open to questions and clarification prior to the meeting and discussions during the meeting. The next convention meeting will be held in May 2012.

### *Espoo Convention on Environmental Impact Assessment (EIA) in a Transboundary Context*

This is a regional convention affecting Europe and was developed within the framework of the UN Economic Commission for Europe. The Convention was adopted in 1991 and entered into force on 10 September 1997. It requires that assessments be extended across borders between Parties of the Convention when a planned activity, such as final disposal of radioactive waste may cause significant adverse transboundary impacts. It sets out the obligations of the Parties to assess the environmental impact of certain activities at an early stage of planning. One of these activities identified in the Convention is disposal of RW. The public, including those in neighbouring countries that may be affected should have the possibility to comment on the EIA. This is typically of concern for the Nordic countries having the Baltic Sea as a common recipient.

### *Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972*

The convention is frequently referred to as the London Convention or LC72. It was developed within the International Maritime Organisation (IMO) and entered into force 1975. Its objective is to promote the effective control of all sources of marine pollution and to take all practicable steps to prevent pollution of the sea by dumping of wastes and other matter. Currently, 85 States are Parties to this Convention which includes Russia. In 1996, the “London Protocol” (1996 Protocol to the Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter, 1972) was agreed to further modernize the Convention and, eventually, replace it. Under the Protocol all dumping is prohibited, except for possibly acceptable wastes on the so-called “reverse list”. Radioactive waste is not included in the “revere list”. The Protocol effectively prohibits dumping of radioactive waste since it requires that material containing contents of radionuclides greater that exempt levels defined by the IAEA shall not be considered eligible for dumping. The Protocol entered into force in 2006 and in 2008 there are 35 Parties to the Protocol.

# 3 General description of final disposal facilities for low level radioactive waste

## 3.1 Design and siting of repositories

The fundamental safety objective of a repository for short-lived low level radioactive wastes (LLW) is to protect man and environment from harmful effects of ionizing radiation. This can be achieved in near surface repositories. The functions of this type of repositories rely on a system of barriers to prevent, or delay, the transport of radionuclides into the biosphere. The barriers can be a combination of engineered and natural barriers; however, the design of the barriers may differ significantly between repositories.

Near surface repositories include a variety of options where the waste is emplaced in engineered structures above or below ground, in trenches, or in engineered structures several tens of meters below ground. There are also some examples where repositories for short lived LILW waste are located at larger depth. Repositories below ground provide additional protection compared to those on the surface against some hazards both man-made, e.g., aircraft accidents or sabotage, and natural, e.g. flooding and erosion. In the short term, < 300 years, the safety of the surface repository relies on institutional control.

A near surface repository typically consisting of vaults is constructed to prevent water from entering into the disposed waste and thus ensure that diffusion is the only transport mechanism for radionuclides. Diffusion is an extremely slow process. In such a repository the waste is emplaced above the groundwater table and the waste stays dry as long as the protective barriers are intact which may be hundreds of years, see Figure 3-1. An advantage with this type of repository is that the requirements on the conditions at the site are moderate and it is therefore normally easy to find a suitable place that conforms to the technical requirements. The disadvantage is that the protective cover and barriers are exposed to weathering, especially erosion that can endanger the integrity of the repository. After the institutional control period, however, the geohydrological conditions at the site are important.

The impact of processes like weathering and erosion is however lower than for the vault type of repository but a location below or close to the groundwater table may imply higher risk for corrosion and degradation of structures.

Waste can also be emplaced in underground cavities with access through ramps or shafts. In this case the waste is normally placed below the ground water table which means that the environment outside the engineered barriers is water saturated soon after closure of the repository.

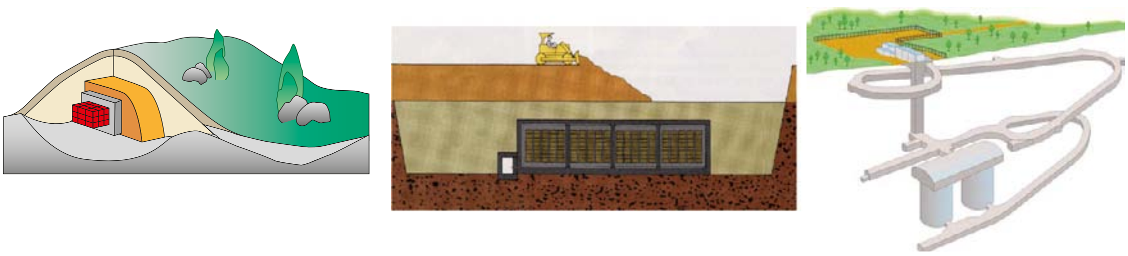

***Figure 3-1.*** *Sketches of three types of near surface repositories illustrating waste packages and engineered structures; a) vault type of repository above ground, b) vault type of repository below ground c) underground cavity repository.*

## 3.2 Waste types and waste acceptance requirements

As mentioned earlier a number of factors and conditions coincide when assessing the long term safety of repositories for low-level waste. The primary consideration is the waste and its properties. The safety assessment places requirements on the characteristics of the wastes which can be accepted into the facility and these are given as waste acceptance criteria (WAC). Briefly they can be grouped like

- General requirements.
- Radiological requirements.
- Chemical requirements.

The importance of waste acceptance criteria is shown in the figure below.

## 3.3 Safety assessments

Regardless of the repository type a detailed and quantitative understanding and evaluation of repository safety is necessary. Such an evaluation of the repository performance or safety is based on a description of repository system and the scenarios to be studied. A scenario is a description of an event or series of actions. Scenarios are consequently used in this context to describe various future developments. The scenarios are translated into calculation cases. These are mathematical models described by various computer codes and input parameter values, giving a joint picture of the impacts on long term safety of repositories. A schematic figure of main activities to be included in a safety assessment is shown in Figure 3-3.

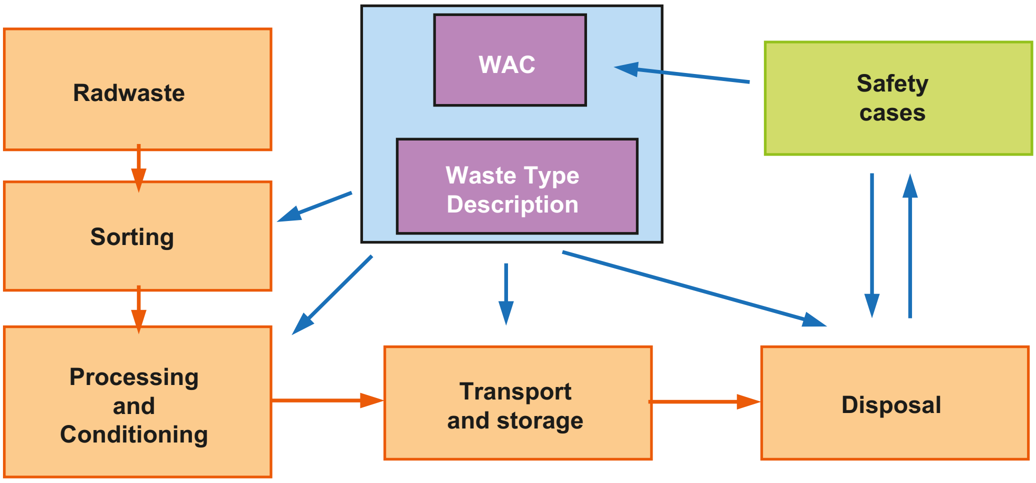

*Figure 3-2. The relations of WAC to all the activities for a safe waste disposal.*

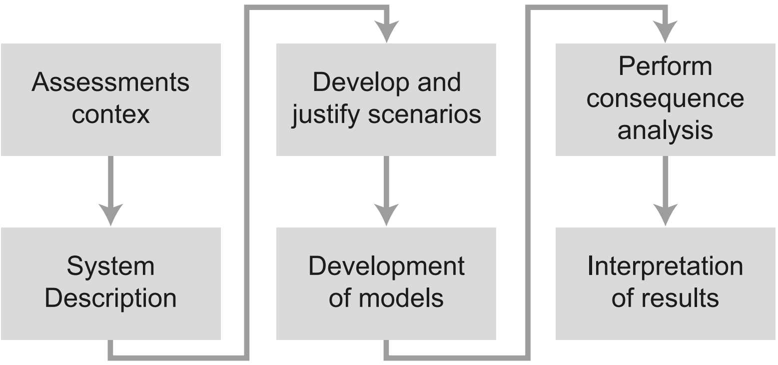

*Figure 3-3. Outline of the assessment process.*

The purpose of the safety assessment (equivalent to environmental impact assessment) – which includes hydrogeological investigations and modelling – is to provide evidence that a disposal facility will obtain the required level of protection to humans and the environment (assessment context according to Figure 3-3). This evidence is generally presented in support of a decision process regarding the development of a waste repository. The evidence is based on the confidence in the safety assessment and in a wide range of other aspects of the safety case.

The assessment context is the framework for the assessment such as the purpose of it and which indicators are to be used for showing repository safety. It is consequently related to national criteria and regulations. Examples of endpoints are annual doses to the highest exposed group, annual risk for the highest exposed group, consequences for non-human biota or annual flows of activity.

The performance of a repository and arriving to scenarios to be handled can be made based on the failure of safety functions. A safety function is a property which contributes to the general long term safety of a repository. Barriers and limited groundwater flows are examples of such safety functions.

Long-term safety assessments of radioactive waste repositories rely to a large extent on analyses based on mathematical models, and the use of a large amount of data, including hydrogeological data. Safety assessments contain system descriptions and supporting databases, scenario analyses, consequence analyses, performance measure calculations, sensitivity and uncertainty analyses, and a comparison of estimated performance to regulatory requirements (criteria).

To evaluate the performance of a repository, assessment must be made on the future evolution of engineered barriers and natural conditions that consider all relevant Features, Events and Processes (FEPs). Based on international cooperation projects an international FEP-list has been established giving support to organisations which will address such questions.

Safety assessment is a continuous tool during the whole life length of a repository from planning and site studies to closure, see Figure 3-4.

There are three dominant paths for radionuclides to reach man or the environment. These are:

- Transport of radionuclides with water.
- Inadvertent contact with the radioactive waste due to intrusion.
- Transport of radionuclides by gas.

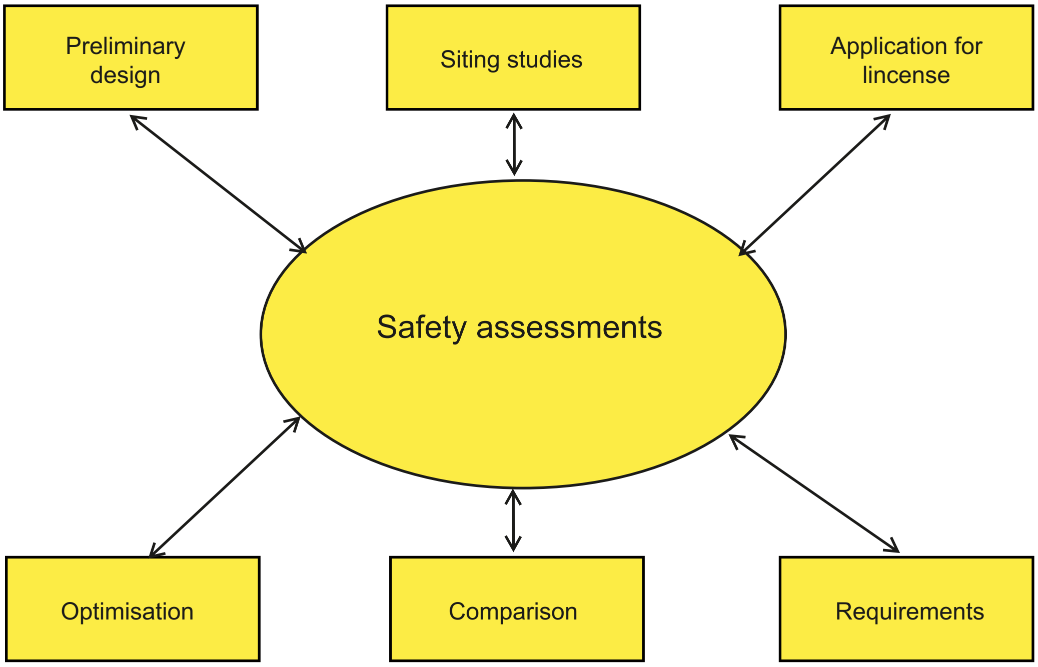

***Figure 3-4.*** *The central role of safety assessments for a repository for radioactive waste.*

## 3.4 Worldwide repositories for low-level waste

There are a large number of repositories for low-level waste in operation worldwide. However, the oldest repositories mainly located in eastern Europe or USA have low volumes and activity capacities, are of a simple structure, such as a concrete vault without engineering barriers. They mainly contain institutional radioactive waste, see Table 3-1. Nowadays the repositories have higher capacities and are equipped with more engineered barriers. The wastes disposed are mainly from production of nuclear energy (operation of nuclear power plants or reprocessing plants and in some cases also decommissioning of the plants), see Table 3-2. Some examples of existing near surface repositories accepting decommissioning waste include Püspökszilagy in Hungary, Mochovce in Slovak Republic, Trombay and Tarapur in India, LLWR near Drigg in the UK, and Barnwell and Richland in the USA. Information on the repositories is found in Appendix A.

Repositories for the disposal of long-lived low and intermediate level waste are planned to be built in France and Japan. They will be of intermediate depth (many tens of metres) and are intended to accept radium waste and irradiated graphite from the decommissioning of gas cooled nuclear reactors in operation in these countries.

**Table 3-1 Examples of old repositories for mainly institutional waste.**

| Country | Repository name | Repository type | Operation time | Waste types |
|---|---|---|---|---|
| **Europe** | | | | |
| Czech Republic | Richard | Undergr. cavity /(Old mine) | 1964– | Institutional |
| | Btatrstvi | Undergr. cavity /(Old mine) | 1974– | |
| | Hostim | Undergr. cavity /(Old mine) | 1959– | Institutional |
| Estonia | Tammiku | Radon[1)] | 1963– | Institutional |
| Germany | Asse | Undergr. cavity | 1965–1978/1992 | Institutional |
| | Konrad | Undergr..cavity/ (Old mine) | 2019 planned | Energy production<br>Institutional |
| Hungary | Puspokszilagy | Vault | 1976– | Institutional |
| Lithuania | Maishiagala | Trench | 1964–1989 | Institutional |
| Latvia | Baldone | Vault | 1962– | Institutional |
| Moldova | Chisinau | Trench | In operation | Institutional |
| Norway | Himdalen – | Rock cavern | 1991– | Institutional, research |
| Poland | Rozan | Vault | | Institutional |
| Romania | Baita-Bihor | Old mine | 1985–stopped | Institutional |
| Russia | Moscow | Radon[1)] | 1961– | Energy production<br>Institutional |
| | Saratov | Radon[1)] | 1964– | Institutional |
| | **Bashkir** | **Radon[1)]** | **1964–** | **Institutional** |
| | Volgograd | Radon[1)] | 1964– | Institutional |
| | Grozny | Radon[1)] | 1964–stopped | Institutional |
| | Murmansk | Radon[1)] | 1964–1993 | Institutional |
| | Nizhny Novgorod | Radon[1)] | 1964– | Institutional |
| | Novosibirsk | Radon[1)] | 1968– | Institutional |
| | Kazan | Radon[1)] | 1964– | Institutional |
| | Irkutsk | Radon[1)] | 1964– | Institutional |
| | Khabarovsk | Radon[1)] | 1964– | Institutional |
| | Chelyabinsk | Radon[1)] | 1963– | Institutional |
| | Sverdlovsk | Radon[1)] | 1964– | Institutional |
| | Samara | Radon[1)] | 1964– | Institutional |
| | Rostov | Radon[1)] | 1964– | Institutional |
| | Leningrad | Radon[1)] | 1962– | Energy production<br>Institutional |
| Ukraine | Kyiv | Radon[1)] | 1961– | Institutional |
| | Dnipropetrovsk | Radon[1)] | 1961– | Institutional |
| | Odesa | Radon[1)] | 1961– | Institutional |
| | L´viv | Radon[1)] | 1962– | Institutional |

| Country | Repository name | Repository type | Operation time | Waste types |
|---|---|---|---|---|
|  | Kharkiv | Radon[1)] | 1962– | Institutional |
|  | Donetsk | Radon[1)] | 1962– | Institutional |
| United Kingdom | LLWR (Drigg) | Vault<br>Trench | 1959– | Energy production<br>Institutional |
|  | Dounreay | Trench | 1959–1977 being upgraded |  |
| **America** |  |  |  |  |
| Argentina | Ezeiza | Trench | 1974– | Energy production<br>Institutional |
| Brazil | Abadia de Goias | Vault |  | Institutional |
| Canada | Chalk River | Trench | 1946– | Institutional |
| USA | Barnwell | Trench | 1971– | Energy production<br>Institutional |
|  | Hanford – | Trench | 1992– |  |
|  | Sheffield | Trench | 1966–1978 |  |
|  | Maxey Flats | Trench | 1963–1977 | Energy production<br>Institutional |
|  | Beatty | Trench | 1962–1992 | Energy production<br>Institutional |
|  | West Valley | Trench | 1963–1986 | Institutional |
|  | Fernland | Vault | 1997–2006 (projected closure) |  |
|  | Hanford ERDF | Trench | 1996– | Energy production<br>Institutional |
|  | Idaho ICDF | Trench | 2003– | Institutional |
|  | Idaho RWMC | Pits and vaults | 1984– | Institutional |
|  | Savannah | Trench | 1978– |  |
|  | Los Alamos | Trench | 1957– |  |
|  | Nevada | Trench |  |  |
|  | Oak Ridge | Vaults |  |  |
| **Asia** |  |  |  |  |
| China | Lanzhou | Trench | 1998 | Energy production<br>Institutional |
|  | Souty China (Guandong) | Vault |  | Energy production |
| India | Trombay | Trench | 1960– | Institutional |
|  | Tarapur | Trench | 1972– |  |
| Pakistan | Pinstech | Trench |  | Institutional |
| Vietnam. | Dalat | Vault | 1984– | Institutional |
| **Remaining** |  |  |  |  |
| Australia | Mt. Walton – | Trench | 1992– | Institutional |

1 Radon" type facility, simple vault construction without engineered barriers typical for eastern Europe and former Soviet Union.

**Table 3-2. Examples of repositories for low level waste from mainly nuclear energy production.**

| Country | Repository name | Repository type | Operation time | Additional waste |
|---|---|---|---|---|
| **Europe** |  |  |  |  |
| Bulgaria | Novi Han | Vault | 1964–1994 | Institutional |
| Belarus | Ekores | Radon[1)] | 1964– | Institutional |
| Czech Republic | Dukovany | Vault | 1994– | Energy production |
|  | Btatrstvi | Undergr. cavity /(Old mine) | 1974– |  |
| France | L'Aube | Vault | 1992– | Energy production |
|  | La Manche | Vault | 1969–1994 | Energy production<br>Institutional |
|  | Morvilliers |  |  | VLLW and |

| Country | Repository name | Repository type | Operation time | Additional waste |
|---|---|---|---|---|
| Finland | Loviisa | Undergr. cavity | 1998– | Energy production |
| | Olkiluoto | Undergr. cavity | 1992– | Energy production |
| Germany | Morsleben | Undergr cavity /(Old mine) | 1978–2000 | Energy production<br>Institutional |
| | Asse | Undergr. cavity | 1965–1978/1992 | Energy production |
| | Konrad | Undergr..cavity/ (Old mine) | 2019 planned | Energy production<br>Institutional |
| Hungary | Puspokszilagy | Vault | 1976– | Institutional |
| | Batapati | Undergr. cavity | 2008 (planned) | |
| Norway | Himdalen – | Rock cavern | 1991– | Institutional, research |
| Russia | Moscow | Radon[1)] | 1961– | Energy production<br>Institutional |
| | Leningrad | Radon[1)] | 1962– | Energy production<br>Institutional |
| Slovakia | Mochovce | Vault | 1999– | Energy production |
| Spain | El Cabril | Vault | | Energy production<br>Institutional |
| Sweden | SFR | Undergr. cavity | 1988– | Energy production<br>Institutional |
| United Kingdom | LLWR (Drigg) | Vault<br>Trench | 1959– | Energy production<br>Institutional |
| | Dounreay | Trench | 1959–1977 being upgraded | |
| **America** | | | | |
| Argentina | Ezeiza | Trench | 1974– | Energy production<br>Institutional |
| Mexico | El Cader – | Trench | 1970–1989 (trenches), facilities in operation | Energy production |
| USA | Barnwell | Trench | 1971– | Energy production<br>Institutional |
| | Hanford – | Trench | 1992– | |
| | Sheffield | Trench | 1966–1978 | |
| | Maxey Flats | Trench | 1963–1977 | Energy production<br>Institutional |
| | Beatty | Trench | 1962–1992 | Energy production<br>Institutional |
| | Fernland | Vault | 1997–2006 (projected closure) | |
| | Hanford ERDF | Trench | 1996– | Energy production<br>Institutional |
| | Savannah | Trench | 1978– | |
| | Los Alamos | Trench | 1957– | |
| | Nevada | Trench | | |
| | Oak Ridge | Vaults | | |
| **Asia** | | | | |
| China | Lanzhou | Trench | 1998 | Energy production<br>Institutional |
| | Souty China (Guandong) | Vault | | Energy production |
| | Tarapur | Trench | 1972– | |
| | Kakrapar | Vault | 1993– | Energy production |
| | Narora – | Vault | | Energy production |
| Japan | Rokkasho | Trench | 1992– | Energy production |
| | Tokai | Trench | In operation | Energy production |
| Pakistan | Pinstech | Trench | | Institutional |
| Taiwan | Lanyu – | Trenches | 1982–1996 | Energy production |
| **Remaining** | | | | |
| South Africa | Vaalputs – t | Trench | 1986 | Energy production |

## 3.5 Selection of repositories for a deeper description

Detailed descriptions of all repositories are not presented due to the large number of repositories, each one with its specific location and conditions. Instead some “typical“ repositories were selected for inclusion in this report according to the following. Emphasis was on whether they represented typical approaches in various nations making it possible to gain some experience from national conditions and regulations. They should also represent various sizes, locations and designs, such as being located above ground, on the surface or deeper down in the ground. In addition they should be constructed with various types of barriers. Another criterion was the availability of pertinent information. The deposited waste should also be of similar type as the one for SFR that is dominated by waste from routine operation of nuclear power plants. Because SFR is to be extended for disposal of decommissioning waste, repositories for such waste where also selected, where possible, in this study. It was also deemed to be of interest to include recently commissioned or even planned facilities.

As the brief summary of conditions given in the Chapter 3 and in the Appendix A shows, the main common difference between the repositories is their depth. Repositories for this study were selected to include the whole range of depth from surface down to 650 meters depth, namely:

- Vault repository above ground – El Cabril in Spain, Centre de l’Aube in France.
- Vault repository below ground – LLWR near the village of Drigg in the UK, Rokkasho-mura in Japan.
- Geological type of repository – VLJ in Finland, and the planned repository at Bruce in Canada.

In addition safety assessments have been performed recently for LLWR and Bruce, which are of high interest regarding the new safety assessment to be performed for SFR. The selected repositories also cover a wide range of sizes, from having only 10,000 $m^3$ capacity at a local repository VLJ in Finland to the largest facilities at LLWR in United Kingdom and l`Aube in France.

The descriptions given in Chapter 4 include information on the site and why it was selected, the repository size, design and barriers, waste packages and accepted waste types and if available also information on levels of radionuclide activity, safety criteria and assessments.

# 4 Description of repositories

This section includes brief overviews of the repositories selected in the previous chapter and the aim is to give information on:

- Where the repositories are located and the prevailing geological conditions at the sites.
- The design and capacities of the repositories including short descriptions of the engineered barriers and other measures taken to contribute to the safety of the repositories.
- The waste disposed or planned to be disposed including conditioning or stabilisation and waste packages design.
- Assessments performed to evaluate the safety after closure.
- Closure of the disposal facility, which is the last major operational step in completing the disposal.

The information has been gathered mainly from documents available on the Internet e.g. OECD/NEA member country information, papers presented at conferences, Home pages of Waste Management Organisations, safety assessments etc.

Safety assessments are described in more detail in Appendix B for respective repositories.

## 4.1 El Cabril in Spain

Spain has solved the issue of managing the short-lived low and intermediate level waste through El Cabril, a centralised disposal facility. The operations carried out at the facility include the reception, treatment, conditioning and definitive disposal of the wastes in the repository.

The facility is built and operated by, Enresa, the organisation responsible for management of all radioactive waste in Spain. El Cabril is planned to receive all LILW-SL generated in Spain and is therefore designed for a volume of about 37,000 $m^3$.

Also connected to El Cabril is a treatment facility for LLW and a disposal facility for very low level waste (VLLW). These are both in operation but are not described here.

### 4.1.1 Location and geological conditions

The disposal facility is located in a very remote part in Southern Spain in Hornachuelos (Córdoba). The origin of the site was as a uranium mine, which at the beginning of the sixties, when it was exhausted, was given to Junta Energie Nuclear for the final disposal of LLW from research activities. The mine was, however, too limited to be able to dispose future waste and a decision was taken to construct a purpose built surface repository, see Figure 4-1.

The low population densities as well as the arid climate are also favourable factors for long term safety. The repository was taken into operation in 1992.

### 4.1.2 Repository design

To achieve isolation, the El Cabril repository has three barriers to limit the releases to the environment:

- a first barrier, made up of the conditioned waste and the container,
- a second barrier, consisting of the engineered structures housing the wastes,
- a third and final barrier, formed by the natural terrain of the site at which the facility is located.

The El Cabril facility accepts only radioactive wastes with very low levels of long-lived radioactive substances (half-life > 30 years). Enresa has established a set of waste acceptance criteria (WAC) linked to the safety assessment for operational and post-closure phases.

*Figure 4-1. El Cabril repository.*

The engineered structures comprise concrete vaults above ground. There are all together 28 vaults with the dimensions 22.5 m · 18 m · 9 m. The walls and base of the vaults have are about 0.5 m thick. The base of the vault is the main element of the storage and it is covered with a waterproof layer of polyurethane and a 10–20 cm layer of porous concrete. A drain control system exists with inspection galleries constructed beneath the disposal vaults. The LLW facility has a total storage capacity of 37,000 m$^3$.

The vaults are protected during the operation by a metallic shelter over the vaults, which also supports the handling crane.

After completion of a disposal area, a multi-layer-engineered cap will be constructed to divert the rainwater and to provide long term protection for the containers as well as to ensure their durability, see Section 4.1.5 (plans for closure).

The disposal facility is designed to withstand extreme site conditions, including earthquakes.

### 4.1.3 Waste packages and amount of waste

The waste accepted comprise:

- Solid or solidified wastes (resins, filters, evaporator concentrates, filtration sludge) from the operation of nuclear facilities.
- Solid technological wastes (gloves, tools) from the operation and dismantling of nuclear facilities.
- Miscellaneous solids and liquids from the application of radioisotopes at radioactive industrial, medical and research facilities.
- Secondary solid or liquid wastes from the activities performed at El Cabril.

Enresa has established waste acceptance criteria (WAC) and also set up characterisation, acceptance and verification procedures. Examples of parameters considered for the WAC are leach rates, mechanical strength, temperatures and maximum activity content.

Waste packages, mainly 200 l steel drums and 1.3 m$^3$ metal boxes, are placed in larger concrete containers (2.2 · 2.2 · 2.2 m) to form an 11 m$^3$ final package or disposal unit, which constitutes the first repository barrier. The internal volume of the concrete containers may be back-filled with mortar grout, or cement mixed with institutional liquid waste or contaminated ashes. The containers are in turn placed in the disposal cells, which are distributed on two platforms. Once the cell is completed with 320 concrete containers, it is backfilled with gravel and a closing slab is constructed and coated with an impervious paint.

Under each row of disposal vaults there is an inspection drift, where two drainage systems are installed, one for rain water collection from the vaults not yet in operation, one for the vaults containing waste packages.

### 4.1.4 Safety assessments

In Spanish regulations criteria to be met are 0.1 mSv per year for the normal evolution case and 1 mSv for the intrusion case. Radiation exposures to non–human biota are at present not considered in the Spanish regulations. Neither there are any demands for showing exposure from heavy metals or other pollutants.

The El Cabril repository is planned to be under institutional control for 300 years, after the engineered barriers have totally lost their retarding function, according to the safety assessments.

The safety assessments consider migration of radionuclides by water passing through the repository and also releases due to gas generation. Doses due to intrusion are also considered.

### 4.1.5 Plans for closure

Once the capacity of the vaults has been reached, they will be covered with a series of earth and clay layers in order to isolate them from the biosphere and ensure their integration into the landscape. The layers comprise a sequence of top soil, thick gravel, a first sand layer, an impermeable layer, a second sand layer, a damp proof course and a third draining sand layer.

The period for institutional control is expected to be 300 years maximum.

## 4.2 Centre de l’Aube disposal facility in France

The Centre de l’Aube disposal facility in France was taken into operation in 1992. The short-lived low- and intermediate-level waste mostly comes from the nuclear power industry and the activities of the French atomic energy commission (CEA). It also includes waste from hospitals, research and university laboratories. In the future, waste from clean-up and dismantling of NPPs may be disposed of at l’Aube.

The repository is managed by the National Radioactive Waste Management Agency, Andra, a public body in charge of the long-term management of all radioactive waste generated in France.

The waste essentially includes waste related to maintenance (clothes, tools, gloves, filters, etc) and to the operation of nuclear facilities, such as treatment of gaseous and liquid effluents. This waste contains short-lived radionuclides, such as cobalt-60 and caesium-137, and may also contain strictly limited amounts of long-lived radionuclides.

### 4.2.1 Location and geological conditions

The disposal facility, located in the Aube district, is built on sedimentary geological formations, a layer of sand underlain by a waterproof clay formation. The layer of sand drains all precipitation waters towards a single outlet, the Noues d’Amance River downstream from the disposal facility. The average annual rainfall is 500–1,000 mm. The clay formation constitutes a natural barrier against release of radioactive elements into the groundwater, and thus prevents any dispersion into the environment.

The Aube site was selected in 1985 based on its suitability after a two year program of geological, hydrogeological and geochemical characterization and assessment of several potential sites.

### 4.2.2 Repository design

The safety of a repository relies on a number of combined factors, according to waste type:

- The package containing the waste.
- The repository structures in which the packages are placed.
- The geology of the site which constitutes a long-term perennial natural barrier.

Since 1992, low- and intermediate-level short-lived waste has been disposed of at the Andra low and intermediate level waste disposal facility (CSFMA), located in the l´Aube district. This is an above ground facility with engineered barriers, see Figure 4-2.

The Andra CSFMA is designed to accommodate 1,000,000 $m^3$ of waste. The waste is disposed of at surface in reinforced concrete vaults with 30 cm thick walls. The cells within the vaults are 25 metres square and 8 metres high. The facility has about 400 above ground concrete vaults and, depending on waste type, they are back-filled with either gravel or concrete, and are then topped with a concrete slab and sealed with an impermeable coating. Each vault can take 2,500–3,500 $m^3$ of waste. Finally, the cell will be capped with a several metres thick layer of clay, to ensure the long-term confinement of the waste. The facility is equipped with inspection tunnels. /www.andra.fr/.

### 4.2.3 Waste packages and amounts of waste

The main types of waste packages used are, steel drums and concrete or steel boxes. The waste is embedded in a concrete matrix, thus a package of LILW-SL is composed of 15–20% radioactive waste and 80–85% embedding matrix.

Containment in the packages is provided by the waste matrix (homogeneous waste) which forms a diffusion barrier. The safety functions set the basis for the waste acceptance criteria which are thecontainment properties (diffusion coefficient, leach rate), package durability, activity limitation and radiation protection. The acceptable diffusion coefficient of concrete (using tritium water as a reference material for diffusion) is specified depending on the thickness of the barrier. Leach rates arein the range of $10^{-3}$ per year and diffusion coefficients in the range of $10^{-14}$–$10^{-12}$ $m^2/s$. (For example diffusion coefficients in water are about $10^{-6}$ to $10^{-5}$ $m^2/s$). The minimum thickness for the concrete envelope is calculated as that needed to provide mechanical strength and containment for a few hundred years.

*Figure 4-2. The l`Aube repository.*

General waste acceptance criteria that apply to all packages that are delivered provide requirements on the physical-chemical properties of the waste: e.g. no free liquid, inert matter. They focus on the radiological characterisation of the package, particularly on the identification of radio-nuclides that may be present. A list of 143 nuclides has been established. The dose rates of all waste packages are measured. The purpose is to detect waste that could contain higher quantities of activity than have been taken into account in the safety assessment. Activity limits are derived from the safety scenarios, see below, and some limits are prescribed to avoid "hot spots" in the repository.

Another key aspect is the identification of materials that might have a chemical impact. These materials are partly identified from regulations relevant for non radioactive repositories, e.g. lead, boron, nickel, chrome (total and VI form), antimony, selenium, cadmium, mercury, beryllium, arsenic, free cyanides, ammonia and asbestos. These materials must be quantified, generally using typical chemical spectra for waste. This inventory provides data to perform chemical impact calculations.

During recent years a number of efforts have been made to decrease the waste volumes to less than a third of the initial volume of LILW to be managed. In the future Andra will work with the waste producers to ensure a continued emphasis on the efforts in innovation and research in the development of treatment techniques for waste volume reduction, along with the complementary development of decontamination and measuring techniques.

### 4.2.4 Safety assessments and waste acceptance criteria

For the assessment of the impact of a near surface repository in France, Andra refers to a basic safety guide. This basic safety guide prescribes that at the end of the monitoring period, (no more than 300 years), safety should no longer rely on the artificial barriers but on the site and on the properties of the site.

The dose limit has been set to 0.25 mSv per year for the general public.

Scenarios are derived that include normal and abnormal situations (intrusion for instance). They take into account water transfers and air transfers (re-use of materials of the disposal site) and they assess the impact for critical groups.

### 4.2.5 Closure

When the facility has reached its disposal capacity, a thick clay cover overlaid with vegetation will be installed over the entire set of cells to protect the repository from external effects. A full scale experimental cover is being used to validate the cover concept which is designed to protect the facility during its monitoring phase.

The institutional control period is stipulated to be 300 years.

## 4.3 Low Level Waste Repository near Drigg in United Kingdom

The Low Level Waste Repository (LLWR) near the village of Drigg is the United Kingdom's national facility for the disposal of solid low-level radioactive waste. The LLWR is owned by the Nuclear Decommissioning Authority (NDA) and operated on behalf of the NDA by a Site Licence Company (SLC) – LLWR Ltd.

An Environmental Safety Case (ESC) (LLW Repository 2011) was recently performed and submitted for LLWR and this has been the main source of information to the descriptions given below.

### 4.3.1 Location and geological conditions

The LLWR facility is located close to the village of Drigg approximately five kilometres south-east of Sellafield. The site was first developed in 1940 as a Royal Ordnance Factory for the production of TNT. The first certificate of authorisation for disposal of LLW was granted in 1958 and disposal operations commenced in 1959. A picture over the area is shown in Figure 4-3.

The geological structure in the region consists of quaternary age deposits, a result of complex glacial processes, overlying older sandstone bedrock. The quaternary sedimentary deposits comprise a sequence of clay, sands and gravels up to 60 m thick. The site is about 100 hectares in area. The ground slopes gently towards the sea, falling from 20 m above sea level at the north eastern boundary to about 7 m above sea level at the south eastern boundary.

The site is situated in an area of low seismicity, and is not particularly subject to surface flooding. The average rainfall at the site is about 1,200 mm/year. The surrounding location is a farming area with a sparse population. The major local industry is the Sellafield Works.

### 4.3.2 Repository design

During the first thirty-six years of operation, disposal was by tipping of drummed, bagged and loose wastes into trenches. The first trench followed the course of a railway cutting through the northern part of the site. Five larger trenches were then excavated parallel to the first trench. The trenches are located in the low-permeability clay at a depth of 5 to 8 m below ground level. The natural clay layer serves as an effective seal between the trenches and the sandstone. If the natural clay was locally absent, bentonite clay was placed at the bottom of the trench to reduce the permeability of the trench bases. A seventh trench, of irregular shape was excavated to fully use the site area towards its north-eastern boundary. The seven trenches, each about 750 m long and 30 m wide, have a gradient and include simple drains which, in conjunction with the underlying clay, serve to direct infiltrating rain or groundwater to the southern end of the trenches for collection in a series of drains. Until 1991, the collected leachate was discharged into the Irish Sea. The total area occupied by the trenches is about 160,000 m$^2$.

After emplacement in the trenches, the waste is capped with 1.5 m of cover materials. Completed trenches have been capped with an earthen mound, incorporating an impermeable layer. During disposals, the waste was covered by soil at the end of each day and, periodically, a hardened layer was added on top to facilitate the continued loading of waste. Trench number 7 was closed in 1995. From 1987 onwards the disposal operations at the site were upgraded. Remedial work was carried out on the trenches, this included e.g. installation of low-permeability cut-off walls to limit lateral movements of groundwater and radionuclides. There has also been interim capping of the filled trenches and upgrading of the leachate drainage system.

The more recently constructed parts of the repository have an engineering system for safety. This includes the various engineered barriers (e.g. cap and cut-off walls), the waste itself, surrounding backfill and waste containers.

***Figure 4-3.*** *The LLWR site.*

The first concrete vault at the LLWR site was taken into in operation 1988. The vault (vault 8) consists of three bays and is approximately 175 m wide by 200 to 265 m long. The average depth is about 5 m and the total capacity about 200,000 m$^3$. The depth allows four high stacking of nominal, half-height ISO containers.

Construction of Vault 9 started in 2008 and construction was completed in December 2010. Up to six future disposal vaults are planned to be constructed. To maximize the use of the site, future vaults will be deeper.

The engineered structure of the vaults consists of a concrete base with an underlying drainage layer and concrete walls. The structure is below ground level. The vault is surrounded by surface water drains, which collect rainwater from the surface of the vault base slab whilst a drainage blanket under the slab and perimeter drains collect groundwater from beneath and around the vault. As with the trenches, the principal means of leachate containment is the naturally occurring clay layer at about 5 m below ground level.

A final repository cap will function to limit any water ingress into the wastes in order to: ensure low releases of contaminated leachate from the facility; reduce the impacts of radioactive gas release by providing a barrier to the release of radon; ensure that erosive effects are limited as far as practicable; and to prevent or discourage human intrusion into the wastes.

### 4.3.3 Waste packages and amounts of waste

The LLWR at Drigg receives wastes from a range of consignors, including nuclear power plants, fuel cycle facilities, defence establishments, general industry, isotope manufacturing sites, hospitals, universities and from the clean-up of historically contaminated sites. The waste comprises e.g. slightly radioactive trash, such as paper, packing materials, protective clothing, electric cables, scrap metals and tools, as well as reactor wastes and other materials.

The original concept of disposal in trenches involved packaging of waste in 200 l steel drums or in paper sacks, or individually wrapped in strong, impermeable packaging material. For vault disposal, new waste packaging (introduced in the mid 1990's) is based on high-force compaction of the waste, emplacement in 20 m$^3$ steel containers and grouting of the void space within the container to form a solid product. Work to identify waste acceptance criteria (WAC) and associated waste control arrangements are developed.

The volumes of waste disposed increased rapidly from the start of site operations (1959) to around the mid 1980s (Trench 7). Thereafter a programme for waste minimisation was initialized which has decreased disposal volumes by a factor of about 3.

The capacity of the trenches and vault 8 is about 1,000,000 m$^3$. Approximately 250,000 m$^3$ of packaged operational wastes and 550,000 m$^3$ of packaged decommissioning wastes are predicted to be disposed in the future vaults. The resulting total volume of packed waste is about 1,800,000 m$^3$.

The nature of LLW is such that it tends to be contaminated routinely with small quantities of a variety of radionuclides, and these are distributed approximately evenly between trenches and vaults, in line with the volume distribution. There are some nuclides that do not follow this, e.g.:

- Calcium-41, nickel-63 and molybden-93 are present as activation products in steel or concrete from nuclear reactors.
- 98% of carbon-14 at the LLWR is expected to be present in the future vaults. Carbon-14 is an activation product present in graphite, steel and concrete arising from the decommissioning of nuclear reactors.
- Betalight disposals to Trench 6 contribute approximately 66% of the LLWR H-3 inventory.

### 4.3.4 Safety assessments

According to British regulations the safety case shall show compliance to an annual risk, i e $10^{-6}$ as is the case in Sweden. In addition, exposure to non-human biota shall be shown as well as exposure to heavy metals.

An Environmental Safety Case (ESC) was recently performed for LLWR. A safety case is defined by the Environment Agency, in their 'Guidance on Requirements for Authorisation', as 'a set of claims concerning the environmental safety of disposals of solid radioactive waste, substantiated by a structured collection of arguments and evidence.'

The safety case is therefore divided into three levels, shown in Figure 4-4:

The documentation of the safety case is extensive, encompassing several reports for the respective levels. A number of scenarios are handled.

### 4.3.5 Plans for closure

The entire area (vaults and trenches) will be closed with an integrated multi-layered barrier system, an engineered dome cap. Each vault will be capped as soon as is practicable after closure.

Active leachate collection and management will continue during operations and up to 100 years after final disposals. The site will remain under active institutional control for a period of at least 100 years after final disposals. During this time, a site boundary will be maintained to prevent access by the public. During the institutional control period, arrangements will be put in place to maintain knowledge of the hazardous nature of the facility following final closure.

## 4.4 Rokkasho in Japan

Shallow disposal has been implemented using concrete vault disposal for solidified radioactive waste from nuclear reactors in Japan. Land disposal of low-level waste follows the basic concept that radioactive waste can be contained by engineered structures such as a concrete vaults at shallow depths.

For waste which has higher concentrations of radioactive substances, disposal at intermediate depth is planned as one of the disposal options.

The Rokkasho Low Level Disposal Centre, which was taken into operation in 1992, is operated by Japan Nuclear Fuel Limited (JNFL).

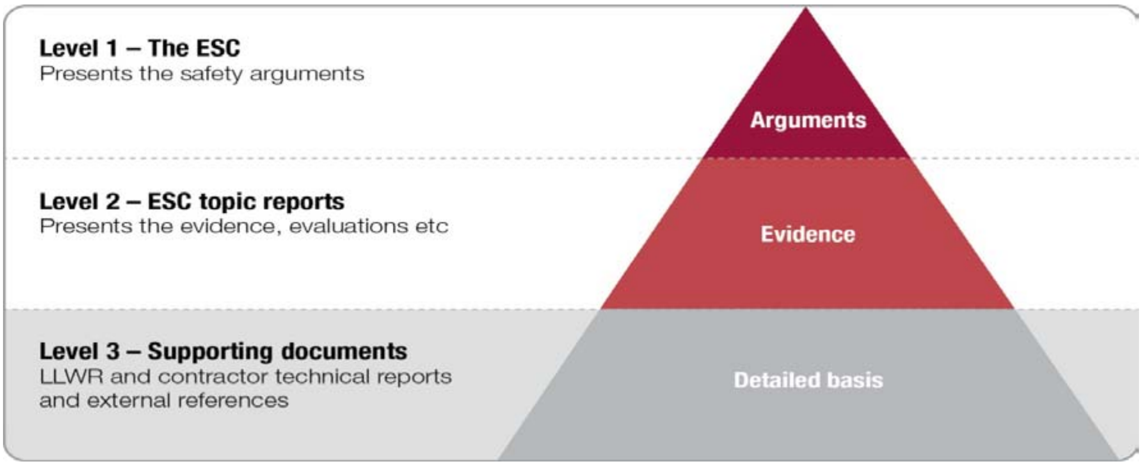

***Figure 4-4.*** *The three levels of the LLWR ESC.*

*(As in Sweden continuous updates of the safety case are strictly regulated. Same as in the Swedish regulations 'The Operator shall update the Environmental Safety Case(s) for the site covering the period up to withdrawal of control and thereafter'.*

*In Sweden it should be done every tenth year but the "intensity" of the ESC is not regulated in the UK).*

### 4.4.1 Location and geological conditions

The Rokkasho LLW Disposal Centre is located at the north eastern part of the mainland of Japan, in Aomori Prefecture on the northern tip of the main island of Honshu on the Pacific Ocean side. The repository is built on hilly terrain, separated from the hills behind it by a valley.

The disposal site is located on marine terraces about 30–60 m above sea level. The bedrock at the site is Tertiary sandstones and tuff. Quaternary deposits, overlying the Tertiary, are extensively distributed in this area, and are divided into terrace deposits (mainly composed of medium to coarse sand), volcanic ash, and alluvium deposits (3 m in thickness).

The site is located in an area with a high water table about 2 m below ground level. The water table fluctuates about 2 m annually, depending on rainfall. Average rainfall is about 1,200 mm/year of which 300 mm recharges the groundwater. The average evaporation is 600 mm per year.

Except for the low-level radioactive waste disposal centre the nuclear complex at Rokkasho comprises a reactor-fuel plant, an interim high-level radioactive waste storage site and a reprocessing facility. The reprocessing facility is not in operation yet. It was therefore deemed to be suitable to also locate the repository for the LLW there. The largest centre of nuclear industry in Asia is located in Rokkasho.

### 4.4.2 Repository design

The safety is addressed by a multibarrier system, consisting of the package, the engineered barriers and the distance to discharge area, see Figure 4-5.

The disposal units are constructed in the Tertiary rocks. The facility design consists of two stages of disposal, each having a capacity of 40,000 $m^3$ (~200,000 drums).

The first stage comprises 40 reinforced concrete pits (24 m · 24 m · 6 m) with each pit further divided into 16 disposal cells (6 m · 6 m · 6 m). Each cell can contain 320 drums.

The second stage facility has a different layout and will comprise a total of 16 concrete pits (36 m · 37 m · 7 m), with 36 cells (6 m · 6 m · 7 m) in each pit. Here, each disposal cell will hold 360 drums with mainly metallic, plastic and other non-flammable waste materials.

The inside of the disposal concrete pits are lined with porous concrete, which allow water to drain away before it can contact the waste drums. When a cell is filled with waste drums, a temporary lid is placed on the cell and mortar is poured into the spaces between the waste drums. Inspection tunnels are constructed around the disposal pits to collect and monitor water discharging from the pits. The drums are placed in reinforced concrete trenches (the disposal cells) with a crane housed within a roof and rain shield.

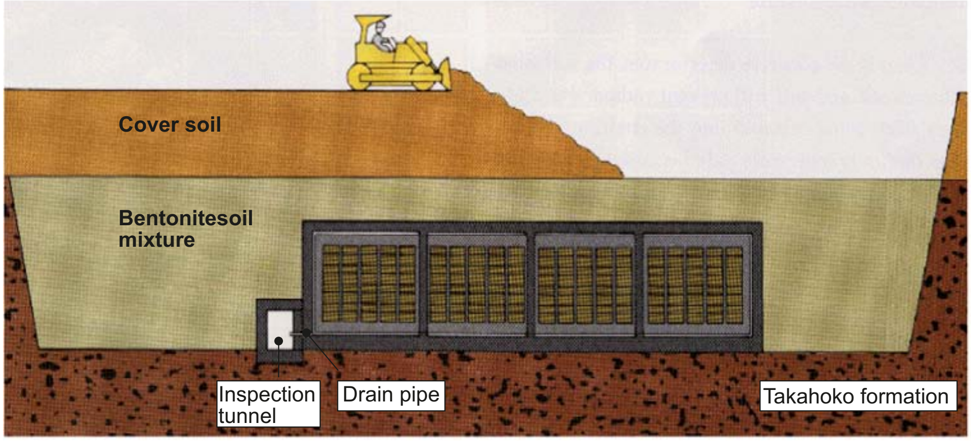

***Figure 4-5.*** *Design of the Rokkasho repository*

After emplacement of waste the concrete pits are surrounded by a mixture of bentonite and sand with low permeability and finally covered by a layer of compacted soil with lower permeability than the surrounding soil. The groundwater table will be located above the concrete pit and the bentonite and sand layer.

### 4.4.3 Waste packages and amounts of waste

The types of waste disposed of at the Rokkasho facility consist of solidified liquid waste concentrates, spent ion exchange resins, filter sludge, and other types of operational waste generated by Japan's NPPs.

In the first stage of the facility homogeneous and uniform solidified wastes of spent resins, filter sludge and concentrated liquid wastes have been accepted. In the second stage of the facility immobilized wastes of metals, plastics and other non-flammable materials is accepted.

The radioactive waste received at the Low-level Radioactive Waste Disposal Centre are already solidified with cement or other matrix material, and encapsulated in steel drums at the NPPs. The waste drums are inspected at nuclear power stations to ensure that they meet the technical standards before shipment to the waste facility.

The facility is at present commissioned for 200,000 $m^3$, corresponding to 1,200,000 drums. There are plans to enlarge the facility to 600,000 $m^3$.

### 4.4.4 Safety assessments

Japanese dose criterion for safety after closure is 0.01 mSv per year. Somewhat higher exposure may be accepted if the probability of occurance is deemed to be reasonably low.

The concept in Japan is that the safety regulations that apply to burial disposal can be reduced stepwise with time. The periods over which safety regulations are applied at each stage are summarized as follows:

- First stage: (10–15 years, until the placement of the cover soils), maintaining the integrity of the engineered barrier.
- Second stage: (30 years, until the cover soils become stable), securing the performance of barriers.
- Third stage: (300 years, from the end of the first stage), prohibition or restriction of specified act.
- Post closure: (After 300 years), people may enter the area.

### 4.4.5 Plans for closure

After emplacement of waste the concrete vaults are surrounded by a mixture of bentonite and sand with low permeability and finally covered by a layer of compacted soil with lower permeability than the surrounding soil. The groundwater table will be located above the concrete vault and the bentonite and sand layer.

## 4.5 VLJ Repository in Finland

In Finland, four nuclear power units have generated LILW operational waste since 1977. The accumulation of LILW from other sources e.g. universities, hospitals, industry etc is only about one percent of that from the NPPs.

The Finnish waste management policy is based on the disposal of LILW into rock cavity repositories located at the NPP sites. The design basis is geological disposal, the safety of which rests on natural and engineered barriers. The disposal system isolates the waste for a few hundred years. Therefore, all low and intermediate level radioactive waste (L/ILW) generated at Olkiluoto NPP will be disposed in the on-site repository commissioned in 1992 (VLJ Repository; VLJ is an abbreviation of the Finnish word "voimalaitosjdte": equal to "reactor operating waste"). The repository, as well as the NPP units, is operated by Teollisuuden Voima Oy (TVO).

A similar facility has been in operation since 1998 at the other Finnish NPP, the Loviisa plant. The designs of Olkiluoto and Loviisa repositories are different due to the difference in the local geological conditions. The repository at Olkiluoto has two vertical silos, whereas the repository at Loviisa has horizontal tunnels.

### 4.5.1 Location and geological conditions

The Finnish waste management policy is based on the disposal of LILW into rock cavity repositories located at the NPP sites. The Olkiluoto site consists mainly of micaceous gneiss intercalated with sparsely fractured tonalite.

### 4.5.2 Repository design

The repository consists of two silos, 24 m in diameter and 34 m high, excavated at a depth of 60–100 meters in the bedrock, see Figure 4-6. The silo for LLW is a rock silo with no internal structure, only shot creted walls. The silo for ILW has a reinforced concrete silo building inside the rock silo.

The repository is constructed so that its long-term safety is based on several consecutive barriers, an engineered barrier system (EBS) and the natural barrier system. The engineered barrier system consists of the solid waste and the concrete boxes, the silo structures; backfilling material as well as closure and sealing arrangements with the function to retard radionuclides and protect the waste mechanically.

The main backfill materials are crushed rock and concrete, which keeps the geochemical changes due to the backfilling moderate. If necessary, the crushed rock can be replaced with sand or moraine, but also in this case the local mineralogical material is to be preferred.

### 4.5.3 Waste packages and amounts of waste

The waste from the NPP's is conditioned, packed, and stored both temporarily and finally at the plants or in their immediate vicinity.

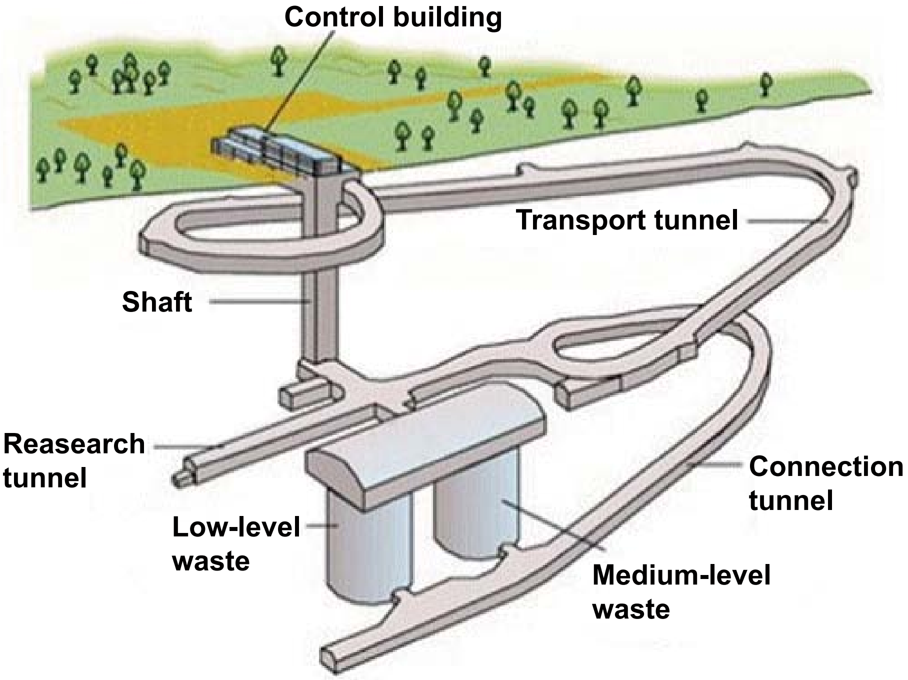

*Figure 4-6. The VLJ repository.*

The operational low-level waste includes fireproof fabrics, protective plastic sheeting and protective clothing used in power plant maintenance, and machine components and pipes removed from the power plant. The LLW is compacted in 200 l steel drum and the drums are packed into concrete boxes. Metal scrap is packed without treatment into concrete boxes. The ion exchange resins used to clean the process water at the power plant are intermediate-level waste. They are mixed with bitumen and cast into drums which are stored in the ILW part of the repository. In addition to the bituminised waste some solid waste in concrete boxes will be disposed in the ILW silo.

The activity inventory for the performance assessment calculations is based on the waste accumulation experience and a reasonable margin, which is introduced to take the related uncertainties and the future unexpected evolution into account. Hence it does not directly represent the expected activity accumulation of the operational waste, but is to be used as a basis for the performance assessment of the final system.

According to the plans, decommissioning wastes will be disposed of in underground repositories co-located with those for operational wastes at the power plant sites.

### 4.5.4 Safety assessments

The Finnish dose criterion is 0.10 mSv per year.

The safety assessment was first set out in 1998 and considerable know ledge and experience has been gained since then. The latest safety assessment for VLJ is not openly available.

The scenarios included for VLJ were mainly of three types. The reference scenario was defined as giving upper levels below which activity concentrations in nature and exposure to man will remain with a high degree of certainty. The realistic scenario employs less pessimistic data while the disturbed evolution scenario assessed the consequences of improbable events and accidents.

### 4.5.5 Plans for closure

At closure the lower parts of the repository will be backfilled with crushed rock. The gap between the rock and concrete silo will also be filled with crushed rock and the lower part mixed with bentonite. Tunnels and shafts will be plugged and closed with concrete at the ground surface.

## 4.6 Deep Geologic Repository at Bruce in Canada

Recently, Ontario Power Generation's (OPG) submitted to the authority an application for construction of a Deep Geologic Repository (DGR) for OPG's low and intermediate level waste (LILW) to be situated on the Bruce nuclear site, near Kincardine Ontario (OPG 2011a).

The Nuclear Waste Management Organization[1] under contract to OPG has managed the preparation of the submission package, and has recently signed a contract with OPG to manage the Design and Construction Phase of the DGR Project.

### 4.6.1 Location and geological conditions

The site at Bruce was selected for two main reasons "*in this case geology that offers multiple natural barriers to safely isolate and contain the waste for tens of thousands of years and beyond: and social acceptance – residents of the host municipality are both informed and willing"*(OPG 2011b). The area is an industrial site, since it has been the site of construction activities and nuclear generating facilities for more than four decades. The site is located on the Bruce nuclear site on the eastern shore of Lake Huron. The area is relatively flat and Bruce nuclear site is located on the Douglas Point promontory, a feature of relatively low relief that juts 2.5 to 3.0 km into the lake over a lateral distance of approximately 5 km. There is no other surface water than the large Lake Huron in the surroundings.

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[1] The Nuclear Waste Management Organisation is owned by Canada's nuclear utilities and is responsible for solving the long term management of Canadian spent nuclear fuel.

The geology at the site is of sedimentary rock. The entire sedimentary sequence at the Bruce nuclear site, ranging in age from Middle Devonian to Cambrian, is comprised of near horizontally layered limestones, dolostones, shales and some sandstone at the base. The repository host rock is an argillaceous limestone formation that varies from very sparsely fractured to unfractured giving excellent rock quality. It is at a depth of about 680 metres.

Water quality in shallow aquifers will be protected by the 200 m thick shale cap rock located directly above the repository. This layer hydrogeologically isolates the shallow water supply aquifer and protects it from the deep saline groundwater system. The deep groundwater is very saline and therefore has no potential as a source of potable water. The area is seismically stable and is located in a region of very low seismic potential.

### 4.6.2 Repository design

The repository is designed for a capacity of 200,000 m$^3$ of LILW and will be situated at a depth of about 680 metres.

Due to suitable geological conditions and the stable environment the design of the repository is of simple construction compared to others as it constitutes a shaft leading to a number of constructed cavities in the rock, see Figure 4-7. No engineered barriers are constructed.

The construction of the repository is not expected to start until 2013, following regulatory agency and public review of the submitted material, a public hearing and the granting of a Site Preparation and Construction Licence.

### 4.6.3 Waste packages and amounts of waste

Radioactive wastes to be accepted are classified as solid low level or solid intermediate level. The low level waste consists of non-fuel waste which contains primarily short-lived radionuclides (half-lives shorter than or equal to 30 years). LLW typically comprises incinerator ash, compacted waste, bulk and drummed non-processible wastes, some low activity ion-exchange (IX) resins and filters from secondary side reactor process systems, and system components such as heat exchangers, feeder pipes and steam generators. Intermediate level waste consists of non-fuel waste containing significant quantities of long-lived radionuclides and typically comprises primary side and moderator IX resins and filters, irradiated core components and reactor fuel channel wastes from refurbishment activities. The LLW normally does not require shielding during handling and storage, whereas the ILW does.

***Figure 4-7.*** *Simplified design of the Bruce repository.*

Waste has been generated since the mid-1970's and there are currently more than 100 different waste container types; drums, boxes and containers. Some waste packages currently stored meet the waste acceptance criteria. Others will require some waste conditioning, additional decay time, and/or container overpacking or shielding.

Based on the existing and projected inventory, it is estimated that approximately 53,000 packages representing a total emplaced volume of approximately 200,000 $m^3$, whereof 80% is LLW.

### 4.6.4 Safety assessments

In Canada the criteria for safety after closure for the normal evolution scenario is 0.3 mSv/year, and that the system "allows for potential exposure from multiple sources in the future, and is approximately an order of magnitude below the individual dose rate received from natural background radiation in Canada".

Potential radiological impacts on non-human biota are assessed for both normal evolution and disruptive scenarios. These potential impacts are compared with screening-level criteria expressed as No-Effect Concentrations (NECs) of nuclide specific radionuclides in water, soil and sediment.

The assessment encompasses more than 1 million years and considers waste and packaging degradation, gas generation and build up, rockfall, earthquakes and, eventually, glacial cycles. Tritium and carbon-14 are released as gases;

### 4.6.5 Plans for closure

Institutional control is to be performed during 300 years.

At closure concrete monoliths are placed at the bases of the shafts and thereafter the shafts are backfilled with a sequence of material, such as bentonite/sand, asphalt, concrete and excavated rock material.

## 4.7 SFR in Sweden

SFR, the Swedish final repository for short-lived low and intermediate level waste, was taken into operation in 1988 and has a capacity of 63,000 $m^3$ waste. It serves as final repository for the low and intermediate level operational waste (LILW) that is generated from the Swedish nuclear power plants. Radioactive waste from medical care, research and industry is also disposed of at SFR. The waste is deposited in underground rock cavities and when SFR was built it was the first facility of its kind in the world.

SFR was built and is operated by SKB, who are tasked with managing the Swedish nuclear spent fuel and radioactive waste. SKB is owned by the nuclear power companies in Sweden.

### 4.7.1 Location and geological conditions

The repository is located close to the nuclear power plant at Forsmark, 50 metres beneath the seabed in crystalline bedrock. At present, the area above the repository is covered by the sea. However, the ongoing shore-level displacement (the land rising after the latest glacial period) at the site will lead to substantial changes of the geohydrological conditions and the surface ecosystem during the next coming 10,000 years. This is considered in the safety assessments.

When siting the repository it was decided to locate it at a nuclear facility. Location at NNPs on the Baltic coast was the focus during site selection. An area outside the coast at Forsmark was selected for site studies. These showed suitable conditions like low hydrological gradients due to the flat landscape and location beneath the bottom of the sea. The location at Forsmark under the water implied a low probability for drilling a well into the repository during the first two thousand years, when the activity levels are highest.

### 4.7.2 Repository design

The repository consists of four 160-metre-long rock vaults, plus a rock cavern with a 50-metre-high concrete silo. Two parallel kilometre-long access tunnels connect the facility to the ground surface, see Figure 4-8.

A 50 m high concrete silo surrounded by a clay buffer contains intermediate level waste (ILW) holding about 90% of the total activity content in SFR. The waste in the silo is solidified with cement or bitumen in containers of steel or concrete (moulds and drums). The containers are embedded in concrete in the shafts in the silo, acting as the first barrier. The next barrier is the silo's concrete wall, which is nearly one metre thick. Between the outer wall of the silo and the rock, which also acts a barrier, is a thick layer of bentonite clay. The impervious clay prevents groundwater from flowing through the silo. It also acts as a filter and captures any radionuclides that might escape from the silo. Moreover it protects the silo from movements in the rock.

The remaining 10% of the activity will be disposed of in four more simple rock caverns, each 160 metres long. One of the four rock caverns (BMA) is also used to dispose of some intermediate level waste where the external dose from the wastes is such that radiation shielding is required. The caverns for BTF and BLA are used to dispose of low-level waste.

The packages emplaced in BMA consist mainly of moulds or drums, and the vault consists of a number of storage compartments. The load bearing structural parts of the BMA vault are founded on solid rock. The bottom slab is founded on a base of rock levelled with gravel. The bottom slab, walls and floor structures are made of in situ cast reinforced concrete. The walls and roof of the rock vault are lined with shotcrete. A prefabricated concrete lid is put in place after the compartments are filled with waste. The lids provide radiation shielding and fire protection. Another concrete layer is cast on top of the prefabricated lids to give the structure added stability and tightness. BMA has three barriers; the waste package, the compartment structures and the surrounding rock.

The long term safety of the SFR repository is dependent on a number of components with different safety functions, see Figure 4-9.

### 4.7.3 Waste packages and amounts of waste

The original licence comprised a total waste volume of 63,000 $m^3$ with the possibility to expand the facility.

In 2010 SFR had received 33,900 $m^3$ wastes. About 1,000 $m^3$ of waste is added every year.

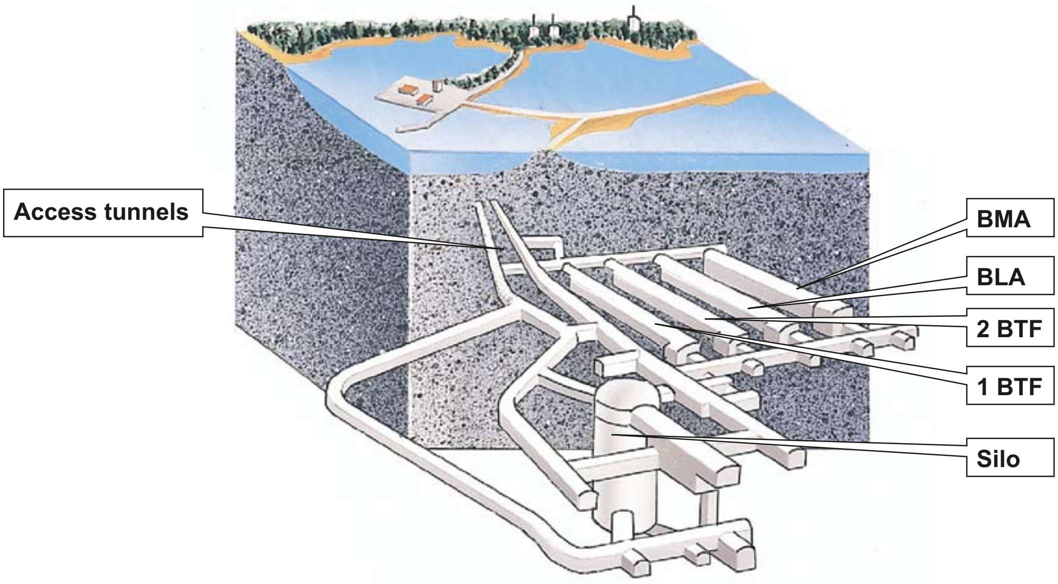

***Figure 4-8.*** *Overview of the SFR facility.*

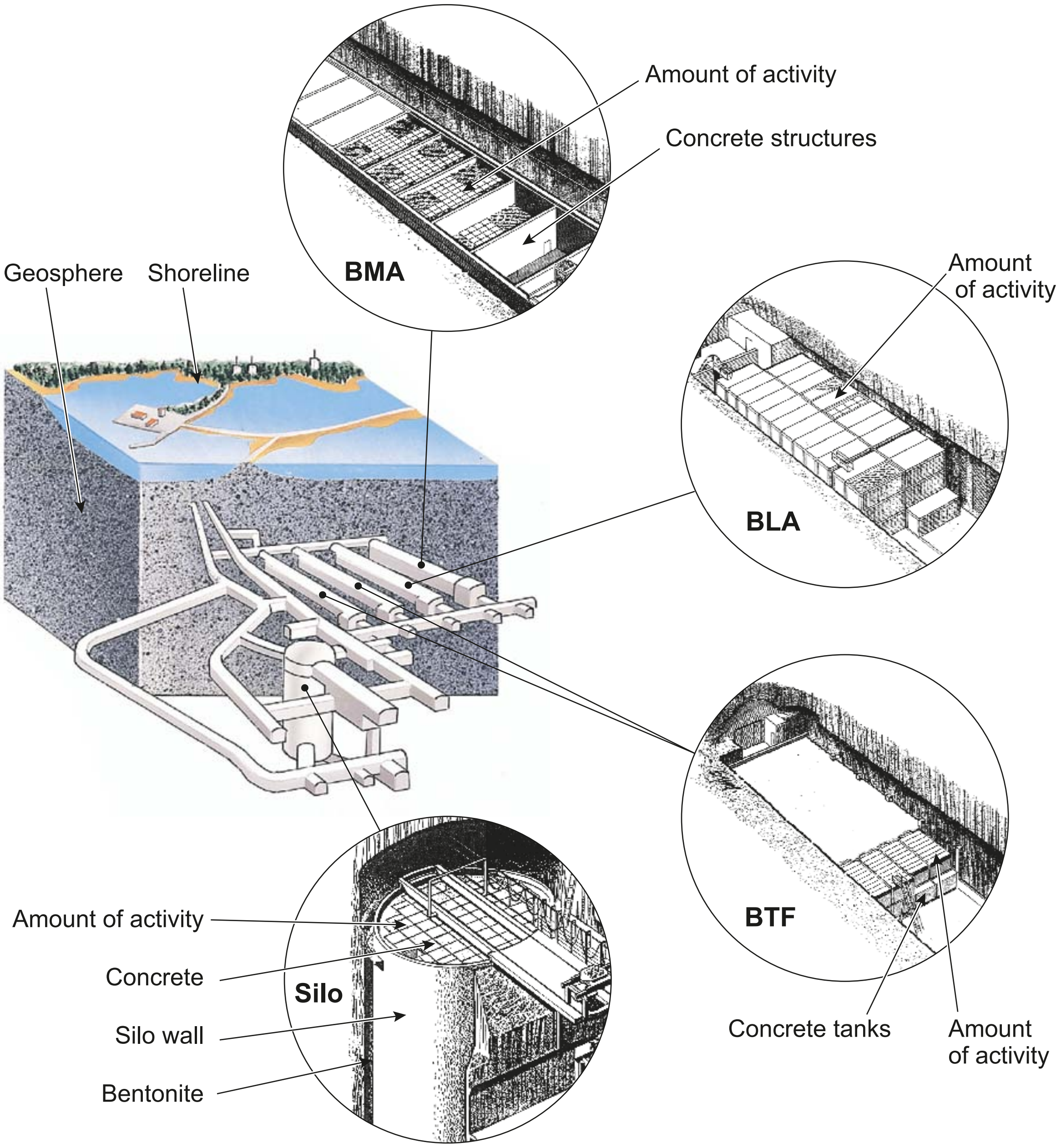

*Figure 4-9. Illustration of components that have a safety function in SFR.*

The waste in the silo consists mainly of solidified filter resins classed as intermediate level waste and contains the majority of the activity in the facility (it is licensed for 92% of the total activity content in SFR).

Low level waste mainly consisting of protective clothing is deposited in standard ISO freight containers in one of the four rock vaults (BLA).

A large portion of the waste volume in SFR consists of metals, mainly carbon steel and stainless steel. Scrap metal arises mainly during maintenance outages when equipment is discarded, modified or renovated.

In the future, it is the intention of SKB that the facility will also accommodate decommissioning waste as well as long-lived LILW.

The radionuclide inventory in SFR is based on measurements of cobolt-60 and caesium-137 in waste packages and on measurements of plutonium-239 and plutonium-240 in reactor water. Inventories of activities from other radionuclides are obtained by multiplication of the measured activities with nuclide specific correlation factors. The decay calculations of the activity in the waste emplaced in SFR imply that 100 years after repository closure the activity is less than half, and after 1,000 years only about 2% of the original activity remains.

### 4.7.4 Safety assessments

The Swedish regulations state that the following undertakings must be included in the safety assessment for SFR:

- "The annual risk of harmful effects after closure does not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk" resulting in a dose of 1.4 $10^{-5}$ Sv/year.
- Description of the effects on biota.
- Consequences of intrusion.
- More detailed assessment for the first 1,000 years after closure.
- Collective dose commitment integrated over 10,000 years from releases during the first 1,000 years.

In the safety assessments, which have been prepared at intervals since 1983, SKB has considered potential impacts through analysis of a number of possible developments in the repository. There is an expected "main scenario" where different possible and plausible variants have been taken into consideration.

In addition, the authorities require evaluation of some less probable scenarios and so-called "residual scenarios", which are scenarios that are selected and studied independently of probabilities in order to shed light on the importance of individual barriers and barrier functions.

### 4.7.5 Plans for closure

Closure measures have been planned since the design of SFR. Complete sealing and closure of the facility is assumed to take place after all waste has been deposited. The different parts of the facility require different means of closure. Some measures are carried out during the operating period, for example closure of boreholes and filled disposal chambers For example, as soon as a compartment in the BMA vault is full, it is closed with a concrete lid and concrete is poured over the lid. When the vault is full and ready for closure a concrete plug will be cast against the rock vault tunnel, and the rock vault will be filled with gravel. After complete filling, concrete plugs are cast against the tunnel junctions at both ends of the vault. These plugs are about 5 m thick, and their purpose is to prevent water flow via the tunnel system and direct contact between different rock vaults. A support fill, of e.g. till and shot rock, is placed on the outside of the plugs.

# 5 Similarities and differences of national repositories for disposal of LLW

The main objective of this study is to gather information about repositories for LLW in other countries and understand similarities and differences between them and the Swedish SFR. It should, however, be pointed out that this is not a strict detailed comparison. Comparisons are difficult due to various definitions of terms, different content and structures of safety assessments reports, national differences and availability of data. Also the conditions at the repository sites vary; favourable conditions may allow simplifications of engineered structures and these may not be comparable to what could be used at other sites.

The study focuses on observations made, general conclusions drawn and explanations to various disposal systems.

## 5.1 General

One criterion for the selection of some repositories for closer study was the availability of information. Canada, United Kingdom and Sweden have published their safety analyses on the Internet. English versions of assessments of the other repositories, including the last assessment for VLJ in Finland was not available on the Internet. This has limited the extent to which any the comparison or description of the respective safety assessments could be made consistent.

In general, there is a national cooperation within the countries to solve the disposal of LLW. This often results in regional repositories receiving waste from either the whole national nuclear programme (France, Spain, Japan, and Sweden) or from a main part of the programme (Canada). Finland is an exception where each reactor owner operates its own repository for LILW.

That fact that some countries have selected a regional repository reflects the need for a cost-effective waste management system.

Commissioning and operation of a nuclear facility are guided by strict rules with the main purpose being to protect man and environment from any hazardous consequences of radiation exposure. This remains a valid objective also after the closure of a repository.

## 5.2 Location of sites and geological conditions

Most repositories are located, like the Swedish SFR facility, in the vicinity of a present nuclear facility. This is the case for Rokkasho in Japan, LLWR near Drigg in UK, VLJ in Finland and the planned Bruce in Canada. Rokkasho is a large centre for the Japanese nuclear industry where e.g. a future reprocessing plant is under commissioning. El Cabril is located at a former uranium mine. Location of repositories at sites where people have experience from the nuclear area is therefore typical. The need to dispose of the waste close to existing facilities implies logistics advantages. In some cases, for instance the LLWR near Drigg in the UK, there was the convenience of an existing railway track. An exception is the siting of l´Àube. Although the community is positive it has not been a nuclear site.

However, the siting of the nuclear power plants took factors such as, stable geological conditions, low productive areas, sparse population and closeness to cooling water into account, i.e similar factors usually addressed for site selection for waste repositories.

In many cases, natural barriers with an isolating capacity, such as clay formations, exist at the selected site. Examples are l'Aube in France and LLWR near Drigg in the UK where the repositories are located in or underlain by natural low-permeable clay.

Abandoned mines also offer natural favourable conditions for repositories. El Cabril, Spain and Morsleben, Germany are examples of locations at former mines, when analysing the experience from the summary of repositories given in the Appendix A:

LLWR, SFR, VLJ, Rokkasho and Bruce are all located in coastal areas while l'Aube and El Cabril and are located inland. Water volumes are in general larger and water retention times shorter at coastal areas compared to fresh-water systems. Another aspect is that coastal areas are affected either by erosion or by shore-line displacement. The area around LLWR is a typical example of the former whereas the areas around SFR and VLJ are affected by the latter. The very deeply located Bruce repository at a large fresh water lake is not at all considered to be affected by erosion or shore-line displacement. The coastal location is also reflected in the safety assessments as biosphere receptors of calculated radionuclide leakages from the repositories located at sea-shore change with the change of shoreline. The calculations for SFR illustrate such evolution with sub-models based on the Geographical Information System which predicts the creation and potential lifetimes of lakes in the former area covered by sea. It is only at SFR, where the overlying rock of the repository is covered by water when closing the repository. This implies that, for SFR, the early human intrusion in to the repository is very unlikely and all short-lived radionuclides have had time to decay considerably before any scenario that includes drilling of a well is plausible.

## 5.3 Repository design

It becomes obvious from the list of repositories in Table 4-5 that most repositories are constructed on or just below ground level or in a former mine. To construct repositories in underground cavities is a more recent approach applied in Sweden, Finland and Hungary.

Most of the near surface located repositories like l´Aube, El Cabril and Rokkasho are equipped with inspection tunnels.

### 5.3.1 Barriers and engineered structures

The repositories included in this study are, as a whole or partly, of recent design, taking into account experience from facilities already in operation earlier. There are experiences from more than 40 years of operation of near surface repositories worldwide. Some early repositories were constructed with almost no engineered structures or where the selection of structures was based on insufficient information. It can, however, be concluded that barrier systems have been developed and applied over time. Important drivers for this are e.g. the ongoing development of international and national regulations, exchange of information provided by international forums, development and results from performed safety assessments, increasing funds and research and development programmes in progress.

The engineered barriers are designed to complement the natural conditions at a site e.g. the hydrogeological, geological and hydrological conditions. The main strategy for the above ground repositories is to rely on the functions of engineered barriers during the three hundred years of institutional control. Thereafter the safety properties of the natural barriers and the environment are assessed to be sufficient to maintain radiological safety.

Concrete structures are applied both in repositories located below (LLWR near Drigg and Rokkasho) and above the groundwater table (El Cabril and l`Aube) or deeper down in the rock (LVJ, SFR). These structures provide mechanical stability and containment of the waste by limiting water infiltration and providing of sorption capacity. Backfill materials such as cement, clay or gravel around the waste packages inside the concrete structures enhance the mechanical stability and containment. The structures are in some cases also complemented with water-proof liners of e.g. bitumen, asphalt, and rubber. When a trench or vault is full with waste packages, it is often backfilled and covered with both a concrete cover and a cap with multi-layers e.g. a drainage layer that aims to divert rainwater away from it and impermeable clay layers to prevent infiltration.

The repositories that are located above ground, e g El Cabril and l´Aube, are under institutional control typically for a period of 300 years which means that the barriers shall provide containment during this time period.

The repositories located above groundwater levels have mainly barriers of two types, one type shall provide isolation and the other type shall have high porosity providing good conditions for the precipitation water to flow around the repository structures and not through it.

The repositories located below the groundwater table have barriers to prevent groundwater migrating through the repository.

The Finnish VLJ, an underground cavity, has barrier systems very similar to those of the vaults. There are two concrete silos, one made of shotcrete for LLW and one made of reinforced concrete for MLW. The structures and underground openings are backfilled. There is no bentonite layer surrounding the silos in VLJ as in SFR. On the other hand the activity in the SFR silo is considerably higher than in VLJ.

The planned repository in Bruce in Canada has no engineered barriers. The safety relies on the overlaying 650 meter thick geological structures.

### 5.3.2 Repository size

The sizes of the repositories for LLW reflect the size of the national nuclear programmes and also the classification of the radiological waste. Some countries dispose of their VLLW in the repository designed for LLW while others e.g. Sweden make a distinction between the two classes and dispose of the VLLW in local shallow landfills at the nuclear power plants.

In the compilation below the planned repository volume capacities are shown for the countries included in this study. France has the most extensive NPP programme of the considered countries and has the second largest repository. The United Kingdom has the largest repository which has been in operation for a very long period of time and includes large amounts of relatively "old" waste. The Finnish repository VLJ, which is constructed for disposal of waste from one nuclear power plant, is the smallest one.

| Country, repository name | Planned repository capacity (m$^3$) |
|---|---|
| France, L'Aube | 1,000,000 |
| Spain, El Cabril | 36,000 |
| Japan, Rokkasho | 600,000 |
| United Kingdom, LLWR | 1,800,000 |
| Finland, VLJ Oilkiluoto | 8,000 |
| Canada, Bruce | 200,000 |
| Sweden, SFR | 63,000<br>(203,000 after extension) |

## 5.4 Waste

### 5.4.1 Waste and packaging

The low level waste (LLW) disposed in the repositories has very similar origin. In many of the countries specific efforts have been devoted to the development of methods to reduce the waste volumes e.g. by compaction. Solid waste is placed in packages whereas liquid waste and ash are conditioned/solidified in e.g. cement or bitumen. To limit the waste forms accepted and the content of activity as well as the occurrence of long-lived radionuclides all repositories have set out Waste Acceptance Criteria (WAC) for the waste to be disposed of at the respective facility. Briefly the requirements comprise:

- General requirements.
- Radiological requirements.
- Chemical requirements.

The most common waste packages are steel drums, concrete or steel boxes. In some cases these units are loaded in to larger concrete or steel containers prior to emplacement in the repository e.g. in El Cabril or LLWR near Drigg. The packaging contributes to the operational safety and is recognized as one of the repository barriers in most systems.

### 5.4.2 Activity content

In order to make a comprehensive comparison of the activity content in the various repositories, the radionuclides, reported in respective safety assessment have been grouped according to physical half-lives and transport properties. All radionuclides having physical half-lives shorter than 31 years, were put into one group. The radionuclide carbon-14 was handled separately due its dominating contribution to calculated dose in many safety assessments (SKB 2008, Vieno and Nordman 1998). Alpha decaying radionuclides were grouped together, due to their specific radiological properties. Finally, remaining radionuclides were split into one group of mobile and one group of non-mobile nuclides, based on their sorption properties in soils and rocks. How to make this last division strictly correct could be discussed but it has been judged to be of minor importance for this comparison. The division of radionuclides in the groups is shown in the table below. The reported numbers of radionuclides vary as expected between the repositories. Special consideration must be taken regarding the short-lived radionuclides as it was not possible to find complete information regarding their content. On the other hand, the interest of these radionuclides from a long term safety point of view is limited due to the effective decay of the activity with time.

| Group | Radionuclides |
|---|---|
| Short-lived (Half-lives shorter than 31 years) | tritium, mangan-54, iron-55, cobolt-60, strontium-90, rutenium-106, tin-119 m, antimon-125, barium-133, caesium-134, caesium-137, europeum-152, europeum-154, europeum-155, lead-210,californium-252 |
| Long-lived mobile | chlorine-36, selen-79, molybden-93, technetium-99, argentum-108 m, iodine-129, platinium-193 |
| Long-lived non-mobile | nickel-59, nickel-63, zirconium-93, niobium-94, tin-121 m, tin-126, cesium-135 |
| Alpha-decaying | radium-226, isotopes of uranium, plutonium, americium and curium- |
| Carbon | carbon-14, organic and inorganic |

The activity content in the repositories according to this grouping are shown in Figures 5-1 to 5-10.

The radionuclide content for the different facilities shown below reflects the calculated activity content used in the latest safety assessments. For l`Aube (Bouchet et al. 2000) and El Cabril this also represents licensed inventories. This is not the case for SFR and LLWR as their present regulated activity content are not deemed to be the most probable inventories at the time of closure. The activity content is, by necessity, based on estimates and therefore has an inherent uncertainty, which will decrease with time.

The amounts of activity considered in the safety assessments partly reflect the extension of the nuclear programmes in the particular countries. Some countries may also dispose of old waste from research and development. However, without doubt, the French repository l´Aube is licensed for the highest activity content mirroring the fact that France has the largest production of energy from nuclear power plants of the countries presented in this study.

As expected the French repository l'Aube has the highest activity content of the short-lived radionuclides, while the smallest repository, VLJ has the lowest, see Figure 5-1. Cobolt-60, followed by caesium-137 dominates the activity in l'Aube. In El Cabril repository cobolt-60 dominates totally the reference inventory, expressed as the inventory at the end of the operating period.

Inventories of short-lived radionuclides, divided by repository volumes (normalised activities), are shown in Figure 5-2. The differences between the repositories decrease, although l´Aube together with El Cabril have the highest values. The other repositories have activity contents at least two orders of magnitude lower than these based on normalised activities and VLJ has the lowest.

The activity content of the long-lived mobile radionuclides are shown in Figure 5-3 and 5-4, respectively. The latter shows the values divided by repository volume.

Technetium-99 is the dominant long-lived mobile radionuclide for all repositories except for Bruce and l´Aube, where silver-108 m dominates. The inventories of long-lived mobile radionuclides in Rokkasho and VLJ repositories are not visible in the figure as they are about 0.02 and 0.004 TBq, respectively.

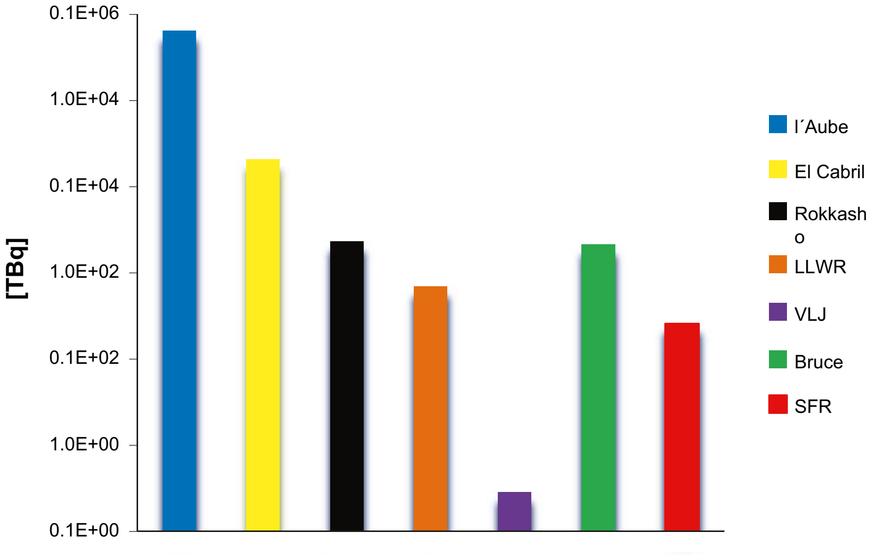

***Figure 5-1.*** *Total Activity of short-lived radionuclides ($T_{half}$ shorter than 31 years).*

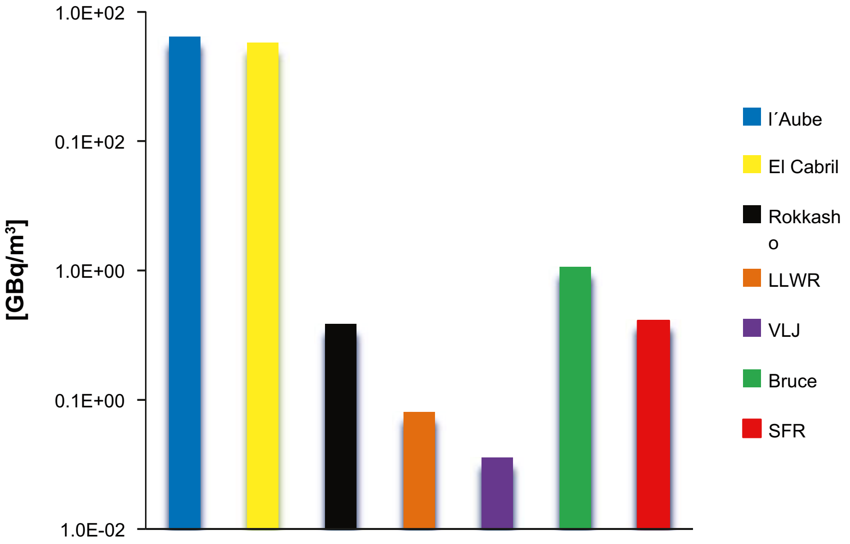

***Figure 5-2.*** *Activity of short-lived radionuclides ($T_{half}$ shorter than 31 years) divided by volume capacity of repository.*

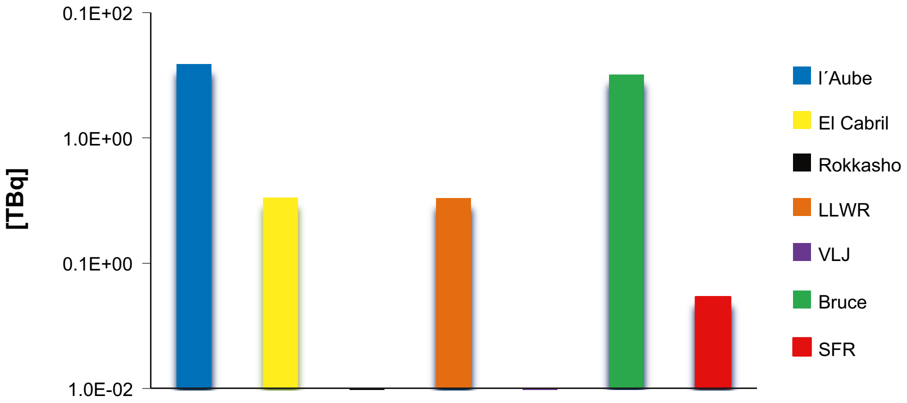

***Figure 5-3.*** *Activity of long-lived mobile radionuclides. The inventories for Rokkasho and VLJ are below 0.1 TBq, and hence are not visible in the figure.*

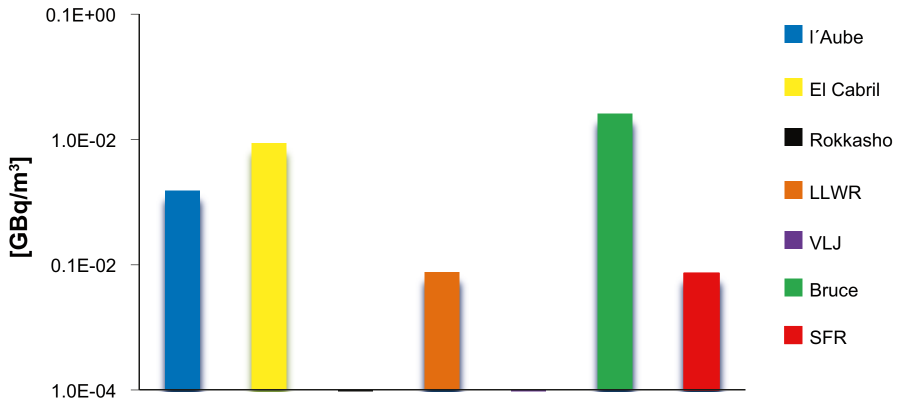

***Figure 5-4.*** *Activity of long-lived mobile radionuclides divided by the volume capacity of repository. The inventories for Rokkasho and VLJ are too low to be visible in the figure.*

The normalised activity content, Figure 5-4, shows that the proportion of long-lived mobile radionuclides is highest for Bruce, and the ratios for El Cabril, l´Aube and Bruce vary by a factor of four. LLWR and SFR have similar ratios that are somewhat lower.

The activity content based on long-lived non-mobile radionuclides are shown in Figure 5-5 and 5-6, respectively. The latter shows the values divided by repository volume. L`Aube, the largest repository, shows the highest content of long-lived non-mobile radionuclides. The activities of nickel-63 and samarium-151 dominate the inventory of long-lived non-mobile radionuclides in l'Aube. These radionuclides have physical half-lives of 96 and 90 years, respectively. About 10% percent of the long-lived activity remains in the l'Aube repository also after 300 years.

The normalised activity content of the long-lived non-mobile radionuclides show, as expected, minor variations compared to total activity content. The normalised value for SFR coincides well with values for l´Aube, El Cabril and Bruce. The activity in SFR is solely dominated by nickel-63. The largest repository LLWR shows the lowest inventories, for the total as well as the normalised case.

The activities of alpha decaying radionuclides are shown in Figure 5-7 and 5-8, respectively. The latter shows the values divided by repository volume.

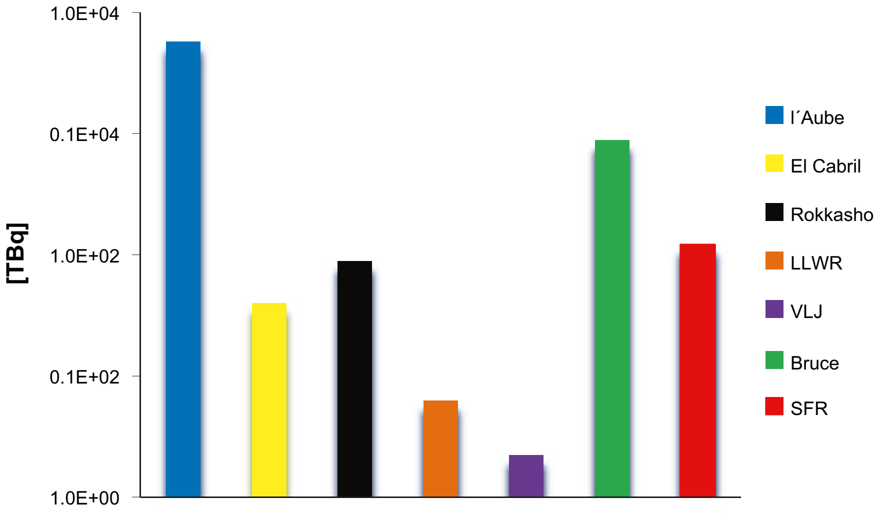

***Figure 5-5.*** *Activity of long-lived non-mobile radionuclides.*

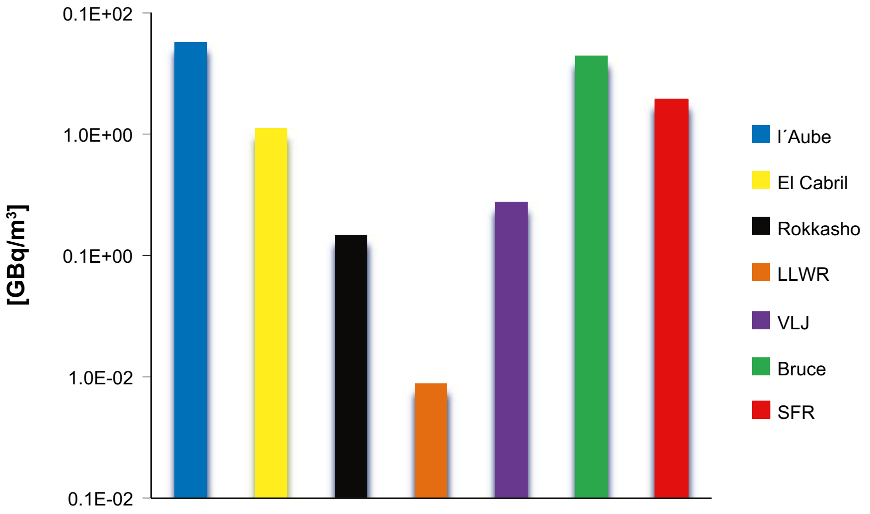

***Figure 5-6.*** *Activity of long-lived non-mobile radionuclides divided by volume capacity of repository.*

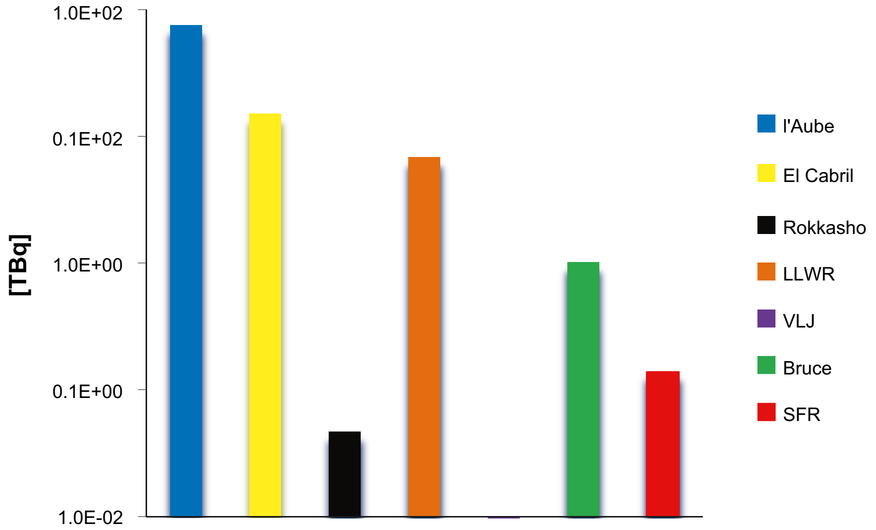

***Figure 5-7.*** *Activitys of alpha-decaying radionuclides. The inventory for Rokkasho is below 0.1 TBq and is not visible in the figure.*

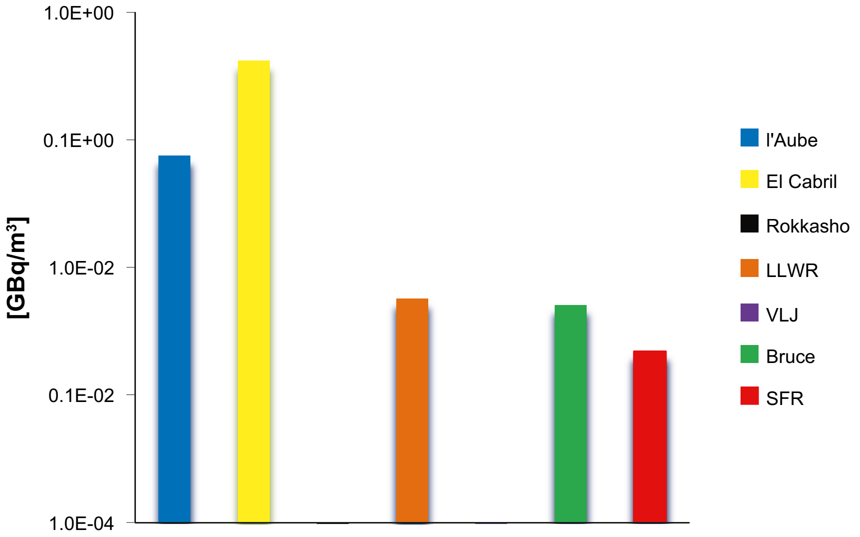

***Figure 5-8.*** *Activities of alpha-decaying radionuclides, divided by capacity volume of repository. The ratios for Rokkasho and VLJ are so low that they are not visible in the figure.*

L´Aube being the largest repository contains also the highest activity of alpha-decaying radionuclides followed by El Cabril, which is one of the smallest repositories, see Figure 5-6. However, for l´Aube the inventory shown corresponds to the inventory 300 years after closure i.e. after the institutional control time. VLJ has the lowest activity content due to the limited amounts of waste. Repositories reporting nuclide specific activities have Pu-241 as a dominant contributor to the activity of alpha decaying radionuclides as the inventories decrease effectively with time because the half-life of Pu-241 is 14 years. Pu-241 is the only alpha-decaying radionuclide we found in the El Cabril´ s inventory.

One radionuclide of importance in many of the safety assessments, which also totally dominates the calculated doses for SFR, is carbon-14 (SKB 2008). The reported activity of carbon-14 for respective repositories is shown in Figure 5-9. The activity content of C-14 in the repositories varies significantly and the variations in total activity content do not correlate to the size of the repository. For example, the relatively small Bruce facility has the highest total activity content, 1.6 $10^3$ TBq and also the highest normalised activity, see Figure 5-10.

It should be noted that in this context the chemical form of carbon is not taken into account, only the whole pool as this information was not available for all repositories. Still, SFR has among the lowest total content and normalised activity of carbon-14.

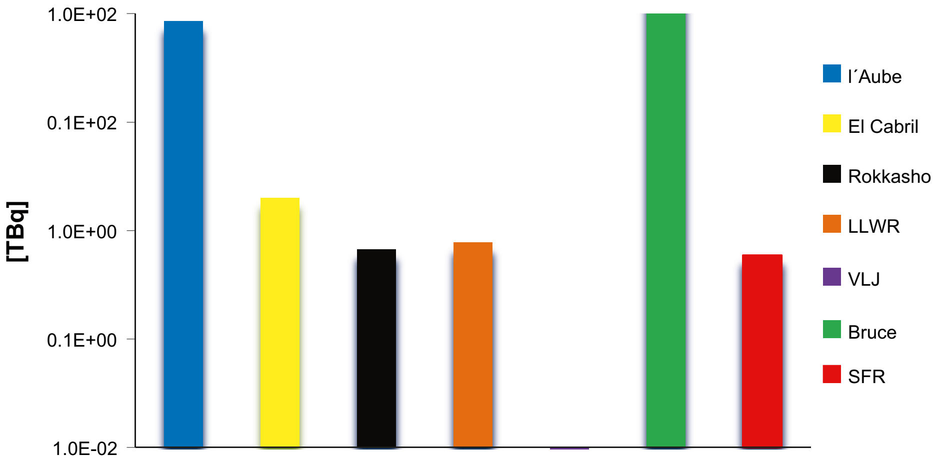

*Figure 5-9. Activities of carbon-14 in the repositories. The inventory for Rokkasho is below 0.1 TBq and is not visible in the figure.*

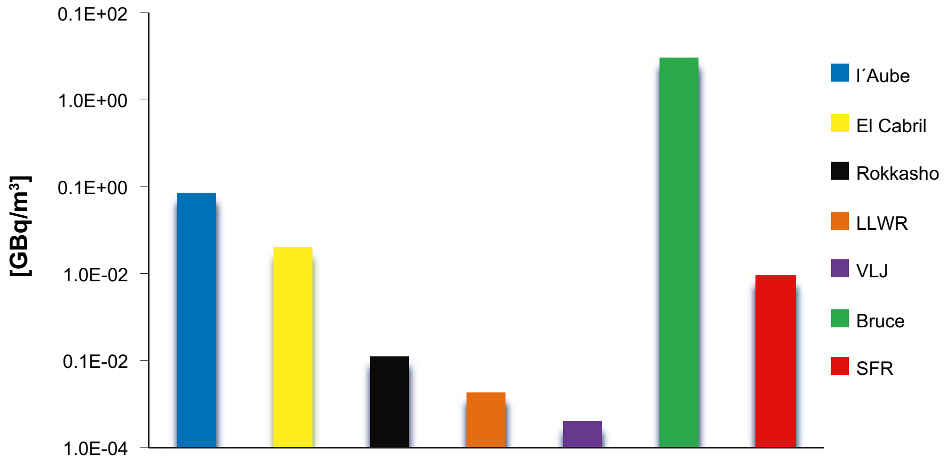

***Figure 5-10.** Activities of carbon-14 divided by volume capacity of repository.*

### 5.4.3 Conclusions

The repository volume capacities and also the amounts of activities vary between the repositories partly reflecting the extent of the national nuclear programmes.

As expected the short-lived radionuclides dominate the total inventories in all repositories, and after normalisation to repository volumes l´Aube and El Cabril have the highest relative inventories of short-lived radionuclides.

The local and very small repository VLJ has the lowest total and normalised activity content when compared to all other repositories. The largest repository, LLWR in United Kingdom, has the second lowest normalised inventories for all groups of radionuclides except for the group se with alpha decay.

## 5.5 Safety assessments

The context for the safety assessment states what is being assessed and why it is being assessed. It is strongly aligned to the national regulations and requirements from stakeholders. The assessments included in this overview are undertaken to demonstrate compliance with regulations.

Safety assessments are performed in a similar way for all repositories. A scenario, covering all assumptions leading to a specific development, is either based on probable evolutions of the site or present day conditions. The latter is valid for the inland surface located located repositories like el Cabril, L´Aaube and Rokkasho. Usually there is one so called reference scenario, sometimes named the most probable evolution of the repository or more realistic case. These scenarios are modelled and radionuclide releases to the biospere and resulting doses are calculated with relevant modelling tools. In addition, less probable scenarios are set up and results are obtained. The international FEP-list is a list of features, events and processes which may influence the repository. The list is derived from international cooperation work and is a common base usually referred to in the safety assessments.

Due to the work of ICRP there is a general consensus about dose criteria for each respective country, varying up to 100 µSv per year. Criteria based on the risk concept ($10^{-6}$ per year ) as it is applied in Sweden corresponds e.g. to a dose of 14 µSv per year.

All safety assessments performed for the studied repositories, together with other studies considering also the safety after repository closure, have shown that transport by groundwater is the main path for radionuclides to reach man and the environment. Transport of radionuclides by gas was, however, more pronounced for the surface located repositories than for the deeper located VLJ, SFR and Bruce. For the latter, the assessments show that the limited amount of gas generated will be absorbed by the surrounding rock.

The time frames during which calculations are performed differ between the repositories. For Bruce the Canadians encompasses over 1 million years in their assessment while the calculations for Drigg encompass some thousands of years. This reflects also the environmental conditions, LLWR located at the sea-shore is strongly affected by coastal erosion and rising water levels while Bruce is 650 meters down in stable rock. Regarding these type of local conditions SFR is the opposite to LLWR, as SFR is located in an area strongly affected by landrise, causing former water covered areas to be “dry” ground. Longer time frames also imply climate changes. Therefore the calculations for SFR were performed considering climate changes during the future 120,000 years similar to those from the former 120,000 years, the Wechselian ice glaciations. The former safety assessments for SFR (SAFE) encompassed about 10,000 years. In that timeframe the dose peak values have not been reached for all radionuclides and consequently it was a request from the authorities to show calculated peak values for all radionuclides. However, the maximum total dose is obtained within the first 10,000 years, caused by the release of organic carbon-14 with cautious assumptions such that the whole annual consumption of foodstuff is taken from a small lake.

In some countries there are also regulations regarding protection of the environment such as no hazardous exposure to non human biota. This issue has been in focus for the last 10–20 years e.g. one group within ICRP addresses the protection of the natural environment. Due to the complexity of this issue, radiological consequences shown in the safety assessments are due to comparing calculated levels of radionuclides in various environmental media against internationally determined levels. The safety assessments considering exposures to non–human biota have shown that calculated levels of radionuclides in soil water and sediments are several orders of magnitudes lower than the levels used for evaluation.

### 5.5.1 Results

The maximum calculated doses for the reference scenario for the respective repositories are shown in Figure 6-7. In the figure a general exposure from normal background radiation in Sweden is also shown. As can be seen, all calculated doses are well below the exposure from this natural background exposure. The values should all represent the so called main case or reference case etc. However, some of the assessments have several similar named cases and then the highest value wasselected among the cases.

Carbon-14 is the radionuclide that is predominant in the results of the dose calculations for El Cabril, LLWR and SFR. Chlorine-36 dominates the dose from l´Aube. The calculated dose from SFR is higher than the doses from all the other repositories except for VLJ. This is mostly due to a cautious approach in the assessment for SFR. The whole annual food consumption for the critical group, expressed as 110 kg carbon, was produced in a small lake which received the calculated total annual peak releases of carbon-14 from SFR.

### 5.5.2 Conclusions

All safety assessments consider migration of radionuclides by water passing through the repository as the main path of any activity to the environment. The migration of gas released from a repository was also considered in the safety assessments. Gas releases for SFR are shown to be so small that they will be absorbed by the surrounding rock and not give contribution to total dose.

Barriers in near surface located repositories are assumed to lose their retarding functions directly after the institutional control time of 300 years have passed.

All the repositories fulfil their national criteria, some with /nine orders of magnitude ($10^9$) like Bruce in Canada. Others with much less margins like SFR, however this is mostly a result of a cautious approach when performing the assessments.

Due to the work by ICRP there is a general consensus about dose criteria for each respective country, varying up to 100 µSv per year. The dose criteria based on the risk of $10^{-6}$ per year as it is applied in Sweden corresponds to a dose of 14 µSv per year.

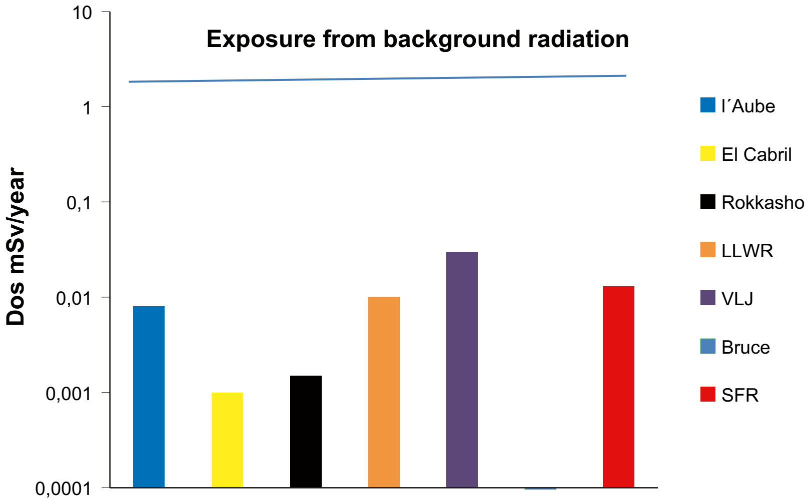

*Figure 5-11. Maximum calculated annual dose from respective reference scenario for the various repositories, the dose from Bruce is so low $10^{-15}$ mSv per year why it is not visible in the figure.*

## 5.6 Closure

Closure of a disposal facility is the last major operational step in completing the disposal system. The closure is needed to complete the design of the disposal system as the entire system is intended to isolate radionuclides and other harmful constituents for a sufficiently long period so that risks to humans and biota are acceptable and inadvertent intrusion into the repository is minimised. Important functions of the closure are to promote drainage and gas release and minimise infiltration of water and erosion. The closure is also required to protect the workers, performing institutional control. Further the closure system is expected to function with minimal maintenance and without losing integrity by promoting drainage to minimize erosion, infiltration and accommodate settling and subsidence.

The closure of the vault and trench types of repositories commonly comprise caps, with a soil layer on top of either a thick clay layer or multi-layers with a sequence of impermeable clay and permeable sand.

The underground repositories e.g. VLJ will be backfilled with gravel and the accesses will be backfilled and plugged.

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**OPG, 2011b.** OPG's deep geological repository project for low and intermediate waste: environmental impact statement summary. Toronto: Ontario Power Generation.

**SKB, 2008.** Safety analysis SFR 1. Long term safety. SKB R-08-130, Svensk Kärnbränslehantering AB.

**Vieno T, Nordman H, 1998.** VLJ repsitory safety analysis. Report TVO-1/98, Finnish Nuclear Waste Companies.

# Appendix A

## Compilation of worldwide repositories for low level radioactive waste (LLW)

The main references used for the compilation of this appendix are sources from NEA and IAEA web pages. The web sites of different national waste management organisations have also been scanned for information.

http://www.oecd-nea.org/general/profiles/

http://www.oecd-nea.org/rwm/profiles/

http://newmdb.iaea.org/reports.aspx

### A1 Argentina

Argentina currently has two nuclear reactors in operation. The Radioactive Waste Management Responsible Organisation (RWMRO) owns and operates the Ezeiza facility, which is a near-surface disposal facility with engineered barriers. It is a trench type repository for conditioned waste in drums. The trench walls are lined with bricks, and the bottom covered with compacted soil. After emplacement of waste packages it is covered with a cap of layers of impermeable foil (PE sheet), earth and grass.

The Ezeiza facility is also used as interim storage for certain waste types that cannot be finally disposed of at the present repository.

### A2 Australia

Australia does not use electricity, produced from nuclear energy. The country uses radioactive materials in medical, research and industrial processes that generate small amounts of radioactive waste. Australia has research reactors, the High Flux Australian Reactor (HIFAR), was permanently shut down in January 2007 and is now replaced by the 20 MW Open Pool Australian Light water (OPAL).

Generators of radioactive waste are responsible for managing the waste that they generate, and each of the Federal, State and Territory governments is responsible for regulating the radioactive waste generated within its jurisdiction. Almost half of Australia's radioactive waste is stored at hospitals and universities in more than 50 different locations around Australia. In addition radioactive waste is generated from mining activities and stored at the mine.

The Australian Government started discussing siting and selection criteria for location of a national repository in 1985. Numerous proposals to establish a national, purpose built facility for the storage and disposal of radioactive waste have been put forward since that time.

A near surface repository without engineered barriers (Mt.Walton) commissioned 1992 is located in Western Australia, 130 km from Kalgoorlie. The 25 km$^2$ large Integrated Waste Disposal Facility (IWDF) site is geologically stable, with deep clay soils, low rainfall and low erosion potential. The repository is of near surface type, constructed in the natural kaolinitic clay profile, which has a low hydraulic conductivity. The engineered barrier is a 5 m thick layer of clay on top of the disposal unit encompassing the waste packages (bags and steel drums). It can be noted that a large fraction of the waste being disposed of at the IWDF consists of non-radioactive wastes, such as chemical waste containing arsenic, pesticides, mercury, etc.

### A3 Bulgaria

There is one nuclear power plant with six reactors in Bulgaria, Kozloduy NPP (the first reactor was started in 1974 and the latest in 1991). In pursuance of the Bulgarian commitments made for the country's accession to the European Union, Kozloduy NPP stopped the operation of the first four units in 2002 and 2006. The remaining two reactors, Units 5 and 6 VVER-1000 type , are still in operation, providing more than one third of the total annual electric energy production in Bulgaria.

### Novi Han

The Novi Han repository is currently the only national radioactive waste repository in Bulgaria. It is located in the Losen Mountains 35 km from the capital, Sofia. The repository accepts radioactive waste generated from nuclear applications in industry, medicine, research and education. The facility was specially built for the needs of a research reactor.

The Novi Han facility is a near-surface type repository. It is owned and operated by the Institute of Nuclear Research and Nuclear Energy of the Bulgarian Academy of Sciences. Operations started in 1964 but were suspended in 1994 by the Bulgarian Nuclear Safety Authority. The main reason was that the repository did not fully comply with the international safety criteria for similar facilities. Currently, the repository is undergoing upgrading and licensing.

The repository consists of several different disposal vaults:

- A concrete vault for low and intermediate level solid wastes.
- A concrete vault for biological wastes.
- Steel tanks for storage of low level liquid wastes.
- A special 1 $m^3$ concrete vault for spent sealed sources.
- A concrete trench for solid waste.

The total capacity, as per the original design, is approximately 570 $m^3$. All disposal units are engineered structures, constructed from reinforced concrete and lined with stainless steel and bricks. Vaults are in-ground; only the roof is above the ground level. The steel tanks for liquid waste are situated in a reinforced concrete underground room. There is a reinforced concrete well for sealed sources, located below ground level. The engineered trench for accidental waste is the only disposal unit at the site that has a drainage system.

Approximately 900 TBq ($9 \cdot 10^{14}$ Bq) of alpha, beta and gamma emitters were disposed of at the facility during ~30 years of operation.

The Geological Institute of the Bulgarian Academy of Sciences has conducted a geological survey of the Novi Han repository site. According to the geological investigations, the geological strata have safe bearing capacity, providing a safe suitable foundation base for the disposal vaults. The repository area is not endangered by subsidence or significant settlement of the soil base. The bedrock in the region is a low water bearing and of low permeable formation. The permeability is higher in the tectonic, strongly fissured and faulted zones and in the upper weathered layer. The groundwater is recharged by precipitation only. A regular aquifer has not been formed. An unstable water table of shallow groundwater at a varying depth from the surface (from 6–7 m to 15–17 m) is found in the shallow boreholes in the repository area. The hydrogeological conditions are complex. Additional site investigations are planned to provide data for the safety assessment and for the construction of additional facilities on the site.

### Future final repository for LILW

The Bulgarian government has decided that a national repository for short-lived LILW disposal is to be built by 2015.

- It will be a near-surface facility built in modules, allowing for flexible extension of the repository to increase capacity.
- The duration of active control after repository closure must not exceed 300 years.

## A4 Belarus

Belarus does not have any nuclear power production, but it was affected by the nearby Chernobyl accident in 1986. As a result of the accident, a total of 46,450 $km^2$ (23% of the country) of Belarus territory was subjected to radioactive contamination with caesium-137 content in soil over 37 $kBq/m^2$. Decontamination and remediation activities in the affected areas just after the accident resulted in thousands of tonnes of low-level and very low-level waste.

Owing to contamination of the 23% of Belarus territory from the Chernobyl fallout the tasks of safety management of so-called “Chernobyl wastes”, generated in the course of clean-up, economic and other human activities in the contaminated territory became highly acute. The waste consisting of removed soil, roofing slate, boards, household articles, domestic garbage and structural elements was put into 82 interim storage sites, arranged mostly in ‘natural’ locations (ravines, sand pits, foundation pits, trenches, etc.). In the period of 1986–1991, eight repositories were constructed from type designs in the abandoned areas specifically for Chernobyl waste storage. Additonally waste has been generated by nuclear applications in industry, medicine and research.

### Ekores

The Ekores facility is a former “Radon” type facility (near surface disposal in vaults lined with concrete). The facility is situated in hilly terrain, consisting of medium sand and clay, approximately 10 km from Minsk and close to a nuclear research facility. The facility hosts a variety of solid low- and intermediate level waste, derived from the nuclear applications in industry, medicine and research.

The waste is not conditioned or volume reduced prior to emplacement in the repository.

At present, the site comprises:

- Two closed “old repositories” (1963–1979).
- Two “new generation” near surface repositories intended for solid waste and sealed radioactive sources.
- Storage for sealed radioactive sources.

The two old repositories represent rectangular reservoirs, the walls and bottom being a concrete monolith structure with the covering of precast concrete slabs.

Closure of the vaults is carried out by the upper surface being covered by hot bitumen and by layers of asphalt and soil.

The two new repositories (constructed in 1977) have ab above-ground floor with a precast metal frame and the underground floor consisting of vaults made of a concrete monolith. The facilities are equipped with a suspension cat-crane, with which one or two floor slabs are removed, and the radioactive waste packages are loaded into the vaults. Each vault is covered by a simple building to provide environmental protection and acceptable working conditions to operate the facility throughout the year.

## A5 Brazil

Brazil has two nuclear reactors generating a few percents of its electric energy, and a third under construction at Angra NPP. Additionally four large reactors are planned to be commissioned by 2025. One repository is in operation for the radioactive waste generated by the accident at Goiana. The National Nuclear Energy Commission (Comissão Nacional de Energia Nuclear, CNEN) is responsible for the management and disposal of radioactive wastes. Legislation in 2001 provides for repository site selection, construction and operation for low- and intermediate-level wastes. A long-term solution for these is to be in place before the new reactor Angra 3 is commissioned (planned for 2016).

## A6 China

China has a rapidly expanding nuclear programme. Above all, the country is increasing its nuclear power production capacity. It is however very difficult to obtain any information about radioactive waste management.

According to a report made by Japanese JAERI in 1998 and published on the IAEA web site (Chen 1998), the Chinese strategy for long-term management can be broadly stated as follows:

- Any discharge of radwastes to the environment should be as low as reasonably achievable.
- Solid wastes, and solidified wastes resulting from conditioning of waste concentrates or liquid wastes generated during operation of reactors and research laboratories are to be disposed of in shallow land facilities. Low and intermediate level wastes from operation of fuel reprocessing plants are also permitted in shallow land repositories.

- High level liquid wastes from fuel reprocessing facilities, are to be initially stored in near surface engineered storage facilities, with appropriate cooling and surveillance provisions for a period of decades.
- Disposal of high level vitrified and cooled wastes will be in deep geological formations.

The policy of regional shallow land repository sites for LL/ILW was promulgated by the Chinese government in 1992. The main points of the regional repository site policy were as follows:

- Establishing the regional disposal repository and disposing of the wastes as near the origin as possible. The repository should be selected in a favourable location, taking into account the factors of safety, economy, technology and society, and adjoining to existing or planned large-scale nuclear enterprises. It serves not only the nuclear industry and nuclear power plant, but also the nuclear application users.
- Construction of the low and intermediate level waste repository shall be regarded as a prerequisite for development of nuclear power and as an important aspect of the examination of safety and environmental impact assessment of nuclear facilities by the environment protection and safety supervision authorities.
- When new nuclear power plants and nuclear facilities are put into operation, the waste disposal shall be taken into consideration. The temporary storage of LLW/ILW in situ is limited to be five years.
- It is forbidden for any institution to manage and own LLW/ILW repository, or to use its interim storage facilities as a permanent one, and it is stipulated that all the LLW/ILW must be collected and disposed of at a regional disposal repository with the state license.

According to information from World Nuclear Association (www.world-nuclear.org), China has on an industrial-scale disposed of low- and intermediate-level wastes at two sites; near Yumen in northwest Gansu province, and at the Beilong repository in Guangdong province, near the Daya Bay nuclear plant.

The Beilong repository has a similar construction the French l`Aube, vaults in trenches, equipped with galleries for control.

## A7 Czech Republic

Commercial utilization of nuclear power in the Czech Republic started in 1985 and there are six nuclear power units connected to the electricity grid. Short lived LLW will be disposed of in existing near-surface repositories whose operation will be continually assessed and optimised. There is one LLW repository in operation in the Czech Republic; the Dukovany near surface disposal facility for radioactive waste from Dukovany and Temelin nuclear power plants. There are also three repositories for institutional waste and NORM. The Bratrství repository in Jáchymov for naturally occurring radionuclides and the Richard repository for waste from institutional generators are in operation whereas the Hostim repository is closed. These three facilities were established during the communist regime without any potential for public involvement in the siting process.

### Dukovany

The near surface disposal repository, Dukovany (above ground) was commissioned in 1994 and is located at the site of the Dukovany NPP. The geology of the site is formed by weathered rocks which are underlined by granulites and gneiss. At present, drums containing radioactive waste from the Dukovany NPP are disposed of at this repository while in the future it is envisaged that low-level radioactive waste from the Temelín NPP will also be disposed of there. The Dukovany repository consists of shallow reinforced concrete vaults arranged in rows. Once the vault is full, the space between the drums is filled in with concrete backfill and the vault is covered with a thick sheet of polyethylene which prevents rain water from infiltrating the vault. When the repository is completely full, the vaults will be covered by a number of insulating and drainage layers. The repository will then be closed and guarded and its impact on the surrounding environment constantly monitored. The period of surveillance and monitoring of the repository site is estimated at about 300 years; after that, the activity of the waste disposed of in the repository will have decreased enough as not to pose any threat to the environment and to allow the site to be used for other purposes.

### Bratrství

The Bratrství repository is located in a disused uranium mine located in a water bearing crystalline rock complex. A drainage system has been built in the repository surrounding with both a central retaining tank and flow-through retaining tanks. The repository has been in operation since 1974 and is used for radioactive waste consisting of or contaminated with naturally occurring radioactive material (NORM) (radium and thorium series), e.g. radioactive radiation sources from health care facilities, depleted uranium and natural thorium. The radiation sources are stored in lead containers placed in concrete and sealed in steel drums. These and other wastes in inner drums are overpacked into 200 l steel drums. The drums are stacked and the space between the drums is filled with concrete.

### Richard

The Richard Repository, originally a limestone mine that was enlarged to host an underground facility for military production during World War 2, is designed for disposal of institutional short-lived LILW. The repository has been in operation since 1964 and the waste is stored in mined cavities with various dimensions. The majority of waste disposed of until 1975 is deposited in drums (usually of 60-litre which are galvanized or coated with anticorrosive asphalt paint). Since 1975 packages consist mainly of galvanized 100-litres drums which are subsequently loaded into 200-litre drums (overpacks). The space between the two drums is then filled with concrete thus forming a 5-cm thick concrete radiation shielding. Both the inner and outer surfaces of the overpack are galvanized, the outer surface is coated with bitumen to prevent corrosion. The drums are stacked. The plan is to close the repository, which has a disposal capacity of 8,500 m$^3$, in 2070. During closure, the cavities and tunnels will be filled with a mixture based on of cement or clay.

### Hostim

The Hostim repository is a rock cavity type of repository located in a disused limestone mine. It was operated between year 1959 and 1963 when it was closed. In 1997 a major remediation was performed. The waste comprises LLW from research and production and utilisation of radioisotopes stored in different types of boxes, bags, drums and canisters. The galleries were filled with special concrete during the closure in 1997.

## A8 Estonia

There are no nuclear power plants, research facilities or facilities for radioactive material production in Estonia. However there are two PWR-type reactors from submarines in temporary storage. There are however facilities using radioactive sources in medical, research and industrial applications. Radioactive waste facilities include one interim storage facility for LILW at Paldiski, one LLW repository undergoing decommissioning and a remediated uranium mining and milling tailing pond. The LLW repository in Tammiku is a “Radon” type repository that was in operation between 1963 and 1996, when it was closed.

The Tammiku facility was designed according to criteria developed in the Soviet Union in the late 1950’s and the disposal units comprise one near surface vault lined with concrete and one cylindrical concrete tank lined with concrete and stainless steel. The accepted waste is low- and intermediate level institutional waste, the majority is unpacked but part of the emplaced waste is contained in various packages, such as boxes, bags, drums, bottles and containers of various types.

## A9 Finland

Nuclear waste in Finland arises from the two nuclear power plants at Olkiluoto and Loviisa, together comprising four units, and from a small research reactor. Low- and intermediate level wastes from reactor operations are disposed of in the bedrock of the power plant sites. The repositories at the Olkiluoto and Loviisa NPP sites were commissioned in 1992 and 1998, respectively. Facilities for the conditioning of the waste are available.

The disposal facility in Olkiluoto is a rock cavity type of facility comprising of two concrete silos, one for bituminized spent ion exchange resin waste and the other for dry solid waste, at a depth of 70–100 m in crystalline bedrock. The facility has been in operation since 1992. Both silos are provided with concrete lining, the silo for bituminized waste is provided with an extra barrier, consisting of a reinforced concrete wall. The low level waste accepted at the Olkiluoto facility is mainly maintenance waste generated during NPP operation, scrap metal, solidified liquids and filter cartridges. Intermediate level waste is primarily spent ion exchange resins. The total capacity of the silos is about 40,000 drums of 200 l. Waste packages are emplaced into the silos in large self-supporting concrete boxes, which are stacked on top of each other.

The Loviisa disposal facility is a rock-cavity type facility at intermediate depth in crystalline rock. The bedrock at the Loviisa site consists of homogeneous Rapakivi granite with low permeability and two major fractured zones with high permeability. The repository is constructed at a depth of 120 m in the crystalline rock. Three tunnels are used for the disposal of dry maintenance waste from the power plant, two separate tunnels are used for combustible and non-combustible waste and one cavern (silo) is used for the disposal of all solidified waste. The total disposal capacity is 5,400 $m^3$. After operation, the repository will be backfilled and sealed in order to prevent ingress of ground-water into the disposal cavern and tunnels and to prevent inadvertent intrusion into the repository during the post-closure phase.

## A10 France

Commercial utilisation of nuclear power in France started in 1959 and by 2007 there were around 60 nuclear reactors. France has nuclear fuel fabrication and commercial reprocessing is carried out at the La Hague plant. Most of the radioactive waste in France is generated as a result of electricity production. The remainder arises from the use of radioactive materials in medical, research, defence and industrial applications.

They consist mainly of maintenance waste, worn equipment, cleaning rags and protective clothing. In the past, this type of waste was disposed of at the former Centre de stockage de la Manche (CSM) waste disposal facility located in the Manche district, near the La Hague facility. Waste reception has stopped in 1994 and this disposal facility has now entered the post-closure monitoring phase (2003). Initially, two burial trenches with gravel base were used for disposal. From 1978 rectangular concrete trenches with drainage were used. The disposal area was shaped as a tumulus of concrete packages and metal boxes encapsulated by backfilling with concrete and the whole monolith was capped with reinforced concrete. A multi-layer non-permeable cover protects the waste disposal area. Its main function is to prevent rainwater from reaching the disposal structures.

Short-lived low- and intermediate-level wastes have been disposed of since 1992 at the near surface disposal facility with engineered barriers (CSFMA) located in the Aube district. The disposal facility is built on sedimentary geological formations, a layer of sand underlain by a waterproof clay formation. The clay formation would constitute a natural barrier against any release of radioactive elements in groundwater, and thus prevent from any dispersion in the environment. The overall capacity of the CSFMA waste disposal facility is 1,000,000 $m^3$. The facility has about 400 above ground concrete vaults with 30 cm thick walls and, depending on waste type, they are back-filled with either gravel or concrete, and are then topped with a concrete slab. The used packages are metallic drums and boxes or durable concrete containers.

### Morveilliers

The repository for disposal of VLLW in France is a central facility constructed similar to those for disposal of non radioactive hazardous waste. The disposal cells are excavated in a clay layer and are covered by a clay capping layer when filled (Figure 4-3). They should receive both radioactive and non radioactive wastes. Large components having low level activity from decommissioning are planned to be disposed of in the shallow landfill repository. The landfill is operated by the national waste operator ANDRA.

## A11 Germany

Commercial utilisation of nuclear power in Germany started in 1961 and by 2002 there were around 20 nuclear power units connected to the electricity grid.

### Asse

In 1965, the Federal Ministry for Scientific Research and Technology (Federal Ministry for Education and Research) instructed Gesellschaft für Strahlen- und Umweltforschung (today: Helmholtz Zentrum München) to explore the disposal of radioactive waste in the abandoned Asse mine. Following corresponding reconstruction, trial emplacement of radioactive waste started in 1967. The original goal was to make use of the salt deposit in the Asse as effectively as possible. In the course of this, chambers were mined that reach up to the outermost edge of the salt layer From 1971 it was used as a repository for the storage of the major part of the German low-level and intermediate-level radioactive waste. The radioactive waste was stored in a total of 13 chambers: Ten are located in the southern flank of Asse II in a depth of 750 metres and two in the central part in depths of 750 metres and 725 metres, respectively. Emplacement stopped in 1978 after the Atomic Energy Act had been amended in 1976. Now a nuclear law plan-approval (licensing) procedure is required as a condition for radioactive waste disposal.

In January 2009, the operator changed. Since then, BfS has been operating the Asse mine under nuclear law. Nuclear law makes greater demands on the operation, decommissioning, and radiation protection of the facility than Mining Law does. The numerous cavities caused by salt extraction that are located close together at the mine's southern flank have lead to problems regarding stability and the associated risks of an increased inflow of saline solutions. According to the present state of knowledge, the best variant of how to deal with the radioactive waste emplaced in the Asse II mine is to retriev the waste.

### Morsleben

The Bartensleben rock-salt mine near Morsleben, in Saxony-Anhalt, was between 1994 and 2000 a federal repository for low- and intermediate level radioactive waste with rather low concentrations of alpha-emitting radionuclides. The repository is located at 500 m depth. During its operation, the Morsleben repository accepted low-level waste and certain categories of intermediate-level waste, derived primarily from NPPs and from hospitals, industries, etc. No heat-generating intermediate level waste was disposed of at Morsleben. The waste originating from NPPs is mainly miscellaneous trash, evaporator concentrate and spent ion exchange resins, and compacted waste. The waste derived from other generators consists of miscellaneous trash, compacted waste, evaporator concentrate or solutions, and disused radioactive sources. The waste packages usually consist of 200 to 600 l drums, containing solidified or compacted waste. The packages are stacked in layers. When the emplacement room is filled with waste packages, the remaining space is backfilled with lignite filter ash. When the disposal was stopped in 2000, a total volume of 37,000 $m^3$ of solid and solidified waste and 6,700 sealed radiation sources had been disposed of in the Morsleben repository.

### Konrad

When the former iron mine Konrad was closed due to unprofitable mining, it became investigated as a possible host for a repository for radioactive waste. The geo-scientific investigations showed that this was the case. The area for disposal is 800 to 1,300 metres depth. The rock above has a layer about 400 thick, consisting of different clay stones acting as a natural barrier. The iron mine was in operation for a limited time, which is why there are few cavities and the rock is stable. The local government granted the plan-approval decision (licence) in 2002. This was confirmed by the superior court in 2007. It is the first repository to be licensed according to nuclear law in Germany. It is planned to be in operation in 2019, receiving low- and intermediate level radioactive waste.

## A12 Hungary

Commercial utilisation of nuclear power in Hungary started in 1983 and by 1987 there were 4 nuclear power units connected to the electricity grid. Currently, the solid and liquid LLW/ILW wastes arising from operation of the nuclear power plant are processed and stored temporarily at the plant waiting for a geological repository to be built. The repository for operational and decommissioning LLW and short-lived ILW of NPP origin will be located near the village of Bátaapáti, some 60 km south of Paks NPP. It will be constructed at a depth of 200–250 m below the surface, at 0–50 m above sea level, in granitic bedrock. The waste will be in the form of compacted solids or cemented liquid in metal drum with an overpack of reinforced concrete complemented with a backfill layer.

Hungary also has the Puspokszilagy Radioactive Waste Treatment and Disposal Facility. The repository is a near surface facility for low and intermediate level institutional waste. The facility is constructed at a depth of about 6 m below ground level and has a total capacity of about 5,000 $m^3$. The facility has both concrete lined vaults and boreholes located inside a concrete monolithic structure lined with stainless steel for disposal of spent radiation sources.

## A13 India

India has a flourishing and expanding nuclear power program and expects to have 20,000 MWe nuclear capacity on line by 2020 and 63,000 MWe by 2032. It aims to supply 25% of its electrical energy production from nuclear power by 2050. India has extensive and varied experience in the operation of near surface disposal facilities (NSDFs) in widely different geohydrological and climatological conditions. As a national policy, each nuclear facility in India has its own NSDF. There are seven NSDFs currently operational within the country e.g Trombay, Tarapur, Kakrapar, Rajastan, Kalpakkam and Narora. The waste is mainly packed in steel drums, concrete containers, cartons or polyethene bags depending on its origin and nature is stored either in unlined earth trenches or in concrete lined trenches.

## A14 Japan

Commercial utilisation of nuclear power started in 1966 and there are around 50 nuclear power units in operation and some have been closed for decommissioning. In Japan, the disposal of low-level radioactive waste has taken place since 1992 at the Rokkasho low-level radioactive waste disposal centre at Rokkasho-mura. The disposal site is located on marine terraces about 30–60 m above sea level. The bedrock at the site is Tertiary sandstone and tuff. The types of waste disposed of at the Rokkasho facility consists mainly of low- and intermediate level waste. Specifically, the waste comprises liquid waste concentrates, spent ion exchange resins, filter sludges, and other types of operational waste generated by Japan's NPPs. The facility design consists of two areas of disposal in reinforced concrete vaults. The inside of the disposal pits are lined with porous concrete, which allow water to drain away before it comes into contact with the waste drums. The ultimate disposal capacity of the facility is 600,000 $m^3$, which corresponds to 3 million drums of 200 l capacity. Inspection tunnels are constructed around the disposal pits to collect and monitor water discharge. The closure plan includes restoring the trench area to its original topography and re-establishing the native vegetation. Post-closure monitoring will be carried out. The institutional control period is supposed to last between a few tens and three hundred years. At the end of institutional control, unrestricted access to the site is presumed.

## A15 Latvia

Institutional waste is disposed of in the Baldone repository, a "Radon" type disposal facility from when Latvia was a state in the Soviet Union. It has been in operation since 1963 and by 2004 held about 800 $m^3$ of waste. It was then still in use for disposal although on a very small scale.

The Baldone facility is situated in a hilly terrain, about 60 m above sea level. Geologically the site is characterized by quaternary deposits of interbedded lacustrine, fluvioglacial and glacigene sediments of sands and clay, overlaying dolomite and gypsum layers. No surface geological processes, such as erosion, landsliding or weathering are known at the disposal site and in its close vicinity. However, during its operation, the disposal site presented evidence of karstic formation processes resulting in collapses at the surface. The groundwater table is maintained 10–25 m below level surface at the site. The groundwater level is 12 m below the repository structures.

Altogether there are six concrete vaults of varying dimensions with a total capacity of about 1,900 $m^3$. The barriers consist of concrete lining. In addition, there is an underground stainless steel tank for storage of liquid waste.

Caesium-137, tritium, nickel-63, cobalt-60 and strontium-90 represent the key radionuclides in the Baldone facility.

## A16 Lithuania

Lithuania has long experience of nuclear power production at Ignalina NPP from the at present closed two-unit RBMK-1500 nuclear power station in Visaginas, eastern Lithuania. Due to the plant's similarities to the failed Chernobyl Nuclear Power Plant in both reactor design and lack of a robust containment building, Lithuania agreed to close the plant as part of its accession agreement to the European Union. Unit 1 came online in December 1983, and was closed in December 2004. The remaining Unit 2 accounted for 25% of Lithuania's electricity generating capacity and supplied about 70% of Lithuania's electrical demand; it came online in August 1987 and was closed on December 31, 2009.

### Future repository for short-lived low- and intermediate level waste

Some 100,000 m$^3$ of conditioned short-lived low- and intermediate-level radioactive waste from the Ignalina NPP is to be disposed of in a near-surface repository with reinforced concrete vaults. Short-lived low- and intermediate-level radioactive waste is to be stored in the near-surface repository for at least 300 years. In accordance with the results of an environmental impact assessment study conducted in 2009, the repository is to be constructed close to Ignalina NPP. The design work is presently ongoing and the detailed design of the repository is planned to be ready in 2013.

### Maišiagala

The Maišiagala Radioactive Waste Repository was constructed in 1963 as a "Radon" type disposal facility in the former Soviet Union and was closed in 1989. It is situated 9 km away from the town of Maišiagala and 40 km away from Vilnius, in a hilly terrain (about 150 m above sea level) in the Baltic highlands. The bedrock consists of about 1,000 m of glacial sediments. The upper 100 m consists of sandy loam and clay loam from the quaternary period. The groundwater table is at an average depth of 5 m.

Radioactive wastes generated at industrial, medical and scientific research facilities were accumulated at the Maišiagala Repository. They were received not only from Lithuania but also from the Kaliningrad and Grodno Regions of the Soviet Union.

The Maišiagala Repository is a cast-in situ vault of 200 m$^3$ capacity. It is designed as one disposal vault subdivided into sections (constructed at a depth of 3 m). The walls and the bottom consist of reinforced concrete, the bottom is covered with bitumen and two layers of rubber. The outside walls of the vault are also covered with bitumen. Radioactive waste used to be placed into the vault and then covered with liquid concrete. The concrete absorbs and contains radionuclides as well as prevents water from leaching into them from the waste and transferring elsewhere. Storage facilities of this type were constructed at numerous sites of the former Soviet Union and Eastern Europe.

Waste types accepted at the facility were institutional waste from hospitals, industries and research centres. The waste consisted of neutralizers of static electricity and targets of neutron generators, a variety of chemicals, sources of gamma radiation with their biological shielding, different isotopic instrumentation with beta sources, blocks of gamma relay, radium salts, radioactive light emitters, smoke detectors, ionizing radiation sources, high-activity gamma sources. Spent sealed sources (with biological shielding) were packaged in stainless steel containers, each with a volume of 10 litres for disposal. Shielded sealed sources were disposed of without packaging.

The main radionuclides in these wastes are tritium, carbon-14, chlorine-36, cobalt-60, strontium-90, caesium-137, europium-152, radium-226 and plutonium-239. Tritium represents a large fraction of the activity inventory.

In 1989 the decision was taken to close the repository as it did not meet modern environmental protection requirements. The wastes there were not sorted, i.e. long-lived and short-lived wastes used to be accumulated in the same place. In accordance with modern requirements wastes of each type must be disposed of separately, in special packages and in expressly constructed repositories. At the time of closure about 60% of the facility was filled. The remaining space was filled with sand, covered with concrete, bitumen, asphalt and a thick layer of soil.

Today, the facility is owned by the Lithuanian Radioactive Waste Management Agency (RATA).

Monitoring wells were drilled around the facility to sample groundwater on a quarterly basis. Tritium has been detected in the water samples. Very low activities of caesium-137 have also been detected.

## A17 Mexico

Mexico has an installed nuclear power production capacity of 1,300 MW(e) from the two BWR units of Laguna Verde NPP. The LLW generated is treated, conditioned and interim stored at the NPP site. Radioactive wastes arising from medical, industrial and research activities (e.g. from the TRIGA Mark III research reactor) are treated and conditioned at the ININ radioactive waste treatment facility and stored temporarily at the radioactive waste storage centre (CADER).

At present work is ongoing to design a new final repository for LLW in the country.

## A18 Moldova

Moldova does not have any nuclear power production. The country has a facility in Chisinau for disposal of solid waste and spent radiation sources from medical and industrial applications. The total capacity of the facility is 900 $m^3$ divided into four disposal vaults. The bottom and walls of the vaults are lined with concrete.

The key radionuclides disposed of in the Chisinau facility are caesium-137, chlorine-36, plutonium-239, radium-226, cobalt-60, thorium-230, strontium-90 and carbon-14.

## A19 Norway

Norway does not have any nuclear power plants. The radioactive waste is generated from the operation of the Institute for Energy Technology's (IFE) two research reactors, IFE and other research institutes, hospitals and the oil industry.

The Himdalen facility for disposal and storage of LILW has been in operation since 1999 and is expected to be in operation until 2030. It will take care of all Norwegian LILW, including waste that will be generated during the decommissioning of IFE's nuclear facilities. The capacity of the facility is approximatel 2,000 $m^3$ (10,000 drums of 210 l). The total radioactivity inventory will be approximately 570 TBq.

The Himdalen facility is built into a hillside in crystalline bedrock. It has four caverns (halls) for waste packages and one slightly inclined 150-metre long access tunnel for vehicles and person-nel. In each cavern, two solid sarcophagi have been constructed with concrete floors and walls. Three caverns will be used for waste disposal, with drums and containers stacked in four layers. When one layer in a sarcophagus section has been filled with waste packages, it will be encased in concrete.

The rock caverns are excavated in such a way that about 50 metres of rock covering remains. This natural geological covering is for protection against intruders, plane crashes and other untoward events, although it is not intended to act as a main barrier in long-term safety calculations. Long-term safety will rely on the engineered barriers.

The engineered barriers comprise concrete floor, roof and walls, and a waterproof membrane affixed to the roof.

All the caverns and the access tunnel have a monitored water drainage system. A service and control room with service functions for personnel and a visitor's room are located along the tunnel.

One of the caverns is used for storage for certain waste packages (old, retrieved waste packages containing some plutonium). The decision on whether to retrieve the waste in the storage cavern or dispose of it by encasing it in concrete will be made on the basis of experience during the operational period and the safety reports to be prepared for closure of the facility, expected about 2030. There are no plans to retrieve any of the waste placed into the storage facility during operation.

The radionuclide inventory in the Himdalen repository mainly constitutes tritium, caesium-137, cobalt-60 and strontium-90 (Jan 2005).

## A20 Pakistan

Pakistan has a small nuclear power program, with 725 MWe capacity located at two sites (Karachi NPP and Chashma NPP), but plans to increase this. However, because Pakistan is outside the Nuclear Non-Proliferation Treaty, due to its nuclear weapons program, it is largely excluded from trade in nuclear plant or materials, which hinders its development of civil nuclear energy.

The Pakistani nuclear power plants are owned and operated by Pakistan Atomic Energy Commission (PAEC). The low level solid waste arising from nuclear power production is stored in concrete trenches located in an isolated area near the plants. The trenches are capped and their surface is regularly monitored for any activity.

Waste from nuclear research reactors (operated by Pakistan Institute of Nuclear Science & Technology, Pinstech) is disposed of at the Pinstech facility which is a near-surface disposal facility of trench type, located about 20 km southeast of Islamabad. The bedrock at the Pinstech site consists of sedimentary rocks, composed of fine-grained sandstone, overlain by a varying thickness of alluvium. In the past, there were no engineered barriers, but since 1998 the trenches have been lined with brick.

When a trench is full, it is covered with a layer of clay. The trench cap is prepared to facilitate water run-off. There are also ground seepage pits. The area around the seepage pits is controlled and monitored. Shielded trenches, located in the storage area, are used for interim storage of intermediate level waste, including spent radioactive sources.

A national repository for low- and intermediate-level wastes is due to be commissioned in Pakistan by 2015.

## A21 Poland

Poland does not have nuclear power production. Institutional waste is disposed of in the Różan facility, a surface type repository commissioned in 1961. By 2004 it contained a waste volume of 2,800 $m^3$.

## A22 Romania

Romania has nuclear power production at the Cernavodă NPP with a current total installed capacity of two 700 MW reactors of Canadian CANDU type (plans exist for expanding the NPP with two 750 MW reactors, also of CANDU design).

Cernavodă Nuclear Power Plant has its own handling and storage facilities, the most important being: a storage facility for low level waste, a cellular storage facility for intermediate level waste, a storage facility for spent filter cartridges and a dry spent fuel storage facility.

Currently, the radioactive waste resulting from the operation of Cernavodă NPP is stored within the Intermediate Storage Facility for Radioactive Waste (DIDR). Work for a repository for low- and intermediate level waste is currently ongoing and in the stage of site authorization.

### Baita-Bihor

The Baita-Bihor facility is designed to receive institutional low- and intermediate level waste, containing solid and liquid waste and some animal carcasses. The site is situated in the Northwest Carpathian Mountains. The repository is situated in an abandoned uranium mine at 840 m above sea level. The waste is packaged in 220 litre steel drums. The total capacity of the facility is 21,000 drums (4,200 $m^3$) in total volume. Additional galleries could be dug in the future thereby extending the disposal capacity up to 40,000 $m^3$.

The Baita-Bihor repository consists of two galleries at depths of 840 and 870 m. Disposal caverns are excavated transversally to the central gallery. Bentonite is used as filling material between the drums and cementitious backfill as cover material.

## A23 Russian Federation

Russia’s nuclear programme is extensive and ongoing since the 1940ies, including military use and research in addition to civilian use. The waste derived from Russian nuclear activities is therefore diverse and in many cases complex.

Management, disposal of radioactive waste from medical, scientific and technical facilities are carried out at so-called “Radon” facilities. The “Radon” facilities were not originally intended to handle waste from nuclear power plants, however, there are exceptions. There are 16 “Radon” facilities in Russia, most of them still in operation but some are closed but not decommissioned. All were commissioned during the 1960ies and are of similar type in design. “Radon” facilities are near surface facilities with trenches for solid waste, tanks for liquid waste and storage vaults or containers for spent radiation sources, which are long-lived and highly radioactive. The activity at the “Radon” sites is mainly formed by caesium-137, strontium-90, cobolt-60 and tritium.

The trenches are usually constructed of monolithic reinforced concrete with bitumen waterproof lining, covered from above with concrete plates of 30 cm thickness. Wall and bottom thickness is around 30–50 cm.

The barriers of the repository are formed by the waste matrixes, packages, backfill, walls, bottom and sealing, and a cap for closed units. A removable hangar is used during the operational stage to protect the vault against atmospheric precipitations.

In some cases, the disposal licence has been changed into so-called “long-term controlled storage”.

## A24 Slovakia

Slovakia has four nuclear reactors generating half of its electricity and two more under construction. Prior to its acceptance into the European Union, Slovakia shut down two of its older reactors at Bohunice. Radioactive waste is generated by nuclear power production and by the use of radioactive materials in medical, research and industrial institutions.

A treatment and conditioning plant for low- and intermediate-level wastes is operated at Bohunice, and a near-surface repository (the National Radioactive Waste Repository) at Mochovce began operation in 2001. It is a vault type repository with engineered barriers. The sides and bottom of each row of vaults are covered by a layer of compacted clay. There is a gravel drainage on the bottom. At the top, vaults are covered by hydro-insulation coating. The total capacity of the Mochovce facility is 22,000 $m^3$. Waste types accepted at the facility are waste from operating NPPs, decommissioning waste from shut down NPPs, and institutional waste. The main part of the wastes comprises concentrates from the NPPs in the form of bituminized products and solid wastes from the NPPs conditioned through high-pressure compaction.

## A25 Slovenia

Slovenia operates the Krško nuclear power plant, a one-unit 696 MWe pressurised water reactor (PWR) connected to the grid in 1981 and co-owned with Croatia. The reactor supplies 25% of the country’s electricity demand.

There is a central interim storage of radioactive waste in Brinje, which is operated by the agency for radwaste management (ARAO). It is used for interim storage of radioactive waste from industry, research and medicine.

Work with the realisation of a final repository for LILW is currently ongoing in Slovenia (according to the original plan it should be operational by 2013). It will be a modular design repository and the expected waste streams are:

- Operational short-lived LILW from Krško NPP.
- Krško NPP short-lived decommissioning LILW.
- Research reactor short-lived decommissioning LILW.
- Institutional short-lived LILW.

## A26 Spain

Commercial utilisation of nuclear power in Spain started in 1968 and today there are eight nuclear power units connected to the electricity grid, providing a fifth of the country's electricity production. Spain has capacity for fuel fabrication for light water reactors.

Radioactive waste generation began during the 1950s with the use of radioactive isotopes in industrial, medical and research institutions. Most radioactive waste is however generated from operation and dismantling of nuclear power plants and small quantities from fabrication of fuel.

In 2008 about 28,000 m$^3$ of conditioned LILW was in storage in Spain of activity. Based on the current installed nuclear capacity and power plant life-time (40 years) the total amount of LILW will be approximately 200,000 m$^3$.

Spain has since 1992 a centralised near surface repository in operation. The repository is located in the north west of part of the Córdoba province and has a total capacity of 100,000 m$^3$, which is sufficient until 2020. The El Cabril estate was used for uranium production in the 1950s and later on parts of it was used for waste storage. The El Cabril installations were extended by a modern disposal facility which was taken into operation in 1992.

The disposal concept is based on a multi-barrier system with the aim to isolate the steel drums containing the wastes that are stored inside concrete containers, which are allocated in the disposal vaults. All together there are two esplanades with 28 vaults. The vaults have bottoms of water-tight concrete. A drain control system exists in inspection galleries constructed beneath the disposal vaults. These vaults are protected from the weather during their operation by a metallic shelter, which also supports the handling crane. After completion of a disposal area, a multi-layer-engineered cap will be constructed to divert the rainwater and to provide long-term protection for the containers as well as to ensure their durability.

The wastes accepted comprise:

- Solid or solidified wastes (resins, filters, evaporator concentrates, filtration sludges) from the operation of nuclear facilities.
- Solid technological wastes (gloves, tools) from the operation and dismantling of nuclear facilities.
- Miscellaneous solids and liquids from the application of radioisotopes at radioactive industrial, medical and research facilities.
- Secondary solid or liquid wastes from the activities performed at El Cabril.

The site has a complementary facility for the disposal of very low level wastes where the wastes are stored in an orderly manner below a mobile roofing structure. The operation of it was initiated in 2008.

## A27 South Africa

Koeberg nuclear power station is the only nuclear power station in South Africa and the entire African continent. It is located 30 km north of Cape Town. During 1978 a programme to select a suitable site for the disposal of nuclear waste was commenced over large parts of South Africa. The programme leader had to keep a variety of socio-economic and geology-related parameters in mind. Pioneer investigations indicated that the Northern Cape was the most feasible area. Vaalputs is a near surface disposal facility with engineered barriers where low- and intermediate level radioactive waste from the Koeberg NPP is disposed. The facility has two disposal trenches with a total capacity of approximately 1,500 m$^3$. One trench is used for disposal of LLW in steel drums and the other for intermediate level waste in concrete containers. The trenches, about 400 m apart, are excavated in a clay-rich layer of about 20 m thickness overlying the granite bedrock. The closure plan calls for restoring the trench area to its original topography and re-establishing the native vegetation. Post-closure monitoring will be carried out. The institutional control period is supposed to last between a few tens and three hundred years. At the end of institutional control, unrestricted access to the site is presumed.

## A28 Switzerland

The main sources of radioactive waste in Switzerland are the nuclear power plants. There are 5 reactors in operation – 3 PWR (Beznau 1 and 2 and Gösgen) and 2 BWR (Mühleberg and Leibstadt) at 4 sites total around 3,200 MWe.

Apart from nuclear power production, radioactive waste also arises from the use of radionuclides in medicine, industry and research.

The amounts of conditioned low- and intermediate radioactive waste in storage in Switzerland by the end of 2005 is about 5,000 $m^3$. There are yet no radioactive waste disposal facilities in Switzerland.

Assuming an operation time of 50 years for the existing nuclear power plants a total volume of 85,000 $m^3$ of low- and intermediate level waste (including decommissioning waste) is expected to arise.

The responsibility for radioactive waste management lies with the waste producers. The legislation requires in principle disposal of Swiss radioactive waste in Switzerland. The option for the disposal of radioactive waste within the framework of a bilateral or multilateral project is kept open.

All radioactive waste is to undergo final disposal in repositories situated in suitable geological formations; near-surface disposal is not allowed. Two repositories are foreseen, one for mostly short-lived low and intermediate level waste and the other for high level waste and spent fuel as well as long-lived intermediate level waste, mainly from reprocessing. Prior to the realisation of the repositories, the feasibility of safe and permanent disposal has to be demonstrated.

Since there is currently no repository available, all radioactive waste is stored in interim storage facilities. The radioactive waste from medicine, industry and research is stored at the Federal Storage Facility. Radioactive waste returning from reprocessing abroad is stored at the Central Storage Facility.

### Geological repository for low- and intermediate level waste

The Nuclear Energy Act specifies that low- and intermediate-level waste has to be disposed of in a deep geological repository. The facility will have caverns capable of accommodating a volume of around 100,000 $m^3$ of packaged waste.

A vertical shaft or a tunnel will provide access to the disposal caverns, located at a depth of 300 to 500 metres. The caverns can be completely backfilled after several decades. Once the main repository has been closed, the behaviour of the safety barriers can continue to be monitored in the pilot facility.

The repository for low- and intermediate-level waste will have four different safety barriers: three engineered and one geological.

The waste will be solidified in a matrix and enclosed in drums (first engineered barrier).

Several of these drums will be placed in concrete containers which are filled with cement (second engineered barrier).

The concrete containers will be stacked on top of and adjacent to one another in large caverns and the spaces between the containers will be backfilled with a special mortar (third engineered barrier).

Together with the overlying formations, the host rock will form the geological barrier.

## A29 Taiwan

There are currently five nuclear reactors operated at three sites in Taiwan. Liquid and gaseous wastes are stored at the reactor sites for short periods to allow for decay of short-lived radionuclides and are then disposed of to the atmosphere and sea. Solid wastes, which are split into dry-active and wet wastes, are cemented and drummed. In the past, drummed LLW from the NPPs was sent for interim storage to a covered shallow trench facility at Lan-Yu Island, which has been in operation since 1982. The capacity of that (98,112 drums), was fully utilised by 1997. It had originally been planned to extend the Lan-Yu facility, but after intense public opposition, the government announced in July 1996 that this would not happen. A site still has to be found, and no waste has yet been moved from Lan-Yu.

## A30 Ukraine

In Ukraine, in addition to the shut-down Chernobyl NPP, there are currently four nuclear power plants in operation. The country also has facilities for nuclear research and operational uranium mines.

There are six State Interregional Special Plant (SISP) facilities for management of radioactive waste in Ukraine. They are specialized regional utilities of "Radon" type and are located near the cities of Kiev, Donetsk, L'vov, Odessa, Dnepropetrovsk and Kharkov.

The "Radon" repositories are designed mainly for low- and intermediate waste disposal. All operating repositories for solid waste at the "Radon" utilities are near-surface concrete vaults with concrete covers above ground.

Regarding barriers, the trenches for solid waste are of reinforced concrete; storage tanks for liquid waste are made of stainless steel and coated with reinforced concrete; Storage facilities for high-level spent ionizing radiation sources are made of stainless steel and are concreted at 6 m depth.

The Kharkov, L'vov, Odessa and Dnepropetrovsk SISP utilities accept low- and intermediate level solid waste for disposal. The Kiev SISP accepts solid low- and intermediate level waste only for interim storage. Liquid radwaste is accepted only by the Kharkov and Kiev specialised utilities. Liquid wastes are temporally stored, and their treatment is performed only by Kharkov utility with cementation technique.

A "Radon" facility typically includes trenches for solid waste disposal, tanks for liquid waste, tanks for biological waste, and vaults for spent radiation sources.

## A31 United States of America

According to NEA, the United States had 104 nuclear power plants connected to the grid in 2009, with an electricity generation of approximately 800 TWh (net). This corresponds to 20% of the total electricity production in the country.

U.S. legislation has established roles for a number of different organizations for the management, disposal, and regulation of low-level radioactive waste as follows:

The Department of Energy (DOE) is responsible for and performs most of the low-level radioactive waste management activities for government-owned and generated waste located, for the most part, on government-owned sites. In addition to managing waste onsite, DOE also operates its own disposal facilities.

The Nuclear Regulatory Commission (NRC) is responsible for regulating the safety of private sector and non-DOE governmental activities, including all aspects of LLW management and disposal.

The Environmental Protection Agency (EPA) is responsible for the regulation of the hazardous component of mixed waste, i.e. waste that contains both hazardous chemicals and low-level radioactive waste.

At the end of September 2007, a total of about 13 million $m^3$ of LLW and mixed LLW (MLLW) had been disposed of in the United States. Of this total, about 4.4 million $m^3$ of commercial LLW and MLLW has been disposed of at commercial disposal facilities. The remaining 9 million $m^3$ of DOE-owned LLW and MLLW have been disposed of at DOE sites, with a majority of the volumes resulting from cleanup activities.

Various states have banded together in so-called low-level waste compacts, with a plan to have one disposal facility per compact.

DOE low-level waste is stored at generator sites while awaiting treatment and disposal. DOE currently operates low-level waste disposal facilities at six sites. There are also three commercially available LLW disposal sites, with an application submitted for a fourth regional facility (in Andrews county, Texas). DOE waste generators without an onsite waste disposal facility ship waste to a DOE operating site for disposal and in some instances to commercial facilities when practical and economical.

There are a number of disposal facilities for LLW in the U.S., as shown in Table 3-1 in Chapter 3 of this report. They are all near-surface, trench type repositories with or without engineered barriers.

There are two low-level disposal facilities that accept a broad range of low-level wastes. They are located in Barnwell, South Carolina, and Richland, Washington. In addition, Envirocare of Utah is licensed by the NRC to operate a facility near Clive, Utah, for disposal of uranium and thorium mill tailings and decommissioning waste.

Four former low-level radioactive waste disposal sites are closed and no longer accept wastes. They are located in or near Sheffield, Illinois; Morehead, Kentucky; Beatty, Nevada; and West Valley, New York.

At closure, the low-level wastes will be buried under several feet of soil in near-surface shallow trenches, usually in the containers in which they were shipped.

## A32 United Kingdom

The United Kingdom has more than 20 nuclear power reactors. Radioactive wastes arise from the generation of electricity in nuclear power stations and from the associated fuel cycle, from use of radioactive materials in industry, medicine and research, and from military nuclear programmes. Most LLW is disposed of at the Low Level Waste Repository (LLWR) near Drigg in Cumbria. The waste consists of slightly radioactive trash, such as paper, packing materials, protective clothing, electric cables, scrap metals and tools, as well as reactor wastes and other materials. The majority of the waste disposed of at LLWR originates from the Sellafield Works and some from the UK Atomic Energy Agency. The facility comprises trenches and vaults. The original concept of disposal in trenches involved packaging of waste in 200 l steel drums or in paper sacks, or individually wrapped in strong, impermeable packaging material. For vault disposal, new waste packaging (introduced in mid 1990s) is based on high-force compaction of the waste, emplacement in 20 $m^3$ steel containers and grouting of the void space within the container to form a solid product. For the trenches, a final cap with a clay layer, acting as a low-permeability barrier, is to be installed prior to site closure. For the concrete vaults, after completion of the operational phase, the vaults will be capped with a multi-layer structure and drainage layer, which includes low-permeability materials to divert infiltrating rainwater away from the vault.

## A33 Vietnam

Vietnam has a near surface repository located at the Dalat Nuclear Research Institute. The main source of waste is derived from the Research Complex, which generates a wide variety of low-activity waste, including spent sealed sources, spent ion-exchange resin, used air filters of exhaust ventilation, irradiated samples or containers, and contaminated clothing, tissues, glassware. The facility comprises eight pits with concrete walls and bottom and concrete slabs on the top of pits. The oldest wastes is unpackaged (1984–1992) but, thereafter the wastes are conditioned or compacted prior to packaging in 200 l steel drums.

# Appendix B

## Safety assessments for some selected repositories

### B1 El Cabril, Spain

Doses are calculated for the normal evolution scenario, accidental releases and intrusion scenarios. Calculations were performed for a time period of up to 100,000 years after closure. Infiltration of rain water is assumed to occur directly after closure of the repository. A stream in the vicinity constitutes the interface between the geosphere and biosphere for the normal evolution scenarios. Exposure due to intrusion is considered. Having a residence just above the repository or constructing a road gives the highest exposures, but below the dose criteria. The calculated doses are based on exposure of a minor group living in the vicinity of the repository and using water and food locally produced. The assumptions for exposures were constant over the time period considered.

Maximum doses occur within the period from 100 to 10,000 years. In general, three ranges of doses were obtained in various time intervals. After closure to 100 years the maximum radiological impacts vary within the upper and lower bounds $10^{-7}$ and $10^{-8}$ Sv / year, respectively. Thereafter to 10,000 years, the levels would be in the order of the order of $10^{-5}$ and $10^{-7}$ Sv / year. For times over 10,000 years the maximum effective doses vary from $10^{-6}$ to $10^{-8}$ Sv / year.

The calculated doses obtained in the short-term after closure, are due to radionuclides with no retention in the engineered barriers and a short half-life. Doses obtained during the second phase, after the complete degradation of engineered barriers, are largely due to the radionuclides having low values for their distribution coefficient[2] (on the engineered barriers) and an intermediate or long half-life, such as Sr-90, Mo-93, Tc-99 and Cs-137. The third phase, long time after closure, immobile radionuclides with high values of distribution coefficient and/or long half-lives such as I-129, Pu-239, Ni-59, Nb-94, U-234, U-236 and U-238 dominate.

### B2 l´Aube, France

For the assessment of the impact of a near surface repository in France, Andra refers to a basic safety guide (RFS 1.2). This basic safety guide prescribes that at the end of the monitoring period that should be no more than 300 years safety should no longer rely on the manmade barriers but on the properties of the site. Therefore Andra considers in its assessment the different phases of the life of the repository: operation phase, institutional control phase and post institutional control phase. At the beginning of the post institutional phase it is assumed that the memory of the facility is lost, and that the engineered barriers are no longer watertight. Scenarios are considered that include both normal situation and abnormal situations (intrusion for instance). They take into account water transfers and air transfers (re-use of materials of the disposal site) and they assess the impact on critical groups.

The maximum calculated impact occurs, according to the model, in the first hundred years in the post institutional control period, and is the consequence of mobile nuclides including I-129, Cl-36, Tc-99 or C-14. The calculated doses are in the range of a few tens of microSieverts with the described assumptions. Later the impact may be provided by Cs135 and calculations are performed for a few tens of thousands of years, just to check if there may be additional contributors to the impact, even if this time scale is not relevant for the disposal for short lived waste.

Other radionuclides may contribute to the impact as alpha emitters, Cs137, Nb 94 in intrusion scenarios.

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[2] Distribution coefficient is used to describe the concentration of an element between solid and liquid phase [Bq/kg divided by Bq/m$^3$], high values represent high sorption.

## B3 LLWR: United Kingdom

The LLWR repository is to be permanently closed in year 2080. At present continuous measurements of leaching water and a controlled discharge to sea via the Marine Pipeline are carried out. This active collection and management will continue during operations and up to 100 years after final disposal. This period is called the authorisation period.

The siting of the repository at the coast means that the area is affected by erosion, making the shore-level to rise, of high importance for the long term safety.

Risks were therefore assessed for the four pathways:

- migration in groundwater,
- migration in gas,
- natural disruption and dispersion (coastal erosion),
- human intrusion.

Each of the pathways is analysed and modelled independently, taking account of the uncertainties for the defined scenarios and uncertainties related to the contaminant release, migration and exposure processes for each pathway.

The migration of radionuclides in groundwater exposes man either by a well, or gives additional exposure via the marine environment, such as an estuary or a stream. The exposure pathways considered are as shown below:

| **Pathway** | **Risks due to** |
|---|---|
| Well located between LLWR and the coast. | Use of contaminated water, a number of exposure pathways. |
| Marine | Time spent on the intertidal zone and to consume marine food products, in particular fish, molluscs, crustaceans and seaweed. The inadvertent ingestion of sea water and beach sediments is also considered. |
| Estuary | External exposure from the contaminated intertidal sediments on pasture and salt marsh.<br>External exposure from the estuary water, ingestion of soils and sediments.<br>Inadvertent ingestion of estuary water. |
| Stream | External exposure from the contaminated soils.<br>– Inadvertent ingestion of soils and sediments.<br>– Ingestion of contaminated animal products. |

When calculating the risk from the well scenarios the probability of having a well located in the discharge area from the repository was considered. The well caused the highest risk compared to the marine, estuary and stream receptors. Carbon-14 and chlorine-36 were the key radionuclides and the peak values occurred about 150 years after the planned closure (about 2080) years. The risk was $10^{-7}$ that is one tenth of the criteria.

Gas migration was of interest for carbon-14 and radon-222. Much effort was made to model the uptake of carbon in the vegetation, this being the most important exposure pathway for carbon-14. Under extremely conservative assumptions the maximum risk to a limited number of people was $4\ 10^{-5}$. The highest risk $10^{-6}$ for the coastal erosion pathway occurred about 1,500 years after closure.

For realistic and foreseeable human intrusion events, doses to the intruders and those exposed in the longer term as a result of prior intrusion events were calculated to be consistent with the dose guidance level in the range of 3 to 20 mSv per year.

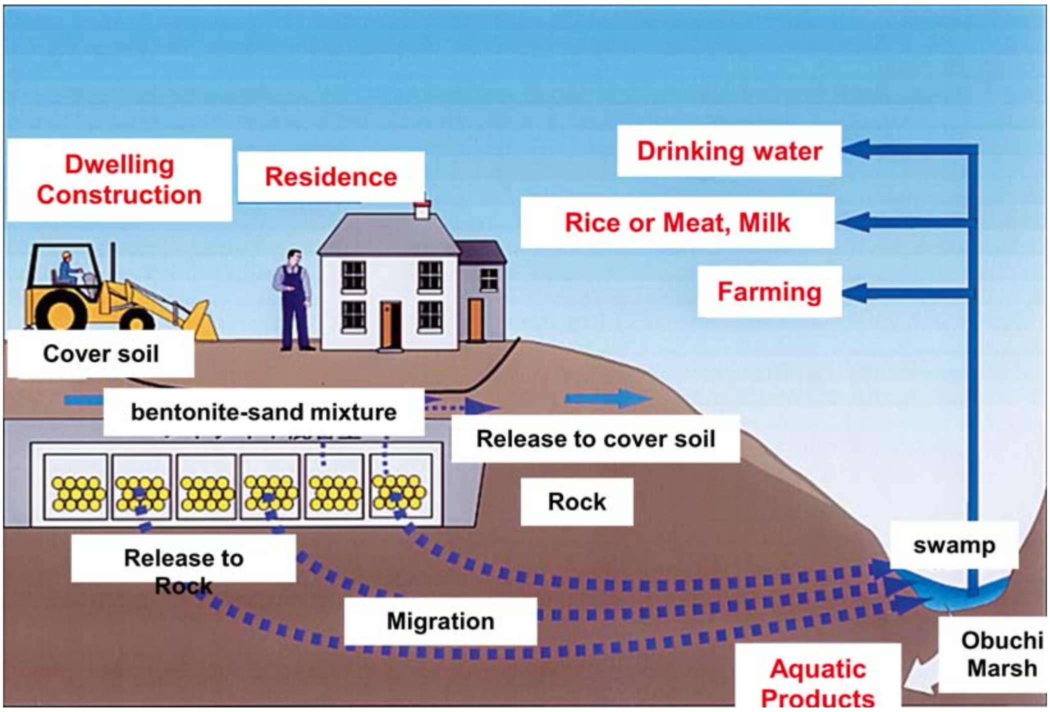

*Figure B-1. Illustration of exposure pathways for the dose assessments for Rokkasho.*

## B4 Rokkasho, Japan

Scenarios are considered for calculating the exposure to man from migration of radionuclides by groundwater, releases by gas or direct intrusion into the repository. The engineered barriers are considered to have lost their function after the three hundred years of institutional control.

The exposure pathways considered after the institutional control time are typical, exploring the area above the repository for residential purpose, using water and consuming aquatic foodstuffs from a minor swamp, see figure below. The biosphere conditions are constant over the time period considered. The water is used for irrigation of terrestrial foodstuffs. The main dose is from external exposure and consumption of drinking water, about 0,001 mSv.

In the low probability scenario a well is being dug is dug and the area above being heavily exploited for residence purposes the dose rate increases to about 0,003 mSv.

## B5 VLJ, Finland

The assessments for VLJ were performed by using 4 separate deterministic numerical models: groundwater flow model, near-field model, migration model and biosphere model. The groundwater flow model took landrise into account.

The assessments consider that the engineered barriers function fully during the first few hundred years. Thereafter the barriers start to degrade and the calculated safety after closure is based entirely on the influence of natural barriers. No active control is planned and the area around the repository is to be fenced to prohibit entrance.

Investigations of the bedrock carried out at the site from 1980 onwards gave input data for the groundwater flow analysis. New information was acquired in the course of the construction of repository.

In addition to the reference case, analyses were made of the flow regime in a situation after the degradation of the sealing structures, of an alternative sealing method in which a plug is inserted between the hall and the auxiliary rooms. Finally the effects of land uplift on the flow regime were considered.

Transit times for groundwater from the repository to reach the biosphere vary due to type of silo and local conditions, however in general all times are calculated less than 2 years for the silo with ILW and less than 50 years for the silo with LLW.

Sorption on the concrete and crushed rock is taken into account.

Radionuclides are assumed to be leached from the bituminization product over the course of 500 years, the concrete silo for the medium-level waste is assumed to degrade and crack and its structure to collapse after 5,000 years and the concrete is assumed to completely degrade also chemically in the course of 6,000 years in the reference scenario. The sealing structures of the facility are assumed to lose their performance in 12,000 years.

The only phenomenon causing retardation and dispersion that is taken into account in the migration analysis is matrix diffusion. All activity released from the repository is assumed to migrate along a flow channel towards the well and the biosphere.

The safety assessment includes a discussion of the probability of the location of wells in the drainage area of the repository.

The additional scenarios handled were:

- gas generation in the waste and overpack materials,
- early damage to the concrete silo as a result of an earthquake, or for instance, glaciation and other long-term phenomena,
- rare random events (meteorite impact, etc),
- human intrusion.

The maximum calculated dose for the reference scenario is 0.03 mSv/year, which is below the limit of 0.1 mSv per year. The realistic scenario, however gives an insignificant dose of 0.0002 mSv per year. These doses are due to use of water from a well drilled in the outflow area. Doses from the LLW silo occur much earlier in time (about 200 years after closure) than those from the MLW silo. The latter peak is about 15,000 years after closure and isotopes of plutonium dominate the calculated doses. Exposure from the inflow of radionuclides to lakes and the costal area are considerably lower than from a well when comparing the reference cases. For the realistic case the differences are much smaller.

## B6 Bruce, Canada

The low-permeability geosphere and shaft attenuate the release of contaminants, providing time for radioactive decay to decrease the activity in the repository. The calculated dose from the most expected case, the reference case is therefore totally insignificant giving an exposure, about $10^{-15}$ mSv per year. The maximum calculated dose as a result of all calculated cases is more than five orders of magnitude below the 0.3 mSv/year public dose criterion. (In general, peak doses to children and infants are within a factor of three of the adult dose.)

These results apply to a simplified biosphere with a hypothetical family assumed to be living on the site in the future, and obtaining all of its food from the area. The potential dose would decrease rapidly with distance from the site. For example, calculated doses to a “downstream” group exposed via consumption of lake fish and water from Lake Huron are more than three orders of magnitude lower than the dose to the family living on the site.

The major reason for the extremely low doses is due to the long time period it takes to fill the repository with water in the reference case. The radionuclides are contained within the repository and host rock, thereby limiting their release into the surface environment and their subsequent impacts. In the Reference Case calculations less than 0.1% of the initial waste activity is released into the geosphere around the repository, and much less is released into the shafts. Gases are contained within the repository and geosphere. The gas will be primarily methane in the long-term.

Higher doses are obtained from the so called “what if” scenarios” in similarity to the other assessments. The highest calculated dose is 1 mSv from intrusion into the repository. If considering the likelihood of intrusion the risk should be lower.

The assessment considered potential impacts through consideration of a range of possible future cases. The most detailed analyses were carried out for an expected evolution scenario (the Normal Evolution Scenario). However a lot of variation of certain conditions and assumptions are included as cases in this normal evolution scenario.

In addition four disruptive (“what if”) scenarios were also evaluated. These were:

- Unintentional intrusion into the repository as a result of an exploration borehole (the Human Intrusion Scenario).
- The unexpected poor performance of the shaft seals (the Severe Shaft Seal Failure Scenario).
- Poor sealing of a site investigation/monitoring borehole in close proximity to the repository (the Poorly Sealed Borehole Scenario).
- A hypothetical transmissive vertical fault in close proximity to the DGR footprint (the Vertical Fault Scenario).

The Normal Evolution Scenario Reference Case draws on the results of the site investigations and geosynthesis, and represents the site in the most detail. However, there were a number of variations considered and results calculated as variations to the normal evolution scenario.

## B7 SFR: Sweden

The Swedish regulations state that the following undertakings must be included in the safety assessment for SFR:

- “The annual risk of harmful effects after closure does not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk” resulting in a dose of $1.4\ 10^{-5}$ Sv/year.
- Describe the effects on biota.
- Show the consequences of intrusion.
- Provide more detailed assessment for the first 1,000 years after closure.
- Provide collective dose commitment integrated over 10,000 years from releases during the first 1,000 years.

The initial step in the long-term safety assessment for SFR is to identify all the factors that are important for the evolution of the repository and that should be studied in order to gain a good understanding of the evolution and safety of the repository. The method applied comprises a systematic identification and prioritization of processes and interactions between processes that act in the system followed by the assessment evaluation.

The ongoing shore-line displacement causes former coastal areas to become transformed into ground containing a fresh water system. Gradients for groundwater will also be steeper implying an increased groundwater flow with time. Ecosystem changes consequently with time.

In the safety assessments, which have been carried out at intervals since 1983, SKB has considered potential impacts through analysis of a number of possible developments in the repository. There is an expected “main scenario” where different possible and plausible variants have been taken into consideration.

In addition, the authorities require evaluation of some less probable scenarios and so-called “residual scenarios”, which are scenarios that are selected and studied independently of probabilities in order to shed light on the importance of individual barriers and barrier functions. The different scenarios are listed below:

- Main scenario:
  - Wechselian variant (reconstruction of the latest glacial cycle).
  - Greenhouse variant (taking increased greenhouse effects into account).

- Less probable:
  - Earthquakes.
  - Taliks during permafrost (discontinuities in the permafrost).
  - Increased content of complexing agents.
  - Earlier freezing.
  - Gas generated advection.
  - Intrusion (e.g. drilling of wells in the repository area).
- Residual scenarios (e.g. abandoned un-closed repository).

In the opinion of both SKB and the regulatory authorities, the first thousand years are the most important period and require the most detailed analysis, The presentation of the evolution of the repository has thus been divided into three time periods: i) the first 1,000 years after closure at 2,000 AD, ii) 3,000 AD to 20,000 AD and iii) 20,000 AD to 100,000 AD.

The outcome has been derived both as calculated doses and as a risk criterion defined as “the annual risk of harmful effects after closure does not exceed $10^{-6}$ for a representative individual in the group exposed to the greatest risk”. The term “harmful effects” means cancer and hereditary defects. According to the regulating authority, Swedish Radiation Safety Authority (SSM), this risk limit is equivalent to a dose limit of about $1.4 \cdot 10^{-5}$ Sv/year, which is about one percent of the natural background radiation in Sweden.

The results of SKB’s safety analysis after closure show that the radiological risk from the repository does not exceed $10^{-6}$ during the next 100,000 years.

The results from the calculation cases show that it is only a few nuclides that contribute to the highest doses. They also show that the doses during the first 1,000 years after closure are low, due to low releases of all radionuclides, except for organic carbon-14, to a brackish water area with good water exchange and large water volumes. Organic carbon-14 gives the highest flows of activity to the biosphere for most calculation cases. Radionuclides with half-lives shorter than 100 years do not make any significant dose contributions.

The collective dose commitment integrated over 10,000 years from releases during the first 1,000 years after closure shall according to Swedish regulations, also be calculated. The organic carbon-14 dominates and gives a collective dose commitment of about 8 manSv in the Weichselian variant.