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NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

# NWMO BACKGROUND PAPERS
# 6. TECHNICAL METHODS

## 6-3 STATUS OF GEOLOGICAL REPOSITORIES FOR USED NUCLEAR FUEL

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## NWMO Background Papers

NWMO has commissioned a series of background papers which present concepts and contextual information about the state of our knowledge on important topics related to the management of radioactive waste. The intent of these background papers is to provide input to defining possible approaches for the long-term management of used nuclear fuel and to contribute to an informed dialogue with the public and other stakeholders. The papers currently available are posted on NWMO's web site. Additional papers may be commissioned.

The topics of the background papers can be classified under the following broad headings:

1. **Guiding Concepts –** describe key concepts which can help guide an informed dialogue with the public and other stakeholders on the topic of radioactive waste management. They include perspectives on risk, security, the precautionary approach, adaptive management, traditional knowledge and sustainable development.
2. **Social and Ethical Dimensions** - provide perspectives on the social and ethical dimensions of radioactive waste management. They include background papers prepared for roundtable discussions.
3. **Health and Safety –** provide information on the status of relevant research, technologies, standards and procedures to reduce radiation and security risk associated with radioactive waste management.
4. **Science and Environment –** provide information on the current status of relevant research on ecosystem processes and environmental management issues. They include descriptions of the current efforts, as well as the status of research into our understanding of the biosphere and geosphere.
5. **Economic Factors** - provide insight into the economic factors and financial requirements for the long-term management of used nuclear fuel.
6. **Technical Methods** - provide general descriptions of the three methods for the long-term management of used nuclear fuel as defined in the NFWA, as well as other possible methods and related system requirements.
7. **Institutions and Governance** - outline the current relevant legal, administrative and institutional requirements that may be applicable to the long-term management of spent nuclear fuel in Canada, including legislation, regulations, guidelines, protocols, directives, policies and procedures of various jurisdictions.

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# Contents

# 1 Summary

The aim of this report is to give an objective appraisal of the development of the concept of geological disposal of radioactive wastes and of its status today. It is an overview document that has been prepared for a general readership. It addresses the key issues associated with geological disposal of used nuclear fuel and other high-level radioactive wastes. The depth of the treatment varies for two reasons. Firstly, some aspects are examined in more detail because they are of fundamental importance in geological disposal. A particular example concerns the issue of the siting of deep repositories. The second reason for treating some issues in more detail is that these are topical issues that reflect a raised level of interest in a general public. Some of the most topical issues are addressed in more detail in appendices A to D.

In an abbreviated form, the main text addresses the following issues:

- the need to protect humans and the environment from the hazards and the risks presented by radioactive wastes in general, and by used nuclear fuel in particular
- the strategies for minimising long term risks and the reason why this goal has led to the development of the geological repository concept
- the different technical, societal and economic challenges faced by a geological disposal programme.
- the description of the multiple safety barriers in a geological repository and of how they function
- the series of activities performed throughout the several decades for which a repository programme must run
- the status of geological disposal programmes in various nations around the world.
- the key challenges and outlook for further developments in the implementation of geological repositories.

The appendices are on:

- the nuclear fuel cycle and the hazards associated with its wastes
- the ethical basis underlying geological disposal
- the procedures for assessing long-term safety of repositories
- the diversity of views held by different societal groups on the feasibility of safe geological disposal

- the topical debate on retrievability of wastes from geological repositories.

Sufficient references are given throughout the report to allow specific issues of interest to be followed up further. In addition, the following overview books or reports are listed as a guide to the entire field of geological disposal: Chapman and McKinley 1987, Savage 1995, NEA 1999b, Witherspoon and Bodvarsson 2001; NRC 2001, Chapman and McCombie 2003.

# 2 Development of the Concept of Geological Disposal

## 2.1 Radioactive materials like many other materials produced by society are potentially harmful and must be properly managed

Radioactive wastes are a by-product of the fuel cycle used in nuclear power production, but also in other activities such as defence programmes, medicinal and industrial applications of nuclear technology and research. The wastes with which this report is directly concerned are the used fuel that is unloaded from reactors (if this fuel is to be treated as waste) and the highly active residues that result if the used fuel is reprocessed.

All radioactive wastes present a **potential hazard** to human beings and the environment. Direct exposure to any intense radiation emitted can cause immediate harm to living creatures and ingestion or inhalation of radioactive isotopes into the bodies of human beings can be harmful even at low concentrations. A potentially hazardous radioactive substance will, however, result in an actual **radiation dose** to persons only if there is a credible chain of events (a scenario) that can allow the radioactive isotopes in the waste to be transported to man. The **risk** associated with this scenario depends not only on the potential danger posed but also on the likelihood of events occurring that may result in exposure to radiation .Therefore, to quantify the associated risk, we also need to estimate the probabilities to all the process and events involved in the description of scenarios that could result in man being exposed to. . To use a simple example, the consequences of being hit by lightning are almost always very serious; however, the risk to the public of dying from a lightning strike is small because of the low probability of being hit.

In any discussion on hazards and risks, it is also important to appreciate the differences between the **perceived** hazards and the **actual** objective risks to humans. Perceived risks are commonly higher than the actual risks for events like the lightning strike mentioned above; they are often lower than the actual statistical values for common events like traffic accidents. For radioactive wastes, as we shall see below, the risks of persons being exposed to radiation can be estimated quantitatively. The health risk resulting from exposure to radiation has also been quantified. For the low radiation doses with which we shall be dealing the health risk is not directly measurable. It must be derived by extrapolation from results of the statistical records of persons who have been exposed to much higher doses (in accidents or bomb survivors). Human perception of hazards or risks, on the other hand, is subjective and can not be directly measured; it can be assessed only by soliciting opinions or by observing how human behaviour patterns are influenced by these opinions. People tend to focus more on the consequences of events than their probabilities. Events with dramatic consequences are more likely to capture their attention, even if the probabilities are low.

It is a well known fact that radioactivity has associated with it a highly significant "dread factor". This may originate in the nuclear weapons background or may, as claimed by Weart in his book, "Nuclear Fear. A history of images " (Weart 1988) be an older and more basic reaction to dangers which "cannot be seen or heard or smelled". This fear of radiation in general is carried over to radioactive wastes, in particular. It affects all aspects of radioactive waste management. The present report, however, restricts itself largely to considerations of the quantifiable and objective hazards associated with the wastes. This narrowing of focus in no way reflects a view that subjective fears of the public are not to be taken very seriously by repository implementers and regulators. On the contrary, the entire progress of any waste disposal project is strongly influenced by how successfully communication between involved parties takes account also of such concerns.

Because of the harm that they can potentially cause, radioactive materials must be isolated from the human environment. There are different strategies that can be employed for safe management of wastes. The three main options are often labelled:

- Reduce and Recycle (RR)
- Dilute and Disperse (DD)
- Concentrate and Confine (CC)

Reducing or even avoiding wastes is obviously the ideal course to follow. Ultimately, however, all industrial processes produce some wastes. In practice, radioactive wastes present a small fraction of the waste volumes produced by modern societies - but some of the radioactive wastes are extremely hazardous. The most hazardous fraction includes used nuclear fuel. The dilute and disperse strategy can be used only when dilution and dispersion of the radioactive isotopes will result in concentrations in water or air that are so low that they will certainly never cause harm. For some pollutants, such as the carbon dioxide gas and other effluents from coal or gas fuelled power stations, dilution in the atmosphere is still the common approach, although gaseous emissions are causing increasing concern associated with both respiratory illnesses and global warming. Throughout the nuclear fuel cycle, only a very small fraction of radioactive wastes are released to water bodies or to the atmosphere and even these small quantities are being continually reduced.

The management strategy that is most common for radioactive wastes is concentrate and confine, i.e. radioactive isotopes are separated out from non-active waste streams to the greatest extent possible and are then put into a physical and chemical form suitable for long-term confinement. The goals of this confinement are to protect against *external* radiation by shielding tha wastes, and to protect against *internal* radiation through ingestion (e.g. through drinking water) by limiting the release of radionuclides into the biosphere. If the period of confinement is sufficiently long, many radioactive isotopes can decay to insignificantly low levels. This strategy is practicable because the volumes of the wastes are very modest compared with most major industrial undertakings.

How long is "**long term**"? Here is where the challenge arises. Radioactivity reduces with time (unlike the permanent chemical toxicity of some materials such as heavy metals) and therefore one way to ensure safety can be to confine the wastes until the activity has decayed to negligible levels. Some radioactive wastes, however, including used nuclear fuel, will remain hazardous for hundreds of thousands of years, as illustrated in Figure 1. (after Hedin 1997), although the level of the hazard does diminish significantly with time. This spontaneous decay of radioactivity over long times is the characteristic of the wastes which led directly to the concept of geological disposal, as described in the following section 2.2.

It is important to note that some of the radionuclides – namely the fission and activation products decay relatively rapidly. The two dominating fission product nuclides at the start are Caesium-137 and Strontium-90; these both have half-lives of around 30 years so that in 300 years, the activity level has reduced by a factor 1000 and in 600 years by one million. Other important nuclides, however, have much longer half lives, for example Plutonium-239 with 24,000 years or Neptunium-237 with 2.1 million years

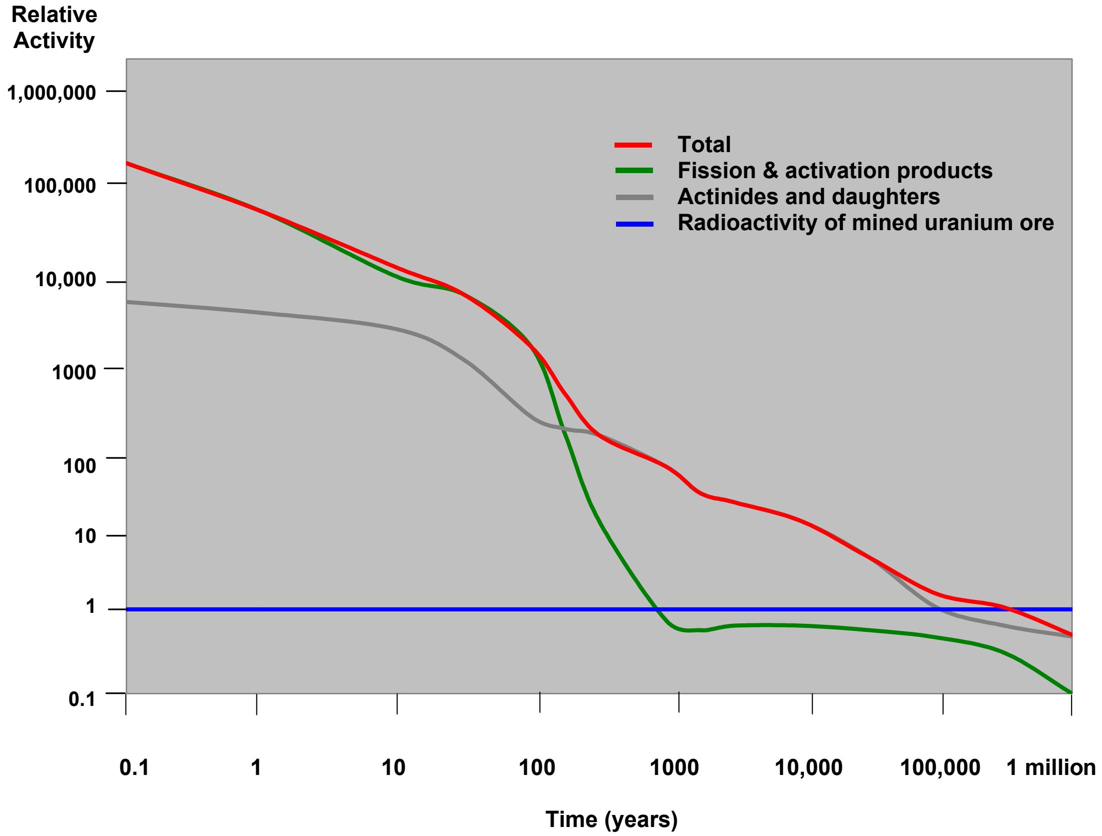

**Figure 1:** Decay with time of radioactivity in used fuel. The fission products that originally dominate the activity decay relatively quickly. With time the radioactivity level drop below those in the uranium ore originally mined to produce the fuel. However, the time for this decay is very long for some radionuclides, in particular the actinides.

## 2.2 Development of the geological disposal concept

Geological disposal was not (despite the assertions of some of its opponents) chosen as a "cheap and dirty" option to get the radioactive waste “out of sight and out of mind”. The concept of geological disposal is a logical consequence of the easily observable decay of radioactivity with time, which leads to a continuous reduction in toxicity of these wastes. Finite hazardous lifetimes (and low volumes of wastes) led to:

- development of concepts where environmental protection could be aimed at by **isolating wastes** from man's surroundings for long enough to allow such decay to occur and

- the search for environments which showed **sufficient stability** for the time periods involved - namely thousands or even hundreds of thousands of years.

There are not many environments for which we have evidence of their evolution and their stability over hundreds of thousands of years. Old, deep geological formations are the most obvious candidate environments that can be accessed with today's technology. Other options have, in fact, been considered. A comprehensive document on all these options was published already in 1974 (BNWL 1974). Concepts that have been examined (more than once) include disposal in space, under ice caps, in subduction zones, etc., but all have been judged infeasible or unsafe. Transmutation is still being studied in various countries. In the view of experts assembled by the US National Academies (NRC 1996), it may eventually change the nature or quantity of radioactive wastes to be disposed, but transmutation will not remove the need for geological disposal.

Consequently, concepts for geological disposal under the continental earth's crust have been developed over many years. Although the concept of disposal in deep geological formations was recognised by the US National Academy of Sciences as early as 1957 (NAS 1957) to be the most promising form of confinement for long-lived wastes from the nuclear fuel cycle, there is not yet any deep geological repository for used nuclear fuel or HLW in operation[1]. The task of implementing such facilities has proven more challenging than it was expected to be.

Nuclear power developers are often accused of having neglected the waste issue. Even a nuclear pioneer like Alvin Weinberg points, in his autobiography (Weinberg 1994), to waste disposal as the issue to which he wishes he had devoted more attention. The fact is, however, that what was neglected was more the social dimension of the waste disposal debate rather than the technical concepts and procedures for disposal. Already in the mid-fifties (i.e. 45 years ago) the topic was debated technically. In the second Geneva conference on the Peaceful Uses of Atomic Energy (1958), Joseph Lieberman could already record that *"much has been written in speculation regarding the impact, or lack thereof, of radioactive wastes on the development of nuclear technology. ..... it has been said that safe and adequate waste management is the major obstacle confronting the orderly economic growth of applications of the benefits of nuclear fission to medicine, agriculture and industry"*. In his paper, Lieberman assumed that geological disposal would be used for high-level radioactive wastes (HLW) or used fuel (also known as spent fuel – SF), but recognised that *"the feasibility of direct disposal ..... into selected geologic formations will be demonstrated only after extensive laboratory and field experiments, which are just now being initiated"*.

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[1] In the Waste Isolation Pilot Plant (WIPP) in New Mexico, USA, which is an operating deep geological repository in a salt formation, the inventory does not include used nuclear fuel or HLW.

It is doubtful, nevertheless, whether Lieberman realised in 1958 just how extensive the work would become, driven in part by the increasing societal pressures on waste disposal programmes to demonstrate the potential feasibility and safety of geological disposal. Since then, billions of dollars have been expended on developing repository projects. Progress has been slower than expected but in the last 30 years there have been significant advances. These will be described below. Firstly, however, a descriptive outline of a geological disposal system is given in the following section.

# 3 Description of a geological repository system

## 3.1 Introduction

A geological repository system is intended to ensure that the radioactive materials it contains never return to the human environment in concentrations that might cause harm. Moreover, the repository should be able to provide this safety function without any active measures being taken by future generations. The radioactivity of all radioactive isotopes decays with time. Figure 1 shows that, for some of the most important isotopes, this decay ensures that they will never leave the repository, provided that they can be contained there for some hundreds of years. Some isotopes, however, are very long-lived so that absolute containment in the repository itself cannot be guaranteed for the many thousands of years that would be necessary. For most of those long-lived radionuclides that do not decay completely in the repository, however, subsequently decay will take place during their very slow transport in groundwater through the specially chosen rocks in which the repository is sited. Thus only a few very long-lived, mobile nuclides, such as Iodine-129, Chlorinie-36 and Caesium-135, are predicted to ever be able to return to the surface environment. These releases can occur only at far future times - normally estimated at hundreds of thousands of years - and never in concentrations that are significant compared to concentrations of naturally occurring radionuclides. How are these extremely long-term containment times and low levels of release achieved?

The answer is by enclosing the radioactive materials in a carefully chosen system of **multiple safety barriers**. Multiple barrier approaches are common in engineering (e.g. double hulled ships) and especially in nuclear engineering (e.g. in a nuclear power reactor). In repository systems, the same “defence in depth” philosophy can be applied - although the safety barriers, as we shall see below, must function in a complementary rather than a fully redundant fashion to provide the very long term protection aimed at. A typical safety barrier system for a used nuclear fuel repository is described below, with some representative examples of the specific choices made in different national disposal programmes.

Figure 2 is a generic sketch of a deep geological repository consisting of a series of tunnels accessed by vertical shafts. Individual waste packages are emplaced within the tunnels until all wastes have been disposed of and the tunnels and shafts are then backfilled and sealed. The safety barriers that contain the radionuclides or retard their transport back to the human environment are fuel or waste matrix, the fuel cladding, the disposal container, buffer material, backfilling and sealing materials, and the host rock. The last of these is often referred to by specialists as "the geosphere" or the "far-field"; whereas all of the technical safety systems inside the repository are referred to collectively as the "engineered barriers". The uppermost part of the system in which life is abundant ("the biosphere"), is not usually regarded as a barrier although important safety-relevant processes affecting any released radionuclides do take place there.

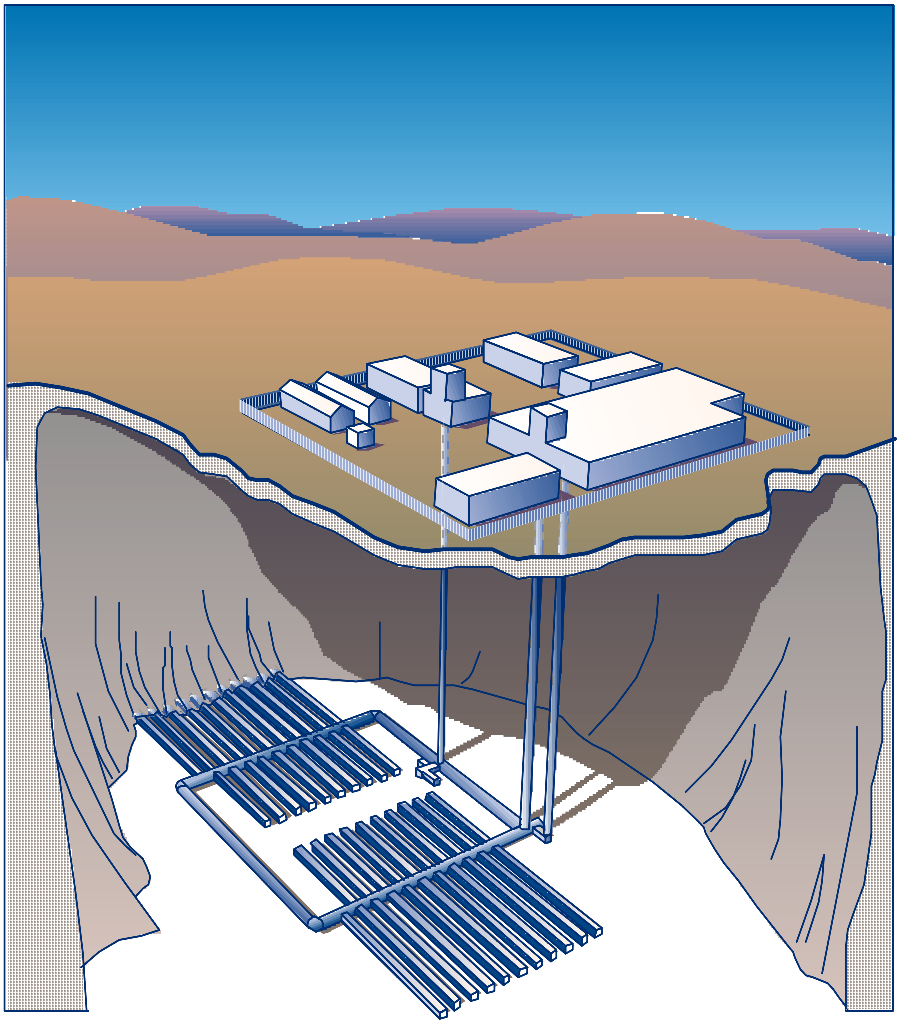
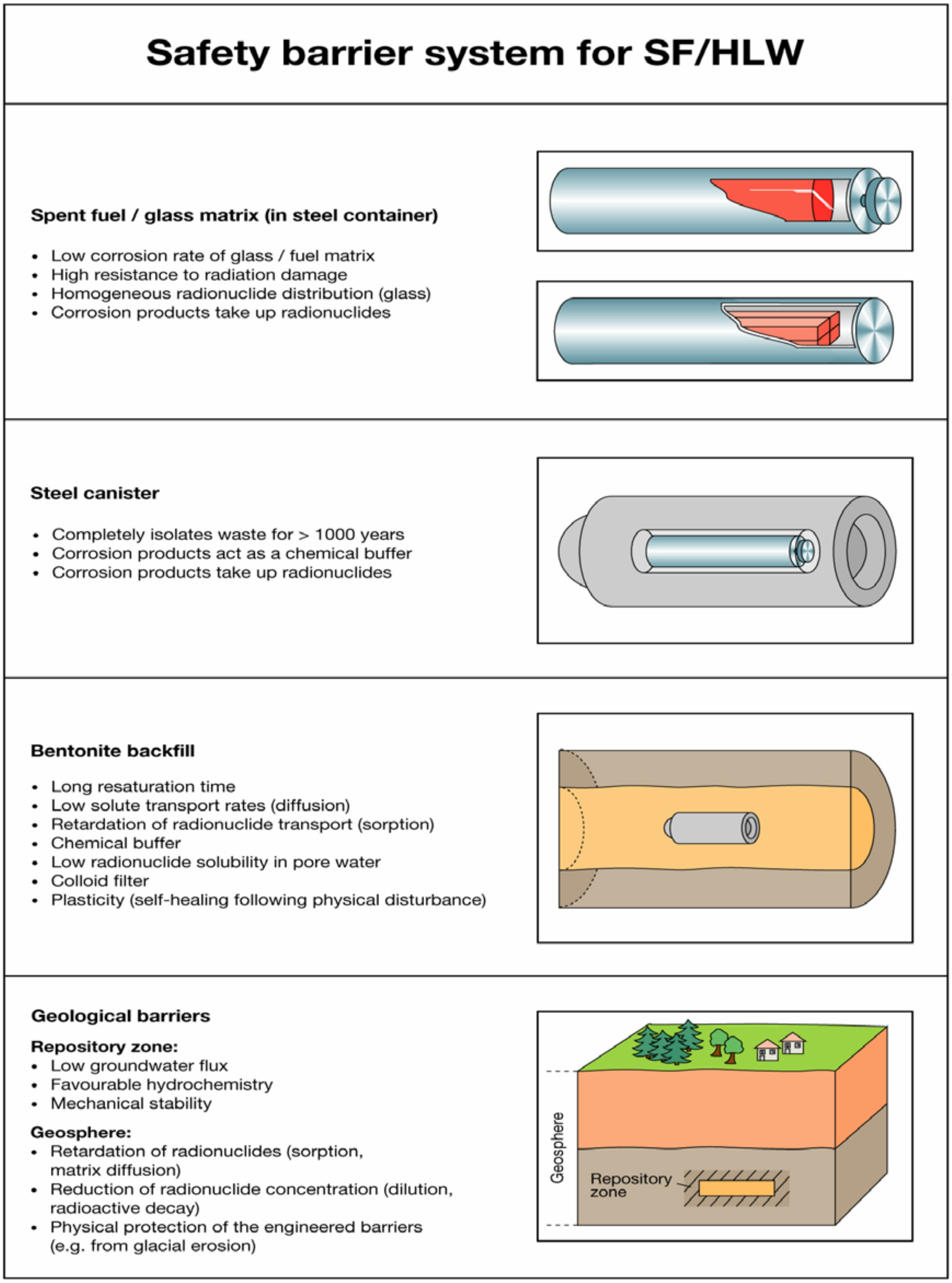


**Figure 2:** Schematic view of a shaft-accessed deep geological repository

There are different choices that can be made for the individual safety barriers. Figure 3 shows and explains the concept proposed for used fuel or HLW disposal in deep clay formations in Switzerland. Figure 4 illustrates the Swedish proposals for disposing of used fuel in crystalline rock.



**Safety barrier system for SF/HLW**

**Spent fuel / glass matrix (in steel container)**

- Low corrosion rate of glass / fuel matrix
- High resistance to radiation damage
- Homogeneous radionuclide distribution (glass)
- Corrosion products take up radionuclides

**Steel canister**

- Completely isolates waste for > 1000 years
- Corrosion products act as a chemical buffer
- Corrosion products take up radionuclides

**Bentonite backfill**

- Long resaturation time
- Low solute transport rates (diffusion)
- Retardation of radionuclide transport (sorption)
- Chemical buffer
- Low radionuclide solubility in pore water
- Colloid filter
- Plasticity (self-healing following physical disturbance)

**Geological barriers**

**Repository zone:**
- Low groundwater flux
- Favourable hydrochemistry
- Mechanical stability

**Geosphere:**
- Retardation of radionuclides (sorption, matrix diffusion)
- Reduction of radionuclide concentration (dilution, radioactive decay)
- Physical protection of the engineered barriers (e.g. from glacial erosion)

**Figure 3:** Swiss example safety barriers in a deep geological repository (Nagra 1996)

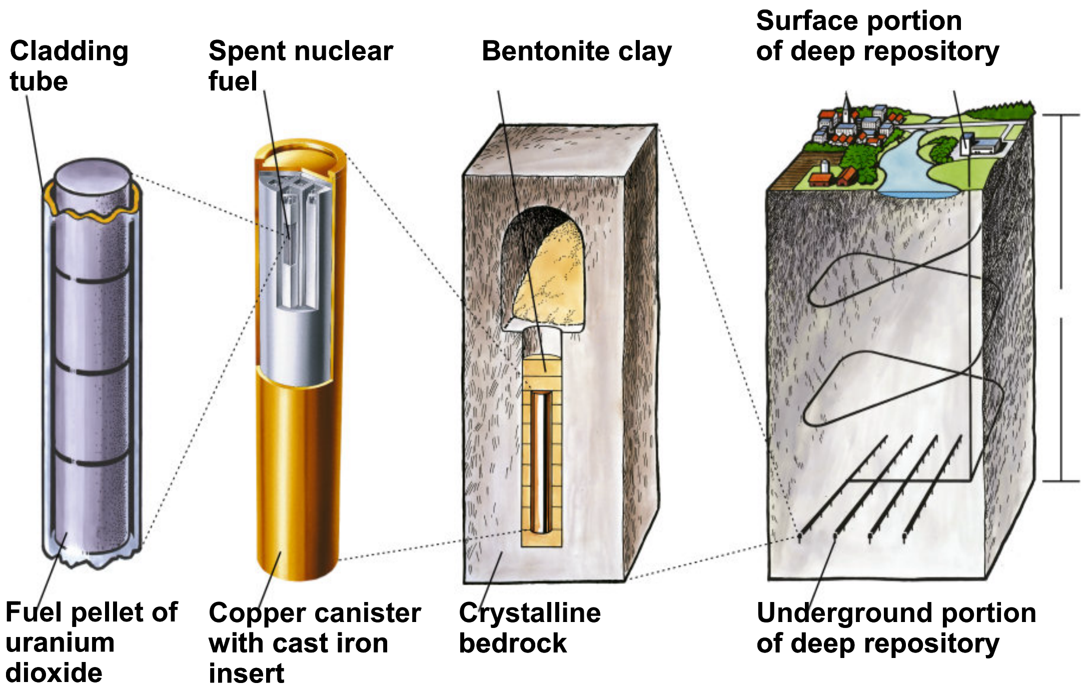


**Figure 4:** Swedish example of the safety barriers in a deep geological repository designed to be implemented in a granite formation.

## 3.2 The safety barriers (for used fuel disposal concepts)

**The fuel matrix:**

Nuclear reactor fuel is usually a ceramic material containing uranium dioxide ($UO_2$) in which the U-235 content has been enriched. In some cases, e.g. in the Canadian CANDU reactors, natural uranium is used, i.e. with no enrichment of U-235 beyond the natural concentration of 0.7%. The ceramic matrix is extremely resistant to corrosion by groundwater and is expected to provide resistance to leaching for tens to hundreds of thousands of years. Figure 5 shows reactor fuel of the type used in the light water reactors that are most common worldwide; Figure 6 illustrates the smaller bundles of natural uranium fuel used in the CANDU reactor developed in Canada.

**Fuel cladding:**

The $UO_2$ matrix is encapsulated in a metallic cladding, commonly a Zirconium alloy. Since the original purpose of the cladding is to separate the fuel from the coolant in the extreme conditions within a reactor core, it is a strong and corrosion resistant material. Scientific evaluations of the time for corrosion in the much more benign repository environment yield lifetimes of many thousands of years.

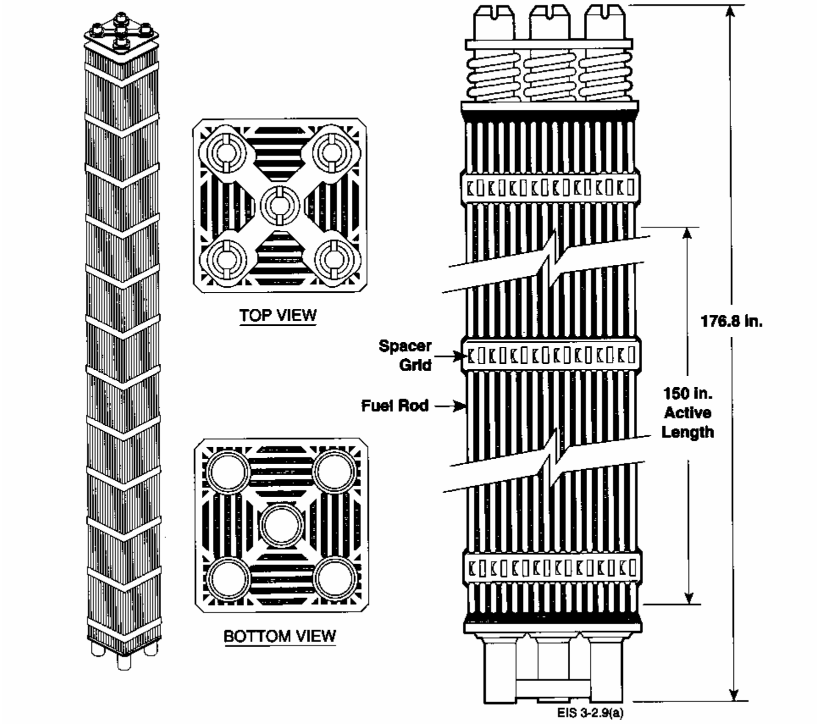


**Figure 5:** Fuel assemblies for a light water reactor (picture from AECL 1994)

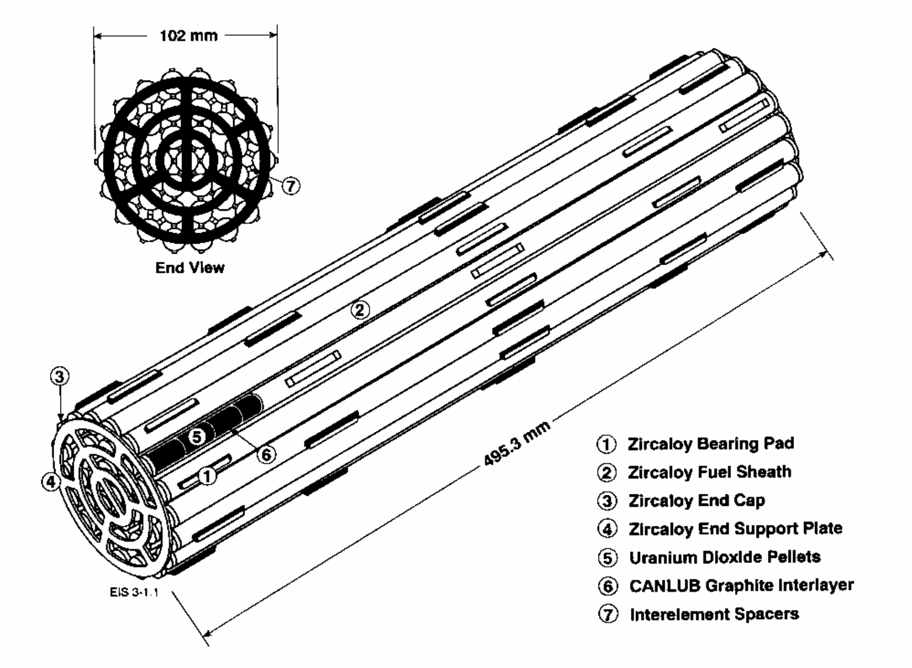


**Figure 6:** Fuel assemblies for a CANDU  (picture from AECL 1994)

## Disposal container:

Before the used fuel is emplaced in a repository, it is encapsulated in a container especially designed to have a long lifetime. Various materials have been proposed for disposal containers. In the advanced Scandinavian programmes, a copper canister with a carbon steel insert to provide mechanical support is the chosen design (Figure 7a and b). In the chemically reducing groundwaters deep in Swedish and Finnish bedrocks, this container is expected to provide complete isolation for around one million years. Other disposal concepts rely on complete containment within the waste container only during the initial thousand or so years, when the radioactivity is most intense and the heat output from the used fuel is highest. This allows simpler steel containers to be employed, as proposed in, for example Belgium, France, Japan and Switzerland (Figure 8 shows the Swiss design). In the last example, analyses performed by the waste disposal organisation, Nagra, and verified by the nuclear regulatory body, indicated that the expected container lifetime would be around 10,000 years. This is also the expected lifetime of the nickel-alloy based container proposed for the Yucca Mountain Project in the USA. In the Canadian concept proposed by AECL a copper/steel container with a predicted lifetime of at least 100,000 years was the reference choice. Advanced designs with multi-component containers have also been suggested; Figure 9 from Apted et. al.2001 is one such case.

**Figures 7a and 7b:** Copper-steel disposal container for used fuel, as designed for Swedish and Finnish used fuel disposal projects. The outer container is of corrosion resistant copper and the inner steel structure holds the fuel elements in place and provides mechanical support for the softer copper.

**Buffer/backfill:**

The buffer and backfill materials are packed between the disposal containers and the rock walls of the underground repository excavations. The functions of these materials are multiple. Typically the buffer is a low-permeability clay that limits groundwater flow around the container, protects against the rock movements and provides a long-term stable chemical environment. The most commonly proposed clay is called bentonite; this is a naturally occurring material that has existed unchanged for millions of years at various locations around the world.

**Seals:**

The shafts, ramps and tunnels needed to give access to the underground workings at a repository must finally be sealed in a way that prevents groundwater flowing though the repository or dissolved radionuclides being transported away. The seals proposed are usually multi-component systems using layers of low permeability clays and special concretes.

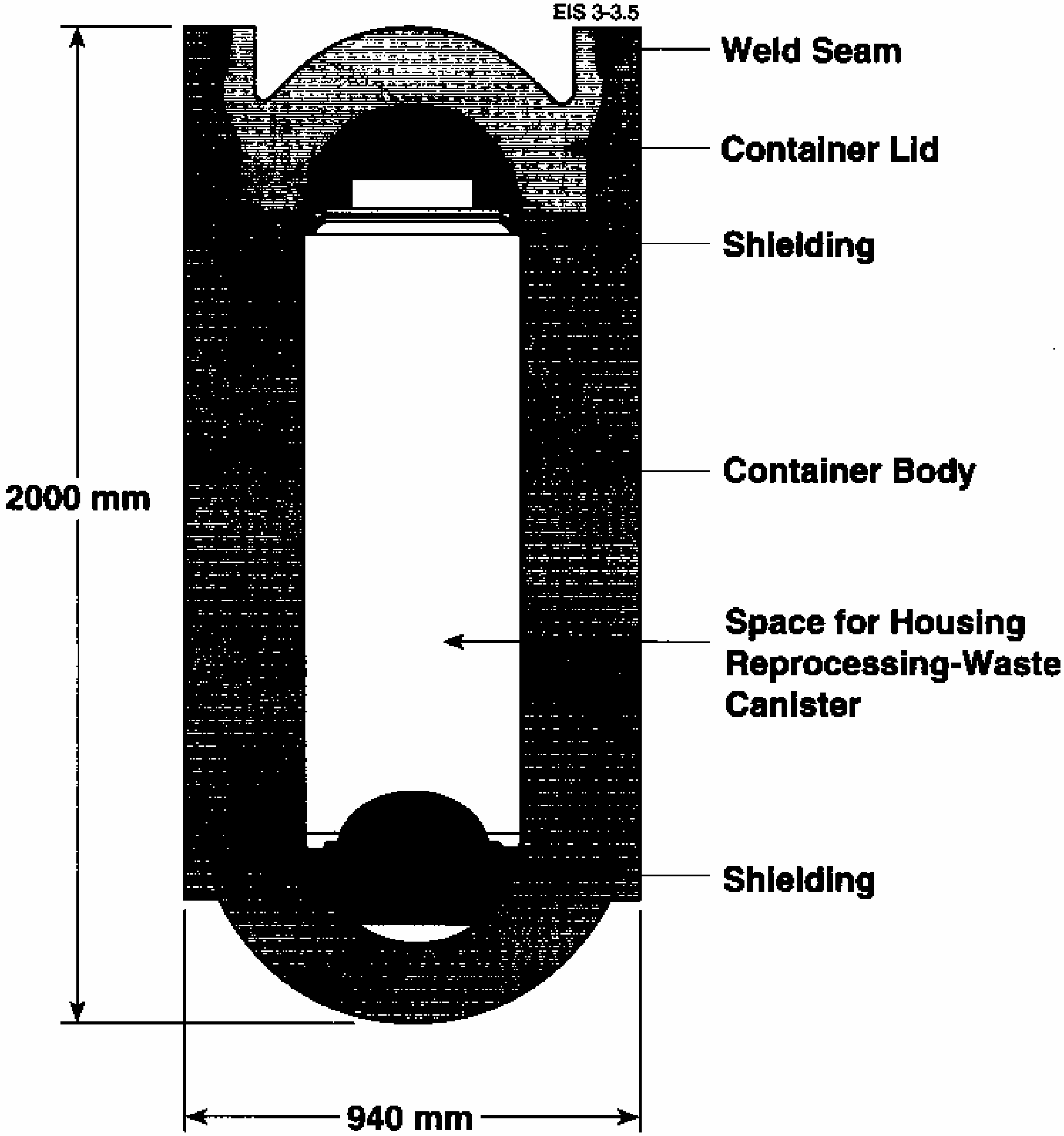


**Figure 8:** Swiss design for a disposal container for vitrified high level wastes

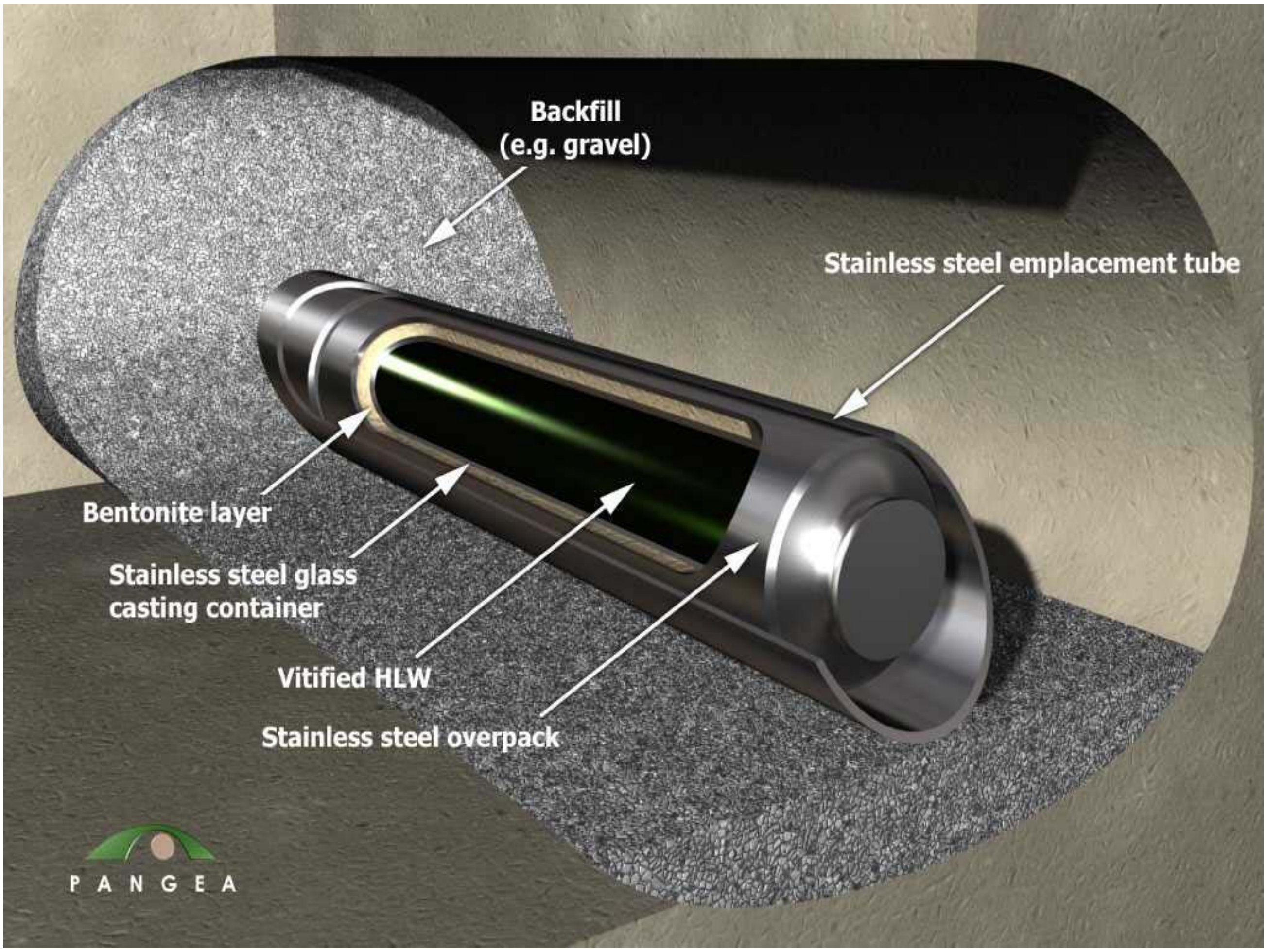


**Figure 9:** A novel disposal container design with an internal clay buffer layer (Apted et al. 2001)**The host rock:**

The name "geological repository" itself indicates the key role of the geological barrier – the host rock. Emplacing the waste in a suitably chosen deep geological formation achieves several objectives. It can:

- reduce the probability and the consequences of any future human actions such as direct intrusion
- limit the flow of groundwater around the repository
- provide a favourable, stable, physical and chemical environment for the packaged used fuel
- retard drastically the movement of any radionuclides that are released
- lead to dilution in larger groundwater systems.

The times required for groundwater to move from depths of some hundreds of metres to the surface can be hundreds, thousands or hundreds of thousands of years. The substances dissolved in the groundwaters move even more slowly, since they are retarded by chemical and physical interactions with the host rock. In nature, one can demonstrate by physical measurements how these processes function. However, relatively rapid transport (tens to hundreds of years) is also possible in certain situations, e.g. with steep topography and rock containing major fracture systems that transport water quickly. Accordingly, the task of measuring in sufficient detail the characteristics of the rocks extending out beyond the repository is one of the most challenging scientific tasks in geological waste disposal.

Various types of geological formations can act as host-rocks for a used fuel repository. The earliest suggestions were that salt deposits could be ideal. Salt is, of course, soluble in water. However, the fact that formations still exist after many millions of years proves that it is possible to find salt domes or beds to which no water has had access for these very long times. The US National Academy of Science (NAS) proposed salt as a host rock in the fifties and the USA, as well as Germany, looked for suitable sites in such formations. This resulted ultimately in an operating deep repository in bedded salt at the WIPP facility in New Mexico, USA, and in comprehensive exploration of the salt dome at Gorleben in Germany. Currently the German government has imposed a moratorium on further work at Gorleben while consideration is given to identifying alternative host rocks and potential sites in order that multiple options can be proposed for societal approval.

The most investigated host rocks to date are crystalline rocks, primarily granite and gneiss. The Finnish government and local population have recently approved a preferred site for used fuel disposal in granite at Olkiluoto on the Baltic Coast. Sweden has narrowed into two granitic areas its siting programme. Other countries that have considered granite siting options include France, Switzerland, Japan, Spain and Canada. The major study in Canada by AECL and Ontario Hydro on disposal in the granitic rocks of the ancient Canadian Shield (AECL 1994) is one of the most comprehensive appraisals, although specific siting was not an objective. The Canadian approach was to investigate crystalline rock types that were sufficiently abundant in terms of locations to provide a variety of sites, but to leave the actual siting until the generic concept had been approved as safe. Problems arose when the Seaborn Committee set up to judge the project concluded that there was too little societal acceptance of geological disposal in Canada to justify proceeding to a specific siting phase.

Another future potential host rock type that has been very extensively studied is clay. Clay is a variable material that can be harder or softer, depending on the temperatures and pressures to which it has been exposed in its geological history. The common features that are of great value when looking for a suitable repository host rock is that clays normally have very low permeability, they tend to have little or no fissures, or have fissures which self-heal under pressure, and they have chemical properties that are very helpful in retarding the transport of radionuclides dissolved in groundwaters. Clays have been studied for a long time in Belgium, which has an underground test facility in soft clay at the Mol site, in Switzerland, which has just chosen a region with a harder clay (opalinus clay) as its preferred siting region, and in France, where an underground laboratory is being constructed in clay at the Bure site.

A final host rock type that is the focus of a waste disposal programme is volcanic rock, tuff. The USA has decided that a license application for a repository for disposal of used fuel and defence wastes should be prepared for the Yucca Mountain site in Nevada. This is a singular choice of host rock and site since the tuff is in a horizontally accessible formation that lies some hundreds of metres below the summit of the mountain but still hundreds of metres above the groundwater table in an oxidising environment.

More details of the national programmes working in various host rocks can be obtained from the waste management organisation web sites noted later in Chapter 6. However, even the above, notes on potential repository host rocks should illustrate the following points:

- there is no single "best host rock type; all have their individual advantages and disadvantages;
- there will likely be used fuel repositories constructed in all of the rock types mentioned, salt, granite, clay and tuff;
- the host rock itself may be less important than the overall "geological setting" of the repository; this considers further factors such as the topography-induced water pressures and flow rates, and the characteristics of the exfiltration zones (i.e. where the groundwater flows out to the surface) now and in the future.

**The biosphere:**

The above remarks on exfiltration zones leads on directly to consideration of the biosphere, and the impact of its characteristics on the potential hazards from a geological repository. The biosphere is the term used to denote the upper layers of the earth in which living creatures exist and also the surface of the earth, including all human and other life forms existing there. It is clear that the biosphere, and in particular the lifestyles of humans living there, will change drastically over the time scales involved in assessing the behaviour of geological repositories. Nevertheless, much effort is expended in the study of how small concentrations of radionuclides released in groundwater might be reduced by dilution processes or increased by concentrating geochemical or biological mechanisms and of how these radionuclides might ultimately lead to internal or external radiation exposures to humans and other organisms. It is important to note that biosphere studies of this sort should not be misconceived as an attempt to predict how human societies will act in the far future. Rather they attempt, using the knowledge of behaviours today and in the past, to scope the range of possible futures.

These biosphere comments touch upon the key issue of how the future behaviour of the overall repository system can be analysed with sufficient accuracy and precision to give confidence that the radionuclides from a repository will never, even in the far-future, give rise to unacceptable radiation doses. The study of the expected or possible behaviours of a repository is referred to as **performance assessment** or **safety assessment**. The process of safety assessment is discussed further in section 4.2 below and in more detail in Appendix C. Providing safety at all times is the most important requirement of a geological repository. There are, however, a range of other requirements that must be satisfied. All of the challenges that a successful repository programme must meet - and how these challenges are addressed - are described in the following chapter.

# 4 Challenges facing geological disposal programmes

The requirements on a deep geological repository can be grouped under the following headings

- **Ethics:** Can geological repositories be implemented without being "unfair" to any of the present day stakeholders or to future generations, who should also not be subjected to unnecessary burdens?
- **Safety:** Are repositories safe? How can we show that they are safe? Can we quantify the safety levels?
- **Security:** Do repositories provide sufficient protection against deliberate misuse of the hazardous materials they contain?
- **Environmental Acceptability:** How can a repository be constructed and operated without undue disturbance of the environment? How will the local community be affected?
- **Public acceptability:** What are the public views on waste repositories? How can the public best be included in the decision making processes? Can a sufficient degree of societal consensus be achieved?
- **Economic viability:** How much do repositories cost? Does geological disposal make the nuclear fuel cycle uneconomic?

Each question is discussed in turn below and those that are more important, or of particular interest to the public, are expanded upon in Appendices.

## 4.1 Ethical issues

The radioactive waste management community has devoted much time and effort over the years to debating ethical issues underlying the concepts developed for safely handling and disposing of long-lived wastes. Regulatory bodies governing disposal in many countries explicitly acknowledge the ethical principles involved and attempt to base their requirements on these principles. Efforts have also been made – although sometimes belatedly – to involve the public in discussions on ethical issues.

Appendix B treats the ethical issues connected with waste disposal in more detail. Here we note that the two principles of most importance are **intergenerational equity** ("fairness towards future generations") and **intragenerational equity** ("fairness across current generations").

The former principle implies that we should avoid passing on burdens to future generations. This is why repositories should be planned, financed and, if possible, implemented by those generations benefiting from the nuclear technologies producing the wastes. The concept of reducing future burdens also leads to repository designs that should function safely even if no control or maintenance measures are taken in the future - although such measures are not ruled out, should future societies choose to implement them. This principle is closely related to the widely quoted principle of **sustainability**. As formulated by the Brundtland Commission sustainability means *'development that meets the needs of the present without compromising the ability of future generations to meet their own needs'* (World Commission on Environment and Development, 1987). Waste safely disposed of in a deep facility requiring no maintenance clearly meets this goal more than do innumerable surface stores containing used nuclear fuel for which future generations may have to provide the technology and the resources for implementing a final disposal route.

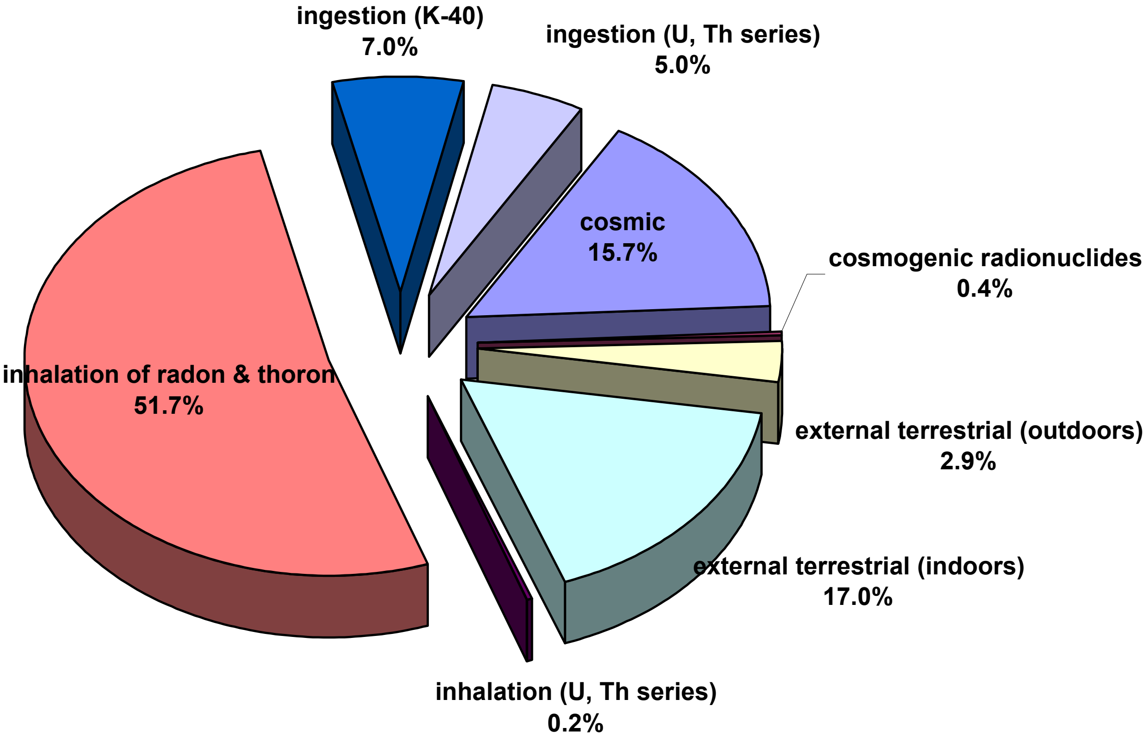
Intragenerational equity principles are satisfied if no sectors of present society are unreasonably burdened by repository projects. This means that there should be a fair distribution of the burdens and benefits associated with a repository. Sites should be chosen in demonstrably suitable regions, with no advantage being taken of politically weak communities. Host communities that accept a repository serving a wider circle of users can expect benefits. Fairness across society also implies that the public must be able to become involved in repository development projects. The topic of public involvement is discussed at more length later.

## 4.2 Safety

The overriding requirement on any geological repository is that it must guarantee the safety of humans and the environment now and at all future times. Because of its central role, more discussion is devoted in Appendix C to the safety issue. Safety during the phases of repository construction and operation is very important - but the approaches used to ensure adequate safety in these phases are largely tried and tested through the implementation of other nuclear and non-nuclear facilities. The issue that leads to most debate in repository planning concerns the long-term safety. Normally humans are not really able to grasp the concept of hazards arising out beyond the next two or three generations and most of technology development has occurred without explicitly considering much longer times. However, in radioactive waste management, the long decay times have led people to focus on previously unthinkable periods, i.e. on the potential consequences of repositories thousands to hundreds of thousands of years into the future. Paradoxically, for wastes such as heavy metal residues that remain toxic for unlimited times, there has been little or no discussion if very long term safety issues. Nor has there until recently been the same level of debate on other technologies that can result in very long term effects on the environment (e.g. climate change, genetically altered organisms).

There are three important aspects to the questions of long-term safety of a repository. What level of safety is to be aimed at? How can we achieve this safety level through appropriate choices of engineered and natural safety barriers? How can we be confident that these barriers will function as intended over the long time periods in question?

There is, world-wide, a rather good consensus on the levels of long-term radiological safety to be aimed at in repository projects. This is largely due to the international guidance given by the independent International Commission on Radiation Protection (e.g. in ICRP 1998). The safety goals are sometimes expressed as limits that must rigorously be shown to be met and sometimes as targets that give less binding guidance.



Typical values are radiation doses of 0.1 mSv/y or less and risks of one in a million per year ($10^{-6}$/y). This risk limit is, for example, the requirement specified in Canadian nuclear legislation (in document AECB 1987, which has been withdrawn to be replaced by new guidance). Radiation dose limits are set so that the increased risk to workers and members of the public is a small fraction of the risks they are already exposed to from other human activities. To put the numbers into context, it is worth noting that the average annual radiation dose to Canadians from natural sources (rocks, cosmic radiation, their own bodies) is 26 times higher than the dose limit (2.6 mSv/y, see Figure 10) or that risks of fatal accidents to car drivers are one hundred times higher than the risk limit, i.e. one in ten thousand per year (Fritsche 1992).

**Figure 10:** Natural radiation arises from different sources. In Canada the total radiation received by an average individual is 2.6 mSv per year. The largest contributor to of natural radiation is usually the radon and thoron gases that are emitted from rocks and can collect in dwellings. The overall figure and most of the individual components are small compared to typical doses of 0.1mSv per year that are defined as upper limits for repositories.

How does a geological repository function so as to ensure that the strict safety requirements mentioned will actually be met over very long times? In the system description in Chapter 2, indications are given of the functions of the various individual safety barriers in a geological repository. In practice, these function as an integrated system in which a variety of physical and chemical processes work together to ensure that no significant quantities of radionuclides can return to the human environment. In the following, the normal evolution of a deep geological repository in a host rock below the water table is described, since this is the most commonly adopted concept. For repositories in salt, there are virtually no natural evolution scenarios that can release radionuclides in time scales of a million years.

Following closure and sealing of a deep geological repository in crystalline rock or in clays, there is an extended period in which the hydrologic system slowly returns to its natural state after the decades of pumping groundwater during repository operations. If the repository is in impermeable clay, or if the canisters in a fractured crystalline rock repository are surrounded by a bentonite buffer, then the times for this buffer to become saturated can be hundreds of years.

The buffer or a tight clay host rock, once saturated with groundwater can allow corrosive materials to be transported from groundwater towards the waste canister but only by a process of diffusion, since there are no cracks through which water can flow. Since diffusion is a very slow process, and the groundwater can be chosen to be chemically reducing (i.e. low in its concentration of corrosive substances), the canister is expected to last a very long time. As mentioned earlier, even iron disposal containers – or overpacks, as they are often called – will have lifetimes of thousands of years; special alloys can last longer and passive materials like copper, hundreds of thousands of years. By then, the natural process of radioactive decay will have greatly reduced the potential hazard of the waste materials.

Eventually, however, the waste overpack can be perforated by corrosion processes, or can crumple under the pressure exerted by the swelling of its surrounding clay buffer. Groundwater accessing the interior of the package must still corrode the zircalloy cladding in order to attack the used fuel itself. This cladding has been estimated in US work to have a lifetime of some 10,000 years. When the cladding is breached radionuclides can escape into the intruding groundwater. A minor fraction of the used fuel radionuclides are in a volatile or mobile form (predominantly Iodine 129) and these can be released fairly rapidly.

Most of the radioactive materials, however, are tightly bound within the ceramic matrix of the uranium oxide fuel. Laboratory tests, as well as observations on natural uranium ore bodies, give confidence that the fuel pellets will dissolve only very slowly. The time to total dissolution in the low flow, chemically reducing groundwater is estimated to be of the order of millions of years. By the extremely long times that have by then elapsed, the natural process of radioactive decay will have reduced the concentrations of all but the very long lived radionuclides to negligible levels.

The remaining long-lived nuclides, moreover, can present a hazard only if they find their way out of the repository. To do so, they must be transported through the diffusive clay barriers to reach flowing groundwaters. The slow diffusive transport of many of these long-lived nuclides is slowed yet further by their chemical interactions (sorption) with the buffer materials. Diffusion times through thick bentonite buffers can be of the order of 10,000 years.

Should some nuclides reach the outer edge of the buffer, they can be dissolved in groundwaters and transported towards the surface. During this transport, however, further retardation will take place and also there will almost certainly be large dilution caused by mixing with other groundwater systems.

Ultimately, at some far future time - estimated in most analyses to be hundreds of thousands to millions of years into the future - trace quantities of nuclides from the repository may be released into the biosphere. If the geological repository system has functioned as intended, however, these quantities are so minute that they will never be significant in comparison with the concentrations of natural radionuclides in our environment.

How can one estimate the efficiency with which the safety barriers described are fulfilling their intended roles? A major challenge to repository implementers has been developing reliable estimates of the doses or risk that can result from repositories, given the fact that the timescales involved rule out any direct observational proof of the correct functioning of a repository. The approach used has therefore been to model the behaviour of the individual safety barriers and of their interactions and hence to produce estimates of potential radionuclide releases or health effects on humans. Increasingly there is a tendency to extend these considerations also to other species in the biosphere. A typical chain of process models used to simulate the future behaviour of a deep geological repository is illustrated in Figure 11. The task of modelling repository behaviour is described in some detail in Appendix C; here we expand only on the description of the Figure.

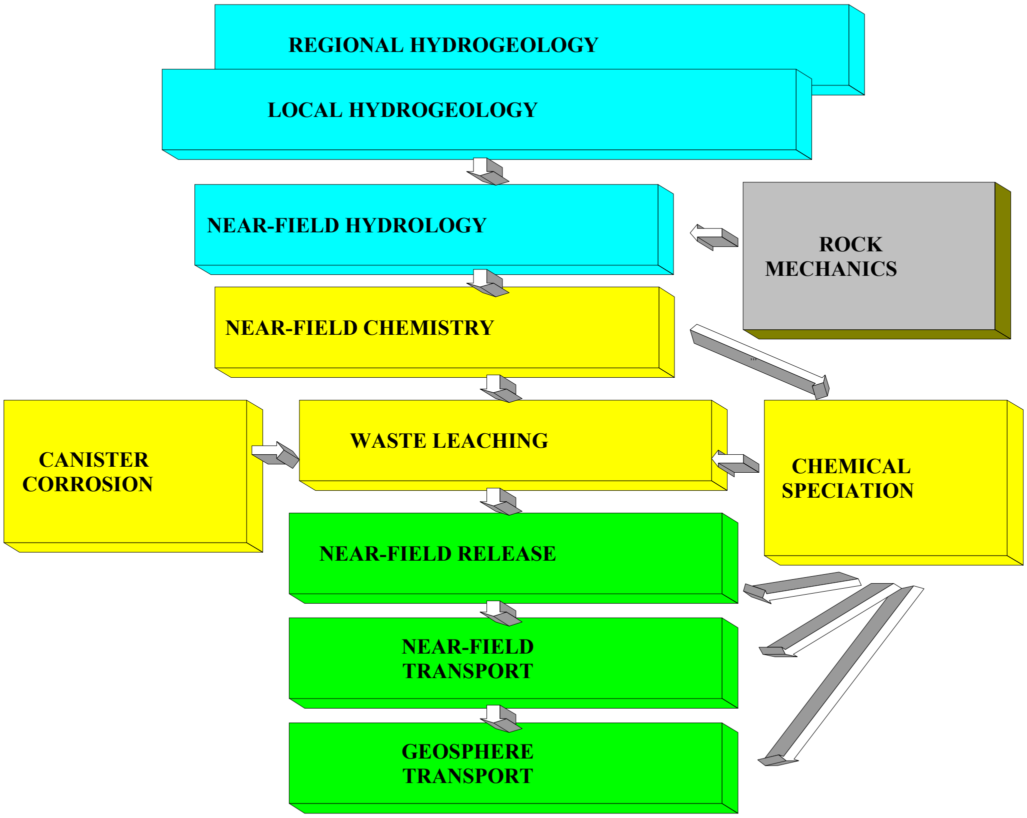


**Figure 11:** The potential release of radionuclides from the repository to the human environment can be simulated using a series of interlinked models of the physical and chemical processes involved.

The blue boxes are all concerned with modelling of how groundwater moves. Three models are commonly used because of the greatly varying spatial scales. The regional model looks at distances up to tens of kilometres from the repository, the local model covers from one to a few kilometres, and the near-field model examines how groundwater moves in and around the filled repository (metres to tens of metres). The near-field behaviour also depends upon the physical state of the host rock, which is predicted using rock mechanics. The hydrological models provide estimates of the water quantities that can corrode materials in the repository and dissolve radionuclides. These chemical processes are also modelled, as indicated by the yellow boxes. This is followed by models estimating how rapidly radioactive substances are released from the waste matrix into the near –field, and then transported through the geological media (the green boxes). Not illustrated are the final steps in the model chain, which transform the predicted releases of radionuclides into radiation dose estimates by examining how the nuclides may contribute to radiation doses through a number of potential exposure pathways. Internal doses can result from radionuclides that are ingested by humans directly or through the food chain in the biosphere or are inhaled as particulate dust; external doses can result from accumulation in soils etc.

This simplified description has not, of course, considered all of the processes that occur in the repository system. It has also not considered numerous process or events that might function at future times and might perturb the normal evolution described above. A full safety assessment of a repository is designed to consider the entire range of features, events and processes that may affect future repository behaviour. Appendix C section describes such formalised repository safety assessment in more detail.

The above remarks and the more extended discussion of safety in Appendix C leads to conclusions on the methodology that can be summarised as follows.

- Quantitative results from safety assessments provide valuable input for decisions throughout disposal system development. The calculated results do not, however, provide hard criteria that obviate the need for human judgement. Safety assessments are necessary decision guides, but they are certainly not the only considerations governing the acceptability of any disposal facility.

- The feasibility of performing assessments of sufficient accuracy is accepted by technical experts within the waste management community. A somewhat lower level of confidence exists in wider scientific circles and, in some segments of the public, severe reservations are still expressed.

- Specific parts of the modelling procedures for geological repositories will continue to be developed and refined. The common timescales for implementation of HLW repositories leave many years for potential improvements. These developments will, however, not result in perfect models that produce unquestionably accurate results. The requirements on human judgement and expert opinion will remain.

- Neither a 100 % level of safety nor a 100 % confidence in the reliability of the safety assessments is possible. This is, of course, a fact which is true also for every other comparable technical undertaking.

If repository systems evolve in the future in the ways postulated by the analysts, a very safe system will result. The most probable dose to future populations will be zero or very close to zero. Figure 12 shows typical results from an assessment of disposal in crystalline rock (Nagra 1994). Even if the parameters that determine nuclide releases all assume their most pessimistic values, the radiation doses predicted by innumerable analyses of various geological repository systems, all lie below regulatory limits and well below natural background radiation levels. Why then is there public concern about safety?

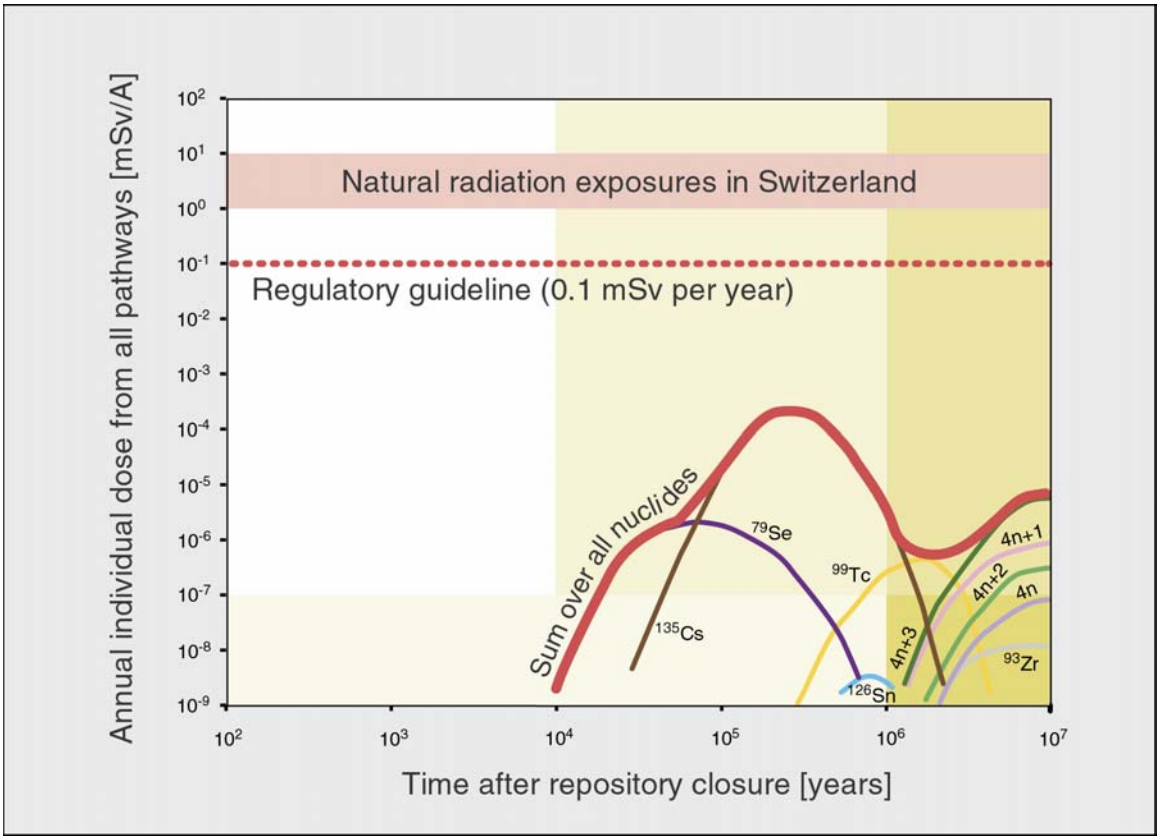


**Figure 12:** The calculated radiation doses illustrated are from Swiss analyses of a deep repository in crystalline rock. They are typical for the many such analyses done in disposal programmes around the world. They predict that releases from a deep repository can occur only in the very far future and at very low levels. The complexity of the processes modeled and the large timescales involved imply that quantifying the uncertainties in the calculations is a major challenge.

There are sometimes doubts expressed that the safety analysts have really thought of all possible disruptive processes and their interactions. There are sometimes doubts expressed that those processes which are analysed in a safety assessment are sufficiently well understood and are correctly modelled. It is argued by some that experience with some of the novel materials proposed for use (e.g. special alloys) is too short to allow long-term predictions; it is argued by some that the complexity of natural geological systems is so great that the simplified models used and the restricted data collected cannot give a proper estimate of their behaviour.

It is in response to such doubts that efforts are made by laboratory and field measurements to **validate** the models used. Laboratory measurements, of course are limited in size compared to repository systems; field measurements are larger in spatial scale - but neither type of investigation can cover the long timescales considered.

This is why there is considerable technical and public interest in so-called “natural analogues” of waste disposal behaviour. These analogues are artefacts found in nature that have existed for a very long time so that their condition today can be compared with what one would predict using the same assumptions and models as the safety analysts do in waste disposal. Analogues can be historical items that illustrate corrosion processes. Examples that have been used in practice are Roman helmets, nails and glass objects that have been buried for over 2000 years. Larger scale analogues are exemplified by the uranium ores bodies that have accumulated at different places around the world and then resisted dispersion for millions of years. The best known example here is the Cigar Lake deposit in Canada (Figure 13). This is a very rich uranium ore that is so well isolated from the biosphere by an overlying impermeable clay formation that no surface expression of the ore can be seen. All of the radionuclides have stayed contained within the ore body for 1,300 million years. Cramer and Smellie (1994) give a full account of the Cigar Lake analogue and the book by Miller et. al. (1994) gives a comprehensive overview of the use of natural analogues in waste disposal.

The diverse approaches to validating the models used in safety assessment of repositories give confidence that the high levels of safety required can indeed be met (NEA 1991, 1999a). Nevertheless, the extensive technical efforts which are being put into specific, technical validation programmes, centred around comparisons of calculations, experiments and observations of analogue objects, should be increasingly complemented by further confidence-building measures. These include peer review, more formalised quality assurance, transparent documentation, large-scale demonstration experiments, and - of great importance - development of processes ensuring open discussion amongst all involved parties.

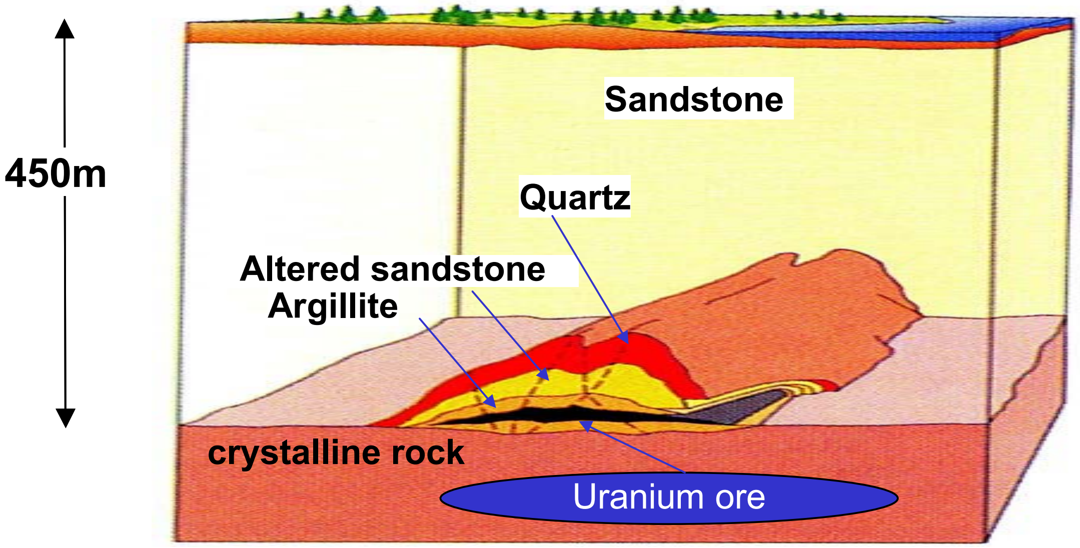


**Figure 13:** In nature it is sometimes possible to locate and observe analogue systems that exhibit many of the features of a deep geological repository. The Cigar Lake uranium ore deposit in Canada is a good example. Because the rich ore body is situated in a favourable hydrogeological environment and is surrounded by a natural low permeability clay layer, no detectable quantities of radionuclides have traveled to the surface, despite the extreme age of the deposit (around 1,300 million years)

## 4.3 Security

Nuclear materials in used nuclear fuel can in principle be used to make bombs, if appropriate knowledge and technical infrastructure are available. Hence used fuel must be safeguarded against misuse by rogue governments or terrorist groups. Radioactive material could also be dispersed using conventional explosives in so-called “dirty bombs”. Thus, security, i.e. ensuring that there can be no unauthorised access to these materials, is vital throughout the whole fuel cycle. This is a national and an international concern. (Bunn et.al. 2002)

The most sensitive nuclear materials in the civilian nuclear fuel cycle are the fissile isotopes of plutonium and uranium, because they can in principle be used as weapons material. Commercial nuclear electricity generation throughout the world currently results every year in discharges from reactors of about 10,000 tons of used fuel that contains about 1 percent fissile plutonium. While this plutonium is not easily separated from the intensely radioactive used fuel and is not of the same quality as plutonium removed from weapons, it can still be used as a threat or in a crude weapon. Smaller quantities of highly enriched uranium are used as fuel for some research reactors around the world, although many countries are moving toward lower levels of enrichment for this kind of fuel.

There are technical reasons why the potential problem of nuclear proliferation could increase with time. The amounts of nuclear materials will increase if the use of nuclear power expands. Moreover, the older the used fuel becomes the more attractive it might be as a source of fissile material. This is because the radioactivity of used fuel decays over time so that it loses its natural proliferation protection and becomes more easily handled. Thus long-term storage is not an ideal solution to assure security.

Today, most commercial used fuel is maintained under a strict safeguards regime worldwide and therefore presents no urgent security threat. Ultimately, however, the material should be made as inaccessible as possible. This is a strong argument in favour of implementation of geological repositories; there are very useful safeguards advantages to collecting materials from numerous locations into a carefully selected site that is technically easier to safeguard. But such sites must be available for all of the over 30 nations that currently have commercial nuclear power programs or research reactor programs. It is unlikely that every one of these countries will possess the political, economic, and geological factors necessary to implement a national geological disposal programs for their materials soon or ever. Thus, from a security angle, a global system of fewer international disposal facilities (possibly in isolated areas under multinational scrutiny) may be preferable to many small national facilities that often are located in less than ideal conditions (Stoll and McCombie 2001) – although the potential problems created by the increased transport requirements should not be underestimated.

## 4.4 Environmental acceptability

Implementing a deep geological repository involves relatively large industrial and mining operations. What are the environmental impacts of these? Are they acceptable? The radiological or health impacts have been discussed under the above section on safety. Here we are addressing the non-radiological effects.

During the phases through to site selection and characterisation there are few significant environmental impacts. Deep and shallow boreholes will be sunk and there will be surface-based surveys using seismic techniques, all of which are normal activities used in exploration programmes for natural resources. They can be carried out with only minor localised effects on the public. Figure 14 illustrates a heavy vibrator vehicle used in seismic survey work operating in a village in Switzerland.

**Figure 14:** Field investigations to characterise the deep underground commonly include a seismic campaign used to map the geological strata. The illustration shows a heavy vibrator inducing pressure waves that will be reflected at the different geological interfaces. This technique is most successful in layered sedimentary geological structures.

Construction of the repository will involve mining and transport away from the site of the excavated rock. To keep such mining activities in perspective, it is worth noting that the excavated volumes for a repository are far lower than for a mine. For example **in one year** Canada excavates around 75 million tonnes of coal (half of which is exported), while the **total amount** of used fuel from all Canadian reactors over their lifetime will less that 200 thousand tonnes, i.e. a few hundred times smaller.

Operation of the repository will last for some decades. During this time there may be continued transport of rock spoil, if further underground storage space is excavated in parallel with waste emplacement. The used fuel will also be delivered to the site, but the numbers or frequencies of transports are modest. If, as in usually foreseen, encapsulation of the fuel for disposal is planned to be performed at the site, a relatively high-technology nuclear facility will be needed.

Following closure of the repository, all surface facilities can be decommissioned and dismantled. Most likely, monitoring operations with little environmental impact would continue for some time and access to the land will be controlled, even though the surface may be used for other activities.

All of the above potentially negative environmental impacts must be set against possible benefits to the siting region. Obviously there will be employment possibilities at the encapsulation plant and the repository. Many of the positions to be filled will be long-term, high-tech posts; but the absolute number of employees is relatively modest. The employment figure quoted even for the relatively large facility that was projected in Canada (AECL 1994) was only around 1000 persons.

Further potential benefits could also accrue to the siting region. Various national programmes have proposed that the host community be directly compensated for providing a service to a wider circle of users (Richardson 1998). Japan and Switzerland are examples of such programmes. In other nations it is foreseen that benefits be provided by means of improving the regional infrastructure. In Nevada, for example, implementation of a repository at Yucca Mountain will lead to a major enhancement of the road and rail systems. In some countries, such as Russia, the suggestion has been made that areas that are contaminated by earlier (primarily military) nuclear operations could be cleaned up using the profits gained from implementing a commercially operated deep repository at the site, with wastes being accepted from foreign customers.

## 4.5 Public acceptability

Attaining a sufficient level of public acceptability and of societal consensus has been one of the major factors that have prevented implementation of geological repositories. The clearest single example of this is perhaps in Canada where the Seaborn panel came to the direct conclusion that

> *"As it stands, the AECL concept for deep disposal has not been demonstrated to have broad public support. The concept in its current form does not have the required level of acceptability to be adopted as Canada's approach for managing nuclear fuel wastes."* (CEAA 1998)

In fact, in all countries with geological repository programmes there has been some degree of public lack of acceptance or even direct opposition. As a committee of the US National Research Council recently pointed out, "*the main challenges are societal rather than technical*" (NRC 2001). This can have various reasons. The opposition can be part of the widespread genuine anxiety about nuclear matters (originating in part from the military origins); it can be a deliberate tactic to hinder the development of nuclear power; it may reflect public scepticism towards any new, major technological development; or it may result from the failure of the nuclear industry to accept the importance of interacting with the concerned public.

In fact, the shortcomings of the industry's policies for public involvement have been recognized by the responsible persons themselves and various initiatives are underway to try to improve the situation. For example, the OECD/NEA has established a Forum on Stakeholder Confidence (NEA 2000), which aims at sharing experience in this area and in developing new approaches.

One approach to providing increased opportunities for interactions between nuclear experts and the interested public is to adopt a phased or staged procedure for implementing major projects. The most comprehensive discussion on this issue is in a further report by the US National Research Council (NRC 2003), which describes a process labelled as "adaptive staging". This is described more fully in section 5.1 below. The key aspect of relevance here is that adaptive staging involves repeated consultation of a wide range of stakeholders, including the public. No major decision should be taken without ensuring that there is sufficient acceptability of the choice made.

It must be noted that "sufficient acceptability" does not imply a universal consensus. In the question of repository implementation there will continue to be opposition from some sectors of the public. Each nation considering geological disposal as an option must make a political decision on the level of acceptability that is required and on how this level is to be assessed. In Chapter 5 we shall see how the current situation differs markedly from country to country. Appendix D which is based on the reference (McCombie 1997) lays out the views on disposal of various stakeholder groups, in a manner that brings out the sometimes extreme contrasts.

## 4.6 Financing waste repositories

A geological repository is an expensive facility. Typical total costs for site selection and characterisation, repository construction, and some decades of operation are between a few and a few tens of billions of US dollars (USD). The total cost depends upon the engineered features such as the size, depth and detailed design of the repository, but also upon scientific programmes in the earlier phases and, importantly, on the institutional framework in which the project is developed.

At one end of the spectrum, just the encapsulation and disposal costs for 100,000 tonnes of used fuel at the Yucca Mountain Facility in the USA have been estimated at 10,000M USD. At the other end, the small Finnish disposal programme, which aimed to dispose of 1,840 tonnes of fuel from the two currently operating power plants was estimated to cost 760M USD (NEA 1994a). Commonly, around half of the funding is for financing all activities up to beginning disposal and the remainder is needed for the operational phase. Estimated costs in different countries vary widely not only because of the design differences but also because some cost items - such as compensation payments to a host community, or legal proceeding costs - vary enormously. The costs are today uncertain because these are first-of-a-kind, very long-term projects.

The encouraging news is that these seemingly huge costs do not dominate the entire nuclear fuel cycle costs. Fuel purchase, reactor operation and decommissioning are additional important components of the cost. In the following table selected results are extracted from the 1994 NEA study on costs. These are used with estimates of typical fuel burn up and of reactor efficiency (33%) to give a rough idea of the costs as a function of electricity usage, since this is a figure to which the public can more easily relate.

### Table 1: Selected results of study on costs

| Country | Packaging & Disposal of fuel (M.USD) | Assumed Average burn-up[1] | Used Fuel (t) | Unit cost $/kg | Disposal costs cents/kW.h |
|---|---|---|---|---|---|
| USA | 10,000 | 33,000 MWd/t | 96,300 | 104 | 0.04 |
| Canada | 8,700 | 8,000 MWd/t | 191,000 | 46 | 0.07 |
| Sweden | 3,214 | 33,000 MWd/t | 7,840 | 410 | 0.16 |

[1] The burn-up represents the total energy produced per unit mass of fuel. Burn up values vary for different reactor types and there is a strong tendency to increasing values. The figures used here are illustrative values of the burn up that might be averaged over a complete nuclear programme. The burnup rates for Canada are much lower as Canadian CANDU reactors burn unenriched fuel and consequently more spent fuel is produced per Kw.h of electricity produced.

The figures illustrate that the cost of used fuel disposal corresponds to only a fraction of a cent per kWh – a minor part of the electricity prices paid by consumers. Accordingly, the establishment of a financial framework to ensure that disposal costs for used fuel disposal are covered is relatively straightforward. In most countries the costs are included in the electricity price, i.e. they are "internalised", and mechanisms are established to secure the resulting funds. In some countries the accumulated funding is left with the utilities. In others (e.g. the USA), the government collects and controls the fund. A system that is being increasingly employed is that the funds are placed in a segregated fund that is managed or controlled by government authorities.

In Canada, the nuclear utilities have established segregated funds for long-term management of radioactive waste and decommissioning of the facilities. The government provides oversight through the licensing process.

# 5 Activities in development of a geological repository

## 5.1 Overview

Development of a deep geological repository is a process that lasts for many years until waste emplacement operations can begin, continues for some decades through the operational phase, and may have a final observational and monitoring phase lasting decades or even hundreds of years. This results in unusual and challenging tasks in planning, implementation and operation of major engineering facilities. The times needed to complete even the early phases involving choice of a disposal concept and repository sites have been massively underestimated in virtually all national repository programmes.

The unexpected delays have been in part due to the complexity of some of the technical tasks involved. For example, characterisation of the deep geological environment around a repository required development of new measurement techniques, new analysis methods and even new ways of thinking about how natural systems behave over long time periods. More often, however, delays have resulted from a failure to integrate sufficiently well the technical and the societal issues associated with repository development. These issues were mentioned in section 4.5 above. One consequence that has been drawn by many national disposal programmes is that a phased or staged approach, allowing one to learn from both technical and societal developments, is more constructive than a purely technocratic project aimed at rigidly defining all steps and deadlines at the outset.

The most comprehensive discussion on staging is contained in the report “One step at a time” produced by the National Research Council of the USA. This report describes an approach called "adaptive staging” (NRC 2003). This concept has several key characteristics:

- A reference staged process is defined at the outset - but it is **not** assumed that adaptations will occur only if forced by circumstances.
- Rather, the stages are deliberately planned with the objective of gaining further knowledge or experience that might lead to amendments of a subsequent stage.
- At the decision points between stages (and at any other major decisions that might arise) a broad and open participation in the decision process is designed into the overall staging.
- To the maximum extent possible, the steps are designed to be reversible, in case subsequent experience reveals that the chosen direction does not help progress towards the chosen goals.

These project management features are not new, of course; however, the view expressed was that, used together, they enhance the prospects of making progress in controversial, first-of-a-kind projects such as the implementation of a deep geological repository.

## 5.2 The staged activities in repository development

In this section, the sequential phases of development are first described. These are concept development, site selection and repository design, licensing, construction, operation, monitoring and sealing. Throughout all these phases, other accompanying activities are required; these include research and development, iterative safety assessments and continual interaction with the public and other stakeholders. Brief comments on each activity mentioned follows.

### Concept development:

The selection of a concept or concepts to be followed is a serious step since it can set in motion many years of work for large numbers of persons and can impact directly on the probability of success further down the line. Some countries have divorced the generic question of choosing concepts from further site-specific work. Sweden, Switzerland, Belgium, Japan and Canada are all examples of countries that have completed one or more major integrated projects aimed at providing a decision basis for the choice of a national disposal concept. In Sweden (SKB 1983), the generic studies led on to specific siting work in crystalline rock. In Switzerland concept studies have been performed for both crystalline (Nagra 1985) and clay options (Nagra 2002), with the latter being chosen thereafter as the first priority option. Belgium has also studied clay concepts, using data obtained from their underground laboratory (ONDRAF 2001). Japan has not yet chosen a preferred host rock and is retaining concepts for both clay and crystalline rock (JNC 2000). In Canada, where perhaps the largest of all studies of a concept was carried out (AECL 1994), the decision taken at government level was that, although disposal could be technically safe, the level of public acceptance of the concept was insufficient to allow the proponents to progress to a siting stage.

### Siting:

Because of its crucial role in repository development, the challenges associated with siting repositories are selected for more extensive discussion in section 5.3 below.

### Repository design:

It is important to note that this activity is in practice performed originally iteratively along with site selection. The reason is that the geological setting of the repository **together** with the engineered design features form an integrated system that is intended to provide long term safety. Similarly, design work on the repository excavations is linked to the design of the engineered barriers system described earlier in Chapter 3. As is the case for siting, the long-term objectives strongly affect design. The container must be compatible with the rock mechanical and geochemical conditions in the repository. The disposal tunnels or deposition holes must minimise rock disturbances, optimise the temperature profile through the repository and allow emplacement of high quality buffers and seals. The short-term or operational safety requirements also affect the repository design, of course. For a facility in which highly active used fuel will be handled, these requirements go beyond the safety objectives to be met in conventional underground mining.

**Licensing:**

In all developed nations, nuclear activities of all kinds must be overseen and licensed by an independent regulatory body, as is specified by the IAEA (IAEA 1997a, 1997c). Licensing steps actually occur at various phases through most disposal development programmes. Often, however, the first major license application occurs when the proponent wishes to proceed to construction. The next licensing step is then, in many cases, the license to emplace waste, working on the premise that construction activities may yield important new data for influencing the safety case for licensing. The formalised organisational structure ensures that licenses are issued only following intensive review by experts from the regulatory body. The table below lists the repository proponent (the licensee) and the regulatory bodies in various countries.

**Table 2: Key Nuclear Waste Organisations in Representative Nations**

| NATION | Implementing Agency | Standards Body | Regulatory Review | Permit Authority | Advisory Body |
|---|---|---|---|---|---|
| Canada | NWMO | CNSC | CNSC | CNSC | Seaborn Commission (disbanded) |
| Finland | POSIVA (utility) | STUK | STUK | Council of State | |
| France | ANDRA | DSIN | IPSN | Ministry of Industry | CNE |
| Germany | BfS | BMU with RSK, SSK | States (with TÜV, SGS, MA) | States | RSK<br>AkEnd (disbanded) |
| Sweden | SKB (Utility) | SSI | SKI | Cabinet | KASAM |
| Switzerland | NAGRA, GNW | HSK, BAG | HSK | Ministry of Energy | KNE<br>EKRA (disbanded) |
| USA<br>Yucca Mt. | USDOE | EPA | USNRC | USNRC | NWTRB<br>BRWM |
| USA<br>WIPP | USDOE | EPA | EPA | EPA | EEG<br>BRWM |
| UK | Nirex | EA | NII, EA | | RWMAC |

Acronyms are listed in Chapter 9

*Implementing Agency*: Organization responsible for preparing for and/or operating waste management facilities (i.e. repositories, with the exception of Canada and the UK that have no policy committing them to geological disposal).
*Standards Body*: National body responsible for setting environmental radiological standards required to be met by a repository and associated facilities.
*Regulatory Review*: Organisation that verifies the technical adequacy of analyses provided by the implementing organisation in support of permit or license application.
*Permitting Authority*: Organisation that issues permit or licence for activities related to disposal facility.
*Advisory Body*: Any independent (of licensing authority and implementing agency) body created to advise national or local governments on nuclear waste issues.

## Construction:

This is the major engineering phase. Access to the deep underground is gained by excavating shafts (e.g. at Gorleben and Konrad in Germany), inclined ramps (as planned in Sweden, Finland and Switzerland) or horizontally in the case of Yucca Mountain in the USA. Underground excavation can be more challenging than in conventional mining because of the need to plan for appropriate radiation protection and because of the wish to avoid unnecessarily disturbing the host rock in any way that might affect safety. A disturbed rock zone around repository tunnels could represent a preferential pathway for groundwater. Hence, excavation work in a repository is often planned to be carried out using techniques such as full face drilling or “soft” blasting that do less damage.

The duration of the construction phase can be a few to several years, depending upon the extent of the disposal area to be prepared before waste emplacement begins. A common feature of construction plans is that excavation of additional disposal space continues in parallel with waste emplacement activities since these extend over may years. Because of the strict radiation protection requirements during operation, excavation and emplacement activities, if running in parallel, should be strictly separated spatially. Excavation produces rock spoils to be managed on the surface, but the volumes involved are far lower than in conventional mining.

## Operation:

During the operational phase, used fuel is transported to the repository site, encapsulated in a disposal overpack (if the facilities for encapsulation are located at the repository site and not at another location), transferred to the underground and emplaced in the final disposal configuration. The impacts on the surface environment during this long phase are similar to any other medium size industrial undertaking. In the repository two methods of working have been proposed. One implies that the space around emplaced waste packages (whether in tunnels, caverns or deposition holes) are continually packed with backfill material. The advantage of proceeding in this way is that the final physical and chemical environment is regained sooner - and this environment has been chosen to minimise corrosion, etc. to the containers. The disadvantage is that the waste packages can no longer be visually inspected and are less easily retrieved, should one wish to do this. For this reason some geological disposal projects (e.g. at Yucca Mountain) foresee that the tunnels are kept open for a hundred years or more, with backfilling taking place only at repository closure. Other concepts (e.g. in Sweden, Finland and Switzerland) propose to backfill progressively.

The issue of retrievability of wastes during the operational phase, but also after closure, has been the subject of intense discussion over the past few years, with international reports being produced and meetings organised on the topic (e.g. IAEA 2000a). The fundamental question – first raised by the KASAM committee in Sweden (KASAM 1988) is whether the additional flexibility in keeping options open by storing wastes retrievably outweighs the safety advantages of having the wastes as completely removed from possible interference as is possible. In practice, the choice is simplified by the fact that engineering methods to allow retrievability are available, even though they become more complex and expensive as the step-wise closure of the repository progresses and with increasing time after closure of the repository. This conclusion must, however, be demonstrated to the public on the basis of specific studies on retrieval concepts and techniques. Because it is a topical issue and the debate has been intense, retrievability is addressed more completely in Appendix E.

**Monitoring:**

Again, this is not an activity that is restricted to a single development phase. In fact monitoring the natural conditions at the undisturbed site should begin before any major excavation work. Monitoring will also continue, both in and around the repository, during the operational phase, since this is obligatory for nuclear installations. The monitoring activities that have given rise to most discussions over the past years are those that may be continued or initiated after completing emplacement and also after all backfilling and sealing is in place.

A basic principle of geological disposal is that a passive safety system is implemented, in which safety is guaranteed without active measures being taken by future generations. This approach does not, of course, rule out monitoring activities. In fact, it appears that populations around a newly sealed repository would certainly require monitoring activities to be continued. The rationale is that these could detect any malfunction that could result from processes or events not considered by the repository developer.

There is a continuing debate on how a monitoring programme can be designed to provide relevant, reliable data over long times. The probability of any monitoring results directly indicating a malfunction is ranked as very low by the developers, who believe that there will be no releases for very long times into the future. Scientists argue that some parameters may give indirect indications and that it is in any case of interest to monitor the evolution of the repository system. The public simply wants an additional mechanism, beyond the technical arguments of the experts, to enhance their confidence in repository safety. Since the implementation of a reasonable monitoring programme is not a costly item, the debate is not particularly productive. All post -closure phases of geological repositories will certainly begin with a monitoring programme in place.

The principle purpose of a well designed and conceived monitoring plan at a repository in fact not to try and detect "leakage" from the repository. Rather it is to collect information during the construction and operation of the repository that will aid in understanding its post closure behaviour. As this information is gained it provides that basis for staying with the original design concept or alternatively modifying the design to adapt to the new information.

**Closure:**

The closure phase, as indicated above, may be initiated immediately following emplacement of the last waste package. Alternatively, it may be separated from this by a period of monitoring that could last years or decades. The closure activities, themselves, involve backfilling and sealing all access routes to the repository. A topical issue related to closure is how the repository site should be marked thereafter. In the advanced geological programmes in the USA (WIPP and Yucca Mountain), a complex system of markers and monuments at the site is foreseen. In addition, documentation on the location and the contents of the repository is planned to be deposited at multiple locations around the globe. In other programmes, no firm decisions on physical markers have been taken, but all are in agreement with the need for properly archiving all necessary data on the repository.

The purpose of the markers is to reduce the probability of inadvertent human intrusion at some far future time. It has, however, been argued that markers are more likely to attract intruders than to warn them off, and that the best defence against inadvertent intrusion is to locate the repository in an area with no natural resources that might attract exploration. In fact, many believe that the most likely type of intrusion is deliberate, because the repository is seen as a resource, for energy, weapons or other purposes.

The above more or less sequential activities during repository development must be accompanied by some parallel actions that extend throughout.

**Research and Development (R&D):**

Over the past 30 years huge efforts have been devoted to R&D in the area of geological repository development. These have included laboratory studies into waste matrixes, container material and buffer properties. There have also been extensive field studies in hydrogeology, geo- and hydrochemistry, rock mechanics and tectonic evolution. Has all the necessary R&D been done?

The proponents of geological disposal believe that sufficient research has been done to allow the implementation of safe repositories - not because everything is known, but because existing knowledge can be complemented by sound engineering and conservative assumptions. The doubters point out the gaps existing, particularly in the accuracy with which one can describe the spatial characteristics of host rocks or the temporal evolution of all safety barriers. Given the enormous times for which the repository behaviour is to be assessed, they believe that there is a justification for taking more time for R&D before beginning implementation.

A compromise that can be easily reached is that R&D continues into and throughout the operational phase, a solution that takes account of the fact that new knowledge might emerge over the coming decades. This compromise does not, however, define the level of investment in continuing R&D, and this will remain a hotly discussed issue for a long time. The most recent development in this area is that the USDOE, the implementer of the Yucca Mountain project, has in 2003 initiated a long-term R&D programme that will run, at a funding level of some USD 20 M/year, in parallel with other repository implementation activities.

## 5.3 The greatest challenge is in the siting procedure

### 5.3.1 Siting approaches have evolved with time

There has been an evolution in approaches to selecting specific potential sites over the past decades. In the early days of nuclear technology, sites for facilities were commonly chosen to be remote, occasionally because of the military connections, often simply to minimise numbers of directly affected persons. Subsequently, additional facilities were often sited adjacent to existing installations because the infrastructure was available and often public acceptance was easier because of prior familiarity of the locals with nuclear technology.

With time, new locations were needed for different facilities like repositories, which must fulfil very site-specific requirements. This was the phase in which “expert judgement” was common – often exercised, however, behind closed doors. Groups, primarily of technologists, would in good conscience gather in order to select specific sites and they would proceed then to plan how best to “decide, announce and defend” their decisions. This was not highly successful. Following this, hope was then placed in developing a logical, traceable procedure, which would narrow in progressively to single sites, which everyone must logically recognize as the “best choice”. This kind of approach was described in early international documents, e.g. in (IAEA 1980). It would, of course, be a dream solution for politicians who would have the perfect defence of siting choices. Unfortunately, the approach is not feasible. The element of subjective judgement in narrowing in choices remains high enough to fuel disputes amongst the experts; the technical criteria that were proposed for use commonly neglected key societal aspects.

The next approach – and currently the most common – is to use a multi-attribute analysis. This is a technique that attempts to identify all criteria influencing the choice of options, to quantify how well each option marches the criteria, and to combine the quantified scores, using appropriate weighting factors in order to give a ranking of preferences. The scores and especially the weightings can be allocated by different stakeholder groups, which allows one to include also the wider non-technical issues. This approach is promising – provided that there is full transparency concerning the parameters and also the weighting factors, which are employed when combing judgements on the individual parameters.

A final approach is to select potential sites by soliciting volunteer communities. Latest siting guidelines from the IAEA (IAEA 1994) recognize the validity of the volunteering approach with one key provision, namely that *"the selected site provides an adequate level of safety"*. One of the most important developments in the geological disposal field over the past decades has been the methodology for quantitatively assessing the level of safety. This is done by safety analysis or safety assessment. Although not a precise tool, the methodology is mature enough to allow traceable analysis and therefore makes it legitimate **from a safety angle** to bring any potential site into the discussion, regardless of how it was selected.

### 5.3.2 Development of specific siting criteria

Numerous national programmes have gone through the exercise of developing siting criteria. The IAEA has published overviews listing and discussing individual criteria (IAEA 1994). Table 3 gives a typical set. The real challenge is in deciding which criteria are most relevant for any national situation, how should these be combined, which can be quantified numerically, etc.

**Table 3: IAEA Siting Guidelines – Examples**

| **Technical** |
|---|
| • The geological setting should be amenable to characterisation, should have geometrical, geomechanical, geochemical and hydrogeological characteristics that inhibit radionuclide transport and allow safe repository construction, operation and closure. |
| • The host rock and repository containment system should not be adversely affected by future dynamic processes of climate change, neotectonics, seismicity, volcanism, diapirism, etc. |
| • The hydrogeological environment should tend to restrict groundwater flow and support waste isolation. |
| • The physicochemical and geochemical characteristics should limit radionuclide releases to the environment. |
| • Surface and underground characteristics should allow optimised infrastructure design in accordance with mining rules. |
| • The site should be located such that waste transport to it does not give rise to unacceptable radiation or environmental impacts. |
| **Societal** |

| | |
|---|---|
| • | Potential future human activities should be considered in siting and the likelihood that such activities could adversely affect the isolation capability should be minimised. |
| • | Site choice should mean that the local environmental quality will not be adversely affected, or such effects should be mitigated to an acceptable degree. |
| • | Land use and ownership in the area of the site should be considered in connection with possible future development and regional planning. |
| • | The overall societal impact of developing a repository at the chosen site should be acceptable, with beneficial effects being enhanced and negative effects minimised. |

A particular question, which has led to debate in various national programmes, concerns the advantages and disadvantages of "exclusion criteria". This type of approach is valuable at the regional level for the repository implementer since it allows one to focus on remaining regions and thus concentrate resources. It is also useful for the public, since those communities in excluded areas need not feel threatened by the possibility of having to host a repository. One must be very certain, however, that the areas really are excluded for very good reasons (e.g. closeness to known geological features that would make the repository unsafe, or the existence of protected regions such as national parks, etc.). If areas are too hastily excluded and then re-introduced again later there will be a large resulting loss of credibility.

At a more specific level, exclusion criteria based on single characteristics of a site can be very dangerous. There is often a public pressure for pre-definition of threshold values for characteristics of the rock, e.g. hydraulic conductivity, fracture density, etc. The problem is that such parameters do not determine repository safety on their own. The correct way to assess the safety offered by a specific site and design is by total system safety assessment. Such assessments depend upon analyses involving many parameters simultaneously. No-go decisions based on measured values of a single parameter are therefore not scientifically defensible. The proper approach is not to withhold such individual measurements from the public but rather to make the public and especially the critics aware that an overall decision must await the total system analysis based on a complete dataset.

Some key conclusions, which can be drawn from reviewing how different national programmes have approached the problem of specifying siting criteria, can be summarised as follows:

- The long history of studies and the existing extensive literature (including IAEA reports) constitute an excellent basis.

- National programmes must, however, select and weight criteria according to local geological and societal situations.

- Most criteria are qualitative guidelines rather than firm numerical threshold values.

- The technical/geological/safety criteria cannot be considered in isolation from other societal and economic criteria.

- A key factor influencing the probability of success in siting is trust in institutions and in decision processes.

- At all times it must be borne in mind that **total** system performance is the ultimate measure of acceptability in the technical arena.

### 5.3.3 Controversial issues in the siting process

The biggest - mostly unsolved - challenge in waste disposal today is selecting sites that are demonstrably safe and which can achieve the necessary level of public acceptance at local regional and national levels. The process chosen will depend on the answers to a list of important, general questions:

- Can we find the “best” site? We can certainly never assert that we have found the “safest” site. The tools of safety assessment will not allow fine discrimination amongst candidates and the candidates will in any case be a sub-set of all possible sites. The word “best” can be used only if it is understood within the framework of a multi attribute analysis comparing a limited set of candidates. In fact it may well be the case that the non-technical criteria turn out to be more important than the others as recognized in the IAEA 1994 Safety Standard which states that *“factors not related to technical safety ... may indeed, dominate the final site selection, and this is acceptable provided the selected site provides an adequate level of safety”*. More productive is to avoid superlatives like best, or safest and to seek “demonstrably suitable sites”.

- Should the process be strictly technical, pragmatic or dependent upon volunteers? The ideal situation is to have willing, volunteering hosts and this has happened in some countries. The extremely polarised situation in many other countries makes it unlikely at present. The strictly technical or objective approach should be recognized as unfeasible. The only practicable approach at present seems to be multi attribute analyses performed as transparently as possible.

- Who chooses the candidates and the final site? Conventionally, the implementing body is charged with proposing a site (usually from a list of candidates that it has also been responsible for selecting) and the regulator’s role is to judge the acceptability of the proposed site. In practice, this can leave the regulator out of the process until very (or too) late in the process. Even if the regulatory and legal system does not explicitly require agreement of different stakeholders on the candidates, it is a sensible approach to encourage full exchange of information and of opinions throughout the siting process.

- How should the public and other stakeholders be involved? This is the big question! There is universal acknowledgement that involvement of interested and affected parties is absolutely necessary but no consensus on how it is best achieved. Recently there have been various new attempts to broaden participation, e.g. in Sweden (Ahagen et al 1999), Canada (Brown 2000), Switzerland (EKRA 2000), Germany (AkEnd 2001), the UK (Defra 2001) and internationally (NEA 2001a,). It is obvious that processes must be open and transparent. The public is no longer content to passively receive information; participation in the decision process is demanded. They may also feel the need for independent technical advice, which leads to the question of the sources of funding for expertise provided to potential host communities. When dealing with the public it is important that their subjective perceptions are not treated any less seriously than the objective facts that the scientists present. One extremely important issue in dealing with the local public affected by a repository is that the whole spectrum of pros and cons involved in hosting a repository must be openly discussed. A key aspect of this is the subject of direct financial compensation of host communities. This was for a long time regarded as a delicate or even taboo topic. In many countries, it still appears to be the subject of little or no open discussion. World wide, however, it is accepted that a host community is entitled to negotiate compensation for providing a service for the common good. Specific examples have been discussed in various countries including the USA, France, Switzerland, Taiwan, Canada, etc. (Richardson 1998)

- How wide should the selection process be? There is no obvious a priori way of determining how many potential sites should be considered. This depends primarily upon judgements on the probabilities of candidates providing ultimately unsuitable, and upon the costs entailed. It is noteworthy that, even in the USA, a full characterisation programme for three sites was found by Congress to be too expensive, which resulted in the political choice of the single Yucca Mountain site (USC 1982, 1987).

### 5.3.4 Overall conclusions on repository siting

Below is a list of broad conclusions based on international experience concerning the technical procedures and the non-technical aspects of site selection.

**Technical conclusions:**

- It is neither possible, nor necessary to select the “safest” site; demonstrably suitable sites are needed.

- The feasibility of properly characterising the site (i.e. understanding and quantifying the geological parameters determining its behaviour) is a key issue; hence extremely complex geologies are best avoided.
- A strictly objective selection process is not possible; subjective judgements are unavoidable
- Existing sites or volunteer sites can also be assessed for suitability; the methodology for assessing the overall system performance and comparing this with regulatory requirements has been developed.
- The technical issues may in the final selection process be outweighed by non-technical (i.e. societal and/or economic) factors. This is justifiable, as long as the repository system is sufficiently safe.

**Non-technical considerations:**

- The process must be open, transparent and inclusive; the days of "decide, announce, defend" are past.
- All stakeholders (i.e. interested and affected parties) must be included.
- The breadth of the siting process is a societal and economic issue, as well as technical.
- Implementation of a repository without local assent is not realistic in any democratic country today, independent of the legal situation
- Direct and indirect compensation of local communities willing to host a repository is common and should be an integral part of negotiations.

# 6 Status of geological disposal programmes

## 6.1 Overview

For at least 25 years after the original 1950's publications on the concept of geological disposal, the validity of this approach was not questioned. It was formally adopted as a final goal, through policy or legal decisions, in many countries, including the USA, Canada, Sweden, Finland, Belgium, Switzerland, France, Spain, South Korea, and Japan. Several of these countries initiated active scientific and technical programmes aiming at implementing disposal, usually some 20 years or so into the future. International organisations such as the OECD/NEA, the IAEA, and the EC established working groups and networks of the organisations involved. Special journals started up. Innumerable conferences were organised around the world; for example the major annual International Waste Management Conference in Tucson, Arizona, USA will be held in 2004 for the 30th time.

However, virtually every geological waste disposal programme in the world ran into difficulties in keeping to originally proposed schedules. For example, in the US programme, in 1982 (EnPA 1982), a target date for repository operation of 1998 was set. Currently the target for a US repository at Yucca Mountain is 2010 and this goal will be met only if all outstanding technical, licensing and legal issues can be clarified without incurring further delays. Other programmes have also been compelled to move target dates back. Through to the year 2000, the only active programme that met its original deadlines, even for selection of a preferred site, was Finland.

Slippages in deadlines, however, are common in large projects; disposal programmes are not unusual in this respect. Less common are decisions of the type taken in some countries – namely to indefinitely postpone implementation of geological repositories. This has happened several times, in each case due to public opposition leading to governmental decisions to halt the siting process. Examples are the Netherlands, Spain and the Czech Republic (although efforts are underway in the last of these to re-start the siting programme).

In a few countries, there has been a still more radical political reaction to problems encountered by geological disposal programmes. This began in France, where intense opposition to siting efforts in crystalline rock areas, together with growing opposition to disposal per se, led in 1990 to a new law in which the geological disposal option was treated as one of three lines to be followed. The other two, transmutation and long-term storage, were to be studied with equal intensity at least up to a decision date set for 2006.

Backing off from the choice of geological disposal as the preferred national strategy has since taken place in two further countries, namely the UK and Canada. The UK government decision was to re-open all alternatives and to have a very wide public debate before choosing a preferred future course. This decision followed on the loss of the proposed Sellafield site[2] as a result of a public hearing that severely criticised the scientific, engineering and societal aspects of work by UK Nirex. In Canada, the Government also decided to re-open discussion on all conceivable long-term used fuel management options following the review by the Seaborn Committee (CEEA 1998) of the major study submitted by AECL. In the Canadian case, the science and technology was not faulted; the proposed repository concept was judged technically capable of providing safety. However, it was also judged that the public confidence in the safety was insufficient to allow an implementer to proceed to specific repository siting.

As a complement to these overarching comments on the status of geological disposal, Section 6.2 presents an abbreviated picture of where some of the major countries stand today in their geological disposal programmes. Recent publications including good overviews of programmes world-wide are Witherspoon and Bodvarrson 2001 and NRC 2001. In addition the IAEA maintains a web site that documents current general trends and also developments in individual countries. In addition most national waste disposal organisations have their own web sites.

## 6.2 Status of geological disposal projects in selected countries

### Table 4: Overview of status of deep geological disposal in selected countries

| Country | Host rock option(s) | Status |
|---|---|---|
| USA<br>http://www.wipp.calsbad.nm.us<br>http//www.epa.gov | Bedded salt | The WIPP facility, in which long-lived wastes from defence applications have been disposed since 1999, is the first custom-built deep geological repository to operate. It is located 650m below the surface at a site in New Mexico, which was first identified in 1975. It took two decades of work before an application for opening the repository was submitted in 1996. |
| USA<br>http//www.rw.doe.gov<br>http//www.nrc.gov | Tuff | A license application is currently being prepared by USDOE for the Yucca Mountain site in Nevada. This site was nominated, from a short list of three, by the US Congress as the single site to be studied as a potential host for disposal of used fuel and high-level waste. The target date for operation is 2010. |
| Finland<br>http//www.posiva.fi | Crystalline | The site at Olkiluoto was selected from a short list of four and has been accepted by the government and the population as the preferred |

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[2] Although intended for the disposal of low and intermediate wastes rather than HLW or used fuel, the UK proposal was for a deep geological repository at Sellafield.

| Country | Host rock option(s) | Status |
|---|---|---|
| http//www.stuk.fi | | site for a repository for used fuel. Foreseen before operation are around 10 years of underground investigations and 10 years of construction work. |
| Sweden<br>http//www.skb.se<br>http//www.ski.se/se<br>http//www.ssi.se | Crystalline | Following local referenda, two local communities have agreed to specific site investigations. The target date for deciding upon implementation at one site is 2010 and repository operation would then begin in 2015. |
| France<br>http//www.andra.fr<br>http//www.irsn.org | Clay, Crystalline | Shaft sinking at the Bure site in consolidated clay is in progress. After rejection of a proposed crystalline site, no alternative has been yet named. A key milestone is 2006, when the French policy on long-term management of high-level wastes will be reviewed. |
| Switzerland<br>http//www.nagra.ch<br>http//www.hsk.psi.ch | Clay<br>Crystalline | The preferred host rock option is now clay. A major feasibility study based on the Opalinus clay region north of Zürich was submitted to the government in 2002 for review. Crystalline rock is viewed as a reserve option, based on the extensive investigations done earlier. Repository implementation is foreseen only around 2050. Participation in a multinational disposal project is also an option that is kept open. |
| Belgium<br>http//www.nirond.be<br>http//www.sckcen.be | Soft clay | Underground research has been carried out for already 20 years in the boom Clay 220 m below the site of the nuclear research facilities at Mol. This is the only current candidate for a deep repository. The operation of a repository is not considered necessary before 2035, so that there is no need for final decisions as yet. |
| Netherlands<br>http//www.covra-nl.nl | Salt | After performing extensive studies on salt domes, the Dutch government opted for a policy on long-term storage (at least 100y). Geological disposal is still viewed as the approach that will be ultimately used. At present, however, focus is on retrievable storage. |
| Czech Republic<br>http//www.surao.cz/zacateka. htm<br>http//www.sujb.cz | Crystalline | Efforts are underway to restart a siting programme The Target date for selection of two deep geological repository sites is 2015, with |

| Country | Host rock option(s) | Status |
|---|---|---|
| | | selection of the final site 2025 and, following construction of an underground laboratory, commissioning of the deep geological repository only in 2065. |
| Germany<br>http//www.bfs.de<br>http//www.dbe.de | Salt,<br>Sediments,<br>Crystalline | Although the site at the Konrad iron ore mine has been judged as suitable and the site in a salt dome at Gorleben has been extensively investigated, the German Government is considering widening the search for potential deep disposal sites. |
| Canada<br>http//www.nwmo.ca<br>http//www.aecl.ca<br>http//www.cnsc-ccsn.gc.ca | open | Canada is currently reviewing all options for long term management of its used nuclear fuel. This is the consequence of a government decision following review of a 16 year research programme based on the concept of deep disposal in crystalline plutonic rock in the Canadian shield. The decision was that, although it was judged safe from a technical perspective, there was insufficient public support for the concept of geological disposal to allow the programme to move into a siting phase. |
| United Kingdom<br>http//www.nirex.co.uk<br>http//www.defra.gov.uk/ environment/radioactivity | open | The UK is currently reviewing all options after the failure in 1997 to receive permission to build an underground laboratory for low- and intermediate level wastes at Sellafield. The UK programme for HLW disposal has been inactive for many years. |
| Spain<br>http//www.enresa.es<br>http//www.csn.es | Clay<br>crystalline | All field-work was stopped following public opposition but engineering and safety studies are still in progress and Spain participates in the underground rock laboratory programmes of other countries. Neither a host rock nor a target date has been set. |
| Japan<br>http//www.numo.or.jp<br>http//www.jnc.go.jp<br>http//nsc.jst.go.jp | Crystalline<br>clay | Generic rock laboratory work is being carried out, but there has been no choice of host rock or site. At the end of 2002, a major consultation exercise was launched with the objective of attracting volunteer communities as potential repository hosts. Operation of a repository is foreseen only in 2040. |

| **Country** | **Host rock option(s)** | **Status** |
|---|---|---|
| Russia<br>http//www.minatom.ru | Crystalline | Despite having large inventories of radioactive wastes that require deep geological disposal, Russia does not have a very active programme in progress, in large part due to lack of funding. Candidate sites have been identified in remote areas in the Urals, in Siberia and on the Kola Peninsula. Proposals have been made to implement facilities at the Krasnoyarsk or Krasnokamensk potential siting areas (both in Siberia), with the financing of the work being achieved through charging for importing foreign used nuclear fuel. |
| China | Crystalline | Specific site characterisation work is in progress at a remote granitic site in Beishan on the edge of the Gobi desert. China plans to reprocess and to dispose of the vitrified high-level wastes from the year 2040. |
| Diverse<br>http//www.iaea.or.at<br>http//www.nea.fr<br>http//radwaste.org<br>http//www.enviros.com/vrepository | Diverse | A number of other, smaller countries have initiated studies on geological disposal but none are very close to specific field work or to implementation. The question of whether small countries need to have national disposal programmes is addressed in section 6.3. |

## 6.3 Shared disposal facilities

For small countries the small volumes of used fuel or other wastes produced, or the scarcity of available space, or the complexity of the geology or the high costs of geological repositories can all be arguments in favour of seeking shared solutions (McCombie 1999). Although ethical considerations and international rulings correctly emphasise that each country must bear the responsibility for ensuring that its radioactive wastes are safety managed, this does not necessarily mean that each must have a national disposal facility.

This fact is recognised in the Joint Convention on Radioactive Waste and Used Nuclear Fuel of the IAEA (IAEA 1997a). It is also recognised in the Directive on Waste issued by the European Commission (CEC 2002), which points to the potential advantages of regional solutions shared by various countries. In fact, radioactive wastes from abroad have in the past been accepted by various countries, including the UK, France, USA and Russia. Today, however, there is increased sensitivity towards potential negative public reactions and several countries, e.g. France, Sweden and Finland have passed laws against import or export of radioactive material. Nevertheless, there is continuing support in numerous countries for the concept of shared repositories and the concept is being studied also by the IAEA (IAEA 1998, 2003)

# 7 Conclusions and Outlook

## 7.1 Conclusions

This report begins by confirming that used nuclear fuel and high-level waste are hazardous materials. They are hazardous because of their radiotoxicity, and this radiotoxicity lasts for a very long time. Because the materials are hazardous they must be properly managed to ensure safety for the public. By safety here we mean radiological safety. No person, now or in the future should ever be exposed to radioactive materials in concentrations that could lead to radiation doses that are hazardous. Another aspect concerning the safety of society, an aspect that has become increasingly important in recent years, is the security issue. By this we mean the risk posed by used nuclear fuel because it contains fissile materials (predominantly plutonium) that could be used by governments or by terrorists to produce illicit nuclear materials. The safety and the security issues together explain the great importance attached by society today to the proper management of these nuclear materials.

The safety and security goals can, in principle, be addressed in various ways. Currently, they are being addressed primarily by keeping the nuclear materials in safe and secure surface storage facilities. This surface storage can continue for many years into the future; it has been shown to be a safe methodology. However, surface storage requires monitoring and control, and also at some stage will require maintenance and even renewal of facilities. If safely and securely managing used nuclear fuel, without requiring future effort on maintenance and control, is accepted as a goal, then the only feasible approach today is recognized to be deep geological disposal. The high importance attached to the long-term management of used nuclear fuel has resulted in large efforts being expended on such programmes in many countries around the world. A safe solution to the nuclear waste disposal problem is widely recognized as being a pre-requisite for the continued use of nuclear power. In fact, the existing stocks of used nuclear fuel around the world imply that a safe permanent long-term solution is essential, independent of future uses of nuclear energy. This should imply that there is widespread support for finding and for implementing solutions.

What is the actual situation around the world today? The present position is that technologies for implementing deep geological disposal have been developed and extensively tested in a number of countries, although fully implemented in only very few cases. These technologies are based on different conceptual designs for a deep repository, including the choice of the engineered barriers that enclose the used nuclear fuel and also the geological medium in which the repository will be sited. In all of these different programmes the safety of the deep geological system - as assessed by the range of methodologies developed for this purpose - is invariably shown to be very high. The development of the safety assessment methodology itself has involved many man-years of intellectual effort and also extensive collaboration between researchers in different countries around the globe. Assessing the safety is based upon analysing how the entire repository system will behave far into the future. This estimation in turn is based upon a sound scientific understanding of how the materials will evolve in the deep geological environment, and of how any radionuclides released might be transported through the deep underground, back towards the environment of humans. The safety assessment is not a purely theoretical desk exercise. The models are based upon experimentation in the laboratory and in the field. The understanding that is built up is checked by observing, how natural systems with similar properties behave over the very long time-scales considered.

Nevertheless, there is extensive scepticism in some circles concerning the ability of scientists to actually model how the system will evolve for tens of thousands or hundreds of thousands of years.

This issue of the extremely long time-scales involved is the single factor that has most prevented acceptance of repository projects by a large sector of the public, and also by some scientists. They doubt the ability of the experts to model future system behaviour with sufficient accuracy. Supporters of the repository concept point out that sufficient accuracy does not necessarily mean high accuracy, and modelling the future behaviour does not necessarily mean describing the exact course of the events that will take place. Rather they point out that the modelling of future behaviour need only scope all credible developments that could take place in the repository. If all of these developments lead to a system that provides adequate safety, then it is justifiable to implement deep geological repositories.

These arguments have not convinced all stakeholders in various countries, and accordingly the progress of deep geological disposal projects has been different in countries around the world. There is much common ground in the approaches that have been developed in different nations, both technically and socially. Currently, one of the most active societal developments is the elaboration of a stepwise or phased process that could lead to repository implementation. Stepwise procedures lead down a path which at any time must provide proper safety and security, which can be reversed if the path chosen is shown to be non-optimal, but can also lead ultimately to safe, sealed, deep geological repositories.

The different degrees to which countries have subscribed to the geological disposal approach, the different stages reached in their long-term waste management programmes and possible future development are summarized briefly in the following section.

## 7.2 Outlook

In the next few years, there will be highly significant policy decisions taken in some countries with respect to the status of the concept of deep geological disposal. These include France, which in 2006 must reformulate its policy concerning the weighting on the three different long-term management options currently being studied. These are long-term surface or underground storage, transmutation, and geological disposal. Yet more radical policy decisions are expected in the United Kingdom and in Canada. Both of these countries, after major set-backs in highly developed disposal programmes, have decided to open a public discussion on all potential long term waste management options. Both of these countries have ambitious projects in place intended to ensure that the policy finally chosen by the respective government will be firmly based on an analysis of public views on this important issue. Should these countries decide to move forward again with deep geological disposal, it is interesting to speculate how much of the technical knowledge and the human skills that were built up in the earlier programmes, can be retrieved or rebuilt. Rebuilding programmes that have been drastically reduced in size, and where key personnel have moved into other areas or have moved out of the work force will not be an easy task. However, implementation of deep geological repositories is nowhere an urgent task. The target deadlines set for opening and operating deep geological repositories in many countries, including those just mentioned, are fifty or more years into the future.

This rather sobering look at the status of geological repositories in some countries contrast strongly with the advances made recently in some other parts of the world. In the USA, congress decided that a licensing application should be prepared for the Yucca Mountain Project in Nevada. Even if the ambitious 2010-deadline currently aimed at by the USDOE is not maintained, a deep repository for used nuclear fuel is likely to be constructed and operated in the United States in the foreseeable future. In the Scandinavian countries, Finland and Sweden, the deep repository programmes are also very advanced and steering towards a definitive date for implementation. More influential, perhaps, than the technical developments that have been initiated in these countries, are the societal processes that have been invoked to try and ensure that the repository has a sufficient level of acceptance. In most other countries of the world, the combined technical and societal approaches employed in the Scandinavian countries are looked upon as role models for how things might be arranged also in other programmes.

In the European Union, a recent directive has instructed all European Union member states and future member states that specific deadlines for siting repositories and for implementing these facilities must be set. Although the over-ambitious deadlines proposed in the draft European Directive will certainly be amended in discussions amongst the member states, the thrust of the initiative will likely remain. This thrust confirms, at least for the European Union, that deep geological disposal is indeed the preferred waste management strategy for used nuclear fuel and high-level wastes.

Support for the concept of deep disposal is apparent also in many of the small Central European countries that are scheduled to become EU member states. For these small countries, however, and for numerous other small countries around the globe, there is one important difficulty standing in the way of implementing the deep disposal strategy. This is simply that deep geological repositories, if properly designed, sited, operated and closed, are very expensive facilities. There are many countries with small quantities of nuclear wastes; these are either countries with limited nuclear power programmes or, indeed, countries with no nuclear power programmes but, nevertheless, long-lived wastes from nuclear applications in medicine, research or industry. These nations will also need a safe and secure long-term waste management option for these wastes. For this reason, there is increasing interest in the concept of shared deep geological repositories. Most likely, such shared facilities would come into operation either because a large nuclear programme agrees to accept wastes from smaller programmes or else a number of smaller countries agree to cooperate in implementing a regional facility.

In summary, we can make the following concluding statements concerning deep geological disposal.

- Deep geological disposal is an ethically justifiable approach to used fuel management that is widely regarded as being able to provide safety and security at all future times. This judgement is, however, not universal; some scientists and a considerable segment of the public have reservations concerning the feasibility of assessing the very long-term behaviour of repositories.
- Whether deep geological disposal is, indeed, the only solution for long-term waste management, and will remain the only such solution, is also disputed in some circles. The divergence of views is in some cases related to different opinions on the scientific understanding needed to implement repositories, and in other cases to different views on the controversial issue of nuclear power usage. However, countries which do support deep geological disposal include some, such as Japan and China, that are firmly committed to expanding nuclear power, and also others such as Sweden, Italy and Spain that have already decided to shut down their nuclear power programmes.
- In any case, the implementation of deep geological disposal takes decades, wherever it is being progressed. This means that interim measures, namely surface storage facilities, are needed to assure continued safety and security. It also means that ample time is still available for learning. Any scientific advances that could affect disposal safety can be taken into account for many decades into the future.

Finally, a look into the crystal ball. What will the world situation with respect to deep geological repositories likely be twenty-five years from now? Relatively few national repositories will be in operation; the operators of these will be disposing of waste routinely and building up a body of experience that is being intensively observed by numerous other nations. Several national programmes will be in a siting stage, including detailed underground investigations at potential repository sites. Several other countries will still be holding off with specific implementation projects because they have still no immediate need for a deep geological repository. The wastes in these countries must be held in safe and secure surface stores. A few nations may still be holding off from deep geological disposal, because they are still hoping for some major break-through that will provide an equally or even safer final solution. A last group of nations, in 25 years, will be those that are progressing with plans for, or perhaps already cooperating in operation of, a multinational repository.

Finally, in most or all of the countries just mentioned there will continue to be an active research in development programme in the field of geological disposal. This will be necessary to maintain the required level of technical competence; it will also be in place in order to develop concepts and specific plans for a second generation of repositories.

These second generation repositories may use more advanced materials, they may use more optimised designs, and some of the new design features may have been made possible by advances in the conditioning methodologies for nuclear waste or even in transmutation technology that will change the volume and type of some of the long-lived radioactive wastes.

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# 9 List of Acronyms

| | |
|---|---|
| AECL | Atom Energy of Canada Ltd. |
| ANDRA | National Agency for Radioactive Waste Management, France |
| BAG | Federal Office of Health, Switzerland |
| BfS | Federal Office for Radiation Protection, Germany |
| BMU | Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, Germany |
| BRWM | Board on Radioactive Waste Management, US National Research Council |
| CC | Concentrate and confine |
| CNE | National Commission of Evaluation, France |
| CNSC | Canadian Nuclear Safety Commission |
| DD | Dilute and disperse |
| EA | Environment Agency, UK |
| DSIN | Direction of Safety of Nuclear Plants, France |
| EEG | Environmental Evaluation Group, USA |
| EKRA | Expert Group on Disposal Concepts for Radioactive Wastes, Switzerland |
| EPA | Environmental Protection Agency, USA |
| GNW | Co-operative for waste management, Wellenberg, Switzerland |
| HSK | Swiss Nuclear Inspectorate |
| HLW | High Level Waste |
| IAEA | International Atomic Energy Agency, Vienna, Austria |
| IPSN | Institute for Protection and Nuclear Safety, France |
| KASAM | Swedish National Council for Nuclear Waste |
| KNE | Commission on Nuclear Waste Management, Switzerland |
| LLW | Long lived waste |
| MA | Mining Authorities, Germany |
| ONDRAF | National Agency for Waste Management, Belgium |
| NAGRA | Swiss Co-operative for radioactive waste disposal |
| NAS | National Academy of Science, USA |
| NEA | Nuclear Energy Agency, Paris |
| NII | Nuclear Installations Inspectorate, UK |
| NIREX | United Kingdom Nirex Limited |
| NRC | National Research Council USA |
| NWMO | Nuclear waste Management Organisation, Canada |
| NWTRB | Nuclear Waste Technical Review Board, USA |
| POSIVA | Posiva Oy Finland |
| RR | Reduce and recycle |
| RSK | Reactor-Safety Commission, Germany |
| RWMAC | Radioactive Waste Management Advisory Committee, UK |
| RWMC | Radioactive Waste Management Committee of NEA, France |

| | |
|---|---|
| SF | Spent (or used) nuclear fuel |
| SGS | Swedish State Geological Survey |
| SKB | Swedish Nuclear Fuel and Waste Management Company |
| SKI | Swedish Nuclear Power Inspectorate |
| SSI | Swedish Radiation Protection Institute |
| SSK | Radiation Protection Commission, Sweden |
| STUK | Finnish Centre for Radiation and Nuclear Safety |
| TÜV | Technical Inspection Association, Germany |
| USD | US dollar |
| USDOE | United States Department of Energy |
| USNRC | United States Nuclear Regulatory Commission |
| WIPP | Waste Isolation Pilot Plant, New Mexico, USA |

# Appendix A

## Hazards and Risks Associated with Repositories

### A1 Introduction

The nuclear fuel cycle is a chain of linked processes all of which generate some quantity of radioactive wastes. These processes begin with uranium mining, milling of the ores and extraction of uranium. If enriched fuel is to be used (as opposed to the natural uranium fuel in CANDU reactors), then the uranium oxide is converted to uranium hexafluoride before enrichment takes place. Fuel fabrication and reactor operation are part of all nuclear fuel cycles. Reprocessing of the used fuel to recover plutonium and uranium is an option followed by some countries. Disposal either of high-level wastes from reprocessing and/or of unreprocessed used fuel is a responsibility to be faced by all nuclear programmes

The conventional fuel cycle begins with mining or in-situ leaching of uranium ores (containing typically 0.15 to 0.2% uranium, but sometimes up to 20% or higher), which are then processed to produce uranium oxide ($U_3O_8$ “yellow cake”). This oxide passes through a conversion plant, and the product can be handled in one of two ways:

1) A “natural” uranium dioxide powder is produced which is shipped to a fuel fabrication plant where the uranium dioxide is sintered into fuel pellets which are then assembled into fuel bundles or assemblies for use in fuelling Candu reactors. For a 1000 Mwe heavy water reactor (CANDU) around 140 tonnes of fuel is in the core at any time with a fraction being replaced each year. At a medium burn-up of 10 GWd/tU, this fuel will produce a total of around 1.3 GW.a of electricity.

2) A uranium hexafluoride ($UF_6$) product may be produced, which is fed to an enrichment plant. Here the content of the fissile isotope U235 is increased from its natural level of 0.7% to around 3-5%, with 85% of the feedstock being rejected as depleted uranium or tails. The enriched uranium goes to a fuel fabrication plant where it is converted to $UO_2$ and incorporated into fuel assemblies. For a 1000 MWe, light water reactor (LWR), around 80t of fuel is in the core at any time with about one third being replaced each year. At a high burn-up of 50 GWd/tU, this fuel will produce a total of around 3.3 GW.a of electricity.

During its years in the reactor each tonne of fuel will, from the U235 and U238 that are fissioned:

1) In a light water reactor produce around 60kg of fission products, 10kg of plutonium isotopes, and 8 kg of U236 and various other transuranics. If the used fuel is reprocessed, then the fission products are solidified to yield around 50 litres of vitrified high level waste (HLW). A 1000 MWe nuclear power station

therefore produces only 10-20 canisters of vitrified waste per year. The material flows and the resulting waste production are summarised in Figure A1.

2) Heavy water (CANDU) reactors produce (for each tonne of U at medium burn-up), 9 kg of fission products, 4 kg of plutonium isotopes, 0.6 kg of U236 and various other transuranics. A 1000 MWe CANDU power station therefore produces about 6,000 used fuel bundles per year (20 kgU per bundle)

All of the operations listed produce radioactive wastes in solid, liquid or gaseous forms. The greatest environmental challenges may actually be associated with wastes at the front end of this chain - namely managing safely the millions of tonnes of mining and milling tailings that remain on or near the land surface of uranium producing countries. However, most time, effort, resources and public attention are devoted to management of the low volume but highly hazardous wastes from the back-end of the fuel cycle. These are used nuclear fuel, if this is regarded as waste, or else the vitrified HLW and the transuranic wastes from reprocessing.

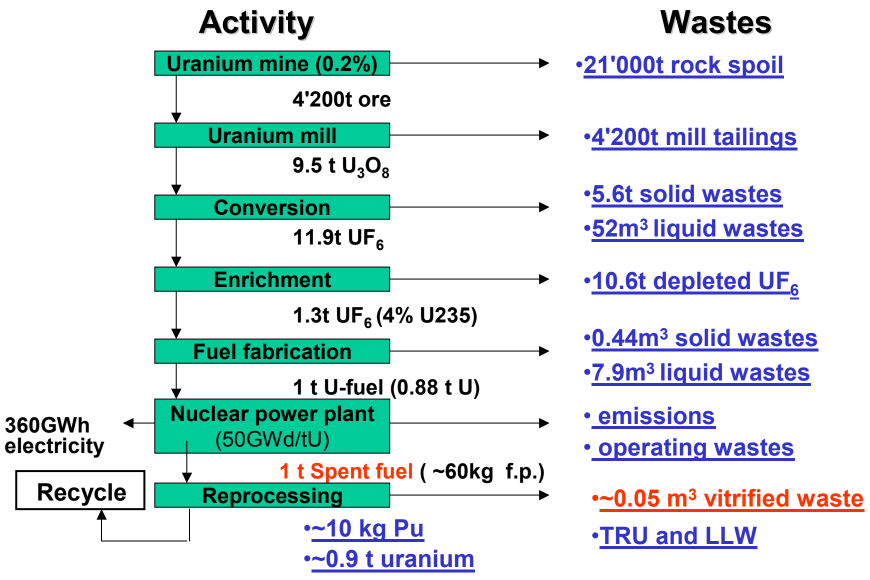


**Figure A1**: Flow of material throughout a closed nuclear fuel cycle together with rounded estimates of the wastes produced at each step. Other assumptions made are a waste to ore ratio of 5 (this will vary greatly depending on whether it is a high grade underground mine or a low grade high stripping ratio open pit mine) and a tails assay of 0.3%.

To translate a hazard potential into a specific estimate of consequence, we need to imagine some particular scenario that allows humans to be exposed to radiation. The scenario most often considered for geological repositories is that the engineered barriers corrode, after which groundwater leaches the wastes and transports radionuclides back into the human environment. Other scenarios are also considered in safety analyses, e.g. the inadvertent intrusion into the sealed repository in some future drilling operation. To quantify the risk associated with such scenarios, we need to allocate appropriate probabilities to all process and events involved in their description. The central aim of repository design is to keep probabilities and consequences of radioactive releases low enough to ensure that risks to humans never reach levels judged to be unacceptable by the standards applied today.

The challenge to the repository designer is, therefore, determined both by the inherent hazardous potential of the inventory and by the strictness of the imposed safety criteria. The following sections examine this hazard potential. They illustrate that, while the toxicity of the wastes is indeed high, it is certainly not unique. The required levels of safety are stringent, but also not unique - risk limits for some chemicals are even more stringent. However, the compliance requirements for demonstrating that safety standards are met are especially demanding for radioactive waste repositories.

## A2 How hazardous are radioactive wastes?

### A2.1 Hazard potential expressed as activity level:

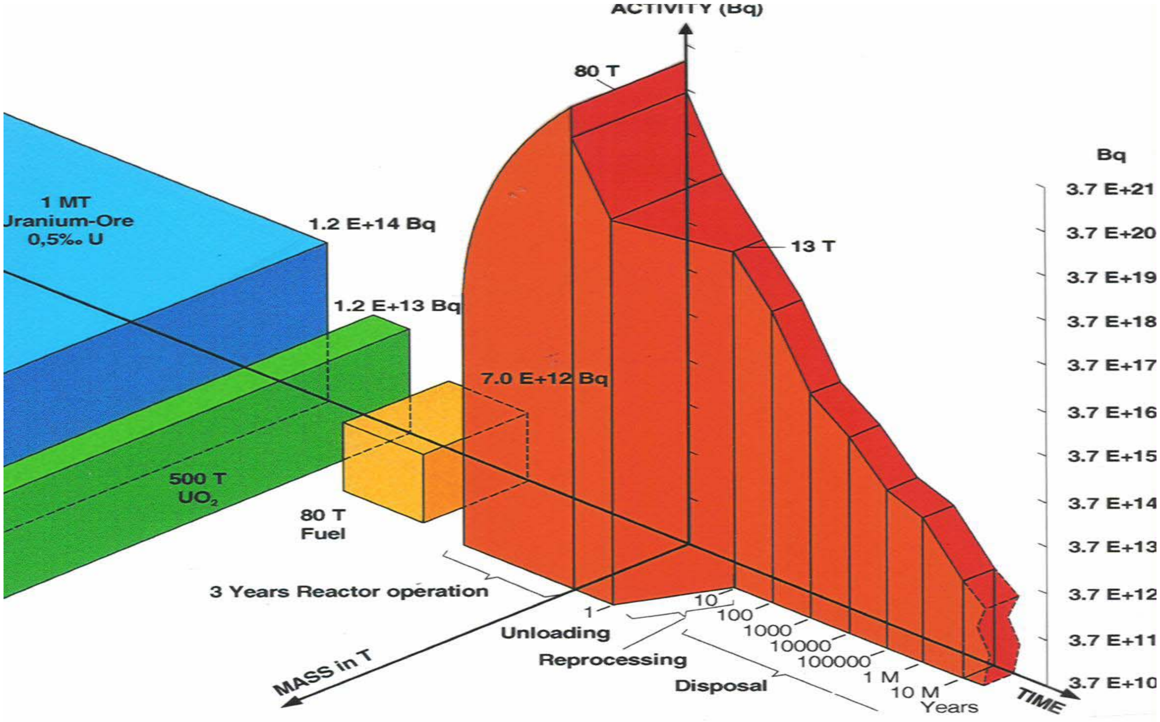
The potential hazards of radioactive wastes can be expressed in various terms. The most common measure is the radioactivity expressed in Bequerels (Bq). Figure A2 shows how the radioactivity levels and masses of materials are changed throughout the nuclear fuel cycle by different processes and with time. The quantities illustrated in the figure are for the 80 tonnes of fuel that would feed a typical light water reactor for three years. It is evident that the burn-up in the reactor leads to an enormous increase in total activity but that this increase decays with time towards natural levels. One can consider the specific case of the $\alpha$ and the $\beta/\gamma$ activity of a waste inventory resulting from 40 GWe.y of nuclear power production (this is what a large reactor will produce during its operating lifetime). The total radioactivity at the time of disposal (about 40 years after unloading from the reactor) is around $3x10^{19}$ Bq and the $\alpha$ component around 1/100 of this. The values for CANDU fuel are similar.

Are these high values? Some comparisons are needed to give perspective. The activity of the uranium ores used to produce the 1200 t enriched? U needed for the quoted energy production is around $10^{15}$ Bq $\alpha$ and $3x10^{15}$ $\beta/\gamma$. These activity levels are reached by the wastes in $10^4$-$10^5$ y. Indeed, given enough time the activity level of wastes produced in the fission process eventually falls below that of the original ore, i.e. we have a small net removal of radioactivity from the Earth. The main problems with this reassuring comparison are, firstly, that the time period of enhanced radioactivity is enormously long and, secondly, that the fuel cycle operations have led to concentration and geographical redistribution of hazardous materials. The resulting consequences or risks to man are not therefore necessarily reduced; exposure scenarios must be evaluated for the new situation.

A further perspective on the radioactivity associated with wastes can be provided by comparing values with radioactivity from natural sources or from other industrial contributions. The natural activity in rocks and soils is such that the radioactivity of the entire inventory of a repository can be easily exceeded by the surrounding rock. For example, the activity of the ~1 $km^3$ of granite above a potential HLW repository in Northern Switzerland is ~$10^{16}$ Bq, a level which the vitrified wastes from a 40 GWe.y nuclear programme would reach after a few thousand years of decay.

Perhaps a more relevant comparison with radioactivity from the nuclear industry is the enhancement of natural radioactivity due to other industrial activities (Baxter, 1993). Coal fired plants producing the 40 GW.y of electricity referred to above would result in environmental releases of fly ash and off-gases of up to $3x10^{13}$ Bq, mainly of Rn-220 and Rn-222. The fly ash contains around 1400 Bq/kg of $\alpha$-emitters. Higher concentrations of naturally occurring radioactive materials can occur in other widely used materials such as phosphate fertilizers. For example, around Rotterdam, more than $10^{12}$ Bq per year of Po-210 and Ra-226 are released in industrial phosphogypsum effluents.

**Figure A2:** The quantities of radioactive material and the level of radioactivity both change markedly through the nuclear fuel cycle. The illustration shows how the mass and activity varies for the fuel need to operate a large light water reactor for 3 years.



Again it would be valuable for the Canadian program to have a CANDU comparison. The concepts are the same and the message the same but the relevance more direct.

## A2.3 Hazard potential expressed as toxicity:

The activity levels of radioactive wastes are, however, insufficient in themselves to give a proper perspective on their hazard potential. The mechanisms by which harm can be caused to humans need also be considered.

Direct irradiation and incorporation into the body are the potential pathways. Harm due to direct exposure to external irradiation from wastes is not a significant problem in waste disposal, even in the initial phases when the level of radiation is still high. Normal radiation protection measures function during the repository operational period and trivial thicknesses of engineered barrier materials or of rock provide adequate shielding following disposal. Forty year old vitrified waste being disposed of in a deep repository still gives at the glass surface the high dose rate of $4.2\text{x}10^{6}$ Sv/y; a 25 cm thick steel canister would, however, reduce this to 4.3 Sv/y and a surrounding bentonite buffer brings the dose rate down to $2\text{x}10^{-8}$ Sv/y, i.e. 4 orders of magnitude below natural radiation at the earth's surface. Direct irradiation is obviously not the problem.

Again a comparison with CANDU fuel may be of more relevance as Canada has made a decision not to reprocess fuel and referencing vitrified waste is of little direct relevance to Canada

The important scenarios are those in which radioactive substances are introduced into the human body. The main text of this report deals with the barriers in a repository system, which should prevent or minimise transport of radionuclides to humans. If some radionuclides nevertheless reach humans, what are the hazards from this released activity? When release scenarios are quantitatively analysed, then it is usual to translate the corresponding quantities of ingested radioactive materials directly into the health effects which they can cause in the human body. Two sub-steps are required. The radioactivity in Bequerels (Bq) multiplied by the dose-conversion factor yields the radiation doses in Sieverts (Sv). The risk, of death from cancer for example, is then calculated from the dose received. Both steps have large associated uncertainties which are often overlooked.

In order to clarify the second issue, i.e. conversion of radiation dose to risk, health effects for a given radiation dose have been far more extensively studied than for doses of any other toxic substance. Nevertheless, large uncertainties remain in this part of repository analyses. This is because the individual dose levels commonly predicted to result from releases from repositories are far below those at which health effects can be directly observed. At the low doses normally calculated, we are in the range of doses where acute radiation effects do not occur and the probabilities of cancer associated with the stochastic risks are so low that any deaths would be masked by the much larger fluctuations due to other causes. Nevertheless, in radiation protection the normal, conservative approach used is to linearly extrapolate health effects observed at much higher doses (above 1 Sv) down to levels a 1000 times lower. This no-threshold, linear hypothesis was not in the past normally applied to other toxic materials; doses below a given level were considered harmless. For radiation, the probabilistic mechanism by which single ionising particles can disrupt genetic material led to the no-threshold assumption. However, the fact that life has developed in a much higher radiation background than the low doses predicted for repositories and the fact that repair mechanisms of the human body can remediate isolated damage have led to repeated arguments that negligible or *de-minimis* dose rates, below which no harmful effects are to be expected, should be defined. There is, in fact a continuing debate on whether low radiation doses are not detrimental and may even be beneficial (the so-called hormesis effect) (Muckerheide 1995, Mossman 2001).

In this discussion we shall, however, stick to the linear hypothesis which is still standard for radiation exposures and, indeed, is being increasingly advocated also for cancerogenic, chemotoxic materials. The linear hypothesis enables the hazard potential of radioactive materials to be quantified in terms of the risks they could present in the unlikely event of their all being available for ingestion or inhalation by humans. The toxicity thus derived is often expressed as an RTI (radiotoxicity index), which gives the ratio of doses due to any intake to that dose deemed to produce acceptably low health effects. The RTI of any particular radioactive material will vary as a function of the quantity, the type of radioactivity (alpha, beta, gamma) and the relative biological effectiveness of the particular radiation. The reference dose rate used is below 0.1 mSv/y, which is a typical guideline for waste repositories.

The radiotoxicity of HLW decays with time more slowly than the activity so that the toxicity level of the 1 $km^3$ of granite referred to above, for example, will not be reached for ~20 000 years. At repository closure, the RTI of wastes from a large 1Gwe reactor is $\sim 3x10^{14}$. Again using CANDU data would be valuable. One alarming interpretation of such a figure is that, at this early time, this enormous number of persons could receive a dose of 0.1 mSv/y from the waste! The figures become less alarming when one realises that the inventory would have to be somehow apportioned for consumption equally amongst those persons. To put another perspective on such apparently high toxicities, we could use the same approach for any chemical toxic substance in a repository. To use an extreme example, if lead were used as in, for example, early Swedish container concepts, then the RTI of the total lead needed to encapsulate the above used fuel inventory (using allowable drinking water uptake as a normalising facture) is around $3x10^{11}$. This is 1000 times less than the previously mentioned radioactivity RTI – but the RTI of the radioactive wastes will decay to that of lead in $\sim 10^5$ years and further thereafter, whereas the lead RTI stays constant. The first message here is that numerical expressions of toxicity, like those for radioactivity are useful only if appropriate reference comparisons are given. The second message is that when such comparisons are made, both the activity and toxicity in a used fuel or HLW repository are high but certainly not uniquely so.

It is important that these messages are introduced into the public debate on waste disposal, since there is a commonly perception that radionuclides present a new kind of hazard. The particular case of Pu-239 has repeatedly been raised as a problem because of its long half-life and its toxicity - often being cited as "the most hazardous substance know to man". This unfounded perception provoked specialists at Lawrence Livermore Laboratory (Sutcliffe et al 1995) to produce, as a response to scare-mongering newspaper reports, a document intended to give a proper perspective on this issue. The authors pointed out that an acutely lethal dose for plutonium is 0.5 g; for cyanide, which is used in large quantities worldwide, it is only 0.1 g; for nicotine it is 0.05 g! In water, which is most relevant for waste disposal, plutonium presents a lower hazard than widely believed because of the low solubility and its relatively low toxicity for ingestion. Using a conservative solubility of $10^{-6}$ mol/l for plutonium implies that a year's consumption of Pu-saturated drinking water would lead to ingestion of less than 0.2 g of plutonium. As mentioned above, 0.5 g is the acutely lethal dose and is, coincidentally, also the estimated quantity of plutonium required to produce one fatal cancer.

### A2.4 Conclusion on hazard potential:

In concluding these comments on the hazardous potential of HLW, we may summarise that these wastes are highly toxic and remain so for very long times. Elaborate measures to protect humans from unacceptable exposures are certainly justified. On the other hand, the radioactivity decays with time and neither the level of the hazard nor the duration is unique (or even extremely unusual) when we compare these to other natural and man-made hazards in the environment

# Appendix B

# Ethical issues

## Introduction

In this Appendix, after an introductory overview, relevant ethical principles are identified, their relevance discussed and "messages" derived which should influence the development of safety criteria for deep geological repositories.

## B1 Early Ethical Considerations

In the early years of radioactive waste disposal studies, the problem was primarily regarded as a technical and economic challenge without much explicit recognition of political, social and ethical aspects. There was none the less direct recognition of the key importance of ensuring the safety of humans and the environment. The guidelines for the US National Academy Committee on Geological Aspects of Radioactive Waste Disposal already in 1955 included the following principles (quoted in NRC 1966):

1. *Safety is a primary concern, taking precedence over cost.*
2. *Radioactive Waste, if disposed of underground, should be isolated as permanently as possible from contact with living organisms.*

In the eighties, explicit attention was paid to ethical issues during development of objectives and principles for radioactive waste management by the NEA and the IAEA (NEA 1984b, IAEA 1989).

The NEA report concentrates on how to apply operational radiation protection principles to practices that might give doses only in the far future. The ethical basis behind such considerations is reflected in the report's statement (p18) that "*the reasons for adopting the same principles when dealing with hypothetical exposures to the public in the far future from today's waste disposal practices are a desire for equity, in that future generations should be given the same degree of protection that is given to the present generation.*"

The Principles in IAEA 1989 were much broader, reflecting various ethical aspects of waste disposal. They were reformulated after much international discussion to give the wording contained in the high-level Safety Series document of 1995, "The Principles of Radioactive Waste Management" (IAEA 1995a), extracts from which are included in the following section.

### B1.1 Ethical principles in IAEA documentation

IAEA 1995a contains the following ethical principles protecting current and future generations:

***Principle 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 also be taken into account.*

***Principle 4: Protection of future generations***
*Radioactive waste shall be managed in a way that predicted impacts on the health of future generations will not be greater than relevant levels of impact that are acceptable today.*

***Principle 5: Burdens on future generations***
*Radioactive waste shall be managed in a way that will not impose burdens on future generations.*

The Safety Principles of the IAEA have formed a basis for the major IAEA Joint Convention on the Safety of Used Fuel Management and on the Safety of Radioactive Waste Management (IAEA 1997a). The above three principles all have relevance for international repositories. Principle 3 was originally intended for application to possible effects of a national repository on its neighbours. It would, however, also oblige a nation sending waste for disposal elsewhere to assume its proper share of the responsibility for the future safety. Principles 4 and 5 are relevant for international disposal for the simple reason that they also apply out to far future generations, i.e. at times when no person can predict if and how national boundaries may have moved. A look at the map of any region of the world illustrates vividly how borders change on the timescales of decades or centuries, without even considering the many millennia being discussed in waste disposal.

The Joint Convention explicitly addresses the issue of transfers of wastes between countries when it states the following:

*" (xi) Convinced that radioactive waste should, as far as is compatible with the safety of the management of such material, be disposed of in the State in which it was generated, whilst recognizing that, in certain circumstances, safe and efficient management of spent fuel and radioactive waste might be fostered through agreements among Contracting Parties to use facilities in one of them for the benefit of the other Parties, particularly where waste originates from joint projects; ......".*

The first part of the statement emphasises national responsibility for wastes; second half makes it obvious that transfer of wastes can be a justifiable approach. The fact is that risks or hazards are routinely transferred between sovereign states, on the assumption that the benefits and drawbacks are weighed against one another. For example, countries that mine raw materials (including uranium ores) for export implicitly accept the risks from what is often the most hazardous part of the life cycle of commodities. Nevertheless, the argument has sometimes been made that there is a principle of ‘self-sufficiency’, which dictates that nations should dispose of their own radioactive wastes. One flaw in such a principle is that it is arbitrarily narrow. If a nation wishes to be self-sufficient and also use nuclear power, one might expect it to engage in all aspects of the fuel cycle on its own territory. Very few countries have the possibility of being involved in mining, milling, enrichment, fuel fabrication, nuclear power generation and waste disposal.

### B1.2 Ethical discussions within the OECD/NEA

A further, equally important international document is the "Collective Opinion on the Environmental and Ethical Basis of Geological Disposal" produced by the NEA/IAEA/ EEC in 1995 (NEA 1995). This consensus view, drafted following a 2-day, wide-ranging workshop on Environmental Aspects of Long-Lived Radioactive Waste Disposal (NEA 1994b), is that the concept of geological waste disposal rests on a firm ethical basis.

A set of guiding ethical principles is developed in the NEA document; these are broadly similar to the above mentioned principles of the IAEA. Two issues, however, are more strongly emphasised. One is that *"a waste management strategy should not be based on a presumption of a stable societal structure for the indefinite future, nor of technological advance"*. This principle leads to rejection of indefinite storage strategies requiring continuing of resources in favour of geological disposal concepts offering permanent protection. The second issue discussed more extensively in the Collective Opinion is the wish to ensure that one does *"not unduly restrict the freedom of choice of future generations"*. These fundamental principles are very much in line with the Bruntdland definition of sustainable development. It is judged that an incremental process, involving development of deep repositories in a stepwise fashion over decades, meets this requirement - even when disposal facilities have no deliberate provisions for waste retrieval following repository closure.

### B1.3 National positions on ethical issues

There have also been, at a national level, numerous meetings and position papers on ethical issues. In Sweden, for example, the advisory council, KASAM, organised a Symposium on the subject in 1987 (KASAM 1988). KASAM was the first organisation to place strong emphasis on the overriding importance of keeping future options open - a topic to which we return below. Other countries have addressed the issue less formally or publicly. In Canada, a workshop was held to give ethical input to the national strategy for disposal of used fuel (AECL 1991). In Switzerland, as a preliminary to revision of the government regulations governing long-term disposal of radioactive wastes, a seminar was held at which ethical issues were presented by experts from outside the nuclear community. The USA has an extensive literature on the general question of achieving equity between successive generations and this discussion has been taken up by those concerned with radioactive waste management.

The following discussion aims at a structured approach linking ethical principles to specific requirements on disposal programmes and thereafter to safety and other criteria established in national programmes. The fundamental principles are **fairness or equity** for current and future generations; these two concepts, as mentioned above, are labelled respectively **intragenerational** and **intergenerational** equity. They are treated separately below.

## B2 Intragenerational Equity Aspects

Intragenerational equity means that within current generations it is important to ensure that our finite resources are spent sensibly on solving environmental problems, taking into account the relative scale of the potential impacts and also the distribution of risks and benefits. It implies also that decisions on how to achieve these aims are made in a fair and open manner, involving all sections of society. In the following, we address a series of intragenerational equity issues and try to derive from this the messages which are valuable for waste disposal implementers or regulators.

### B2.1 Health risks to current populations

The ICRP has an initial principle of radiation protection which holds that any practice leading to radiation exposures to populations must be justified. For waste disposal, the practice is usually taken to be part of the larger issue of nuclear power production, so that explicit justification of disposal in this sense has not been an issue. The criteria set for allowable exposures to current populations from operational activities is also not a disposal specific issue since the relevant facilities and activities are treated like any other nuclear application.

In radiation protection in general, ethical considerations would argue that intragenerational equity would require the levels of risk criteria to be set relative to other activities that are potentially hazardous to the public. In fact, only few countries have a uniform regulatory framework that should encourage this (e.g. USA with the Environmental Protection Agency and the UK with its Environment Agency). Even in these organisations, there is no real pressure to use uniform risk criteria. The widely recognised "nuclear dread" factor associated with radioactivity tends to lead to especially strict formulation and enforcement of regulations in the nuclear area, including waste management.

### B2.2 Social and economic impacts

Despite strict regulation of radiation exposures, there is an additional ICRP requirement to maintain exposures "as low as reasonably achievable, social and economic factors being taken into account". On the one hand, the economic part can justify arguments against exorbitantly expensive measures (e.g. over-design of engineered barriers which do not greatly increase safety). On the other hand, the social argument can justify fully weighting also the subjective arguments of the public – and hence being prepared, for example, to spend more resources per life saved on nuclear than on conventional risk reduction measures.

## B2.3 Spatial distribution of burdens and benefits

At a national, the issue of distribution of burdens and benefits is a key issue in the siting of waste repositories. Today, it is a widely accepted practice that a host community should be compensated for its willingness to accept a common facility which is for the good of a wider population. Specific national negotiations on such issues have taken place in numerous countries, including Canada, Finland, France, Sweden, Switzerland, Taiwan and the USA.

At an international level, the IAEA principle 3 on "protection beyond national borders" addresses the geographical distribution of negative impacts. The IAEA also has guidance on international transfers in its Spent Fuel and Waste Convention and on transboundary effects in its Principles. As previously mentioned, the ethical rules proposed do not exclude transfer of wastes between sovereign States. In practice, this has happened often in the past. For example, the reprocessing nations France and the UK originally accepted that they would dispose of the resulting wastes along with their own national waste inventories. Spent radioactive sources were expected to be disposed of by the country which had bought them. The IAEA is currently studying the conditions which should be fulfilled for multinational waste repositories (IAEA 1998, 2003) and the EU has debated equivalence principles for waste substitution. More recently, however, there have been marked movements towards limiting or banning transfer of wastes. For example, countries like France, Sweden, Finland, and Russia have banned waste imports. The reprocessing countries France and the UK now insist on returning wastes to customer countries. The UK has adopted a policy of "self-sufficiency" in this area. In practice there are no ethical reasons for treating radioactive wastes differently from other commodities, including chemotoxic wastes.

There are, of course, strong ethical reasons for not exporting hazardous wastes to any country that does not have the appropriate technological and societal structures to ensure that these wastes are properly handled. The arguments against waste transfers in the case of willing and capable host nations being prepared to accept waste imports are less a matter of principle and more of political expediency. In developing the international repository concept, the issue of equitable distribution of the benefits between host and partner countries is of even greater importance than in the national case. The benefits offered in both cases are regarded as fair compensation and not as bribes or as risk premiums.

## B2.4 Public Involvement

Intragenerational equity requires that the public be given open access to information, that their concerns are appropriately weighted and that they can participate in the relevant decision making processes. In virtually all countries today, information on waste management is freely available. This position has been reached despite the initial tendency to secrecy bred in nuclear weapons programmes and taken over into commercial power activities. Increasingly there is also a universal trend towards engaging the public in the debate and ultimately in the decision processes. This is sometimes done informally with public fora or public enquiries. In some cases, e.g. in the rule making of the USA, there is a highly formalised mechanism for gathering public comments on key issues. The ultimate instrument of public participation is perhaps that of a referendum in which every person can record his opinion. A caveat, which is often forgotten here' is that the public cannot be expected to master all of the technical issues involved, so that the implementer and regulator have a direct responsibility to make as clear as possible the scientific issues on which there is a broad consensus.

Finally, it should not be forgotten that, at the highest level, the public in a democratic society has the opportunity for involvement through the political processes. Governments, which have broad responsibilities for society, are elected and can be rejected. There are important issues that must be decided at the political level, rather than scientifically. A wise government will make use, where appropriate, of good scientific input to the decision processes – but may abide also to the adage that "scientists should be on tap and not on top".

## B3 Intergenerational Equity Aspects

Intragenerational equity involves ensuring fairness across generations; it is directly related to the topical subject of sustainability. The basic tenets are that we do not pass on burdens unnecessarily; and that we leave future generations with the same freedoms and choices that we have. In the following, we address intergenerational equity issues and try to derive from these the messages which are valuable for waste disposal implementers or regulators.

### B3.1 Risks to future generations

The IAEA Principles maintain that future generations should not be exposed to higher risks than current generations. This would lead to dose or risk criteria for future exposures being set equivalent to those for operating facilities. In practice, the argument is made, e.g. in the Swiss Regulation R21 (HSK 1993), that since the current generation is the beneficiary of nuclear power future doses should be less. This has resulted in dose limits like 0.1 mSv/y being set for the future, whilst current radiation protection limits are significantly higher.

### B3.2 Burdens and benefits for future generations

The potential burdens on future generations do not involve only radiation risks. The most obvious other risk is financial and this is discussed separately below. In any ethical discussion on future impacts of waste disposal, one should also address the benefits which can result. Most of the benefits are associated with the overall practice of nuclear power – and hence subject to controversial discussions. However, serious debate on ethics must acknowledge also the potential benefits of technology advances and increased energy availability. For nuclear power, additional arguments are conservation of fossil reserves and reduction of greenhouse gases. The aspect of disposal of unwanted materials from disarmament also raises a new and powerful ethical argument. A responsible, secure host nation that accepted the responsibility of the guardianship of fissile materials, which might otherwise cause mass destruction anywhere in the world, would occupy high moral ground. The huge importance of these points for all future generations is often insufficiently stressed in debates on the ethics of nuclear power and radioactive waste disposal.

### B3.3 Financial risks to future generations

Implementing repositories will be expensive and postponing this task for long times means that these costs will fall on future generations. For this reason, serious waste management programmes set aside funds to cover these future liabilities. The pioneering example here was Sweden where a fund fully segregated from the utilities and from Government was established early. Many other countries now have funds, although these are sometimes open to (mis)appropriation by Governments for other uses, as in the USA, or are left within the utilities, as was the case in Switzerland until recently. In Canada, the nuclear utilities have established segregated funds for radioactive waste disposal and decommissioning of the facilities.

### B3.4 Maximising freedom of choice

As mentioned first in the section above on national positions, the issue of not unnecessarily restricting the choices of future generations was originally highlighted in Sweden. This aim can obviously cause conflict with the principle of minimising potential burdens. In the extreme case**, all** choices can be left open by current generations postponing all decisions on waste management. Wastes should not be conditioned, in case better methods become available; disposal should not be implemented in case alternatives like transmutation provide perfect solutions; repositories should not be sealed in case we wish to retrieve the wastes with ease; etc. This approach, however, passes on also all burdens and is certainly not ethical.

In practice, there is a strong, and increasing, tendency to try to provide a compromise. Implementers are trying to develop repositories that provide future safety but also retain options for change. Retrievability of wastes has become a major topic (see for example IAEA 2000a). In the ethical debate surrounding disposal, achieving the correct balance between maximising freedom to change direction and minimising future burdens is one of the most sensitive of all issues.

## B4 Other Ethical Principles

### B4.1 Sustainability

The topical issue of sustainability is closely related to intergenerational equity. The most widely accepted definition of "sustainable development" is that of the Brundtland Commission, *"development that meets the needs of the present without compromising the ability of future generations to meet their own needs"* (World Commission on Environment and Development 1987). Most of the relevant points for waste disposal have been touched on above in the discussions on burdens and benefits. Nuclear power with properly implemented, safe disposal is sustainable since it contributes to reducing hazards in the human environment, conserving hydrocarbon resources, etc. Specific repository siting measures can be taken to enhance such attributes; for example locating repositories in areas where intensive human usage is unlikely and where no restrictions are put on the availability of natural resources.

### B4.2 Precautionary Principle

This principle calls upon society to take prudent preventative actions to deal with risks with potentially very serious consequences even if there are doubts and scientific controversy surrounding the evidence. Whilst the concept is obviously laudable, its implementation without misuse of society's resources in a manner which conflicts with the principle of intragenerational equity calls for sound judgement. For radioactive waste disposal, it can be argued that any future impacts will be localised and not of a catastrophic nature so that the precautionary principle has limited impact.

### B4.3 Polluter Pays Principle

The fact that polluters should not be subsidised is widely accepted and influences environmental legislation is almost all countries. Difficulties can arise in assessing the costs, in particular of pollution which is diluted and dispersed (e.g. CO2 emissions). Nuclear power and geological disposal are more straightforward and, as described above, mechanisms to ensure costs are covered are in place in most countries. The more generalised form in which "users pay full costs" is more difficult because the costs of avoiding pollution are relatively well defined compared to the costs of, for example, using up natural resources.

# Appendix C

# Safety Assessment for Repositories

## C1 The challenge of long-term safety assessments

For the decades since the beginning of planning for waste disposal, a prime focus for debate has been the issue of demonstrating long-term safety. Today, this is still the case. The intense debates on safety arise despite the fact that a well-designed repository represents a passive system containing a succession of robust safety barriers and no large energy density that might lead to catastrophic hazards. Our present civilisation designs, builds and lives with technological facilities of much greater complexity and higher hazard potential. What, then, are the new or unusual features of repository safety analyses, which lead to so much discussion? They are primarily the **long timescales** which are explicitly taken into consideration in the analyses and the **prominent role of the geological medium** which has compelled earth scientists who are used to descriptive, deductive reconstruction of the past to aim at quantified, inductive assessments of future system behaviour. In fact, these features are relevant also for other technologies, such as disposal of other toxic wastes, depletion of fossil fuel reserves etc. and work in the field of radioactive waste disposal may even play a pioneering role in developing approaches for long-term analyses.

The timescales of concern for deep disposal are so long (hundreds of thousands of years) that **direct** observations or measurements of temporal alterations in actual repository system components are of limited value (although much can be learned from studies of analogous systems existing in nature). Assessment of future repository performance must be based upon **modelling** of the physical and chemical processes involved. Is our current knowledge adequate to allow sufficiently realistic predictive modelling over the timescales mentioned? Some important points to be made before answering this question are that:

- the laws of natural science which govern key processes like corrosion, fluid-flow, mass- transport etc. do **not** change with time

- the geological database actually extends over very much **longer** timescales (billions of years) than the toxic lifetimes of most radioactive wastes

- **accurate** predictions of actual system behaviour are not required; it suffices to provide conservative estimates of impacts that can be reasonably expected

- the low levels of release which appear to be achievable imply that **precise** estimates are not needed; even with some orders of magnitude of residual uncertainty we may be clearly within defined safety goals or limits.

Taking these points into account, it has been possible for interdisciplinary teams of safety assessors - including representatives from the fields of engineering, physics, chemistry, earth sciences, mathematics, ecology etc. - to develop over the past 20 years a safety assessment methodology capable of providing an **important part of the decision basis** required before implementation of projects for geological repositories for radioactive wastes.

However, a **direct** demonstration of the reliability of the methodology or a rigorous and complete **proof** that models are correct is not possible. Accordingly, the societal acceptability of project decisions based, at least in part, upon the results of safety assessments will depend upon the level of confidence placed in the methodology by the technical experts within the implementer and regulator organisations, by political decision makers and by the public. Assessing the behaviour of engineered and natural systems far into the future, is a novel tasks that requires integration of a wide range of technical disciplines. In each area there will be a divergence of technical views on the maturity of the scientific basis. These diverging “expert opinions” tend to be given equal exposure to the public, independently of the weight of opinion on each side. This makes it difficult for the lay public to form a balanced judgement. The important subject of confidence-levels in different stakeholder groups is therefore addressed below as a major topic.

## C2 Safety assessment methodology

Over the last 20 years, significant effort has been devoted worldwide to development of safety assessment methodology and also to achieving international consensus on appropriate approaches (e.g. IAEA 1981, 1985, 1995b and 2000b, NEA 1991and 1999a). The recognised need for a common understanding of the safety of the different repositories has, during the eighties and nineties, encouraged international discussions on methodologies. There exists today an extensive literature documenting the techniques, the applications and the results of safety assessments. This basis makes it feasible to provide guidance and advice on safety assessments for radioactive waste disposal facilities near the surface or at depth. However, no single approach to assessing safety has yet been identified as optimal. Different assessment groups and different disposal programmes apply methodologies that differ in their broad structure as well as in their detailed modelling. Moreover, in all of the approaches currently in use there are remaining open issues and continuing developments. The following text summarises the common basis of safety assessment methodologies, and points to major topical issues still being debated. Detailed descriptions or exhaustive catalogues of individual modelling efforts are neither possible nor necessary in an overview of the present type.

Safety assessment must address three important topics:

1) The role in determining total safety of the different components of the repository and of the varying processes of interaction that can occur

2) The predicted long-term safety of the repository (i.e. probabilities and consequences of radionuclide releases must be compared with acceptance criteria)

3) The magnitude of the uncertainties involved in predictions of long-term behaviour.

Safety assessments are conveniently divided into scenario and consequence analyses. Scenario analyses look at all of the conceivable features of the system, events and processes that might affect future repository behaviour. These are then grouped to form scenarios, each describing one possible evolution path. It is not necessary to predict the precise evolution if one can be confident that the scenarios postulated cover all futures that can be reasonably expected. The consequences of each scenario are then assessed using a series of consequence models. In safety assessment, models are needed to simulate the behaviour of repository systems because of the long time periods that are of interest. The modelling process consists of five basic steps (see Figure C1):

1) Development of a conceptual model

2) Development of a calculational model

3) Development of a computer code

4) Verification and validation

5) Application of the model.

A conceptual model represents one's understanding of the features and processes of interest. It is an abstraction of reality, which need only include those relationships required to describe the system for the intended model application. For safety assessment, the relationships of the conceptual model are represented quantitatively in a calculational model, which may be as simple as closed-form analytic solution or so complex that only computer solution is possible.

Finally, to ensure that the coded calculational model is adequate for its intended application, it is verified and validated. Verification is the relatively straightforward process of obtaining assurance that a computer programme implements the calculational model. It is usually done by comparing results calculated by the code in question with known, analytical solutions or with results calculated by similar codes. Validation poses a much more difficult problem. It is the process of ensuring that a model, as embodied in computer code, is a sufficiently correct representation of the process or system for which it is intended. Ideally, validation involves comparison of results calculated by the code with direct observations; however, the time and physical scales of most repository models preclude this approach. Validation remains a key issue facing safety assessment.

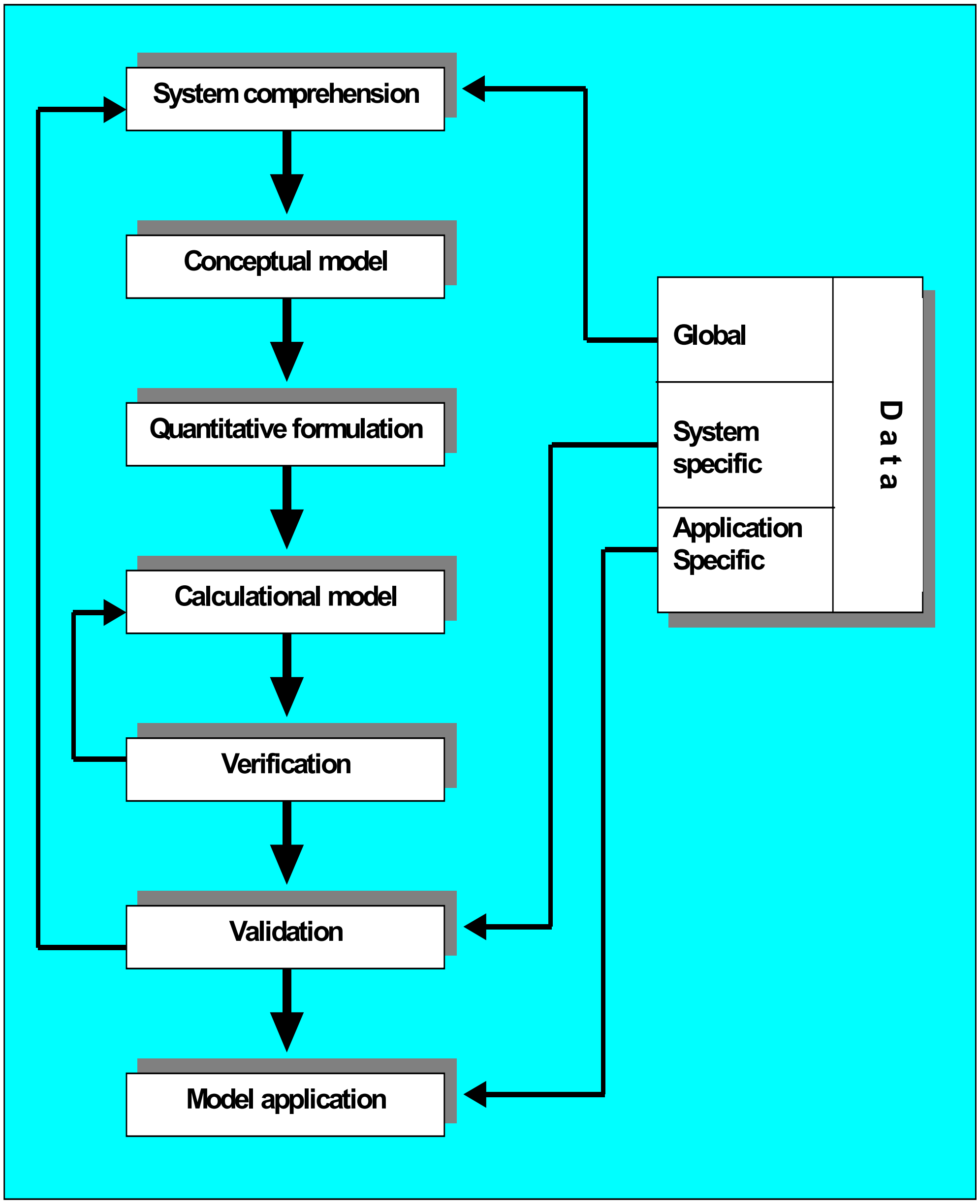


**Figure C1:** Modeling is not simply a numerical exercise. The figure illustrates the importance of understanding the system behaviour and of checking this understanding against data from experiments and observations on natural systems.

## C3 Data requirements

Data are the foundation of both model development and model application. This is one reason why data acquisition is one of the most extensive (and expensive) activities in repository development.

Applicable data may be obtained from any systems in which some or all of the same processes act as in the one which is to be modelled. Once a conceptual model has been formulated, data related to systems that are similar to the one which is to be modelled are needed to formulate a calculational model and to validate it. The actual model application requires data that are site- and design-specific. The relevance of any non-system-specific data to a particular modelling process must be demonstrated by the repository developer.

Data must be of sufficient quality for the model application. The methods of safety assessment can provide important input for determining the quality of data needed for each model parameter. In acquiring the data to be used for the modelling process, it is important that such requirements as to data quality be properly specified and that appropriate controls be exercised to ensure that the requisite quality is achieved.

The key concern at present is how we can demonstrate compliance with a given set of safety criteria. The task of developing criteria that can be unambiguously used in compliance testing is viewed as a challenging task also by the regulators of radioactive waste disposal.

The most important point to be made is that 100 % proof of compliance will never be possible in waste disposal assessments - or indeed in any other comparable fields. A decision that the predicted safety performance of any technical system (other than simple quality-controlled components) is acceptable when measured against specific criteria has always involved elements of scientific, engineering and also social judgement. The imminence of formal licensing procedures - and their increasing tendency to involve legalistic processes in which experts are called upon to deliver their considered opinions on technical questions - has led to intensive discussions on how such judgmental issues can be handled. It is still uncertain how formal compliance issues will be treated in a licensing procedure. Clearly, there will be much technical debate on key issues like uncertainties in performance predictions and model validation. It is important, however, that we do not raise expectations on the technical analysis to an unrealistic, unachievable level. We should openly acknowledge that some uncertainty on the performance and long-term safety of a disposal system will always remain - we should, however, require that judgements on acceptable uncertainties and on residual risks are compatible with those applied in assessment of other technologies.

In summary, compliance will not be based on a simple comparison of calculated results with numerical criteria, uncertainties will remain in the analyses, and judgement based on a range of accompanying evidence will be needed.

## C4 Applications of safety assessment

The tool with which one judges the long-term behaviour of a geological repository is called safety assessment (or performance assessment in the USA). Obviously the ultimate use of a sufficiently reliable methodology for safety assessment is to judge whether the safety levels offered by a facility lie within those which are judged acceptable by society and which, therefore, have been embodied in national licensing requirements. In earlier project phases, however, an assessment of the potential influence of numerous specific project choices on achievable safety is an invaluable decision aid. For this reason, iterative safety assessment is also performed to rank conceptual facility designs, to structure data-collection programmes in laboratory and field, to provide input for site-selection, to guide R&D work and to optimise the selection of specific combinations of safety barriers in the repository.

For differing applications, the requirements on reliability or accuracy of the assessments may vary. For instance, **compliance** with a limit may be shown using deliberately **conservative or robust models** that take no credit for less demonstrable safety mechanisms. The concept of robustness applies to repository systems themselves as well as to theoretical analyses of such systems (McCombie et al 1991); corresponding definitions can be summarised thus:

- A robust repository system has (1) simple and well understood geology, physics, chemistry, design, (2) large safety factors, (3) some degree of redundancy.

- A robust safety assessment is characterised by (1) being based on well validated realistic models or else clearly conservative models and data, (2) ensuring that all potentially negative processes are analysed and by (3) being insensitive to parameter changes.

Conservative models, on the other hand, do not allow **optimisation** of a combined safety barrier system; for this an adequate level of **realism** in the modelling of each component is required. Important nuances of this type will not, however, be discussed further in this summary paper; attention is focused primarily on the ultimate challenge of developing safety assessment methodology of sufficient quality to provide a decision basis within the regulatory process for licensing of a geological disposal facility.

## C5 Current status of safety assessment

Over the years the waste management organisations and the regulatory bodies in many countries have completed safety assessments. These have been published and often formally reviewed by other organisations. The NEA has organised intercomparisons of safety assessments (NEA 1997) and has also addressed the safety issue in a review of all developments in geological disposal in the last decade up to the year 2000 (NEA 1999b). In this review, the following key technical advances were cited as having resulted from work over the past years:

- more realistic modelling of canister degradation and failure
- understanding of waste-form degradation
- the modelling of early canister failures
- the more sophisticated use of geochemical codes and data
- thermal history of the repository
- the use of three-dimensional models of groundwater flow
- use of spatially-variable models of hydrogeological media
- geosphere transport in fractured and unsaturated media
- better-founded models of particular processes (e.g. volcanism and its effects, treatment of colloids, gas-mediated releases)
- better-founded models of interactions between system components.

It was, however, also recognised in the same report that there are still open technical P.A. issues. These are listed as:

- bounding the effects of infrequent, but highly-transmissive pathways
- determining infiltration and groundwater recharge
- the influence of gas on the barrier properties of the host formation
- the characterisation of naturally occurring colloids
- the influence of organic matter as complexants for migrating radionuclides
- natural and induced changes to the geosphere

The overall conclusion of the NEA concerning the technical analysis of repository safety is that this can be done well enough to provide a sound decision basis. Practicable methods have been developed. They will continue to be improved with time, but they offer already a meaningful basis for decisions concerning long-term repository safety – although NOT by means of a simple comparison of calculated results with numerical criteria.

## C6 Conclusions on safety assessment methodology

The following conclusions can be drawn on the status of safety assessment for waste repositories. They are summarized in the main text of this report.

- The necessity of modelling the long-term performance of a repository is universally recognised. Quantitative results from assessments provide a necessary input for decisions throughout disposal system development. The calculated results do not, however, provide hard criteria that obviate the need for human judgement. Safety assessments alone are not the only considerations governing the acceptability of any disposal facility.

- The feasibility of performing assessments of sufficient quality is accepted by technical experts within the waste management community. A somewhat lower level of confidence exists in wider scientific circles and, in limited segments of the public, severe reservations are still expressed. Some of the remaining differences in views could be narrowed if assessors made clearer that their aim is not to exactly predict the future but rather to scope the range of potential future behaviours of the repository system.
- Specific parts of the modelling chain for geological repositories will continue to be developed and refined. The common timescales for implementation of HLW repositories leave many years for potential improvements. These developments may ease the difficulties in future licensing procedures; nevertheless, they will not result in perfect models that produce unquestionably accurate results. The requirements on human judgement and expert opinion will remain.
- The critical issue with respect to safety assessment is the required or the achievable level of confidence in the results of the analyses. Neither a 100 % level of safety nor a 100 % confidence in the reliability of the assessments is possible. This is a fact that is true also for every other comparable technical undertaking and we must take care that unique, unfulfillable requirements to the contrary are not placed on waste disposal.

In this section there should perhaps be a comment of biosphere modelling and the fact that we are of necessity modelling the biosphere as it exists today far into the long-term future. We re doing this in order to demonstrate that future generations will not receive doses in excess of what is acceptable today not because we believe that populations a thousand years from now will have lifestyles and diets the same as today’s population. This often is a point of confusion.

# Appendix D

# Perceptions of problem areas in radioactive waste disposal

The intention of this appendix is to set a broad framework in which an exchange of views on waste disposal issues can be stimulated. The approach chosen is to first list important, objective statements on the status of waste disposal and then to complement these with the key debatable issues, as perceived by the different groups involved. Clearly, the choice of points made in each area is subjective and determined by the present author, who is unavoidably biased to the extent that he belongs to one of the groups discussed. Objections to these choices or proposal of alternatives by readers may provide a good starting point for open discussion, which the following remarks are intended to stimulate.

## D1 Short "objective" overview of the status of radioactive waste disposal today

(The word "objective" is deliberately placed in inverted commas here to acknowledge the fact that it is difficult for any one person to claim objectivity – especially for one who is closely involved with the subject in question.)

- Radioactive wastes are arising today in countries with nuclear power and also in many without nuclear power, e.g. Austria and Australia. Alternatives for long-term management have been studied. The most widespread strategy for the used nuclear fuel or high-level wastes is final disposal in deep geological formations. Even if advances are made in volume reduction, in recycling or in transmutation techniques, there will be wastes remaining for which long-term management is necessary. The geological option, however, is not accepted by everyone as the only safe approach. Some specific groups are not convinced that the behaviour of repositories can be well enough predicted. Some countries (e.g. Canada, the UK and France have not yet designated a preferred strategy, but are planning to do so in the next few years.

- Even if disposal is the chosen approach, there is little technical urgency for realisation of facilities; waste quantities are relatively small and interim surface storage has proven itself over decades to be safe. This conclusion has been recently questioned due to the rise in fears concerning malicious acts by terrorist groups.

- "Solution of the waste problem" is, nevertheless, widely perceived to be an important prerequisite for further use of nuclear power and, therefore, there are societal and political pressures to implement solutions.

- Repositories for low-level waste, LLW, are in operation in several countries The earliest facilities (mainly in nuclear weapons states like the USA, the UK and France) were very simple, but newer repositories, e.g. in Sweden, France and Spain are more sophisticated engineered systems. Siting of new facilities, even for LLW has, however, become extremely difficult because of the lack of public acceptance (recent examples of such problems are to be found in the USA, Switzerland, etc.).

- For used nuclear fuel, concepts have been developed and geological investigation of potential sites has been initiated but no country has an operational repository, or even a fully characterised and accepted site.

- The first deep geological repositories for used nuclear fuel and HLW therefore, cannot commence operation for ten or more years. In fact, because many countries plan a long intermediate storage period to allow the wastes to cool before emplacement in the ground, start-up dates will be, in general, even later.

- Completion of disposal operations will take place, in many cases, after the waste producing nuclear facilities have ceased operation. As well as ensuring that the necessary technology is developed, the responsible facility owners must provide the resources required. In most countries using nuclear power, appropriate funding mechanisms have been implemented.

- In some countries (especially those with a legacy of military wastes) remedial action at contaminated sites is at least as important as repository planning. In some countries with a history of uranium mining operations, clean-up of sites is also an urgent environmental task.

The following section looks at five specific groups that have complementary or conflicting views. For all groups, it is important to note that their attitudes and their influence are strongly affected by the treatment of relevant issues by the media, which is not treated here as a group by itself. (It should be noted that the role of the media is entertainment and controversy and conflict sell. If the media can fan the fires of a controversial issue they will sell air time, pages etc and be successful and profitable. – How can this be delicately put ? as it is a very important part of any debate. The media under the guise of presenting a balanced story will search for the outliers and by giving equal weight create an impression of conflict and uncertainty in the publics mind. A tremendous amount of work is needed by the “public” to become educated enough to understand when they are being manipulated. This is a real problem in today’s society when there are increasing amounts of information (some of good and some of lesser quality) they are being deluged with. Information doubling times are down to something like 16-18 months now)

a) Experts within the waste management community

b) Scientists/technologists (not directly involved)

c) Opposition groups which actively resist the progress of geological disposal

d) The lay public

e) Politicians

## D2 Experts within the waste management community

- Waste disposal concepts are based on sound ethical considerations. The ambitious goal is protection of humans and the environment at all places and times. In particular, burdens to future generations should be minimised, i.e. the present generation should at least make available the technology and the funds needed for implementing facilities. Making tangible progress by advancing geological disposal is more important than keeping all options open or hoping for new "perfect" solutions (e.g. transmutation, disposal in space, etc.). Given the instability of human societies, keeping hazardous wastes in surface facilities for indefinite times is unjustified.

- The safety requirements placed on waste disposal are very stringent when compared to other industries or even to natural radiation hazards. The strong focus on long-term safety, resulting from considerations of the long (but finite) half-lives of important radionuclides, is appropriate; it is, however, paradoxical that similar concerns are seldom expressed for human activities which can have even longer term impacts (e.g. disposal of other toxic wastes, disposal of $CO_2$ to the atmosphere, depletion or exhaustion of natural resources, etc.).

- The relatively small quantities of waste, and the large revenues available from nuclear power production, make elaborate solutions feasible, in particular in comparison to other types of wastes. The monotonic growth in estimates of disposal costs are, however, causing increasing concern because of their impact on the overall economics of nuclear power.

- The safety of waste repositories can be predicted with a level of confidence that is sufficient (even over very long timescales) to allow decision making. This consensus - of those within the waste community - is documented, for example, in the 2nd Common Opinion of the NEA-RWMC.

- Geological repositories can provide adequate safety; the risks to all future generations will be very low if proper concepts are implemented at suitable sites. Many extensive studies have come to this same conclusion.

- There are still challenging technical tasks to be undertaken. The most pressing of these is the geological and hydrogeological characterisation of deep sites to the level of detail needed for planning of facilities, for construction at depth, and for convincing demonstration of long-term safety.

- The biggest challenge for the waste management community today is, however, communicating with other stakeholders in the process (politicians, general public, local communities, media, etc.) and gaining acceptance. Progress is being made - in particular in development of decision strategies which involve directly those persons most affected by a potential repository - but achievement of across-the-board voluntary acceptance at all geographical or political levels (community, state, national) remains an ambitious goal.

- The environmentally orientated objectives of waste disposers are made more difficult to achieve by opposition from groups whose target is not disposal itself but rather nuclear power production. There is insufficient recognition that waste disposal is necessary independently of the further use of nuclear power because significant waste quantities already exist today. The technical challenge of implementing disposal, and even the total costs involved, are not strongly dependent on the waste quantities involved.

## D3 Scientists/technologists not directly involved

- Waste disposal is an interdisciplinary task requiring good communication between scientists and technologists in a wide range of disciplines. In particular, the importance of geology necessitates the participation in decision making processes of earth scientists, the majority of whom have not been used to thinking in a predictive, quantitative mode.

- Even for many scientists, the emphasis on very long timescales like a million years is disquieting. The challenges in modelling the evolution of the engineered and natural barrier systems are large. More particularly, it is recognised that there is no way to realistically model the development of human society over even hundreds or thousands of years so that quantified estimates of repository consequences at far future times must be very uncertain.

- The scientists involved in waste disposal (especially the safety assessors) should be more aware of the shortcomings in their models and should appreciate the uncertainties in data obtained from "softer" sciences. They must also be open-minded to criticism of their analyses and must be careful, themselves, to point out the unavoidable uncertainties in their results.

- There are research oriented scientists who have a vested interest in keeping problems open to ensure future funding. A commonly observed trend is for specialists in a narrow field, which may indeed be of relevance to repository performance, to push for a complete and detailed understanding of all sub-issues involved even when the relevance to overall safety is questionable.

## D4 Opposition groups

- Too little is understood about the deep geology. The spatial heterogeneity is too great to be measured without disrupting the system; the temporal evolution can not be sufficiently well predicted. The proposals of the nuclear community to emplace wastes there is meant simply to remove them from the public sight in the cheapest possible manner.

- Keeping the waste on the surface in controlled facilities is safer because it allows easy inspection and maintenance. It also serves as a lasting reminder to future generations of the burden they have to bear.

- Keeping the waste on the surface allows the widest choice of future options. Success with transmutation technologies might fundamentally change the problem. New, as yet unthought of technologies might remove the problem.

- Disposal sites are selected for the perceived ease of achieving local acceptance, rather than on technical safety grounds. Once a site has been chosen, the nuclear industry will take all possible measures to ensure that it is not subsequently judged unsuitable, no matter how unfavourable the results of subsequent geological investigations might be.

- The motivation of the nuclear industry for progressing with disposal is driven not by the wish to fulfil environmental responsibilities, but rather by the need to remove obstacles to continued or expanded use of nuclear power.

### D5 The public:

- The general fear of radiation plays a powerful role here. The issue of very long timescales is new for the public also (although other similar problems in connection with climate change, exhaustion of resources etc. are being increasingly discussed). Scientists appear arrogant when they claim to be able to predict system behaviour hundreds of thousands of years into the future.

- "Waste" is anyway distasteful, as exemplified by the language of opponents...waste dump, Atommüll etc. There has been bad experience historically with waste problems in many countries (military waste, Love Canal etc.).

- Disposal is "undemocratic" in that the responsible persons for waste production (electricity users) are widespread whereas a repository is localised; siting processes have also been undemocratic with insufficient consultation of affected populations. New approaches are being tried in various countries today (e.g. France, Sweden, Canada, Switzerland).

- Benefits from waste (other than direct compensation of affected communities) are rather abstract; electricity comes in any case out of the wall socket, There is more understanding for medicinal radioactive wastes; however, many waste management organisations, aware of the relative volumes of power plant and other wastes, are reluctant to emphasise wastes from medicine, industry or research.

- Significant public opposition is based on attitudes to nuclear power. Opinion polls show a parallel trend between reactor accidents and confidence in safe disposal. Convinced opponents of nuclear power have a vested interest in hindering solutions.

- The absence of any repository for HLW is perceived as a confirmation that the problem is extremely difficult and that the nuclear community waited far too long before tackling the problem; the fact that there is no technical urgency for a geological repository is not recognised by the public.

- The "controversy" between experts concerning waste disposal (which is fuelled by the media) is confusing for the public. The tendency of the media is to present issues as controversial and equally polarised, even when the large weight of scientific opinion is on one side of an argument. A good recent example of this is the handling of the claims by a few weapons scientists that super-criticality can be possible even in a properly designed and sealed waste repository.

## D6 Politicians

- The problem is technically postponable. Accordingly, there is little incentive for elected politicians to actively seek solutions in a controversial issue that is certain to antagonise some large fraction of voters (NIMTO syndrome = "not in my term of office").

- The disposal question is coupled to the broader issue of nuclear power, which is rarely a vote-winning topic. The only political organisations seeking to win support by focussing on nuclear issues are those which seek to stop nuclear power; such organisations have obviously a direct interest in hindering acceptance of implementation of disposal schemes.

- There are on record numerous decisions concerning waste management strategies or repository siting which are very obviously based on political expediency rather than technical or environmental arguments.

# Appendix E

# Retrievability

## E1 The growing importance of retrievability

The concept of deep geological disposal was developed in order to **permanently remove** radioactive wastes from the human environment. Repositories with multiple passive barriers (engineered and geological) are designed to ensure that the wastes remain isolated from the human environment and inaccessible to man for the very long times needed to allow for the natural decay of their radioactivity. The very foundation of the concept is that wastes deep underground will be contained until they present no significant hazard; retrievability was therefore not a significant issue during concept development.

Retrieval of wastes for safety reasons was reckoned to be a scenario of such low probability that little effort was devoted to its study. Retrieval for other reasons, such as recovery of usable raw materials (fissile isotopes, precious metals etc.) was treated under the heading of deliberate human intrusion. The philosophy which was commonly followed was that no measures should be taken to ease such retrieval and that any future society deliberately embarking on this course is itself responsible for any risks arising.

In recent years, however, there has been an increasingly active debate on what exactly are the prime responsibilities towards future generations by the current one. Do we want to minimise the burdens or maximise the choices of options - or can both aims be fulfilled at the same time? Can fully passive (and safe) systems provide a sufficient level of practicability of retrievability? Should one plan for enhanced future accessibility in order to offer wider choices or should one emphasise passive safety systems that isolate the waste as completely as possible, but may thereby make future access more difficult?

This debate is linked directly to practical, technical matters, such as the design of the facility, the operating procedures and also the institutional programmes (including monitoring) throughout the lifetime of a repository. But there are also philosophical issues involved in addition to these purely technical issues. Most importantly, there is a growing recognition that many societies are uncomfortable with the concept of perceived irretrievable disposal; bitter lessons from the past have too often revealed that technical or societal developments have not always progressed as expected. We have, thus, a perceived potential conflict. Technologists are dedicated to avoiding any compromise of safety by introduction of intrusive, post-closure monitoring or of retrieval measures which might be counter-productive; society at large has less confidence in technology and a stronger desire to keep options open. The public, moreover, is also not convinced of the experts' view that current designs already provide a significant level of retrievability.

Discussions in dedicated working groups such as the IAEA group on Principles and Criteria (IAEA 1997b) or in special fora (e.g. the EU Concerted Action on "retrievability" Euratom (2000), or the NEA (NEA 2001b)) have tackled the key issues directly. For retrievability, the questions are: How easy does retrieval have to be in the different stages of repository development? What is the rationale for requiring a given level of retrievability at any specific phase? What technical measures and methods are feasible? Should specific features facilitating retrievability be introduced into the repository design? How do such measures impact on other aspects of system performance and on other issues (such as safeguards)?

This appendix addresses the questions raised. In the final section, a set of conclusions on retrievability are presented as a means to stimulate further debate on this topical issue.

## E2 Rationale for retrievability

It is possible to advance **technical** arguments for retaining a retrievability capability in a repository. The most obvious argument is that, despite all the safety features in the system, the repository might not perform to the predicted standards with the result that radionuclides are released in unacceptable concentrations. This scenario pre-supposes that monitoring methods have been established to detect any leakage and that an evaluation of the safety has led to the conclusion that the release levels justify remedial action by retrieving the wastes. This scenario is regarded as incredible by many designers and analysts of repositories; however, monitoring to enhance public confidence in safety is accepted as necessary. The comment made earlier on the purpose of monitoring being not to detect leakage but to verify repository characteristics (e.g. groundwater inflow) so as to assist in long term performance evaluation holds.

A period during which the wastes in their final configuration can be observed, monitored and if necessary retrieved has, in fact, been a feature of regulations in some national programmes (e.g. US requirements for an initial 50-year retrieval period). The feasible timescales, however, were judged to be only some decades. This is long for human activities, but it covers only a negligible portion of the relevant containment timescales for a geological repository. Technical arguments concerning recovery of valuable constituents, including fissile materials, after a long period of cooling has made the wastes more amenable to handling and treatment have also been made. If recovery is explicitly foreseen, however, monitored surface storage is a much more obvious approach than geological disposal. Further quasi-technical reasons advanced for maintaining retrievability concern the potential of new, as-yet-undiscovered technologies. A new method of eliminating radioactive wastes might emerge, a hitherto unforeseen application for some constituents of the waste could become important. The counter-arguments to such ideas are more philosophical than technical and are addressed in the following paragraph.

The **ethical** arguments related to final disposal have been increasingly debated in recent years. The starting position was clear and is documented in various international consensus documents. Wastes should be managed by the current generations (who enjoy the benefits of the corresponding nuclear applications) in such a way that the burden on future generations is minimised. Deep disposal in a passive repository system from which retrieval is not foreseen was the proposed answer. Initiated largely by ethical discussions in Sweden (KASAM 1988), an alternative view emerged in the 80's. This view is that we have an even higher responsibility to future generations - namely to give them the widest possible choice of societal options. By making retrieval from a repository more straightforward, the range of future options is extended. The burden imposed by extra future measures is claimed by some to be outweighed by the benefits of wider choice.

This broad moral argument may in fact be a rationalisation of **societal** arguments based on the subjective feelings of a large segment of the population which is still sceptical that geological disposal will fulfil the high safety standards set. The timescales for disposal are too long to be comprehensible; technologies have failed unexpectedly in the past; neither the risks nor the costs nor the time pressures associated with disposal are unbearably high. Given these perceptions, a societal strategy postponing final decisions is tempting and understandable. Responsible technologists must respond to societal wishes, therefore disposal plans will inevitably have to increasingly address also the issue of retrievability.

A final, very pragmatic reason for retrieval options being built into disposal concepts is that corresponding **legal or regulatory** requirements are in force. These can reflect a judgement on technical reliability (e.g. the US 50-year requirements mentioned above) or on ethical priorities (e.g. the Netherlands law making retrievability compulsory).

## E3 Measures to enhance retrievability

Use of the word "enhance" in the title of this section alludes to the defensible view that geological disposal, per se, is always retrievable in principle. At question is the length to which one goes to ease retrievability. It is worth noting, nevertheless, that other disposal options often advocated by repository sceptics (e.g. disposal in space, transmutation) are truly irretrievable and non-reversible.

The retrievability of disposed wastes is directly affected by the strategy and the technical concepts chosen. For example, easiest retrieval is achieved by delaying disposal, and maintaining surface storage, whilst options like sub-seabed disposal make retrieval more difficult. The choice of host rock is important. Stable self-supporting crystalline rocks are less complex with respect to retrieval than soft clays that creep or salt media that flow. A long-lived container with radiation shielding capability will make retrieval simpler. A soft backfill allowing easy re-excavation will do likewise.

It is also certainly possible to conceive of engineering designs which explicitly aim at easy retrievability by automated excavation tools. This approach could affect ultimately the repository layout, the sealing techniques as well as the backfill, buffer and waste package. Extra long-lived overpacks, packages with pre-mounted handling attachments, tunnel liners dimensioned to stay intact for long periods; these are all examples of engineering approaches to easing retrieval. Further possible measures include high-resolution, near-field monitoring and comprehensive data recording and archiving. However, currently the most common approach to enhance retrievability for a limited period of time is through modifying the operational scheme and delaying backfilling and sealing of at least some parts of the repository and thus maintaining easier access to the waste packages for longer periods of time.

In summary, geological disposal is always retrievable in principle – but numerous specific measures can be implemented in order to enable stored or disposed wastes to be retrieved with increasing ease. Any decision on retrievability measures, however, must also consider the impact of these measures on other aspects of the disposal system.

Deep geological repositories will come into operation over the next decades, will in most cases operate for many decades and will be sealed only after a long monitoring phase. Accordingly, there is little operational pressure to finalise retrievability concepts. However, disposal systems are being actively planned and designed, so that retrievability features must be discussed now. More importantly, the whole issue of retrievability is irrevocably linked to the question of public confidence in the safety of geological repositories – and this fundamental issue is directly linked to the ethical and environmental questions concerning continued use of nuclear technologies.

Opponents of deep disposal would prefer to leave wastes indefinitely in monitored surface or underground stores. Proponents argue that this is not a sustainable solution and that one should proceed in a stepwise fashion towards final disposal. In the current climate of opinion, it may be possible to move forward only if the question of retrievability is also tackled head on. Any disposal project submitted for approval should discuss the balance drawn between minimising future burdens and maximising future options; explicit features which ease or complicate retrieval should be pointed out; the cost as well as the cost-benefit of any retrieval option should be addressed. A strategy which allows confidence in the safety of disposal to be built up gradually throughout a series of phased steps has the greatest chance of acceptance – even when these steps involve decreasing levels of retrievability.

There is a real danger today that inadequate discussion will lead to the adoption of waste management strategies which are optimised neither with respect to safety, nor ethically nor economically. A chance alliance between anti nuclear groups (stressing the arguments for full retrievability) and the some segments of industry (wishing to postpone major expenditures on disposal) could well lead to an ill-founded consensus that the non-sustainable option of simply accumulating increasing waste inventories in surface stores throughout the world is the preferred strategy.

## E4 Conclusions

The following subjective conclusions are purposely formulated in a manner intended to provoke further discussion on the important topical issue of retrievability of wastes from deep geological repositories.

1) Public demand is such that disposal projects must directly address the issue of retrievability/reversibility through all phases of the repository development.

2) Retrieval is always possible in principle. Engineering methods to allow retrievability are available, even though they become more complex and expensive as the step-wise closure of the repository progresses and with increasing time after closure of the repository. This conclusion must be demonstrated to the public on the basis of specific studies on retrieval concepts and techniques.

3) Measures to ease retrievability must be carefully chosen to avoid unacceptable impacts on long-term, passive safety and security. However, with an adequate design and operational scheme combined with an adequate organisational framework it is considered feasible to accommodate both the aims of enhanced retrievability and adequate long-term safety.

4) The most obvious method of retaining maximum retrievability is by extended, or "indefinite" surface storage. This approach does not, however, represent a proper solution to "final" waste disposal. It postpones burdens and responsibilities into the future in a manner incompatible with a sustainable development ethic.

5) Storage is nevertheless an important step in the waste management process. A step-wise closure process of a repository, including retrievable storage periods on the surface and/or underground at the chosen site, can maintain the sustainable concept of passive long-term safety minimising future burdens, whilst still providing for a lengthy transition period an appropriate level of reversibility/retrievability. This gives sufficient time for societal decision-making on the path towards final closure of the repository.

6) For HLW without significant content of fissile materials retrievability arguments are related mainly to the confidence of different groups in the long-term safety performance of the repository. For fissile materials, the prime arguments for and against retrievability concern resource conservation and weapons safeguards. However, the public desire to have reversibility as such - without specifying the reason or giving any justification - needs to be acknowledged.

7) The social and technical process for decision-making for closing a deep geological repository (and for reacting to low probability scenarios involving potential remediation measures, up to and including retrieval) has nowhere been completely defined. However, it is envisaged that an institutional programme will

address: (i) the type of activities to be performed at the different development phases (in-situ monitoring, complementary and confirmatory research programmes, periodic re-evaluation of safety, etc.) (ii) the criteria and decision-making process (licensing etc,) to react on these activities, (iii) the options (including retrieval) available at each decision-point.

8) Directly tackling the issue of retrievability can help ensure that repositories are developed in a step-wise or phased procedure which allows time for organisations and individuals involved to build-up a high level of trust, based on open communication and on demonstrably high-quality technical work.