Technical Summary of the Safety Aspects of the Deep Geological Repository Concept for Used Nuclear Fuel

NWMO TR-2009-12 **September 2009**

F. Garisto, T. Kempe and P. Gierszewski

Nuclear Waste Management Organization

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ABSTRACT

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Abstract
This report brings together a technical summary of information on the safety of a deep geological repository for used nuclear fuel. It explains why the repository concept is expected to be safe. The report is non-site-specific; it considers alternative geologic settings, specifically both the Canadian Shield and sedimentary rock formations; and encompasses several design concepts.

The key reasons supporting the safety of the deep geological repository concept are:

1. A geological repository uses multiple barriers that include the waste form, container, sealing materials, and the host rock.
2. The host rock would be stable and predictable over long periods of time.
3. The low-permeable host rock would ensure that the waters in the deep rock are isolated and do not readily mix with surface waters.
4. The deep geological repository system would maintain a chemical and hydrological environment that is favourable to the stability and performance of the repository.
5. Natural analogues provide evidence that engineered barrier materials are stable for very long times under similar deep geologic conditions.
6. The depth of the repository would be such that future inadvertent human intrusion into the closed repository would be very unlikely.
7. International progress on repository implementation gives assurance that geological disposal is a sound technical solution and provides practical experience.
8. Safety assessment case studies indicate that any impacts are likely to be well below recommended dose constraints and natural background dose rates.
9. A geological repository can be built and operated safely using proven technologies.
10. The radionuclides in the used fuel decay with time.
11. The repository site will be monitored to confirm repository system performance.

The safety of any proposed repository site would be tested through a rigorous regulatory system and international peer review of the safety case. The Canadian program continues to develop the scientific tools and understanding that will be applied to test the suitability of any candidate site.

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LIST OF ACRONYMS

AECB	- Atomic Energy Control Board (now CNSC)
AECL	- Atomic Energy of Canada Limited
APM	- Adaptive Phased Management
CANDU	- Canada Deuterium-Uranium reactor
CEAA	- Canadian Environmental Assessment Act or Agency
CNSC	- Canadian Nuclear Safety Commission
EIS	- AECL's Environmental Impact Study
HBC	- Horizontal Borehole placement Concept
IAEA	- International Atomic Energy Agency
IARC	- International Agency for Research on Cancer
ICRP	- International Commission on Radiological Protection
LNT	- Linear No-Threshold
MW	- Megawatts
MWh	- Megawatt-hours
NEA	- Nuclear Energy Agency
NFWA	- Nuclear Fuel Waste Act (Canada)
NWMO	- Nuclear Waste Management Organization (Canada)
OPG	- Ontario Power Generation Inc.
SCS	- Second Case Study (AECL)
TCS	- Third Case Study (AECL)

1. INTRODUCTION

In Canada, used nuclear fuel is stored in water-filled pools for about ten years before it is transferred into dry storage facilities at the nuclear reactor sites. Although safe, these storage practices require continuous institutional controls such as security measures, monitoring and maintenance. Over long periods of time, the fuel storage containers and buildings would need to be replaced, involving periodic transfer of used fuel to new packages (NWMO 2005).

Several concepts for passive long-term containment and isolation of used fuel have therefore been under consideration since the beginning of the nuclear program. These have been extensively studied internationally, and in Canada, primarily by Atomic Energy of Canada Limited (AECL) and Ontario Power Generation, and more recently by the Nuclear Waste Management Organization (NWMO).

In 2005, following an extensive 3-year dialogue which engaged thousands of Canadians, the NWMO presented its recommendations for the long-term management of Canada's used nuclear fuel (NWMO 2005). The recommended approach is Adaptive Phased Management, or APM. In 2007, the Government or Canada selected APM for implementation by the NWMO.

From a technical perspective, APM has the following characteristics:

- Centralized containment and isolation of the used fuel in a deep geological repository in a suitable rock formation;
- Provision for an optional step in the form of shallow underground storage of used fuel at a central site, prior to final placement in a deep repository;
- Continuous monitoring of the used fuel to support data collection and confirmation of the safety and performance of the repository; and
- Potential for retrievability of the used fuel for an extended period, until such time as a future society makes a determination on the final closure, and the appropriate form and duration of postclosure monitoring.

The other important pillar of APM is the management system, which guides how APM will be implemented:

- Flexibility in the pace and manner of implementation through a phased decision-making process, which engages citizens at every stage, supported by a program of continuous learning, research and development;
- Responsive to advances in technology, natural and social science research, Aboriginal Traditional Knowledge, and societal values;
- Open, inclusive and fair site selection process to seek an informed, willing host community; and
- Continued public engagement through all phases of implementation.

1.1 PURPOSE OF THIS REPORT

A key feature of the APM approach is the deep geological repository for used nuclear fuel. The present report provides a technical summary of the reasons why a deep geological repository is expected to be safe and how safety will be demonstrated.

It is intended to provide general technical background information on repository safety to support the NWMO's public dialogue and engagement program during implementation of the siting process for a deep geological repository.

1.2 SCOPE OF THIS REPORT

Any long-term management facility for used nuclear fuel would require licensing by the Canadian regulator, the Canadian Nuclear Safety Commission (CNSC). Obtaining such a licence will require reasonable assurance that the repository will be safe (CNSC 2006), i.e., that human health and the environment will be protected now and in the future.

Given the long timeframe of interest, i.e., hundreds of thousands of years, careful consideration has to be given to addressing uncertainty in predictions of future performance. These uncertainties are addressed in part by compilation of multiple lines of reasoning why the repository will be safe (NEA 2004). Such a safety case would be prepared as part of the assessment and evaluation of a specific repository site.

This document:

- Addresses the **repository** component of APM only, while recognising that other components, such as transportation to the site, will present important constraints and factors to be considered in the overall decision on acceptability of a particular location.
- Is **non-site-specific**. After a candidate site has been identified, all the factors described here, plus others, would be examined in substantially more detail, incorporating site-specific knowledge.
- Considers alternative **potentially suitable geologic media**, specifically both the crystalline rock of the Canadian Shield and sedimentary rock formations.
- Encompasses several **engineered barrier design** alternatives. The design of a repository is not yet fixed. Flexibility in design is an important feature in accommodating site-specific conditions.
- Addresses **postclosure safety** only. Preclosure (operational) safety is an important part of the overall safety case. Facilities handling used fuel are safely operated today, within the same regulatory framework that would apply to a deep geological repository. The assessment of safety during preclosure can also draw from extensive experience in mining and other underground activities.

1.3 STRUCTURE OF THIS REPORT

The first four sections of this report provide the context and a summary of the deep geological repository concept and the foundations for confidence in safety. Section 2 provides a summary of the nature of the potential hazard posed by used fuel. Section 3 provides a brief summary of the deep geological repository concept, the regulatory context and international programs for long-term management of used nuclear fuel. Section 4 summarizes the key safety arguments.

The remaining sections provide further technical information that provides a basis for confidence in safety. Section 5 provides a more detailed description of the Canadian geological repository concept, Section 6 describes the predicted evolution of the system over 1 million years, and Section 7 outlines the use of natural analogues in supporting predictions and increasing confidence in the long term behaviour of the repository system. Finally, examples of Canadian postclosure safety assessments are described and some conclusions are drawn.

2. NATURE OF THE HAZARD POSED BY USED NUCLEAR FUEL

2.1 DESCRIPTION

Almost all of the used nuclear fuel in Canada is produced by CANDU nuclear power reactors in Ontario, Québec and New Brunswick. There are also very small quantities of used fuel from research and isotope-producing reactors in Canada (NWMO 2003).

The fuel for CANDU power reactors consists of ceramic pellets of uranium dioxide (UO_2). They are stacked and sealed inside metal tubes made of zirconium alloy. Up to 37 of these tubes are welded together to make a fuel bundle (see Figure 2.1). A CANDU fuel bundle is about 10 centimetres in diameter and about 50 centimetres long. Each CANDU fuel bundle contains about 19 kg of natural uranium.

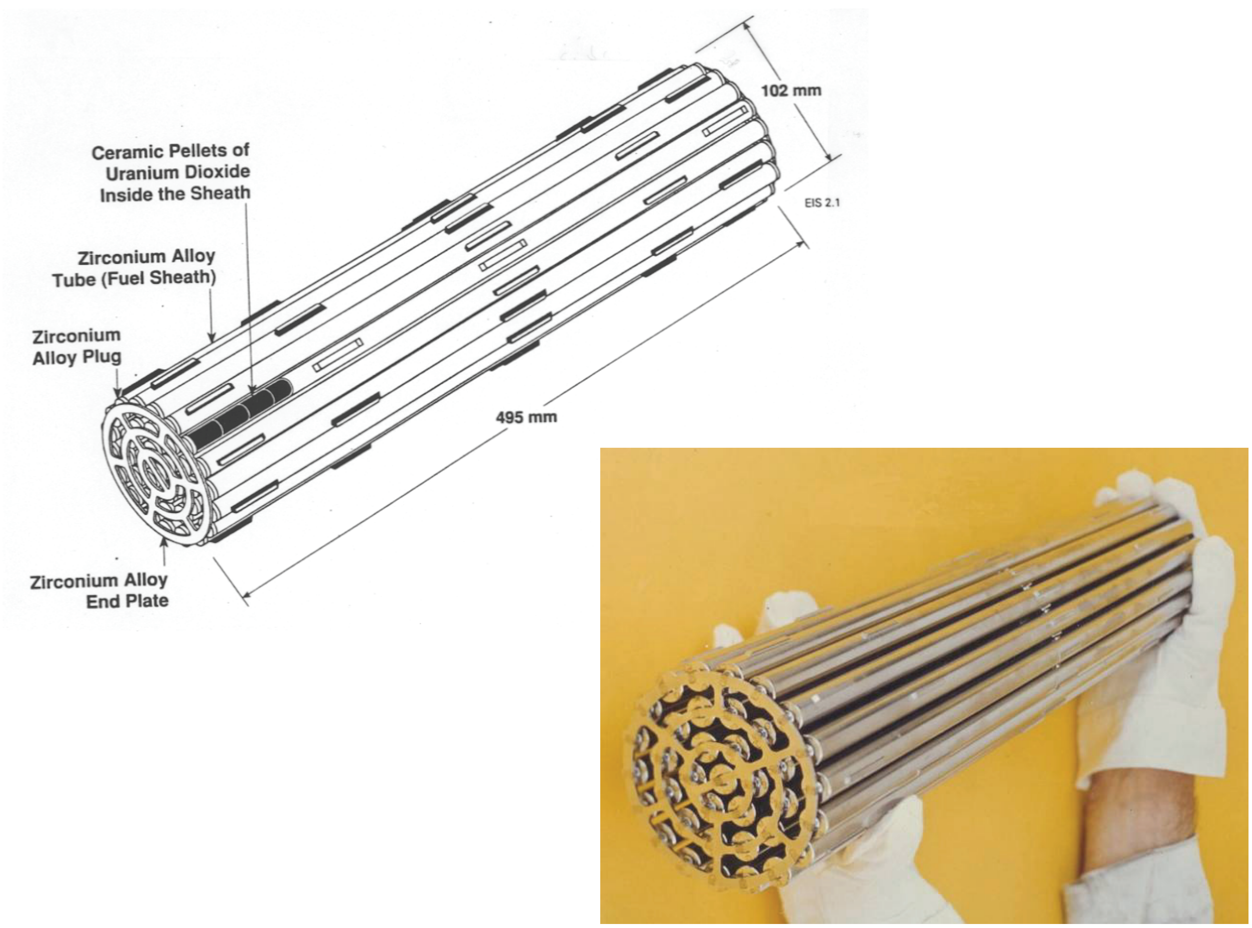

Figure 2.1: A typical CANDU fuel bundle

In a CANDU reactor heat is produced by fission in a controlled chain reaction. Fission occurs within a fuel bundle when a neutron is absorbed by certain heavy elements (such as U-235 or Pu-239) which then split into two atoms (called **fission products**) having atomic numbers about half that of the heavy element. Neutrons are also released during fission, sustaining the nuclear chain reaction. Many of the new atoms formed by fission are unstable and decay, i.e., they are radioactive.[1] Atoms heavier than uranium, such as plutonium, are also generated in the reactor by successive neutron capture. Collectively, these heavy atoms including uranium are called **actinides**. Often, these are divided into uranium and plutonium, and the rest (e.g., neptunium) which are called the **minor actinides**.

As fission continues in the reactor, the concentrations of fission products increase, eventually impeding further fission (since some of the fission products efficiently absorb neutrons, thereby stopping the nuclear chain reaction). At this stage, after 12 to 18 months, the fuel bundle is removed from the reactor. The amount of energy produced by a fuel bundle while in the reactor is called the fuel "burnup". Typical burnups for CANDU fuel bundles are around 200 MW-hours per kilogram of initial uranium.

Before entering the nuclear reactor, CANDU fuel (unirradiated or fresh fuel) consists primarily of natural uranium, which is approximately 99.3% U-238 and 0.7% U-235, and oxygen. After leaving the nuclear reactor, CANDU fuel (irradiated or used fuel) consists of approximately 98.6% U-238, 0.2% U-235, 0.3% Pu-239 and very small amounts of many other radioactive atoms. Table 2.1 provides a summary of the most abundant atoms in typical CANDU used fuel.

When the used fuel is removed from the reactor, it is highly radioactive and generates heat. The radioactivity initially decreases very quickly with time primarily due to the decay of short-lived radionuclides. Initially the used fuel is stored, at the reactor site, in water pools which provide cooling. After several years, the used fuel can be stored in passive concrete containers such as those illustrated in Figure 2.2.

The total radioactivity of used CANDU fuel as a function of time out of reactor is illustrated in Figures 2.3 and 2.4, based on data from Tait et al. (2000) and Tait and Hanna (2001). These figures also show the radioactivity in three categories – the fission products resulting from the fission process, the actinides produced by side-reactions with uranium and similar heavy atoms, and the activity in the Zircaloy metal cladding on the fuel.[2]

The total radioactivity and heat production drops dramatically (a factor of 1000) over the first 10 years. Over the next 500 years, the fission product radioactivity drops significantly. At this point, the remaining activity is mainly due to the actinides present in the used fuel. This continues to decay slowly. After about 1 million years, the radioactivity in the used fuel is primarily due to the natural activity of uranium and its decay chain.[3] The total amount of uranium in the repository would be similar to that in large Canadian uranium ore bodies.

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[1] Radioactivity is a process in which the nucleus of an atom spontaneously releases energy, and changes into a different type of atomic nucleus. Eventually, all radioactive atoms “decay” into stable atoms.

[2] There will also be a small amount of activity due to activation of impurity elements within the used fuel. This is not shown in the figures, but is similar to the total activity in the Zircaloy.

[3] Natural uranium is 99.3% U-238, which decays eventually to stable lead over billions of years through a chain of 12 intermediate radionuclides, notably Th-234, U-234, Th-230, Ra-226, Rn-222, Po-218, Pb-214, Bi-214, Po-214, Pb-210, Bi-210 and Po-210.

Table 2.1: Composition of fresh and used CANDU fuel (30 year fuel, 220 MWh/kgU burnup)

Component	Fresh (Unirradiated) UO_2 Fuel Mass%	Used UO_2 Fuel Mass%
Actinides		
U-238	87.43	86.56
Pu-239	0.00	0.24
U-235	0.63	0.15
Pu-240	0.00	0.11
U-236	0.00	0.07
Am-241	0.00	0.02
Pu-241	0.00	0.01
U-234	0.01	0.004
Others	0.00	0.05
Fission Products		
Xe (stable)	0.00	0.14
Nd (stable)	0.00	0.10
Mo (stable)	0.00	0.08
Zr (stable)	0.00	0.07
Ru (stable)	0.00	0.05
Tc-99	0.00	0.02
Cs-137	0.00	0.016
Zr-93	0.00	0.01
Others (stable)	0.00	0.28
Others (radioactive)	0.00	0.06
Other Elements		
O (stable)	11.80	11.81
Others (stable)*	0.14	0.14
Others (radioactive)	0.00	< 0.01

*Includes impurities naturally present in fuel (Tait et al. 2000)

Figure 2.2: Dry Storage Containers for used fuel at Ontario Power Generation. Each container holds 384 used fuel bundles.

2.2 BIOLOGICAL EFFECTS OF RADIATION

Used fuel is radioactive and releases radiation. The effects of radiation are described by the **radiation dose** and, for humans, measured in units of Sieverts (Sv). Humans are constantly exposed to a background level radiation from naturally occurring sources. The average Canadian background dose rate is about 1.8 mSv per year (Grasty and LaMarre 2004).

The health effects from exposure to radiation have been studied over many years and documented in numerous international consensus reports such as those of the US National Academy of Sciences Board on Radiation Effects Research (BEIR 1990), the International Committee for Radiological Protection (ICRP 1991, 2007) and the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR 2006, 2000).

The health effects of radiation at high doses are well understood. The health effects at the low chronic doses relevant to used fuel long-term management are low. However, as the effects are low there is less precision in our understanding of the effects. There is some on-going debate on whether, at low doses, the risk is significantly underestimated or whether there are potential benefits (hormesis) (see CERRIE 2004 for further discussion).

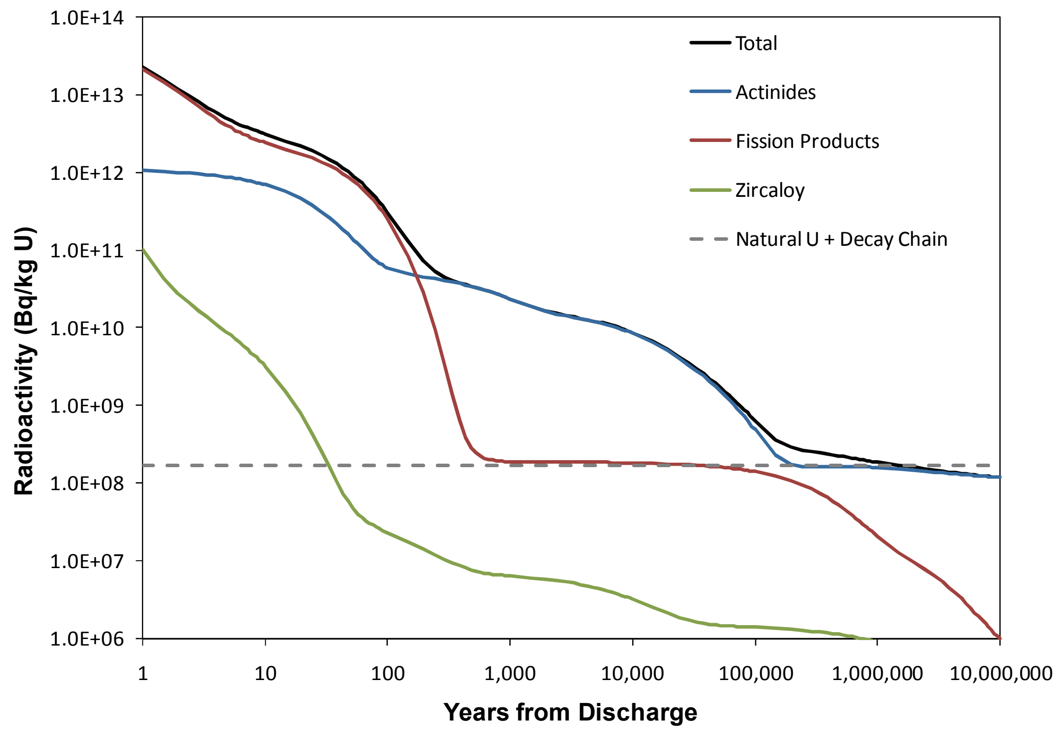


Figure 2.3: Activity of used CANDU fuel with a burnup of 220 MWh/kgU for times up to 10 million years

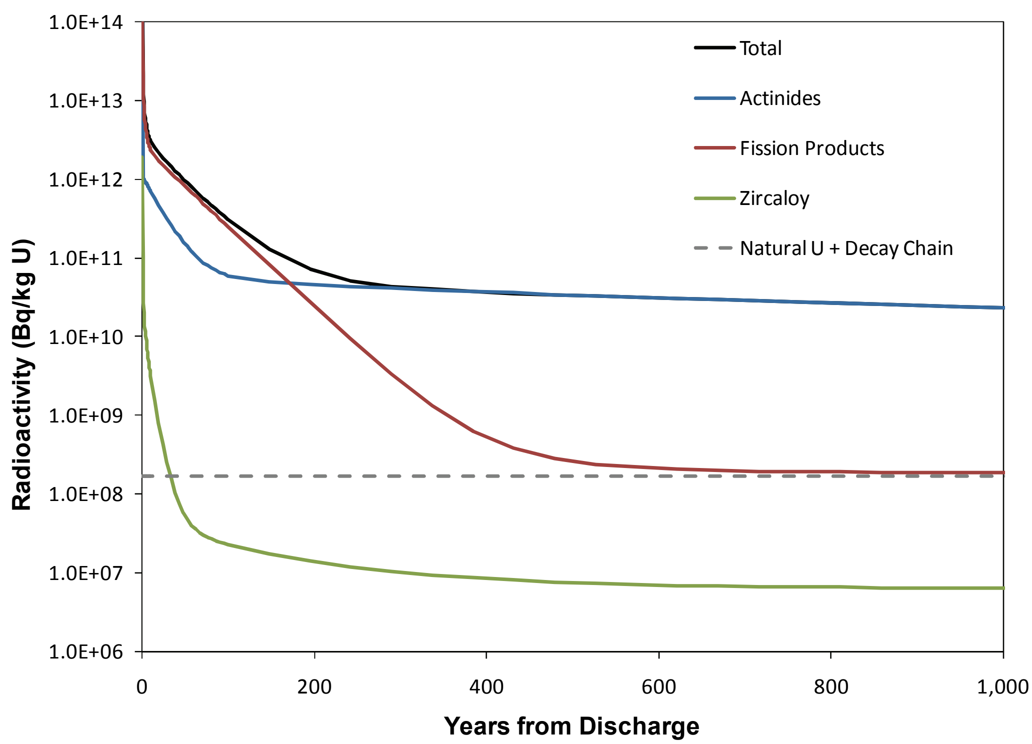


Figure 2.4: Activity of used CANDU fuel with a burnup of 220 MWh/kgU for times up to 1000 years

The linear-no-threshold hypothesis is a widely accepted set of assumptions on which the International Atomic Energy Agency's (IAEA) safety standards and the Canadian CNSC regulatory oversight are based. The assumption is made that there are health risks associated with any exposure to radiation, with the risk decreasing as the dose decreases.

Recent reports provide continued support for the linear no-threshold (LNT) model of radiation health effects. These include the US National Academy review report (BEIR 2005) and the Revised Recommendations of ICRP (ICRP 2007). Also released in 2005 was the largest epidemiological study of low-dose radiation risk ever conducted. Carried out by the International Agency for Research on Cancer, the "International Collaborative Study" (IARC 2005) also appears to support the LNT model at least down to doses of approximately 10 mSv. The latest ICRP review (ICRP 2007) continues to recommend that the LNT model is a prudent basis for radiation protection standards.

In Canada, the regulatory authority that issues licenses to nuclear facilities has set dose limits for members of the public at 1 mSv/a (CNSC 2000). In practice, the regulators and facility operators follow the principle of As Low As Reasonably Achievable (ALARA), and actual doses are much less than these regulatory limits (CNSC 2007).

It may be noted, furthermore, that predictions of radiation dose to members of the public from geologic repositories are very much less than doses for which radiation effects have been demonstrated in studies such as the IARC study, studies of radiotherapy patients, and the studies carried out of the survivors of the atomic bombs at Hiroshima and Nagasaki. Safety assessments carried out for the Canadian repository concept predict a potential maximum annual dose to the most highly-exposed group living on the site in the future of about 0.001 mSv/a. This is also well below the average Canadian background radiation dose rate from natural sources (1.8 mSv/a) and typical per capita average doses from medical procedures (about 1 mSv/a). Ranges of radiation dose of interest are shown in Figure 2.5.

2.3 EXTERNAL RADIATION

Some radioactive atoms release gamma radiation. This is a penetrating radiation that travels beyond the used fuel and can cause radiation dose to anyone in the vicinity, which is why used fuel bundles are shielded. The strength of the external radiation field from used nuclear fuel decreases with distance and shielding.

Figure 2.6 presents the potential external radiation dose from an unshielded used CANDU fuel bundle and compares it to a non-irradiated (or unused) CANDU fuel bundle. The external radiation from used fuel declines rapidly with the passage of time, but remains significant in the long-term because of the uranium content of the fuel. The external radiation dose rate from the non-irradiated fuel bundle increases with time due to the formation of the decay products of natural uranium (U-238), notably Bi-214 and Pb-214.

The external radiation from used fuel is approximately constant after about 1000 years. After this time, a person could remain indefinitely at about 12 m from an unshielded used fuel bundle and stay within the regulated public dose limit of 1 mSv per year. With shielding such as concrete or steel, a person could stand much closer, as illustrated in Figure 2.2.

In a deep geologic repository, used fuel is placed underground. There would be no external dose to anyone standing on the surface above the repository, due to the shielding of several hundred meters of rock.

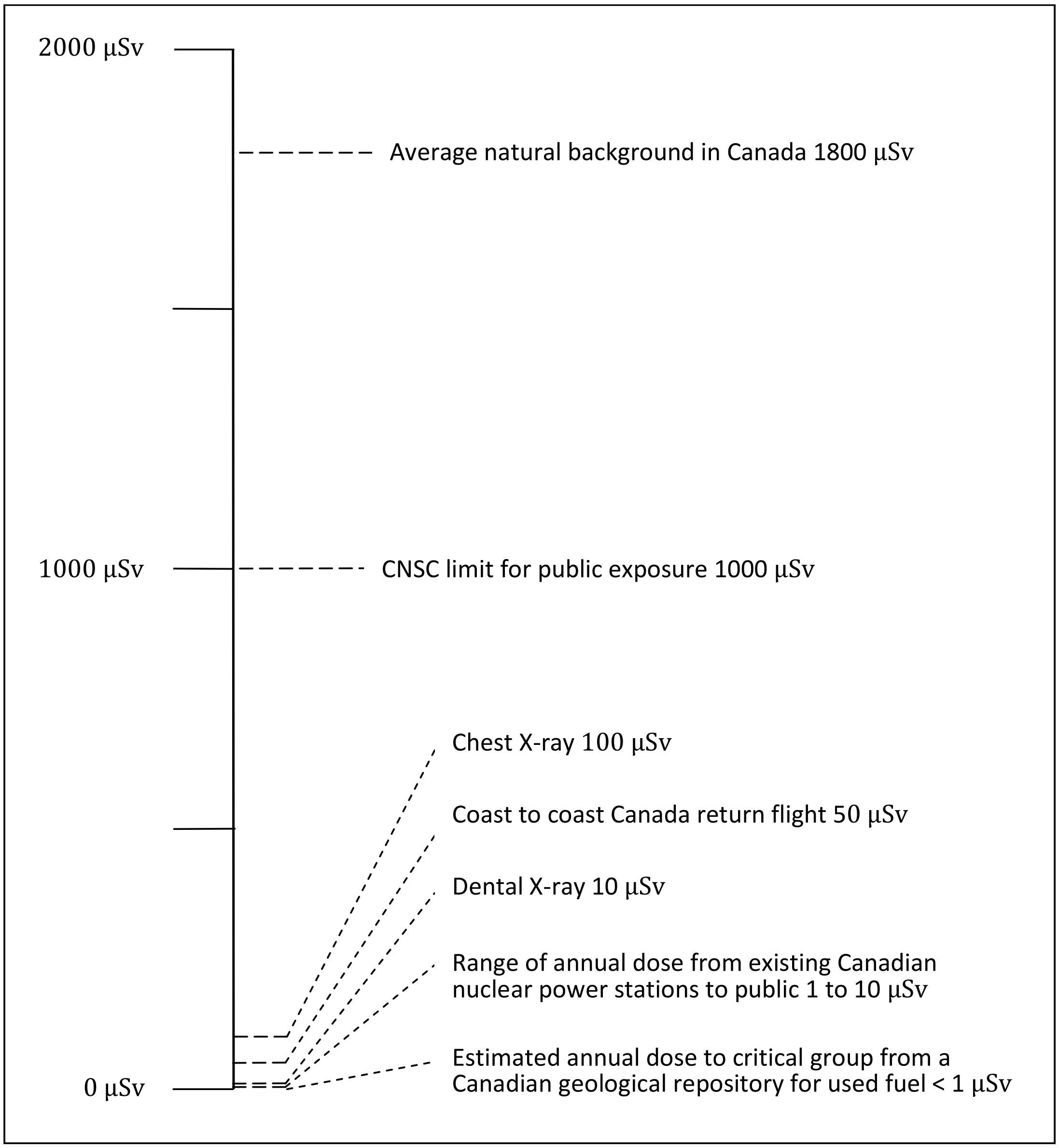


Figure 2.5: Ranges of radiation dose

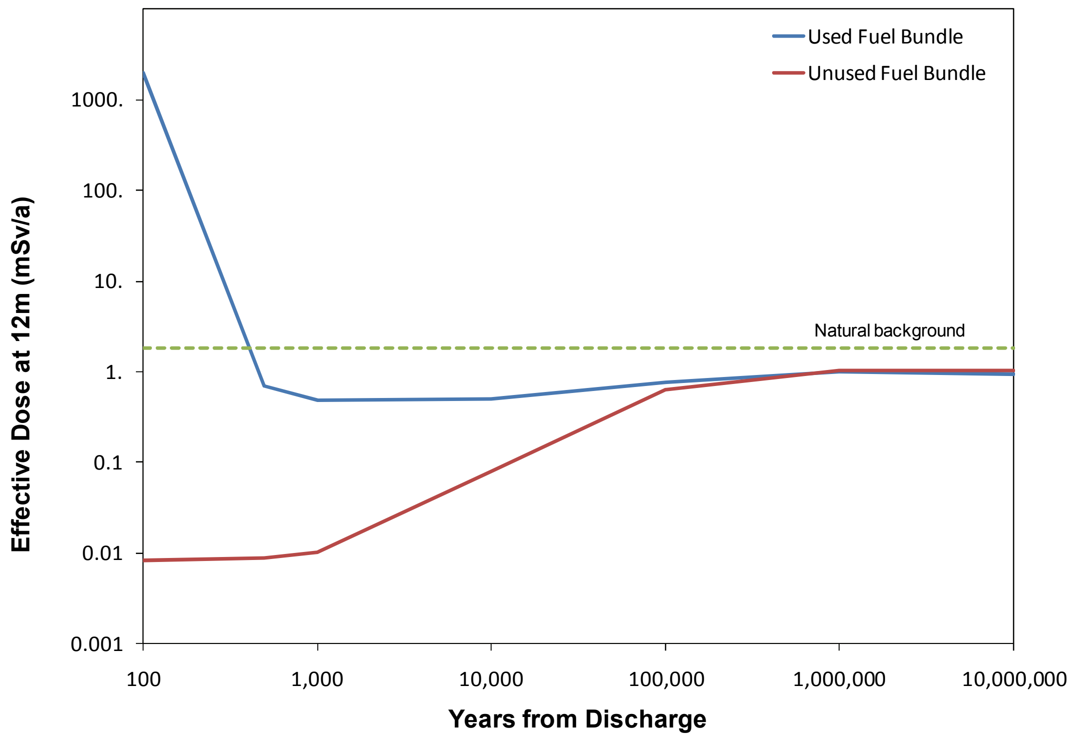


Figure 2.6: Dose rate at 12 m from a typical 20-kg CANDU used fuel bundle. For comparison, the dose rate from an unused fuel bundle and from natural background radiation are also shown.

2.4 RADIOTOXICITY

The second type of hazard associated with used nuclear fuel is from internal exposure, also called radiotoxicity. This hazard would occur if radionuclides from the used nuclear fuel were ingested (for instance, if dissolved in drinking water) or inhaled (from dispersion in the air).

It should be noted that an intact used fuel bundle does not pose any risk of internal exposure, since the radionuclides are trapped within the Zircaloy cladding. Internal exposure requires the fuel bundle to have been corroded or fractured. However, both the Zircaloy alloy cladding and the UO_2 ceramic used fuel are corrosion-resistant materials. Furthermore, the chemical conditions deep underground are reducing (i.e., low oxygen), which further increases the corrosion-resistance of the used fuel bundles. Thus, examination of fuel radiotoxicity is primarily a consideration for protecting people and the environment far into the future, should the radionuclides in the waste somehow find their way from the repository into the accessible environment.

A common index of radiotoxicity is based on the calculated dose from ingestion (Mehta et al. 1991; OECD 2004). Fission products and actinides are the major contributors to the radiotoxicity of the fuel for times less than 1000 years and for times greater than 1000 years, respectively. After 100,000 years, the hazard is largely due to the decay products of natural uranium within the used fuel, in particular Pb-210 and Po-210.

One method of illustrating the radiotoxicity of used fuel is in terms of the quantity of water needed to sufficiently dilute radionuclides that might have migrated from the repository into surface waters (i.e., rivers and lakes) so that a person who drinks 2 litres per day of the (contaminated) water would receive a dose rate of 1 mSv/a (i.e., the CNSC regulatory dose limit for members of the public). This dilution factor is shown in Figure 2.7 for two "what-if" cases in which the entire radionuclide inventory of the repository is released into the surface environment either in 10,000 years or in 10 million years. For comparison, the range of flow rates of major rivers (e.g., St. Lawrence, St Clair), large rivers (e.g., Ottawa, Miramichi, South Saskatchewan), and small rivers (Don River in Toronto and Lepreau River in New Brunswick) are indicated on the right axis of the figure.

Under repository conditions, used fuel exposed to groundwater is expected to dissolve very slowly. A fractional dissolution rate of 10^{-7} per year (i.e., all the fuel is dissolved in 10 million years) is a conservative but realistic rate of fuel dissolution under repository conditions whereas a dissolution rate of 10^{-4} per year could only occur if oxygenated groundwaters reached the repository (Shoesmith 2007). In either case, water would first have to breach the long-lived containers and come into contact with the used fuel, and then the used fuel would have to dissolve into the water.

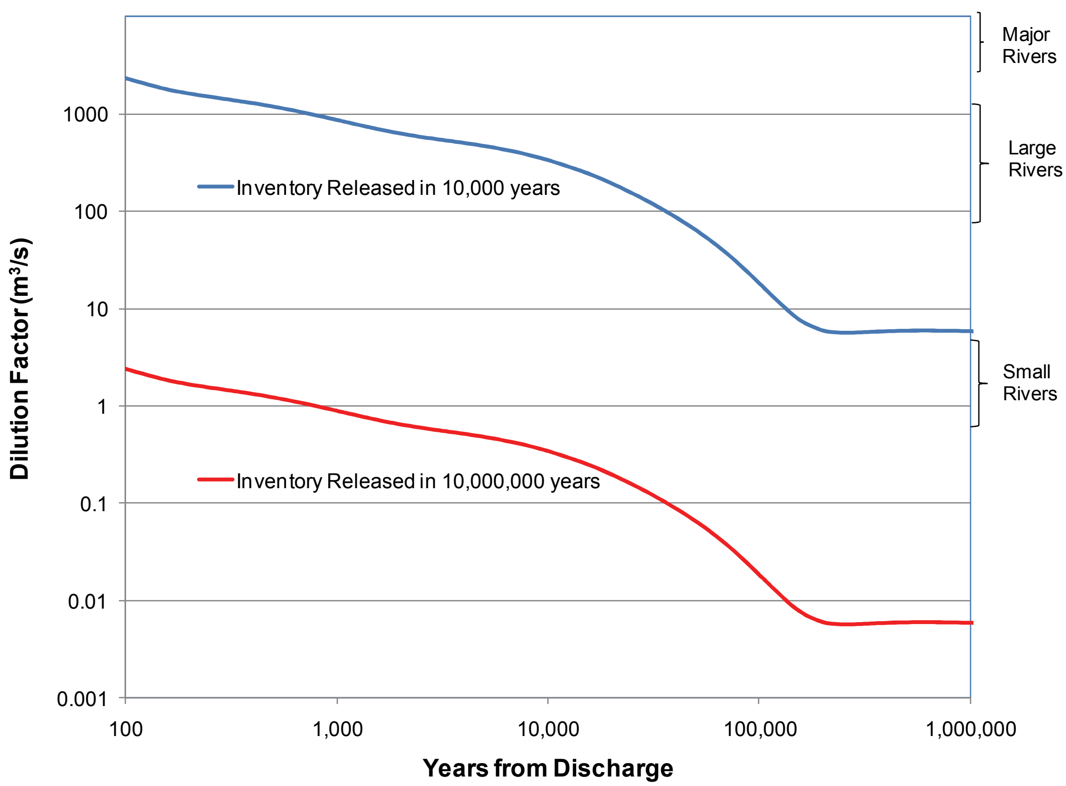


Figure 2.7: Illustration of the radiotoxicity of used fuel if dissolved in water. The figure shows the amount of water needed to dilute radionuclides that may be released into, for example, a river so that a person drinking the (contaminated) water would receive a dose rate of 1 mSv/a. The entire radionuclide inventory of the repository is assumed for illustration purposes to be released in 10,000 years or 10 million years.

2.5 CHEMICAL TOXICITY

Used fuel contains some chemically hazardous elements. Its main constituent is uranium, a heavy metal. The amount of uranium in a repository would be similar to the amount present in large Canadian uranium ore bodies.

Used fuel also contains small amounts of other chemical elements left over from the original ore or produced in the reactor (Garisto et al. 2005b, Bird et al. 1997, Goodwin et al. 1994). The main chemical elements in a used fuel bundle are listed in Table 2.2.

Safety assessments indicate that the biosphere concentrations of any chemically hazardous elements released from the repository would be much lower than the reference concentrations (i.e., safety criteria) for these elements (Garisto et al. 2005b, Goodwin et al. 1994).

Table 2.2: Main chemical elements in a used fuel bundle (30 year fuel, 220 MWh/kgU burnup)

Element*	Element Symbol	Mass (g/kg initial U)
Uranium	U	984.3
Oxygen	O	134.2
Zirconium	Zr	112.3
Plutonium	Pu	4.1
Tin	Sn	2.0
Xenon	Xe	1.5
Neodymium	Nd	1.1
Molybdenum	Mo	0.9
Carbon	C	0.7
Cerium	Ce	0.7
Ruthenium	Ru	0.6
Cesium	Cs	0.5
Barium	Ba	0.5
Iron	Fe	0.5
Thorium	Th	0.5
Palladium	Pd	0.4
Lanthanum	La	0.3
Praseodymium	Pr	0.3
Samarium	Sm	0.3
Technetium	Tc	0.2
Americium	Am	0.2
Chromium	Cr	0.2

*U, O, Zr and Sn are the main components of the UO_2 fuel or Zircaloy cladding. The remaining elements in the list (other than iron) are fission or activation products that are created while the fuel is in the reactor. Lead and arsenic are also present in the fuel as impurities at 0.1 and 0.003 g/kg U, respectively.

3. DEEP GEOLOGICAL REPOSITORY CONCEPT

3.1 HISTORICAL CONTEXT

Long-term management of nuclear fuel waste has been under consideration since the beginning of the CANDU program. The options for long-term management in Canada were reviewed by the Hare commission in 1977 (Aiken et al. 1977). The commission recommended emplacement of used fuel in a deep underground repository within the rock of the Canadian Shield. Subsequently, a nuclear fuel waste management program was formally initiated by the governments of Canada and the province of Ontario to develop this recommended approach. Responsibility for development of the concept was assigned to Atomic Energy of Canada Limited (AECL).

In 1994, AECL submitted its Environmental Impact Statement (AECL 1994) on the deep geological repository concept for review by a federal Environmental Assessment Panel (the 'Seaborn Panel'). The Panel reviewed a large volume of information, and concluded that from a technical perspective, safety of the AECL concept had been on balance adequately demonstrated. The panel also concluded that from a social perspective safety had not been adequately demonstrated. The panel report made recommendations to assist the federal government in reaching a decision on acceptability and on the steps to be taken to ensure the safe long-term management of nuclear fuel waste in Canada (CEAA 1998).

Following consultation with the public, provincial governments, waste owners and other interested parties, the Canadian federal government brought into force the *Nuclear Fuel Waste Act (NFWA)* in 2002. This Act requires:

- The owners of the nuclear fuel waste to establish a waste management organisation to evaluate approaches for the long-term management of used nuclear fuel, and to establish segregated trust funds to finance the long-term management of the used nuclear fuel.
- The waste management organization to submit to the Minister of Natural Resources proposed approaches for the management of used nuclear fuel, within three years of the legislation coming into force, and its recommendation as to which of its proposed approaches should be adopted.

In addition, the legislation authorised the government to decide on the approach, and made the waste management organisation responsible for implementing the selected approach.

3.2 ADAPTIVE PHASED MANAGEMENT

Consistent with the *NFWA*, the owners of used fuel in Canada formed the Nuclear Waste Management Organisation (NWMO). From 2002 to 2005, the NWMO conducted a broad review and discussion with Canadians about options and approaches for long-term management of used fuel.

The NWMO study recommended Adaptive Phased Management as the preferred approach for long-term management of used nuclear fuel. Adaptive Phased Management consists of both a technical method and a management system. Key attributes of the technical approach are ultimate centralized containment and isolation of used nuclear fuel in a deep geological repository in a suitable rock formation, phased and adaptive decision-making, optional shallow underground storage at the central site prior to placement in the repository, continuous monitoring and provision for retrievability, and citizen engagement (NWMO 2005).

This approach clearly identified the technology associated with a deep geological repository as the appropriate end point. Such a facility would be designed to be passively safe over the long term. Thus, it would not rely upon human institutions and active management for its safe performance.

3.3 DEEP GEOLOGICAL REPOSITORY

The objective of placing used nuclear fuel in a deep stable geologic environment is to isolate and contain the radioactive material, such that most radioactivity decays within or near the repository. Any release of radionuclides will be in such low concentrations that they do not pose a hazard to human health and the natural environment.

A deep geological repository consists of a system of multiple barriers (see Figure 3.1) that include the used fuel, container, buffer, backfill and other repository seals, and the repository host rock. The multiple barriers operate in concert to contain and isolate the waste, and to retard, delay and attenuate any radionuclide releases to the surface environment. Thus, the multibarrier concept is robust in the sense that failure or less than expected performance of one component does not jeopardize the safety of the containment system as a whole.

In a deep geological repository, used fuel bundles are encapsulated in durable containers, and the containers are sealed in an engineered vault at a depth of hundreds of metres in a stable low-permeability rock mass.

The repository would be a network of horizontal access tunnels and emplacement rooms designed to accommodate the rock structure, groundwater flow and other subsurface conditions at the site. Several options have been considered for container emplacement in the repository: in boreholes drilled into the floor of the rooms (in-floor design), within the rooms (in-room design) and in horizontal boreholes drilled from the access tunnels (horizontal borehole design). A clay-based buffer material would surround each container in order to ensure low-permeability and chemically benign long-term conditions. The rooms would be sealed with backfill material and other repository seals.

Several different rock types are being considered internationally. Historically, Canada had chosen to focus its research on the plutonic rock of the Canadian Shield (Aiken et al. 1977). However, sedimentary rocks remained under active investigation in other countries. Based on the extensive studies and favourable results noted for sedimentary rock in these countries (notably Switzerland, Belgium, France), sedimentary rocks are now also under consideration within Canada.

After a suitable monitoring period, and in consultation with stakeholders, all repository tunnels, shafts and surface boreholes would be backfilled and sealed such that long-term safety of the facility will be provided by passive means. Post-closure monitoring of the facility would likely continue in order to confirm the safety and performance of the repository.

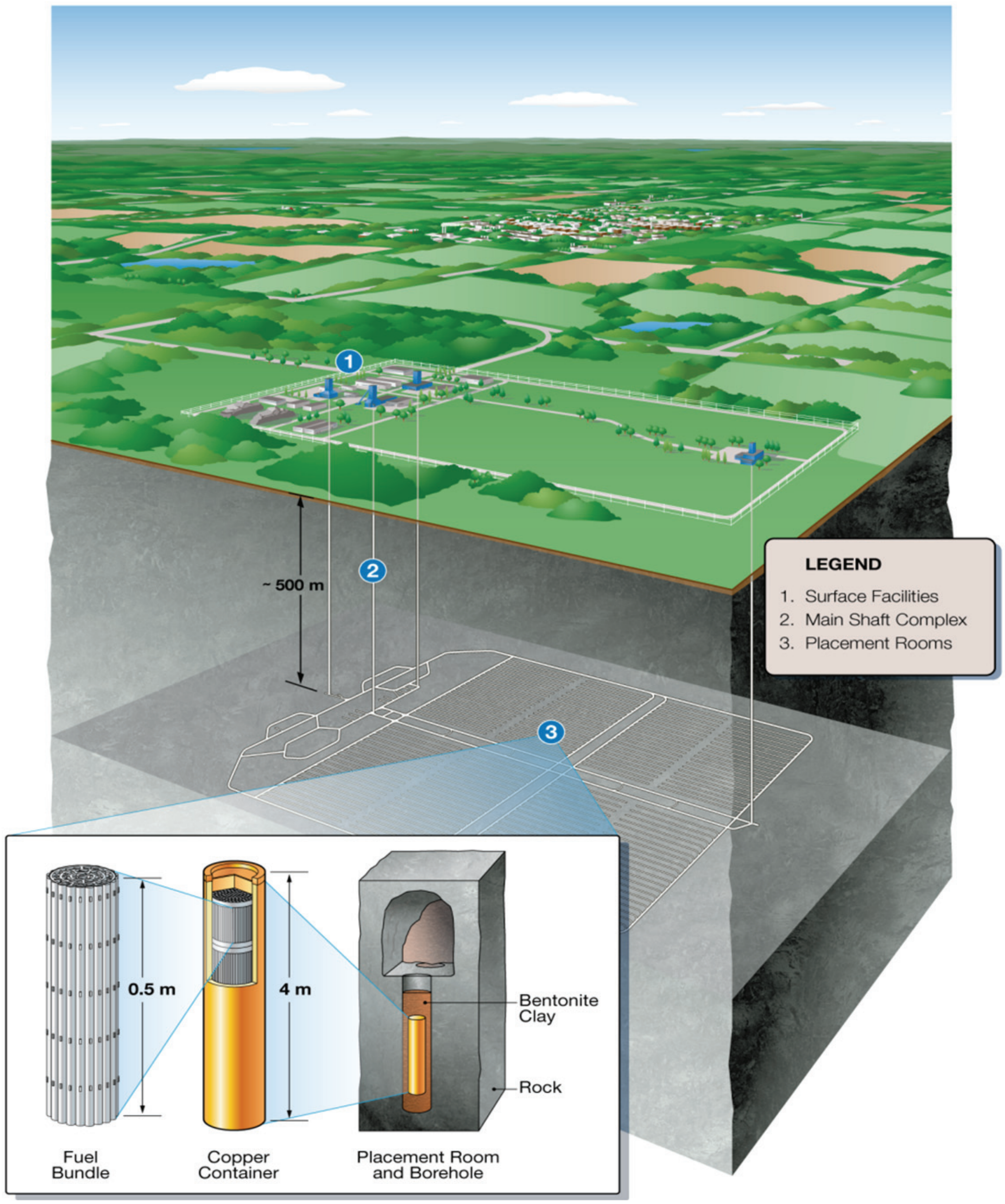


Figure 3.1: Illustration of the deep geological repository concept with in-floor emplacement of the used fuel containers.

3.4 TECHNICAL RESEARCH

A key aim of the Canadian deep geological repository technical program has been to advance our capabilities for characterizing potential repository sites. Specific areas of investigation include structural geology, remote sensing, geostatistics, hydrogeochemistry, isotope hydrogeology, hydrogeology, paleohydrogeology, numerical methods, seismicity, long-term climate change (i.e., glaciation) and scientific visualization (Birch et al. 2008, Russell et al. 2007). Of particular importance has been the development of a coordinated approach for constructing a conceptual model of the site that demonstrates coincidence between independent geoscientific data.

Much of this understanding has come from studies carried out at AECL's Underground Research Laboratory (Figure 3.2). Similar studies have also been completed, for example, at SKB's Äspö Hard Rock Laboratory in Sweden and Nagra's Mont Terri research facility in Switzerland. In fact, Canada's plan envisions the construction of an underground characterization facility at the selected repository site (NWMO 2005). Experiments and studies undertaken in this facility would help ensure that the site would be suitable for a geological repository.

Figure 3.2: Example of an engineering test in Canada. This photo shows excavation of the rock for a full-scale test of access tunnel seal technology at AECL's Underground Research Laboratory (Dixon et al. 2004).

3.5 REGULATORY FRAMEWORK

Canada has a well-developed regulatory and licensing system for evaluation of nuclear facilities. This system is consistent with international best practice, and includes multiple decision steps. Thus, development of a deep geological repository is likely to take many years from initiation to the receipt of an operating licence, including the time needed to construct the facility (6- 8 years).

A used fuel repository is defined as a Class IB nuclear facility under the federal *Nuclear Safety and Control Act* and regulations. Licences are required from the Canadian regulator, the Canadian Nuclear Safety Commission (CNSC), to prepare a site, construct, operate, decommission and abandon the facility. Before the first licence can be issued by CNSC, an Environmental Assessment under the *Canadian Environmental Assessment Act* is required. During these licensing processes, particularly the Environmental Assessment, ample opportunities would exist for public input into the siting, design, and operation of the deep geological repository.

Design and operation of the repository would also be subject to the General Nuclear Safety and Control Regulations, the Radiation Protection Regulations and the Nuclear Security Regulations.

In evaluating any proposed repository, CNSC would consider the extent to which the proposal addresses the following principles set out in their policy document P-290 (CNSC 2004):

a) the management of radioactive waste is commensurate with its radiological, chemical and biological hazard to the health and safety of persons and the environment and to national security;

b) the assessment of future impacts of radioactive waste on the health and safety of persons and the environment encompasses the period of time when the maximum impact is predicted to occur;

c) the predicted impacts on the health and safety of persons and the environment from the management of radioactive waste are no greater than the impacts that are permissible in Canada at the time of the regulatory decision;

d) the measures needed to prevent unreasonable risk to present and to future generations from the hazards of radioactive waste are developed, funded and implemented as soon as reasonably practicable; and

e) the trans-border effects on the health and safety of persons and the environment that could result from the management of radioactive waste in Canada are not greater than the effects experienced in Canada.

Further guidance is given in a number of CNSC Regulatory guidance documents, in particular Regulatory Guide G-320, Assessing the Long Term Safety of Radioactive Waste Management (CNSC 2006).

3.6 INTERNATIONAL GUIDANCE AND EXPERIENCE

Geological disposal of used nuclear fuel and other high-level radioactive waste is accepted internationally as an environmentally and ethically sound waste management solution. It has been adopted in most countries with substantial nuclear power programs.

3.6.1 Guidance from International Organizations

International guidance is provided by two international organisations: the International Atomic Energy Agency (IAEA) and the International Commission on Radiological Protection (ICRP).

The IAEA is an agency of the United Nations, and provides recommendations in the form of standards or guidance that recognize international best practice in the management of nuclear substances. The ICRP is an international technical committee that monitors the development of technical understanding on radiation effects, and offers recommendations on how to assess radiation effects and, in turn, on principles and levels that will provide radiation protection. The recommendations of these agencies are widely referenced or adopted by national programs. Selected documents relevant to development of a repository and its Safety Case are listed in Table 3.1.

Table 3.1: International guidance applicable to the used fuel repository

IAEA SF-1	Fundamental Safety Principles (IAEA 2006a)
IAEA SS111-G-4.1	Siting of Geological Disposal Facilities (IAEA 1994)*
IAEA WS-R-4	Safety Requirements on the Geological Disposal of Radioactive Waste (IAEA 2006b)
ICRP 103	2007 Recommendations of the ICRP (ICRP 2007)
ICRP 77	Radiological Protection Policy for the Disposal of Radioactive Waste (ICRP 1997)
ICRP 81	Radiation Protection Recommendations as Applied to the Disposal of Long-lived Solid Radioactive Waste (ICRP 2000)
ICRP 91	A Framework for Assessing the Impact of Ionising Radiation on Non-human Species (ICRP 2003)

* Update in preparation: IAEA DS 334 (IAEA 2007)

3.6.2 National Programs

Significant progress has been made in programs for long-term management of used fuel and high level waste in a number of countries, indicating confidence in deep geological repository technology. Highlights include:

- In the US, the WIPP site in New Mexico was licensed by the US EPA and has been accepting transuranic wastes (e.g. wastes containing elements such as plutonium) since 1999. They are disposed of in salt rock at a depth of 660 m.
- Also in the US, a license application was submitted in 2008 for a facility for used nuclear fuel at the Yucca Mountain site in Nevada. This application is currently under review.
- In Finland, the government in 2000 selected the Olkiluoto site in principle as the site for a final disposal facility for spent nuclear fuel. The host community of Eurajoki volunteered for this activity. Construction of an underground characterization facility within the granitic rock at the site is proceeding.
- In 2006 the Swiss government concluded that the feasibility of disposal of spent fuel, vitrified high-level waste and long-lived ILW has been demonstrated. The government is now considering the selection of suitable sites for a repository in Switzerland.
- In France, the National Assembly passed an Act in 2006 declaring deep geological disposal as the reference solution for high-level and long-lived radioactive wastes, and set 2015 as the target date for licensing a repository. An underground research facility is in operation in clay rock at the Bure site, and possible sites are being investigated.
- In Sweden, site investigations for a deep geological repository were completed on granitic rock sites near Forsmark and Oskarshamn, both of whom volunteered to become the host community. In 2009, the Forsmark site was selected. Research continues at the Äspö underground laboratory.
- In the UK, the government accepted the recommendations of the Committee for Radioactive Waste Management, and announced that higher activity waste will be managed in the long term through geological disposal. The Nuclear Decommissioning Authority has been given the implementation authority. This program is in a similar stage to the Canadian program with respect to initiating a site selection process.

In addition, several geological repositories for long-lived low and intermediate level wastes are already in operation or under construction worldwide. In Canada, site characterization started in 2006 at the proposed site for a Deep Geologic Repository for low and intermediate level reactor waste at the Bruce nuclear site in the Municipality of Kincardine, Ontario.

Geologic media under investigation worldwide include crystalline, sedimentary and salt rocks. A summary of some of the features of these programs is given in Table 3.2.

Table 3.2: Repositories for used fuel and high level waste – plans and concepts in other countries

COUNTRY	FORM OF WASTE	ROCK TYPE	DEPTH	CONTAINER CONCEPT	EMPLACEMENT CONCEPT	LOCATION	SCHEDULE	CAPACITY OF REPOSITORY
Finland	Used nuclear fuel	Crystalline bedrock	~ 450 m	Outer copper canister; Cast iron structural insert	Canisters emplaced in boreholes drilled from emplacement rooms, surrounded by bentonite clay buffer	Olkiluoto reactor site on the western coast	Construction of facility in progress. In-service 2020	2 600 tU 3 000 canisters
France	Vitrified high level waste from reprocessing (Class C), potentially spent fuel (Class CU), long-lived intermediate level waste (Class B)	Clay	~ 500 m	C: Stainless steel can in 5-cm outer steel canister CU: 10-cm outer steel canister	C: Canisters emplaced in long horizontal boreholes; no backfill CU: Canisters emplaced in horizontal boreholes (3-4 per hole), surrounded with ‘swelling clay’	Siting studies near the underground laboratory at Bure (Meuse-Haute Marne)	In-service 2025	C: 2 500 – 6 300 m^3
Sweden	Used nuclear fuel	Crystalline bedrock (granite)	400 – 700 m	Outer copper canister; Cast iron structural insert	Canisters emplaced in boreholes drilled from emplacement rooms, and surrounded by bentonite clay buffer, or in long horizontal boreholes drilled from the transport tunnels, and filled with bentonite	Near Forsmark on southeast coast.	Permit application 2010	8 000 tU 4 500 canisters
Switzerland	Vitrified high level waste from reprocessing and used nuclear fuel	Opalinus Clay has been investigated but siting process yet to take place	400 – 1000 m	Steel canister	Containers emplaced in emplacement tunnels and surrounded with bentonite clay buffer/backfill	Siting process under development	By 2050	3000 tU
USA*	Used nuclear fuel from power reactors and navy program. Vitrified HLW	Tuff volcanic rock		Steel can in corrosion resistant overpack	Containers emplaced in long horizontal rooms in an unsaturated rock. Surrounded by titanium drip shield.	License application filed for Yucca Mountain site in 2008.	*	70,000 tHM

*Note that US nuclear waste policy is under review in 2009.

4. SAFETY CASE MAIN ARGUMENTS

Adaptive Phased Management envisions ultimate centralized containment and isolation of used nuclear fuel in a deep geological repository in a suitable rock formation (Section 3). Such a facility would be designed to be passively safe over the long term and would not rely on institutional controls to ensure safety.

A summary of the main reasons why a geological repository for used nuclear fuel is expected to be safe is provided in Table 4.1, and each reason is then discussed individually below. Further details on many of the key safety elements of the repository are described in subsequent sections. During the assessment of any candidate site for a repository, these reasons would be tested and evaluated to see if they were supported by the evidence at that particular site. In the overall development of a safety case, these arguments will be put in the context of the views and knowledge within society. This will require development to take place collaboratively with Canadians.

Table 4.1: Summary of main safety arguments

1. A geological repository uses multiple barriers that include the waste form, container, sealing materials, and the host rock. The system is designed such that the failure of one component would not jeopardize the safety of the containment system as a whole.
2. The host rock would be stable and predictable over long periods of time.
3. The low-permeable host rock would ensure that the waters in the deep rock are isolated and do not mix with surface waters.
4. The deep geological repository system would maintain a chemical and hydrological environment that is favourable to the stability and performance of the repository.
5. Natural analogues provide evidence that engineered barrier system components are stable for very long times under similar deep geologic conditions.
6. The depth of the repository would be such that future inadvertent human intrusion into the closed repository would be very unlikely.
7. International progress on repository implementation gives assurance that geological disposal is a sound technical solution and provides practical experience.
8. Safety assessment case studies indicate that any impacts are likely to be well below recommended dose constraints and natural background dose rates.
9. A geological repository can be built and operated safely using proven technologies.
10. The radionuclides in the used fuel decay with time.
11. The repository site will be monitored to confirm repository system performance.

1. **A geological repository uses multiple barriers that include the waste form, container, sealing materials, and the host rock. The system is designed such that the failure of one component would not jeopardize the safety of the containment system as a whole.**

   In Canada, a deep geological repository would consist of a system of multiple barriers that includes the ceramic UO_2 and Zircaloy cladding of the used fuel; a long-lived corrosion-resistant container; buffer, backfill and other repository seals (e.g., shaft seals); and the natural barrier provided by the repository host rock and its geologic environment. Section 5 provides more details of the Canadian approach.

   The multiple barriers operate in concert to contain and isolate the waste, and to prevent, delay and attenuate the potential radionuclide releases to the biosphere. Since more than one barrier acts to either delay the release of radionuclides or retard the migration of radionuclides, the early failure of one barrier does not compromise the safety of the repository system. This robustness has been examined in various safety assessments (Garisto et al. 2004a, Nagra 2002, SKB 2006) by means of “what if” scenarios in which a particular barrier is assumed to fail. Estimated dose rates remain lower than currently accepted dose rates to members of the public, even for these “what if” scenarios, illustrating the inherent safety of the multiple barrier concept.

2. **The host rock would be stable and predictable over long periods of time.**

   Geoscience investigations during site characterization are expected to show that, for a selected site, conditions at repository depth have been unchanged for millions of years, and therefore have been largely unaffected by surface storms, glaciation, earthquakes, isostatic rebound, erosion and similar natural phenomena over timescales relevant to repository safety.

   The repository would likely be located in a low seismic hazard area in a suitable crystalline or sedimentary formation. In addition, it is well established from mine experience and basic physical arguments that the mechanical effect of shaking due to earthquakes is less at depth than at surface.

   Earthquakes preferentially cause movement along existing fractures. The repository will be located so as to avoid fractures, so any seismic activity will not directly intersect the repository.

3. **The low-permeable host rock would ensure that the waters in the deep rock are isolated and do not mix with surface waters.**

   The repository would likely be located in a suitable crystalline or sedimentary formation at a sufficient depth where the hydrogeological conditions are favourable. Favourable hydrogeological characteristics could include elements of the following:

   - Low rock permeabilities, which limit groundwater flow.
   - Saline conditions where lighter freshwater is on top of heavier saline water, which is a stable arrangement that would tend to reduce any vertical groundwater flow. The existence of salinity at depth suggests that the deep groundwaters do not mix with surface waters.

- Groundwater ages, based on isotopic and chemical analyses, that indicate no mixing with surface waters has occurred, even during the multiple glaciations over the past million years.
- Chemically reducing conditions, indicating no mixing with oxygenated surface waters.

Site investigations on the Canadian Shield and Ordovician sedimentary formations generally indicate that deep groundwaters are saline and old. Thus, sites which are technologically suitable for a geological repository would certainly be found in Canada.

4. The deep geological repository system would maintain a chemical and hydrological environment that is favourable to the stability and performance of the repository.

A geological repository for used fuel is located deep underground to ensure that it is isolated from the dynamic natural processes that occur at or near the surface (e.g., oxidation, erosion, and surface waters). By isolating the repository from the surface environment and selecting a site with long term stability, the containers and engineered barrier systems would experience a slowly evolving geochemical and hydrogeological environment. That is, the disturbances caused by the repository and its construction (e.g., thermal heating) would slowly fade away and ambient conditions would prevail.

A feature of suitable deep geologic sites in Canada is that the conditions are chemically reducing and saturated, i.e., there is no oxygen and the pores in the rock are full of water. The repository is designed to take advantage of these conditions – the chemically-reducing conditions are favourable to the stability of the engineered materials such as the copper containers (Maak 1999) and used fuel (Shoesmith 2007).

5. Natural analogues provide evidence that engineered barrier materials are stable for very long times under similar deep geologic conditions.

The long-term stability of engineered barrier materials such as the copper container and the bentonite buffer material can be inferred from the existence of native copper deposits (e.g., in the Permian Littleham Mudstone in southwest England), and bentonite clay deposits (e.g., Avonlea clay deposits in Saskatchewan). Studies of these natural analogues extend the understanding derived from laboratory experiments over much longer time periods. The mere existence of these long-lived deposits suggests that copper and bentonite clay would remain stable for long periods under conditions not very different to those expected in a repository shortly after saturation of the vault.

Similarly, the Cigar Lake uranium ore body in Saskatchewan, for example, can be considered a natural analogue for used UO_2 fuel (see Section 7). Geological evidence from Cigar Lake indicates that natural uraninite under reducing conditions remains stable on a time scale over one hundred million years, with very little uranium dissolving in the groundwater moving through the deposit. Furthermore, the natural clay surrounding the ore body has been so effective in containing the uranium that there is no indication of the ore deposit at the earth's surface. Recent flooding problems at the Cigar lake uranium mine are due to the mining operations breaching the natural clay barrier at this site.

In analogy with the Cigar Lake deposit, because conditions in a saturated deep geological repository are expected to be reducing, the used UO_2 fuel should remain stable over the time frame of interest, i.e., one million years (Shoesmith 2007). Also, the engineered clay barrier systems should be effective in limiting the movement of radionuclides away from the repository.

6. **The depth of the repository would be such that future inadvertent human intrusion into the closed repository would be very unlikely.**

The closure plans for the repository are intended to ensure that future generations will remember that the repository is present. These could include a range from active institutional controls, such as ongoing surveillance and enforcement of local planning bylaws, to passive means such as durable site markers, local memory, and placing records in national archives.

At very long times, it is possible that people may forget about the existence of the repository. It is further possible that some future generation would inadvertently excavate into the repository - for example, during exploratory drilling to check for mineral resources. However, the likelihood of such an intrusion will be low because of the depth of the repository and its geologic setting. In particular:

- The site location would likely be chosen such that there are no known significant natural resources or geothermal heat sources nearby that might encourage exploratory drilling.
- The groundwater at repository depth would likely be undrinkable (too salty) and, moreover, the repository is at a depth that far exceeds the range of interest for water supplies. Bedrock water wells, for example, do not generally exceed 150 m depth. Thus, it is very unlikely that wells would be drilled into the repository.
- The repository would be positioned within a region of rock with low permeability, which would be inconsistent with groundwater resource use.
- The depth of the repository would require specialized drilling equipment and, therefore, any drilling would likely be part of a carefully monitored and controlled exploration performed by technologically advanced people.

7. **International progress on repository implementation gives assurance that geological disposal is a sound technical solution and provides practical experience.**

The concept of containing and isolating used fuel from the environment by placing it in repositories deep underground was proposed more than 50 years ago and considerable R&D effort has gone into the development of the concept (IAEA 2003, IAEA 1997, ICRP 1997, OECD 1995). The progress which has been made in the scientific and technical aspects of geological disposal gives assurance that this is a sound technical solution which is supported by good scientific understanding (Nirex 2001, IAEA 2000, OECD 1999).

Societal and ethical considerations have also been considered in the discussion of long-term management options, and the deep geological repository has also been found to be consistent with general ethical principles (NWMO 2005).

A number of countries are planning to construct a deep geological repository for used fuel. Finland has already selected a site, Sweden is in the latter stages of site selection, and Canada, Switzerland and UK are in the early stages of site selection. Geological repositories are also being used for disposal of low and intermediate level radioactive wastes (Sweden and Finland) and for transuranic waste (USA).

8. Safety assessment case studies indicate that any impacts are likely to be well below recommended dose constraints and natural background dose rates.

The most likely scenario by which any radionuclide from a deep geological repository can reach the biosphere is by movement through the rock groundwater. This scenario has been studied in three major case studies in Canada: the case study for the Environmental Impact Statement (AECL 1994), the Second Case Study (Wikjord et al. 1996) and the Third Case Study (Gierszewski et al. 2004a). These safety assessments were done for a variety of repository designs and hypothetical sites. For all cases, most radioactivity was trapped within or near the repository and decayed there. The small amounts released into the biosphere from the repository over long times led to a calculated maximum dose rate to someone living on the site well in the future that would be much less than the CNSC public dose limit of 1 mSv/a or the Canadian background dose rate of 1.8 mSv/a (Section 8). Similar results have been found in safety studies by other countries for a wide range of designs and site conditions.

Complementary safety indicators, other than the human dose rate, have also been examined (Garisto et al. 2004a, 2005a; Becker et al. 2002). In Canadian and other studies for relevant candidate sites, these safety indicators are also below their reference values (which are typically based on the concentrations or fluxes of naturally occurring radionuclides), indicating that the impacts of any radionuclides released from the repository would be much smaller than the impacts associated with naturally-occurring radionuclides.

Finally, the potential chemical toxicity hazard posed by a deep geological repository was also examined (Garisto et al. 2005a). The safety assessment results indicated that the engineered and natural barriers of the repository system and hypothetical Third Case Study site were robust and provided good protection against potential chemical hazards arising from the presence of a deep geological repository for used fuel. Furthermore, since the calculated fluxes of the potentially chemically toxic elements into the environment were far lower than the corresponding natural fluxes arising from erosion of the bedrock, the presence of the repository did not affect the natural occurring levels of these elements.

The results of these safety assessments indicate that the estimated long-term impacts from geological disposal of used fuel would be small.

9. A geological repository can be built and operated safely using proven technologies.

A geological repository would be located at a depth of about 500 m below the ground surface, depending on site-specific conditions and engineering considerations. It would be accessed by a shaft, ramp or both. The size of the repository would depend on the repository design and the number of fuel bundles to be emplaced.

Excavation and construction of deep underground openings in rock formations generally do not represent a technical problem (Baumgartner 2005, Baumgartner et al. 1996). There is much experience in Canada and worldwide in this type of engineering. The main difference from existing mining projects would be the need to characterize the effect of the excavation technique on the properties of the near field rock as this is not usually of importance in, for example, mine construction. Special attention would also need to be paid to the avoidance or isolation of fracture zones intersecting the repository.

Much relevant experience has been obtained from the construction and operation of AECL's Underground Research Laboratory in Manitoba from 1984 to 1998. Similar international experience includes:

- US DOE's WIPP operating repository in Carlsbad, USA;
- SKB's Äspö Hard Rock Laboratory in Forsmark, Sweden;
- Posiva's ONKALO underground facility in Olkiluoto, Finland;
- Andra's Bure underground facility in Meuse-Haute Marne, France;
- Nagra's Mont Terri research facility in Switzerland; and
- Nagra's Grimsel Test Site in Switzerland.

10. The radionuclides in the used fuel decay with time.

When the used fuel is removed from the reactor it is highly radioactive. However, the radioactivity naturally decreases with time due to radioactive decay. In particular, the radioactivity of used fuel decreases to about 0.01 percent of its initial value after about 100 years. After approximately 500 years the radioactivity of used fuel is even lower and dominated by the actinides and their progeny. The radioactivity and radiotoxicity of used fuel becomes similar to that of naturally occurring uranium ore bodies within approximately one million years (see Figures 2.3 and 2.7).

11. The repository site will be monitored to confirm repository system performance.

The site will be monitored for decades during the licensing, construction and operation process, so there will be a substantial database of information on the deep groundwater system and repository performance before a decision on closure of the repository is made.

Site monitoring will be used to establish baseline conditions against which disturbances associated with the repository can be detected, and with which predictions of repository performance can be validated.

A long-term monitoring plan can be developed as part of the closure plans, based on information and technologies then available, and in due consultation with stakeholders (Simmons 2006).

5. DEEP GEOLOGICAL REPOSITORY SYSTEM DESCRIPTION (MULTIPLE BARRIER CONCEPT)

5.1 CONCEPT OVERVIEW

A deep geological repository consists of a system of multiple barriers (see Figure 3.1) that include the used fuel, container, buffer, backfill and other repository seals, and the repository host rock. Specifically, used fuel bundles are encapsulated in durable containers, and the containers are sealed in an engineered vault at a depth of 500 to 1000 m in a stable low-permeability rock mass. Historically, the research and development focus in Canada has been on the plutonic rock of the Canadian Shield. However, studies have also been carried out on sedimentary rock.

Over the last 25 years, Canada (in co-operation with other international waste management organisations) has developed a broad range of technology and expertise for the emplacement of used fuel in a repository. This work has ranged from experimental studies and model development, to demonstration of site characterisation and repository engineering.

In this section, our scientific understanding of each of the components of the multi-barrier system, including the host rock and geologic setting, is discussed in turn, together with aspects of the biosphere into which any release through the engineered barriers and geosphere may take place.

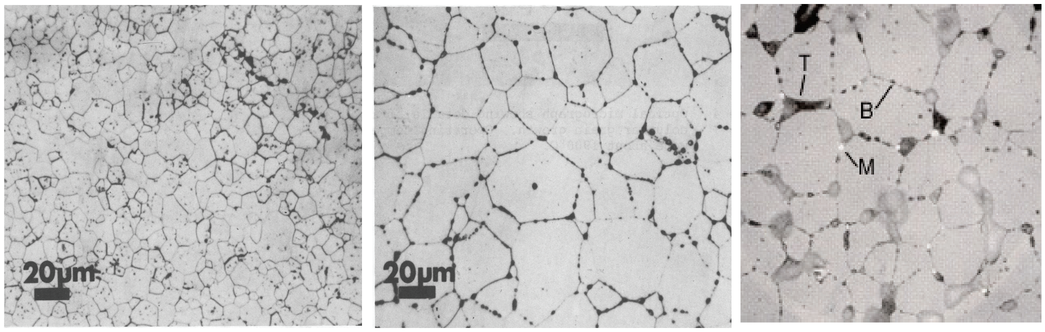
5.2 USED FUEL

The CANDU fuel bundle is described in Section 2.1. The bundle characteristics depend on the particular CANDU reactor. The Bruce-Darlington fuel bundle, which is the most common, contains 37 fuel elements and weighs 23.9 kg, of which 21.7 kg is UO_2 and 2.2 kg is Zircaloy.

When discharged from a reactor, almost all of the fuel bundles are still in good condition. Less than 0.1% have minor damage or defects, such as pinholes through the fuel sheaths (Tait et al. 2000, p. 3).

The radioactivity, heat output, composition and physical structure of used fuel are affected by how many fission reactions have taken place within the fuel while it was in the reactor (Figure 5.1). This is roughly proportional to the energy that was released by the fuel during its stay in the reactor. The energy released per unit mass of uranium is called the fuel burnup. The fuel burnup for a particular bundle depends on many factors such as the type of reactor, the location of the bundle in the reactor, and its residence time in the reactor. The typical burnup range of CANDU fuel is about 120 to 320 MWh/kg U, with a mean burnup value of 200-220 MWh/kg U. At this burnup, about 2% of the initial uranium has been “burned” and converted into other elements.

The Zircaloy-4 cladding consists mainly of Zr (98 wt.%) and Sn (1.5 wt.%). The irradiated cladding is a fine-grained material (grain size typically 10 μm, thickness typically 0.4 mm) containing some neutron activation products, such as C-14, Ni-59 and Ni-63.



a) (b) (c)

Figure 5.1: Microstructure of (a) fresh fuel, (b) low burnup fuel and (c) high burnup fuel. During irradiation, the fuel grains initially grow in size. The radioactivity is distributed partly in the bubbles (B) and gaps (T) between the grains, partly in the metallic particles that form at grain boundaries (M), and mostly within the grains.

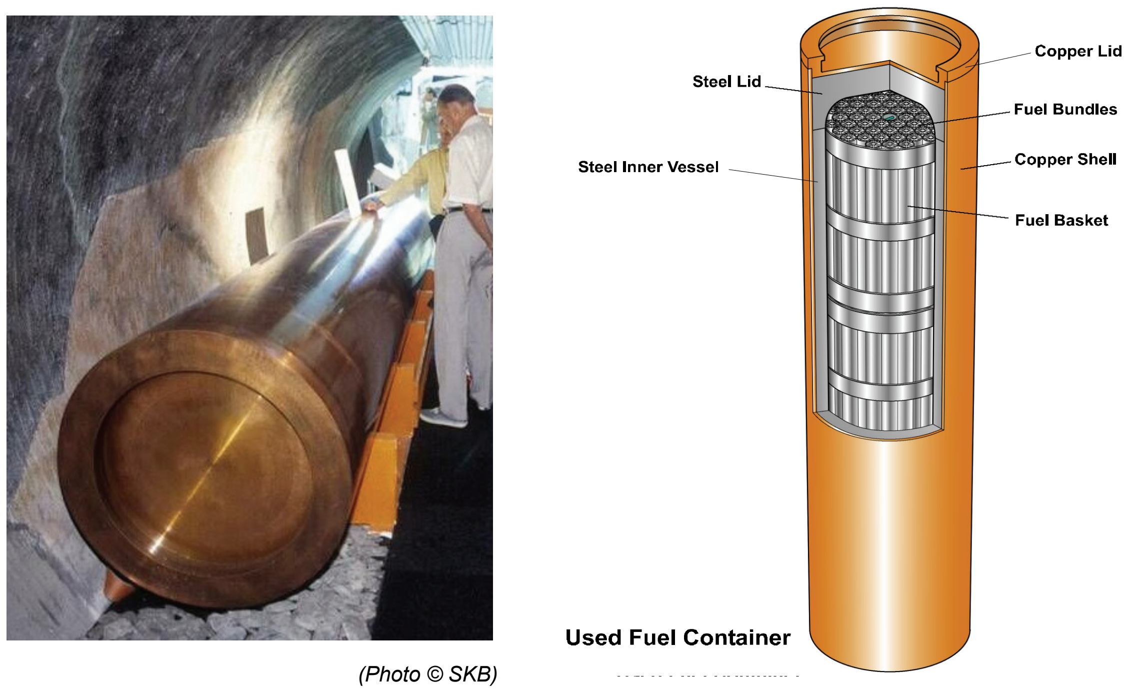
5.3 CONTAINER

The primary purpose of the used fuel container is to isolate the used fuel from the underground environment, preventing water from contacting the used fuel bundles and, thereby, preventing radionuclides in the fuel from escaping into the underground environment.

The compact nature of CANDU fuel bundles permits considerable flexibility in the design of containers for emplacement of used fuel in a repository. The current design concept (Maak and Simmons 2001) uses containers similar to those considered in the Swedish and Finnish programs (Figure 5.2). One particular container design holds 324 bundles in 6 layers, with a total mass (fully loaded) of 23.5 Mg (Russell and Simmons 2003, Maak and Simmons 2001).

The used fuel container design for a repository in crystalline rock has a corrosion-resistant outer copper shell (Maak 1999), with a strong steel inner vessel (Figure 5.2). The reference design copper outer vessel is 25 mm thick and the inner steel vessel is about 80 to 100 mm thick. The interior of the steel vessel would be filled with an inert gas such as helium.

A major reason for the selection of copper is its stability under conditions typically found underground – i.e., water-saturated rock and chemically reducing (low oxygen) conditions. There is thermodynamic, experimental, and natural analogue evidence that copper is stable for very long periods under these conditions.



(Photo © SKB)

Figure 5.2: (a) Full-size prototype copper-shell container from the Swedish program; (b) cut-away view of reference Canadian copper-shell container.

After the container is emplaced in the repository, hydrostatic and swelling pressures would be exerted on the container (as the buffer saturates). The copper shell, if present, would compress onto the steel inner vessel, transferring the external load to the steel inner vessel (Poon et al. 2001). The steel vessel would be designed to withstand the external pressure loads that would be experienced by the container during its design lifetime in a repository, including the external pressure loads caused by the presence of a 3000-m thick glacier above the repository (Poon et al. 2001, Maak and Simmons 2001).

Heat and radiation are emitted from a used fuel container due to radioactive decay of the radionuclides in the used fuel. The heat output of the fuel inside the container (cf. Figure 6.1) must be taken into account in the design of the repository layout (Baumgartner 2005, Baumgartner et al. 1996). Similarly, the gamma dose rate at the container surface needs to be considered when the procedures and equipment for handling the container are being developed. For the reference container filled with 30 year old fuel with a high burnup of 280 MWh/kgU, the gamma dose rate at the container surface is about 0.046 Gy/h and 0.0014 Gy/h in the radial and axial directions, respectively (Hanna 2001).

5.4 BUFFER AND BACKFILL SEALS

In the repository, the containers would be sealed into the emplacement rooms by a variety of clay-based and concrete-based sealing materials. The arrangement would depend on the specific repository design. Three options are illustrated in Figure 5.3. Currently, the reference concept for crystalline rock is a vertical in-floor geometry, while the reference concept for sedimentary rock is a horizontal in-room geometry.

In each case, a clay-based buffer material would surround each container in order to ensure a low-permeability and chemically benign environment around the containers (Russell and Simmons 2003). That is, the buffer isolates the containers from the processes taking place in the geologic environment.

The main constituent of the buffer would be bentonite, a naturally occurring, clay-rich sediment. These natural clays are stable, having typically been formed millions to hundreds of millions of years ago. Bentonite deposits in Wyoming, Saskatchewan, and Japan are among those that have been characterized for potential use as buffer material.

The main mineral phase in bentonite is montmorillonite. Montmorillonite is responsible for the most distinctive property of bentonite - it can swell to several times its original volume when placed in water. In the confined space in a repository, this swelling causes the bentonite to seal fractures and gaps (Dixon et al. 2001, 2002; Dixon 2000, which makes the saturated bentonite nearly impermeable (Baxter and Forsling 2001).

In addition to this self-sealing function, the dense buffer layer also:

- Controls or "buffers" the water chemistry in the vicinity of the container, thereby inhibiting corrosion of the container.
- Holds the container in place.
- Protects the container from mechanical damage due to small rock movements.
- Reduces the potential for microbially-enhanced corrosion of the container by making the environment near the container unsuitable for microbial growth.
- If a container is breached, the buffer retards the migration of any radionuclides by chemical sorption.

A crushed rock backfill would also be used in the repository (Figure 5.3) to fill the bulk of the void spaces in the access tunnels, thereby reducing the hydraulic transmissivity of openings (Russell and Simmons 2003). Two types of backfill could be used: dense backfill and light backfill. Some important functions of the backfill are:

- To slow the movement of groundwater in the repository;
- To provide support after closure by filling most of the excavated space in rooms, tunnels, and shafts;
- To keep the buffer and containers securely in place in the emplacement rooms; and
- To promote reducing (anaerobic) chemical conditions in the groundwater.

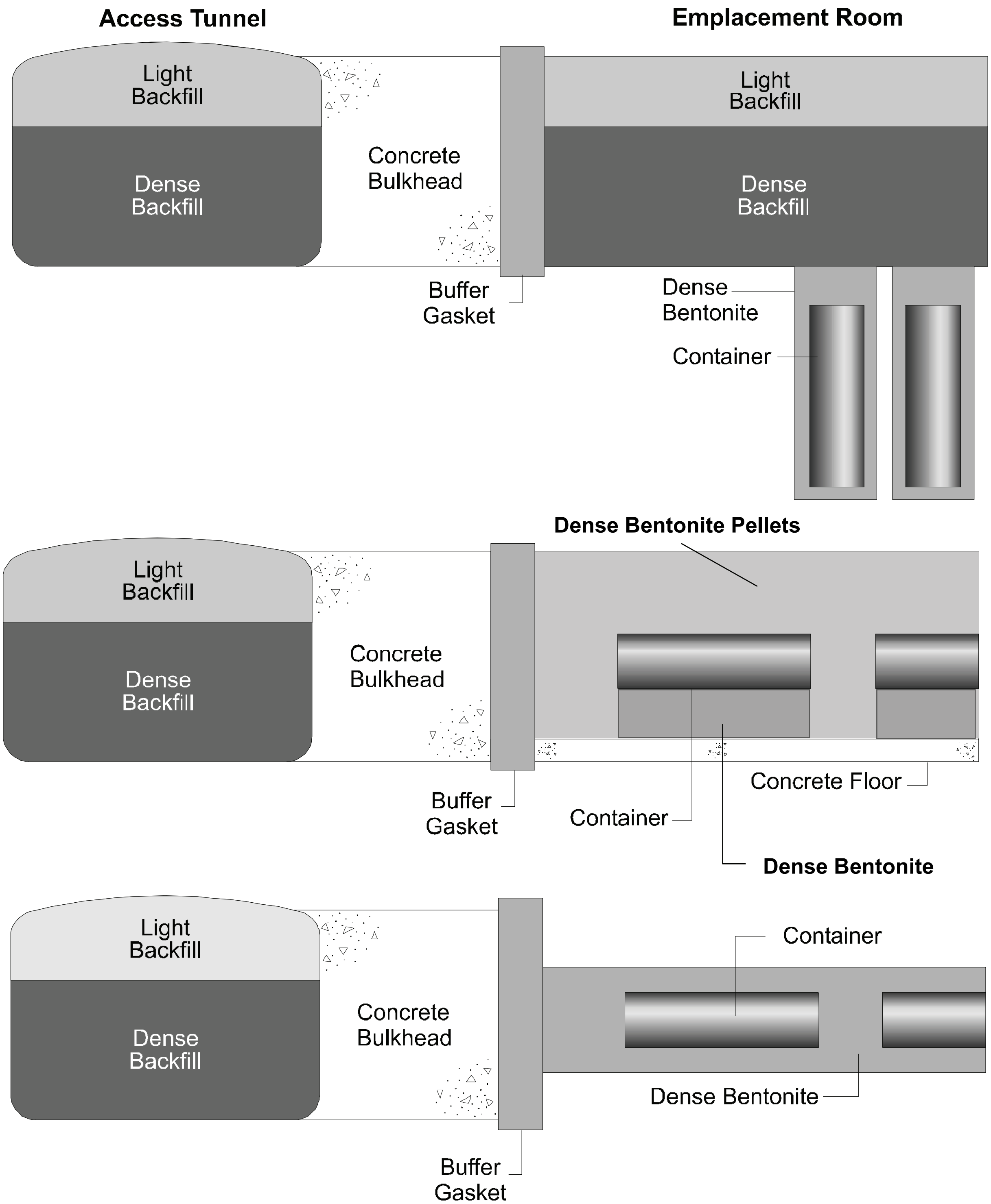


Figure 5.3: Schematic representations of container emplacement options (not to scale): In-floor (top), In-Room (middle) and Horizontal Borehole (bottom).

5.5 REPOSITORY DESIGN AND LAYOUT

The range of repository designs under consideration in the Canadian deep geological repository development program is described in Russell and Simmons (2003). The in-floor, in-room and horizontal borehole designs are illustrated in Figure 5.3. Factors to be considered for repository engineering are discussed by Baumgartner (2005), Baumgartner et al. (1996), and Simmons and Baumgartner (1994).

A schematic of a typical repository layout for the in-room design is shown in Figure 5.4. The repository is accessed by a vertical shaft and includes ventilation shafts. The placement rooms in this example are about 300 m long and the spacing between them is about 50 m, based in part on structural and thermal considerations, e.g., the temperature at the container surface should not exceed $100^{o}C$.

The overall size of the repository would depend on the repository design, the number of fuel bundles and the age of the fuel placed in the repository. (Current repository designs assume that the fuel has a minimum average age of 30 years at the time of emplacement.) Based on an assumed 40-year average life of existing Canadian CANDU nuclear power reactors, a repository would contain approximately 3.6 million used fuel bundles (within approximately 11,000 containers). A repository with an area of a few km^2 would be sufficient to hold this number of fuel bundles (Russell and Simmons 2003).

The principal constraint on the overall design of a geological repository is the mechanical properties of the host rock. For crystalline and other hard rocks, excavation and construction of self-supporting underground openings, at depths considered for a repository, generally does not represent a technical problem. There is much experience worldwide in this type of engineering. Specific attention would need to be given to avoiding major subvertical fracture zones. Although heavy supports or tunnel lining are often not needed in such rock environments (IAEA 2003), there may be a need for concrete floors, concrete bulkheads and local support, for example, by using grout or shotcrete.

In rocks which have less strength (e.g., less consolidated argillaceous and other sedimentary rocks, and plastic clays), a key requirement is for support of the excavations by some form of tunnel and shaft lining, designed to prevent spalling, caving or creep. In this case, the greater the depth of the repository, the greater the thickness and strength of lining is required.

One important aspect of the repository construction, which is not important during mine construction, is characterization of the effect of the excavation technique on the properties of the near field rock around the periphery of the repository, i.e., the "excavation damaged zone" (EDZ). This phenomenon has been investigated in underground research laboratories (Davison et al. 1994). The EDZ is important because it is expected to have a higher porosity and flow permeability than the host rock (Garisto et al. 2004b, IAEA 2003). Excavation techniques will be adopted that minimize the extent of the EDZ.

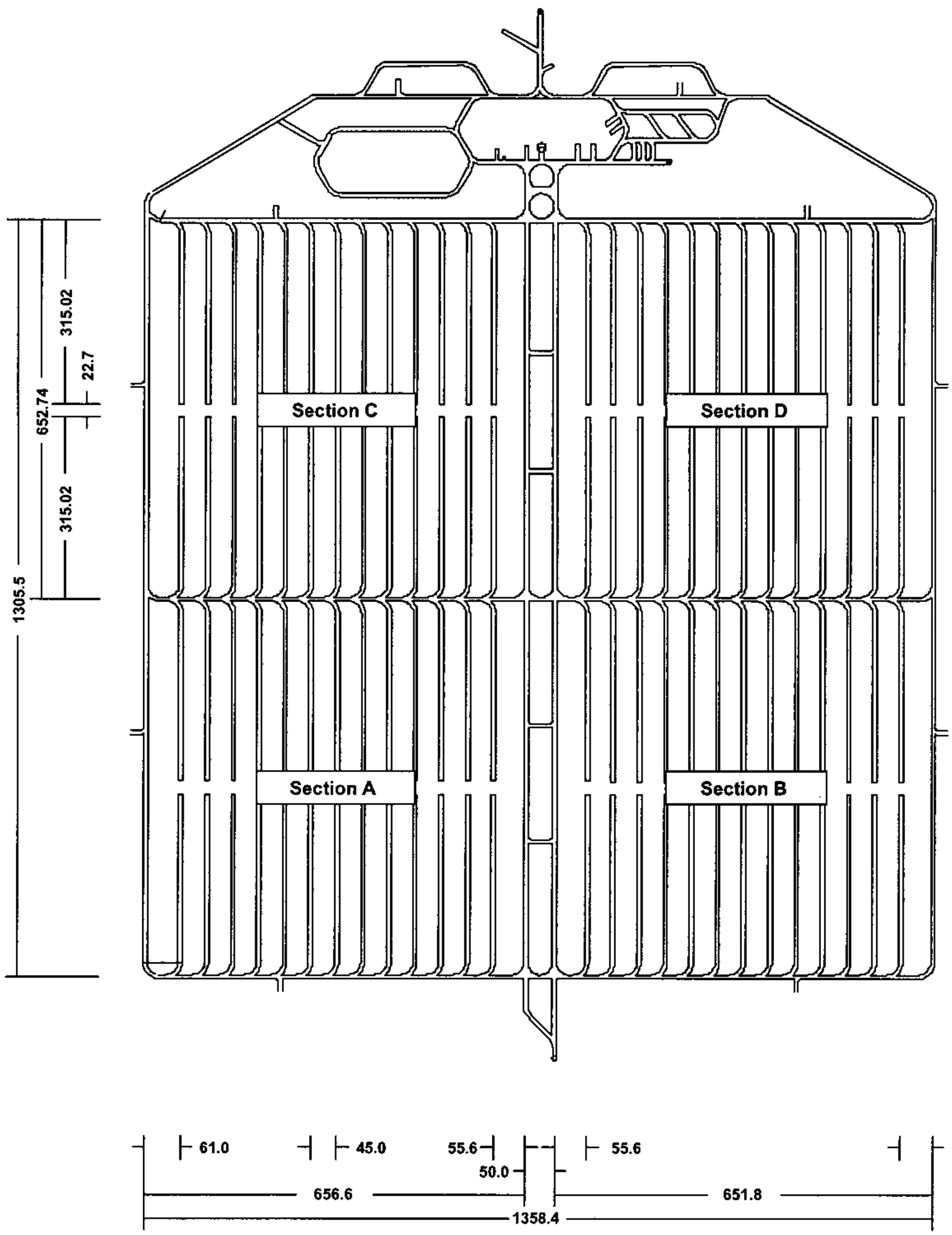


Figure 5.4: Example repository layout for the in-room emplacement design showing the emplacement rooms, access tunnels and general facility support areas. All dimensions are in m. This illustrated vault holds about 11,000 reference containers and was used in the Third Case Study (Gierszewski et al. 2004a).

After a room has been filled, it would be closed off by the installation of a composite seal consisting of a gasket of buffer material and a thick bulkhead of low-heat, high-performance concrete, as indicated schematically in Figure 5.3. Closure of the filled rooms would permit physical isolation of the regions where container emplacement has been completed, improving security and permitting the continued use of the tunnels and access ways for ongoing repository operations in adjacent rooms.

During closure of the repository, the access tunnels and shafts would be backfilled and sealed, with particular care taken at locations where tunnels or shafts intersect hydraulically active regions in the rock.

5.6 GEOSPHERE

The geosphere is defined by the three-dimensional envelope of rock surrounding the repository and extending upwards to the biosphere. The specific characteristics of the geosphere would be highly dependent on the local geology of the selected repository site. Of particular importance for repository safety is the regional and local scale subsurface hydrogeology, which is the distribution and movement of groundwater below the Earth's surface.

Repositories would be sited in stable geologic environments in which the waste and engineered barriers are protected over a long time period. That is, the characteristics of a site that make it suitable for hosting a geological repository, such as mechanical stability, low groundwater flow and favourable geochemical conditions, should not change significantly over relevant timescales.

Suitable sites for a geological repository are generally:

- unlikely to be affected by major tectonic movements, volcanic events or other geological phenomena that could give rise to rapid or sudden changes in geological or geochemical conditions;
- largely decoupled from events and processes occurring near the surface, including the effects of climate change, thereby ensuring stable geochemical conditions at depth;
- lacking in natural resources that might attract exploratory drilling, minimising the possibility of inadvertent human intrusion in the future, when the location of the repository may no longer be known; and
- endowed with good engineering properties which readily allow construction of the repository, as well as operation for periods which may be measured in decades.

Field investigations at potential repository sites would need to confirm these characteristics and other important features, e.g., the distribution of fractures at the site, the hydrogeology of the site, and the chemistry of deep groundwaters at the site.

In terms of its role within the multi-barrier repository system, the geosphere would contribute to the safety of the repository by

- providing physical isolation of the used fuel from the near surface environment and the potentially disruptive events that occur there,

- maintaining a geochemical and hydrogeological environment that is favourable to the preservation and performance of the engineered barriers, and
- acting as a natural barrier restricting the rate at which contaminants released from used fuel could move from the repository to the surface biosphere.

Suitable geologic environments for disposal of long lived radioactive wastes exist widely throughout the world. They can vary considerably in their nature and, thus, provide the desirable features in different combinations and to different extents. Experience in many countries over the last thirty years has shown that acceptable conditions can be found in such diverse rock types such granites, sedimentary formations (e.g., plastic clays and shales) and salt formations (IAEA 2003).

The NWMO (2005) has identified two types of rock formations as potentially suitable for hosting a deep geological repository: crystalline rock and sedimentary rock. Other rock formations may, however, also be potentially suitable.

The potential suitability of crystalline rock for a deep geological repository has been extensively documented in the AECL Environmental Impact Statement (AECL 1994) and supporting technical documents as well as in a number of international studies in Sweden, Finland and Switzerland. Many large areas of intact or sparsely fractured rock have been noted in surface exposures of the plutonic and gneissic rocks of the Canadian Shield (Everitt 1999). Moreover, field studies have found that fractures below depths of several hundred metres in the plutonic rocks were ancient features, suggesting that, at repository depths, new fractures are unlikely to form over the time periods of interest (Kamineni et al. 2002, Everitt and Osadetz 2000, Gascoyne et al. 1997, Sikorsky 1996).

The potential suitability of sedimentary rocks has also been considered, although in less detail within Canada (Baumgartner 2005, Mazurek 2004, RWE Nukem 2004a,b). However, sedimentary rocks have been widely studied internationally, including Switzerland (Nagra 2002), France (Andra 2005) and Belgium, because of their long-term stability and low ground water flow. In Canada, large areas of sedimentary rock exist which have sufficient depth below the surface, and which lack mineral resources, so that they are unlikely to be disturbed by erosion or accidental drilling.

5.7 BIOSPHERE

The objective of emplacing used fuel in a deep geological repository is to isolate and contain the radioactive material, thereby ensuring the long-term safety of humans and the environment. However, the radioactivity may not be completely isolated over geological time periods. Corrosion of the containers would lead to dissolution of the used fuel by groundwater, and the possible subsequent slow transport of some radioactivity through the engineered barriers and geosphere to the surface biosphere.

In the present context, the biosphere includes those parts of the terrestrial environment that lie above the water table (including unsaturated soils and the atmosphere) as well as surface waters, including wetlands, and the mixed layer of lake sediments. These are the parts of the environment that contain abundant living organisms, and that are readily accessible to humans.

The biosphere itself is not a barrier for release per se, but its characteristics define how any radionuclide release results in any impacts on humans and the environment. The movement of radionuclides through the biosphere involves processes such as bioaccumulation that can result in a localized increase in concentration, as well as dilution, dispersion and decay that result in a decrease in concentration (Davis et al. 1993). The movement of contaminants through the biosphere is dependent on the properties of the local environment at the repository site, e.g., the presence of lakes and rivers, and the topography. The principal biosphere components are listed in Table 5.1, and some pathways are illustrated in Figure 5.5.

Table 5.1: Principal biosphere system components[1]

COMPONENT	COMPONENT CHARACTERISTIC IN THE THIRD CASE STUDY	EXAMPLES OF PROCESSES INCLUDED AND/OR KEY ASSUMPTIONS IN THE THIRD CASE STUDY
Climate	Temperate, present day central Canadian Shield	Precipitation rate and wind speed
Water bodies	Lake, river, stream and wetlands exist near the repository	Water outflow from lake and sedimentation. The lake, if used, is large enough to provide water needs of farming household and, conservatively, collects all nuclides discharged from the geosphere.
Biotic communities	Boreal, Canadian Shield	Only domestic plants and animals are considered
Near surface geosphere	Bedrock extends close to surface. Primarily sandy soil type.	Thin overburden. Sediment under lake and river. Fracture zone capable of supplying water to a well at a rate up to 4000 m^3/a.
Topography	Inland, subdued slopes, limited local erosion	Not included in biosphere model but topography is used in the groundwater flow calculations.
Human activities	Local self-sufficient farming household (i.e., the critical group)	Crop production and crop irrigation, animals raised for food, recycling of residues, and use of wood and peat resources. All food is locally produced.

[1]Component characteristics and examples are taken from the Third Case Study (Gierszewski et al 2004a).

Because the used fuel remains hazardous for long times, and because the deep repository will prevent early release of radionuclides, the potential impacts on the biosphere must be considered far into the future. Over these time scales, people and the environment around the repository can and will likely change considerably.

Over the next thousand years, natural or man-induced climate change will affect people and the environment at the site. However, the effect at the repository level would be negligible. Any site would only be selected if it could be demonstrated that surface and shallow groundwaters (which would be affected directly by climate change) were separated from the deep rock porewaters at the repository.

On longer time scales (after 50,000 years or so), however, the global conditions that caused several glaciation cycles over the past million years could initiate another glaciation cycle. Such cycles have a period of approximately 120,000 years. During much of this cycle, the site would be covered with permafrost or an ice sheet, returning during interglacial periods to climate conditions similar to present-day (Peltier 2003, 2006a,b).

It is not possible to precisely identify all the human groups and the ecosystems that might be near the site in the future and could therefore potentially be affected by the repository. Instead, the impacts are assessed based on present-day or plausible future human behaviour and ecosystems, using conservative yet reasonable assumptions (Garisto et al. 2004b).

The radiological dose rate to humans is usually used as the main indicator of the overall safety of the repository system (ICRP 2000). In keeping with the concept of a “critical group”, it is conservatively assumed that the potentially impacted people live near the site in the future, and have lifestyles that maximize their potential exposure doses while behaving in an otherwise reasonable manner, e.g., the food and water needed by the group are taken from the local area around repository, where the radionuclide biosphere concentrations are expected to be highest.

However, because of the uncertainties in human characteristics around the site at long times, the calculated dose rates are more approximate indicators at long times. Consequently, for long times, safety indicators other than the dose rate are also considered (Becker et al. 2002). Other indicators that have been found to be useful are the radionuclide concentrations in surface waters and the radionuclide fluxes from the geosphere (Becker et al. 2002, Garisto et al. 2004a). Reference values for these indicators are the natural background concentrations or fluxes of radionuclides (Garisto et al. 2004a). A similar approach can be used to evaluate the potential radiological impacts on biota, and the potential chemical impacts of non-radioactive elements in the used fuel (Garisto et al. 2005b).

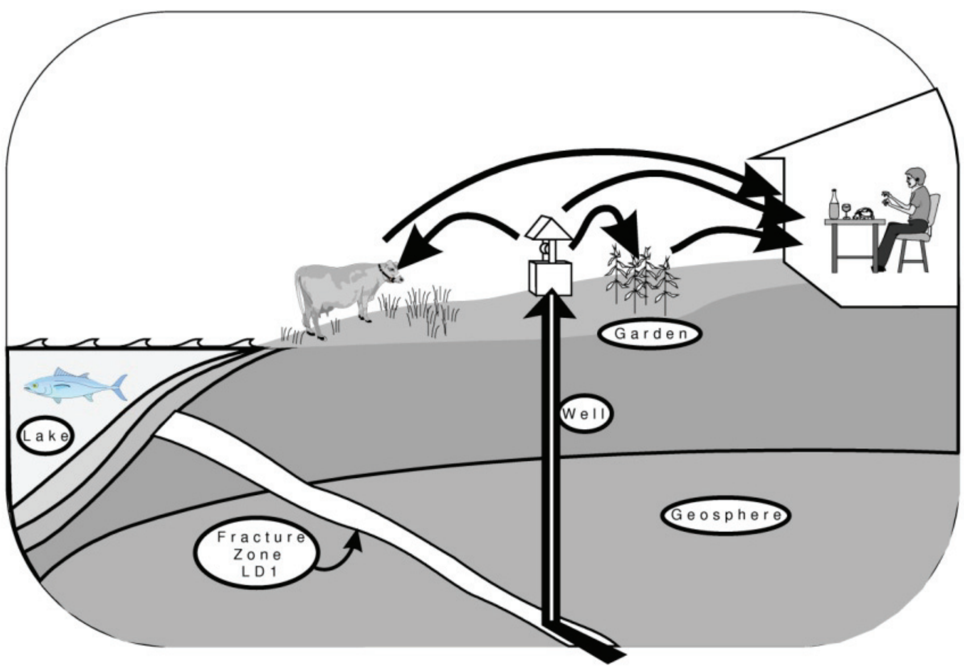


Figure 5.5: Illustration of potentially important exposure pathways. Arrows indicate the possible movement of radionuclides in the biosphere. For example, one pathway leads from the well, to plants irrigated with well water, and then to humans who consume the plants.

6. EVOLUTION OF SITE AND REPOSITORY (SCIENTIFIC UNDERSTANDING)

Any prediction of the long-term behaviour and safety of the deep geological repository for used fuel depends on our understanding of how the repository and its site would change - or remain the same - over the timescales of interest, about 1 million years. This section provides such a description, based on knowledge of the physical processes that are expected to occur. This understanding is based on many years of study, including laboratory studies, underground research studies, and observations of how analogous natural and long-lived engineered systems have evolved. (A review of some of these analogous systems, or 'natural analogues', is given in Section 7.)

6.1 EXPECTED EVOLUTION (BASE SCENARIO)

The following summarizes the main events in the evolution of the repository in broad terms. It is based on the design concept where used fuel is emplaced in the repository in copper-and-steel containers. In the Base Scenario, the system behaves as expected, and no containers fail. There is no release of radioactivity. The scenario considers the occurrence of plausible long-term changes in the geosphere and biosphere due to glaciation.

Most of the processes identified are sufficiently well understood (McMurry et al. 2003). Key points are that the containers and repository are prepared and installed per the design specifications, that the groundwater around the containers maintains the expected chemistry range and low oxygen conditions, and (in the longer term) that the load-bearing capacity of the containers is sufficient for the expected effects of glaciation and earthquakes at repository depth.

<u>0-100 years</u>

The repository is expected to be open and actively monitored for a period of about 100 years. This consists of about 30 years of operation, during which containers are emplaced and rooms are sealed, and 70 years of post-emplacement monitoring, during which access tunnels are kept open. In the operation period, approximately 11,000 containers (containing about 3.6 million used fuel bundles, or 70,000 Mg of uranium) are emplaced in the repository and backfilled with clay-based sealing materials. The initial radioactivity in the repository as a whole is 10^{20} Bq (see Figure 2.3) and its initial thermal output is about 13 MW (see Figure 6.1).

During the first 100 years after emplacement of the containers:

- Radioactivity drops by a factor of ten and the thermal output drops by a factor of four; radionuclides with short half-lives such as tritium (H-3) and cobalt-60 decay to negligible levels.
- Peak temperatures are reached within the repository (values up to about 100°C at the container outer surface and less than 200°C inside the containers).
- The copper container reacts with oxygen from the buffer to form a very thin corrosion layer.
- The buffer material near the containers dries out due to the heat emitted by the containers, forming shrinkage cracks. The initial moisture in the buffer is driven

outwards by this desiccation process and recondenses in a cooler region at some distance from the container, possibly near the rock.

- Mineral salts present in the initial buffer porewater precipitate by evaporation in the region of desiccated clay around the containers.
- Microbes in the buffer material near the containers die or become dormant because of heat, desiccation, and lack of nutrients.
- Thermal expansion and contraction of the rock and concrete combine to create near-field stresses within the low-permeability rock and the concrete bulkhead at the ends of the emplacement rooms, and a limited amount of microcracking occurs.
- In the rock around the repository, groundwater flow and heads are influenced by the presence of the open tunnels and the high-suction clay, which draw water towards the repository. This is countered by the thermal gradient, as described above, which redistributes water away from the containers.

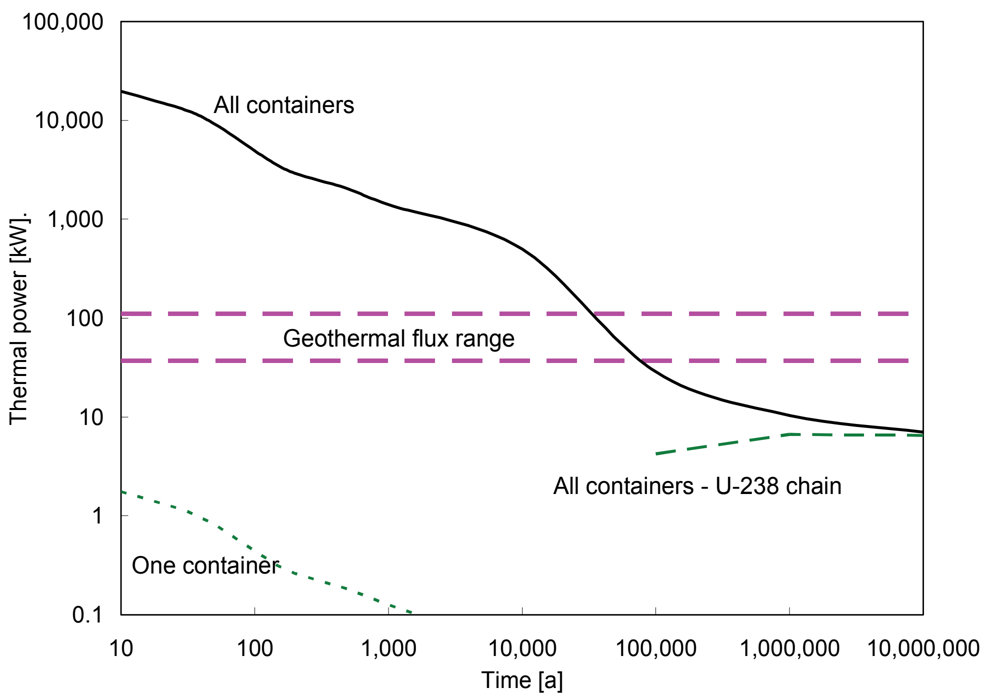


Figure 6.1: Total thermal power of the repository (average 220 MWh/kgU burnup). The power is similar to the natural geothermal flow through the repository area after about 30,000 years. After about 1 million years, the residual power is due to radioactive decay of the decay products of uranium.

<u>100-1000 years</u>

At the beginning of this time period, as part of the closure of the repository, all access shafts and tunnels are backfilled and sealed, and all intrusive monitoring systems and deep boreholes are removed or closed. For several hundred years thereafter, distinct physical and chemical differences (e.g. temperature, porewater composition) will exist between the various components of the repository, and between the repository and the geosphere. Many of the changes that occur within this time frame are driven by these gradients. During this period:

- Radioactivity drops by a factor of 30. Most fission products decay to insignificant levels, including Sr-90 and Cs-137.
- Container thermal power drops to around 120 W per container. Residual heat comes from the decay of the remaining actinides.
- The oxygen initially present in the sealing materials (as trapped air) is consumed and anoxic conditions are re-established. This is typical of conditions in deep rock.
- Groundwater from the geosphere enters the repository. As the clay layers become fully saturated, they start to swell and exert pressure on adjacent materials. The swelling process proceeds slowly and perhaps nonuniformly. Peak swelling loads are less than 5 MPa. The swelling clay fills cracks and voids.
- The mechanical loads from the rock are transmitted through the expanding and swelling clays onto the container. The copper shell is compressed onto the inner steel vessel, which is rigid and maintains its shape.
- By the end of this time, the repository is fully saturated and anaerobic.
- Climate change may have altered the surface waters (e.g. water table, surface aquifer flows), but deep groundwaters are unaffected.

<u>1,000-10,000 years</u>

The next nine thousand years or so is a time in which previously sharp gradients slowly diminish. The repository, with its various components, and the surrounding geosphere gradually achieve equilibrium. During this time, most of the perturbations of the system originate within the repository, and then spread outward.

- Radioactivity drops by a further factor of two.
- The fuel remains intact. Helium from alpha decay increases the gas content inside the fuel elements by 50%, but the additional gas pressure is well within the capacity of the cladding.
- Thermal power drops to 40 W per container. The repository temperature decreases to about 60°C. A thermal plume from the repository extends a few hundred metres in all directions, with temperatures in the rock on the order of 30 to 50°C.
- Corrosion of the container has essentially stopped since the lack of oxygen prevents uniform and localized corrosion.
- The main microbial activity occurring in the repository is due to anaerobic bacteria, including sulphate-reducing bacteria, located mainly at the interfaces with the rock and in the backfill. The buffer remains largely inhospitable because of the high clay density and/or high water salinity, which creates adverse conditions of small pore size and low water activity.

- The porewater in the sealing materials is intermediate in composition between that of the groundwater and the starting porewater in the sealing materials.
- Locally near concrete surfaces, a more alkaline porewater develops in the clay-based sealing materials, resulting in a layer of clay, several cm thick, with a reduced swelling capacity near the contact. However, because the volume of concrete in the repository is limited, no significant alkaline plume develops across the vault as a whole.
- Changes continue to occur in the surface environment. For example, climate change due to global warming could cause more or less precipitation, and higher average temperatures. This would affect the surface waters (lakes and rivers) and shallow groundwaters and also the local ecosystem around the site.

10,000-100,000 years

Over this time frame, quasi-equilibrium conditions will have been reached between the repository and the surroundings. The perturbations to the system will cease to be driven by the repository and instead will be driven by external events, possibly including glaciation (see Figure 6.2).

- The residual radioactivity is dominated by the decay of actinides (mostly the Np-237 chain). The radioactivity of the used fuel is a factor of ten greater than it would be for an equivalent amount of unirradiated natural uranium.
- Thermal output is 3 watts per container.
- The repository temperature returns to near-ambient values (12 to 19^{o}C), depending on site and repository depth).
- The climate may enter a cooling period, with mean surface temperatures over the Canadian Shield dropping to about 0^{o}C. Permafrost develops, disrupting groundwater flow down to a few hundred metres.
- Eventually, if full glaciation occurs, then an ice sheet would form and cross the site.
- The hydrological conditions at the leading and retreating edge of the glacier cause significant perturbations to the regional groundwater movement in the near-surface groundwater flow system. Dense saline waters at depth remain largely unperturbed. In some areas, glacially driven recharge may penetrate deeper, but reactions with minerals and microbes along the flow path of recharging meltwaters consume any dissolved oxygen. Conditions at repository depth remain reducing.
- At its maximum development, the glacial ice sheet could be 2 to 3 kilometres thick above the repository, potentially increasing the hydrostatic pressure at repository depth by a maximum of up to 20 to 30 MPa (and potentially much less, depending on the rock properties, Chan and Stanchell 2004). This value is within the design tolerance of the containers.

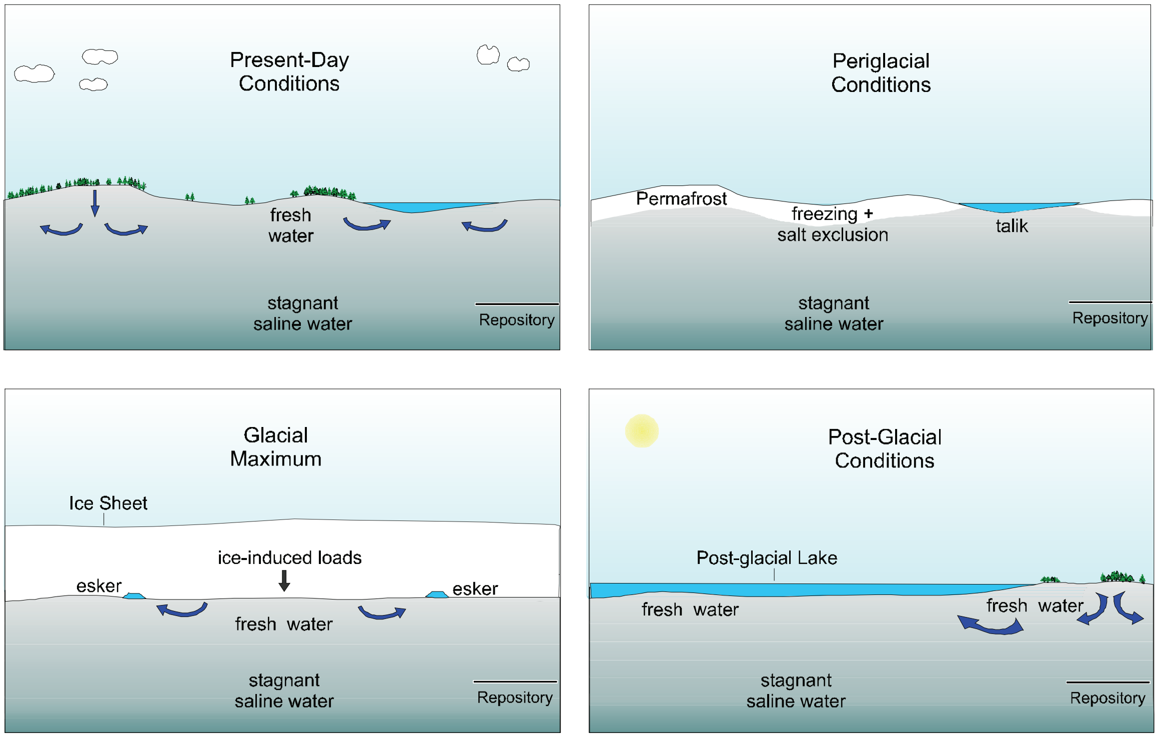


Figure 6.2: Some potential effects of glaciation on groundwater movement. Processes shown are illustrative, and features are not drawn to scale.

<u>100,000-1,000,000 years</u>

Over this period, conditions affecting the repository continue to be driven by external processes. The most important events will be glaciation cycles, which are likely to occur over this time period. These are likely to repeat on a period of roughly every 120,000 years.

- Virtually all the reactor-generated radioactivity decays over this timeframe. At the end of this period, most of the radioactivity in the used fuel comes from its natural uranium content.
- Most of the fuel elements are still more or less intact. In some, the Zircaloy cladding cracks due to creep, delayed hydride cracking, or internal gas pressurization.
- During glaciation, broad regions of the Canadian Shield flex vertically by as much as a kilometre in response to the weight of the ice sheets. Brief but intense periods of post-glacial faulting occur in regions that are tectonically weak. Existing fracture zones may be reactivated in these locations although there is little change in terms of new fracture development.
- The glaciers again perturb the regional groundwater flow, but the effect is more significant in the shallower fracture system than at depth.
- The advancing and retreating ice sheets both erode and deposit rock and till. Since the site has already experienced multiple glaciations in the past one million years, the amount of additional bedrock erosion is expected to be meters to tens of meters.
- The main effect of the glaciers at depth is repeated variation in the hydraulic pressures and mechanical stresses. Isolated by low-permeability rock, saline waters, and clay

sealing materials, the containers experience the glaciation cycles predominantly as changes in hydraulic and mechanical loads. The containers are designed for these loads and so are largely unaffected.

- The chemistry of the porewater within the sealing materials slowly changes to resemble that of the groundwater.
- Along with the porewater chemistry change, the montmorillonite component of the bentonite has lost Na and gained Ca, Mg, and Fe but has still retained its swelling capacity. Due to the low temperatures and low concentration of K^+ ions, very little of the montmorillonite has converted to illite.
- Microbial activity is limited in terms of mobility by the impermeable dense buffer around the containers on one side and the sparsely-fractured rock on the other, and it is limited metabolically by the low rate of anaerobic reactions at the ambient temperatures and by the requirement for nutrients to diffuse through the clay-based sealing materials.

6.2 EVENTS OCCURRING FOR DEFECTIVE CONTAINERS

The previous section described the evolution of the repository without containers failing, i.e., all containers remain intact for millions of years. This is a plausible scenario for the reasons given above. However, some containers may fail due to, for example, the presence of undetected manufacturing flaws in the copper outer vessel. The evolution of these failed containers would be different from the description given above. It is summarized below; a more detailed discussed is given by McMurry et al (2004).

Only the additional events that may occur in the evolution of these failed containers are summarized here, since most of the events occurring for the intact containers (e.g., radiation-related changes, thermal changes, etc.) also occur in the case of the defective containers. For this discussion, it is assumed that some containers are emplaced in the repository with small undetected defects that penetrate the copper shell of the containers. The inner steel container is thus exposed to evolving conditions in the repository.

0-100 years

Over this period the repository is unsaturated. Atmospheric corrosion of the steel next to the defect may occur but only to a very limited extent because the relative humidity near the copper container is low and the oxygen is consumed by other processes.

100-1000 years

During this period the repository becomes saturated. Saturation causes the following to occur at the defective container:

- As the repository saturates, water enters the defect and contacts the steel vessel. Anaerobic corrosion of the steel vessel begins, generating iron oxides and hydrogen gas. The most likely iron corrosion product is magnetite.
- A small amount of water leaks into the interior of the steel vessel and the inside of the steel vessel also starts to corrode.

1,000-100,000 years

Corrosion of the steel vessel continues and the hydrogen gas pressure increases near the defective container. The timing of events depends on the behaviour of the hydrogen.

- Iron corrosion products build up between the steel and copper vessels and exert stresses on the copper and steel vessels (since the corrosion products occupy more volume than the iron metal from which they were formed).
- The stresses caused by the build up of the corrosion products have no effect on the steel vessel (because of its thickness and strength) but the copper shell deforms and the initial defect enlarges.
- Rupture of the copper shell allows more water to contact the steel vessel, accelerating the rate of degradation of the container. The steel vessel fills with water.
- The hydrogen gas generated by steel corrosion forms a bubble or blanket that inhibits further water contact with the container. If hydrogen generation is fast enough, the gas will reach sufficient pressure to create a channel through the buffer and escape into the backfill and geosphere. The pathway through the buffer re-seals after the gas passes.
- The water in the steel vessel contacts the fuel bundles. Local failure or corrosion of the Zircaloy cladding allows water to contact the used fuel in places. The more soluble radionuclides in the fuel/cladding gap and grain boundaries are released into the water inside the steel vessel, typically a few percent.
- Some of the used fuel dissolves, albeit slowly, releasing other radionuclides into the water. The presence of hydrogen gas from corrosion of the steel container sustains conditions that significantly decrease the rate of fuel dissolution (Shoesmith 2008).
- Most radionuclides have decayed, or are trapped within the used fuel. Dissolved radionuclides diffuse out of the container and into the buffer surrounding the container.

100,000-1,000,000 years

The steel vessel continues to corrode until all of the steel is consumed. Corrosion of the copper vessel continues but only a small fraction of the copper corrodes over this time period.

- The steel corrosion eventually ends. Hydrogen gas from the steel corrosion leaks away. Any initial hydrogen gas bubble dissolves, and allows full saturation of the container.
- At some point, the steel vessel is sufficiently weakened by corrosion that it is no longer load bearing and collapses. Any remaining intact fuel bundles are damaged and exposed to water.
- The fuel continues to dissolve slowly. Most of the UO_2 remains undissolved and in chemical equilibrium with the surrounding water.
- Some radionuclides migrate out of the container, through the buffer and backfill materials, and into the nearby rock. Most radionuclides decay within or near the repository. A small amount of the more mobile, soluble and long-lived species (such as I-129) may move through the geosphere and enter the biosphere. However, the impacts of radionuclide releases to the biosphere are expected to be well below regulatory limits, as indicated in Section 8.

7. NATURAL ANALOGUES

The study of natural analogues constitutes one of the multiple lines of reasoning in the safety case for a geological repository, providing evidence supporting predictions of very long term behaviour; in particular, natural analogues can extend the understanding over longer time periods than can be realised in the laboratory or field studies (McKee and Lush 2004).

For example, the size of the repository and the amount of uranium it would contain are comparable to several uranium ore bodies in north-central Canada. An illustration of one of the best-known of these ore bodies, Cigar Lake, is shown in Figure 7.1. These natural deposits of uranium oxide have been stable for billions of years. At Cigar Lake, the containment of the uranium has been so effective that there was no chemical or radiological indication at the earth's surface of the existence of the ore deposit (Cramer and Smellie 1994).

Similarly, many ore deposits of metallic copper and sedimentary deposits of bentonite are known that range in age from millions to hundreds of millions of years. These natural analogues provide evidence that the materials proposed for use in a deep repository can be stable over very long periods of time. This is important because the ultimate fate of the repository and the materials it contains will be largely indistinguishable from that of these natural analogues.

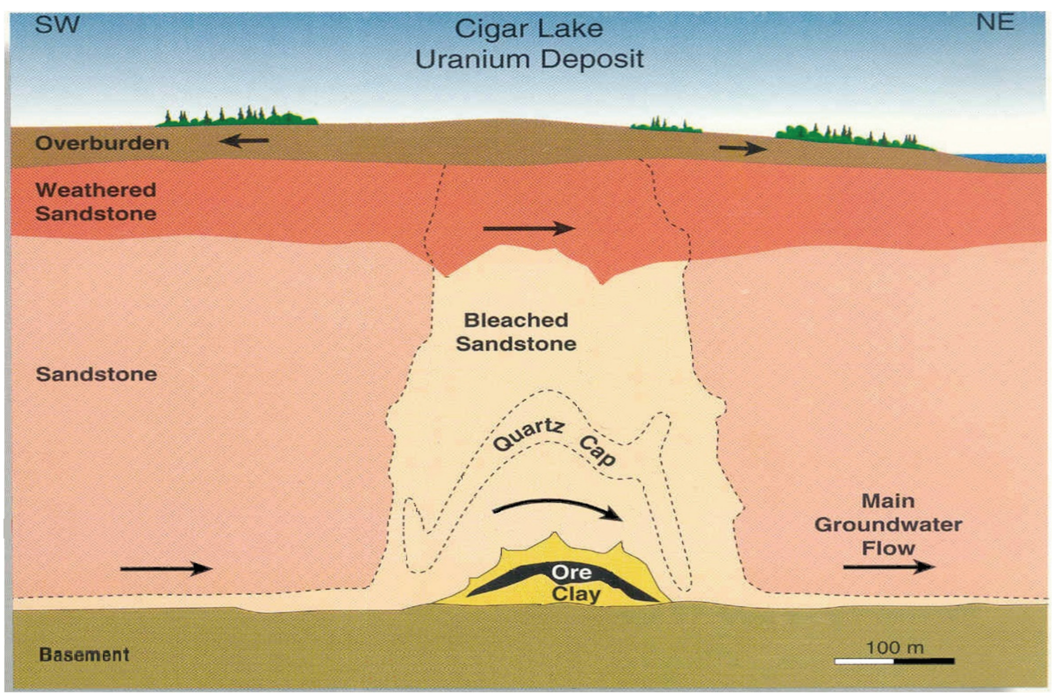


Figure 7.1: Cross-section of the Cigar Lake uranium ore body in Saskatchewan (adapted from Cramer and Smellie 1994). The uranium ore, surrounded by a clay layer at 430 m depth, has remained intact and isolated from the surface environment for over 1.3 billion years. The ore (and bleached sandstone) were formed as a hot groundwater plume moved upwards through fractures in the rock.

Information for a number of natural analogues studies has been summarized in a study sponsored by the Spanish regulator CSN (2004). Table 7.1 illustrates a number of these and other studies supporting the safety of the repository.

Table 7.1: Selected natural analogue studies

NATURAL ANALOGUE	PHENOMONA/PROCESSES
Uranium dioxide (fuel) behaviour analogues; overall system behaviour	
Cigar Lake, Canada	Used fuel dissolution, stability under reducing conditions, stability of overall system, solubility limits.
Oklo, Gabon	Radionuclide release, radiolytic dissolution, groundwater mixing, hydrogeochemical modelling.
Pocos de Caldas, Brazil	Boundary conditions on redox front, redox front propagation, colloid behaviour, microbe behaviour.
Alligator Rivers, Australia (oxidizing conditions)	Matrix diffusion depth.
Copper and copper-iron behaviour analogues	
Littleham Cove, England (SKB 2000)	Stability of copper in compacted clay.
Coppergate helmet, England (SKB website)	Absence of galvanic corrosion
Kronan Cannon, Sweden (oxidizing conditions)	Copper corrosion
Inchtuthill Nails, Scotland	Iron corrosion
Behaviour and effects of sealing materials - clays	
Avonlea Bentonite Deposit, Saskatchewan (Cramer et al. 1999)	Chemical, isotopic and mineralogical stability of bentonite over 75 million years
Kinnekulle, Sweden	Bentonite performance, siliceous cementation, ilitisation
Dunnarobba, Italy	Clay effect on microbial activity.
Behaviour and effects of sealing materials – cement and concrete	
Hadrian's Wall, Great Britain	Cement durability.
Maqarin, Jordan	Effect of hyperalkaline conditions around cement/concrete seals

8. CASE STUDIES (EVALUATION OF SAFETY)

8.1 INTRODUCTION

Three major postclosure safety assessments for a deep geological repository for used CANDU fuel, located at hypothetical sites on the Canadian Shield, have been carried out over the past 15 years (AECL 1994, Goodwin et al. 1996, Gierszewski et al. 2004a). Similar studies have also been published in other countries, notably Sweden (SKB 2006), France (Andra 2005), Finland (Posiva 2007), Japan (JNC 2000) and Switzerland (Nagra 2002). Although the geologic environment and details of the repository concept varied from study to study, all studies found that disposal of used nuclear fuel in a deep geological repository was a safe viable option for protecting humans and the environment from the long-term hazards of used fuel. A brief summary of the results of the Canadian postclosure safety assessments is provided to illustrate this point.

A deep geological repository is expected to be capable of isolating and containing the used fuel such that almost all of the radioactivity would decay within or near the repository. Since 98% of the used fuel is natural uranium, the used fuel content (and radioactivity) in the repository will eventually become similar to that of uranium ore bodies. This occurs on times scales of about one million years. CNSC guidance given in P-290 (CNSC 2004) and in G-320 (CNSC 2006) indicates that the period over which the future impacts of radioactive waste are assessed should include the period over which the maximum impacts are expected. Therefore, the impacts of a deep geological repository are usually assessed over a time period of one million years. Although the calculated impacts become increasingly uncertain at long times, the results are useful because they illustrate that the potential impact remains small.

For a given repository system, the key step in the safety assessment is to define the scenarios to be considered (IAEA 2004). Each scenario is a hypothetical sequence of processes and events; a set of such scenarios is defined for the purpose of illustrating the range of future behaviours and states of the repository system.

For the three major Canadian safety assessments, a set of important scenarios was selected based on the features, events and processes applicable to the assumed (hypothetical) repository design and site, and based on scenarios identified as important in international studies. The two main scenarios identified for quantitative analysis were the defective container or groundwater transport scenario, and the inadvertent human intrusion scenario (Gierszewski et al. 2004a). A safety assessment of a real candidate repository would include these and likely other scenarios.

8.2 EIS CASE STUDY

The first major Canadian case study, the Environmental Impact Statement (EIS) case study (AECL 1994; Goodwin et al. 1994), considered a repository design which included titanium alloy containers with 72-fuel-bundle capacity placed vertically into boreholes along the vault rooms. The EIS case study assumed the repository was located in sparsely-fractured granitic rock with very low permeability, such as found at the Whiteshell Research Area (Davison et al. 1994). The titanium containers were assumed to fail after about 6,000 years.

A safety assessment of the groundwater transport scenarios was undertaken. Simulations were carried out to 100,000 years after repository closure, in line with Atomic Energy Control Board (AECB) regulatory requirements at the time (Goodwin et al. 1994, AECB 1987). The study results showed that the repository system would meet the requirements established by the AECB and indicated that implementation of the deep repository concept could provide safe disposal of nuclear fuel waste. Potential doses were estimated to a farming household living above the repository in the distant future. The calculated average dose rates to these people are shown in Figure 8.1. Iodine-129 was identified as the most important radionuclide.

The EIS case study also considered the (inadvertent) human intrusion scenario, in which a borehole drilled at the repository site breaches a container and used fuel debris is brought to the surface in the form of drilling slurry and a core sample. The effects on drill crew and on future residents living at the site were calculated assuming the material was not recognized as hazardous and was casually handled and discarded. The calculated doses were high, especially if the intrusion occurred soon after repository closure. However, the radiological risks associated with the human intrusion scenario were low because the probability of inadvertent human intrusion was very low (Goodwin et al. 1994).

8.3 SECOND CASE STUDY

The Second Case Study (SCS) considered long-lived copper containers placed horizontally within vault rooms, and assumed the repository was located in granitic rock with substantially higher permeability than in the EIS case study (Goodwin et al. 1996). For the SCS, the defective container or groundwater transport scenario was assessed, in which a few containers were assumed to be emplaced in the repository with initial undetected holes. The results indicated that that the repository system would meet the radiological risk limit for humans (AECB 1987) and would have no impacts of concern on the biosphere. The calculated average total dose rates to the critical group for the SCS are shown in Figure 8.1. Again, the radionuclide I-129 was the largest contributor to the peak total dose rate.

8.4 THIRD CASE STUDY

In contrast to the two previous Canadian assessments, the Third Case Study considered the larger copper container (324-bundle capacity) described in Section 5.3, placed horizontally within the vault rooms. It assumed the repository is located in granitic rock that is characterized by an intermediate permeability and a geostatistically-generated discrete fracture network (Gierszewski et al. 2004b). The Third Case Study also addressed several methodology issues raised by reviewers of the EIS safety assessment (e.g., SRG 1995). These included, for example, the use of regional groundwater modelling to help select the repository location, the coupling of the safety assessment models to the site characterization models, the three-dimensional (3-D) modelling of the vault and geosphere, and the explicit analysis of various "what if" scenarios and of high-dose results (Gierszewski et al. 2004a, Garisto et al. 2004a).

For the reference defective container scenario, in which two containers in the repository were assumed to have initial defects, the average dose rates from the TCS safety assessment are shown in Figure 8.1. The radionuclide I-129 was again the largest contributor to the peak total dose rate.

In a subsequent extension of the Third Case Study, the Horizontal Borehole Concept (TCS/HBC) was assessed (Garisto et al. 2005a). The purpose of this study was to investigate the influence of the container emplacement concept on the postclosure safety. The only significant difference between the TCS/HBC and the TCS was the container emplacement concept – the in-room emplacement concept was used in the TCS and the horizontal borehole emplacement concept was used in the TCS/HBC (see Figure 5.3). It was found that although the container emplacement method had a major impact on the design and size of the repository, the calculated postclosure safety impacts of the repository were not much affected by the emplacement method, for the selected site and geosphere properties. The average dose rates from the TCS/HBC probabilistic safety assessment of the defective container scenario are similar to the TCS results shown in Figure 8.1.

For the TCS/HBC study, potential chemical toxicity impacts on humans were also evaluated (Garisto et al. 2005a,b). Specifically, the potential significance of chemical element releases into the environment from the repository was determined by considering the chemical elements present in used fuel and the container materials. In the analysis, the margin of safety was defined in terms of the ratio of the calculated element concentration in the biosphere and the corresponding (human) safety criterion. Generally, the well water had the highest concentration relative to the corresponding criterion. However, peak concentrations were all well below criteria, for several plausible scenarios, indicating that the engineered and natural barriers of the assumed site and repository system provided good protection against potential chemical hazards arising from the presence of the repository.

The consequences of the inadvertent Human Intrusion Scenario were also evaluated in the TCS (Gierszewski et al. 2004a). As in the EIS case study, the conclusion from this analysis was that inadvertent human intrusion could result in appreciable doses, i.e., much greater than the regulatory limit of 1 mSv/a, to those directly involved in the intrusion (e.g., the drill crew). For people living near the repository site shortly after the intrusion, calculated doses would be less than 20 mSv/a if the intrusion occurred 300 years or more after repository closure and the borehole debris was discarded on the site. However, it should be emphasized that the design of the repository is such that the likelihood of such an intrusion and exposure is very small. Consistent with ICRP 81 (ICRP 2000), the repository design minimizes the possibility of inadvertent intrusion by its depth (i.e., much deeper than the range of interest for a water supply well), by selection of a site with no mineral or other known economic potential, and by the use of records and markers to preserve institutional memory for as long as practical.

In summary, for the defective container or groundwater transport scenario, the postclosure safety of a deep geological repository for used CANDU fuel has been illustrated for three plausible combinations of engineering design and Canadian Shield sites (Goodwin et al. 1994, 1996, Gierszewski et al. 2004a). The calculated dose rates to the critical group (a self-sufficient farmer living near the site of the repository) are compared in Figure 8.1 to the average Canadian background radiation dose rate of 1.8 mSv/a (Grasty and LaMarre 2004) and the dose rate constraint of 0.3 mSv/a recommended by ICRP 81 (ICRP 2000) for disposal of long-lived solid radioactive waste. The calculated average dose rates for all three assessments are well below the background and ICRP 81 dose rates.

The results of these three safety assessments provide increased confidence, from a technical perspective, that a suitable combination of design and site can be found that would permit the safe long-term management of used CANDU fuel in a deep geological repository.

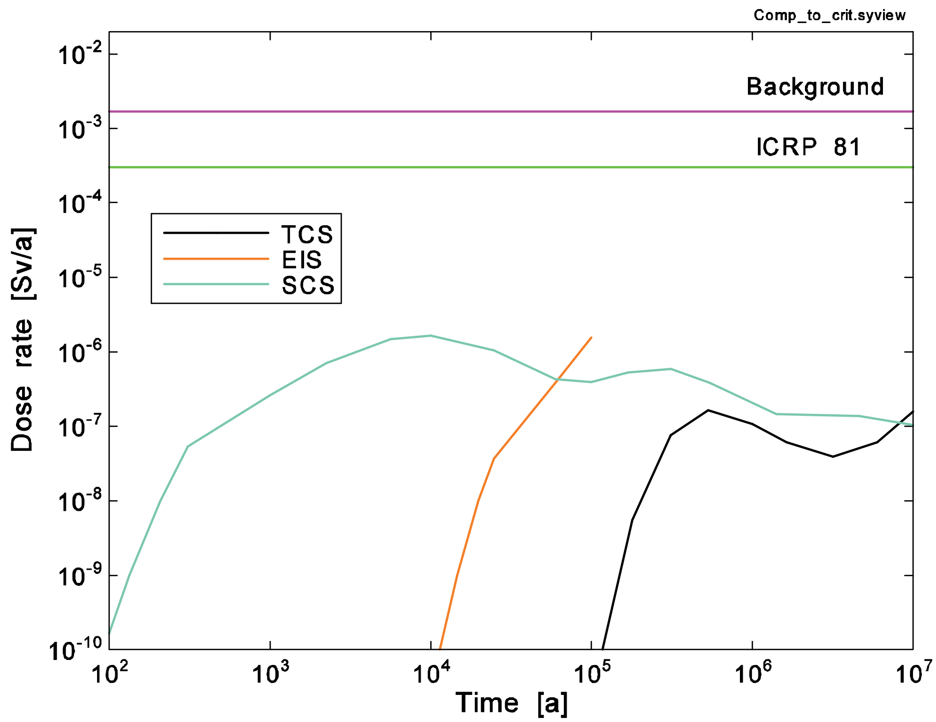


Figure 8.1: Comparison of the calculated average dose rates to a self-sufficient farmer living at the repository site from the EIS, the Second Case Study (SCS) and Third Case Study (TCS) safety assessments. Note that the maximum simulation time in the EIS study was 10^5 years.

9. CONCLUSIONS

This report outlines the body of scientific and technical work relevant to the safety of a deep geological repository for used fuel that has been carried out in Canada and internationally. These results provide confidence that a suitable combination of design and site can be found for long-term management of used fuel in Canada.

Key reasons supporting the safety of the deep geological repository include:

- the robustness of the multiple barrier system,
- the stability of the geologic setting,
- the scientific tools and understanding that will be applied to test the suitability of any site,
- lessons available from international experience and natural analogues,
- the low likelihood of accidental human intrusion,
- the low specific impacts estimated in safety assessment case studies.

These elements can apply to a variety of sites and potential geologic settings, including both the Canadian Shield and sedimentary rock formations; and they encompass several engineered barrier design concepts.

The safety of any proposed site would be tested through a rigorous regulatory system and international peer review of the safety case. The decision-making and implementation processes would involve many decades. The associated uncertainties can be addressed within the flexibility of NWMO's Adaptive Phased Management system, including aspects such as monitoring and retrievability. The program, evolving over a long period of time, would have many opportunities for improvements to address new concerns, improve understanding and increase performance.

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