OPG's DEEP GEOLOGIC REPOSITORY FOR LOW AND INTERMEDIATE LEVEL WASTE – SAFETY ASSESSMENT

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ABSTRACT

Ontario Power Generation (OPG) is proposing to build a Deep Geologic Repository (DGR) for Low and Intermediate Level Waste near the existing Western Waste Management Facility (WWMF) at the Bruce nuclear site in the Municipality of Kincardine, Ontario. The safety of the proposed DGR was assessed under both preclosure and postclosure conditions.

Under normal operation, there will be some release of tritium and carbon-14 as off-gassing from the waste packages, as currently occurs at WWMF, until underground rooms are closed off. The maximum dose to the public due to normal DGR operations is small, similar to the impacts that would be expected from WWMF for similar amounts of low and intermediate level waste.

Accidents during operations were assessed for potential release of radionuclides or non-radiological elements in the wastes. Although unlikely, credible accidents include fires involving packages, package breach accidents, failure of the ventilation system, and inadequate shielding. The assessment results indicate that effects on a member of the public at the Bruce nuclear site boundary are well below criteria. Overall, both WWMF experience as well as the DGR-specific analyses, indicate that the wastes can be handled and emplaced without undue risk to workers or the general public.

The postclosure safety was quantitatively assessed through considering a range of potential future scenarios. Specifically, the assessment considered the expected evolution of the DGR system and the site with time (i.e., the Normal Evolution Scenario) and the potential impacts of unlikely events leading to penetration of barriers and loss of containment (i.e., Disruptive Scenarios or "What If" Scenarios). The safety assessment was conducted in a systematic manner, consistent with Canadian Nuclear Safety Commission Regulatory Guidance G-320 and with international best practice.

The postclosure assessment calculations for the Normal Evolution Scenario indicate that the DGR system provides effective containment of the emplaced waste. Most radionuclides decay within the repository or the deep geosphere. The amount of contaminants eventually reaching the surface is very small, such that calculated impacts are orders of magnitude less than the public and environmental criteria. The isolation afforded by the location and design of the DGR

limits the disruptive events potentially able to bypass the natural barriers to a small number of very unlikely situations. Even if these events were to occur, the analysis shows that the contaminants in the waste would continue to be contained effectively by the DGR system such that the risk criterion is met.

1. INTRODUCTION

Ontario Power Generation (OPG) has proposed a deep geologic repository (DGR) for the long-term management of low and intermediate level waste (L&ILW). The DGR Project involves the construction, operation and eventual decommissioning of a repository situated nominally at 680 metres below the Bruce nuclear site in an argillaceous limestone formation. More detailed information on the DGR Project can be found in companion papers [1-6].

A quantitative assessment of the facility safety was conducted as part of an iterative process in conjunction with site characterization, waste characterization and facility design. The safety of the proposed DGR was assessed under both preclosure (operations) and postclosure (long-term) conditions. The results of this safety assessment are summarized in this paper.

2. PRECLOSURE (OPERATIONAL) SAFETY

2.1 WWMF Experience

The Western Waste Management Facility (WWMF) provides useful context for the DGR, since many of the waste packages to be emplaced within the DGR are currently handled, transferred and stored in the WWMF. WWMF operation over the past 40 years has demonstrated that these waste packages can be safely handled and stored. Worker and public dose rates have been consistently below regulatory limits. The WWMF routinely operates contamination free.

2.2 DGR Normal Operations Assessment

There will be no conditioning or processing of the wastes at the DGR. Waste packages will be received and then emplaced underground. During normal operations, there will be some release of tritium and carbon-14 as off-gassing from the waste packages, as currently occurs at WWMF, until underground rooms are closed off. The maximum dose to the public due to normal DGR operations was estimated to be around 1 μSv/a, similar to the impacts that would be expected from WWMF for similar amounts of LLW and ILW packages.

External (gamma) dose calculations were carried out. The estimated dose rate is well below the non-Nuclear Energy Worker compliance dose limit of 0.5 μSv/hr at the DGR fence line, and well below the site boundary dose target for members of the public of 10 μSv/a (and in both cases much less than the regulatory limit).

The external dose calculations for workers show that high dose rates are possible in specific locations, especially near the face of an array of higher dose rate LLW or ILW packages in emplacement rooms. Generally, workers would not need to spend much time in these locations, nor are most packages at high dose rates. However, it will be planned to monitor the radiation fields in these locations, and if necessary, distribute the higher dose packages, use shielded forklifts and/or use greater stand-off distances to limit the worker exposure. A preliminary ALARA assessment identified the main contributors to worker dose from the conceptual design information; this will be considered further during the detailed design [7].

An assessment of radon risks during construction and operation was completed; levels of radon are expected to be low and will be confirmed during construction [8].

2.3 DGR Accident Assessment

For the accident assessment, a variety of bounding accidents were considered, including the risk of surface flooding of the site [9]. The accidents were quantitatively assessed for several waste categories that represent the range of wastes to be handled. The assessment focused on the potentially hazardous material within the wastes.

The results of the accident assessment are that:

- Major DGR accidents are unlikely to occur;
- Credible DGR accidents do not exceed radiological dose criteria for workers or public; and
- In most cases, the public safety criteria are met by large margins.

The following accident scenarios were identified as having the highest impacts. These are noted here to provide guidance in development of the detailed design and the operating procedures.

- Breach accidents involving ash containers (worker- hazardous elements in the dust);
- Fire accidents involving box compacted and non-processible wastes (worker radiological and hazardous elements in smoke); and
- Fire accidents involving multiple packages in an emplacement room (public- hazardous elements in smoke).

The conventional safety hazards of these accidents are also important. A preliminary assessment of these hazards and mitigations was considered in the Preliminary Conventional Safety Assessment report [10], and will be considered further as part of the detailed design.

Overall, both WWMF experience as well as the DGR analyses summarized here indicates that the wastes can be handled and emplaced without undue risk to workers or the general public.

3. POSTCLOSURE (LONG-TERM) SAFETY

3.1 Safety Case

Canadian Nuclear Safety Commission (CNSC) Regulatory Guide G-320 [11] states "*Demonstrating long term safety consists of providing reasonable assurance that waste management will be conducted in a manner that protects human health and the environment. This is achieved through the development of a safety case, which includes a safety assessment complemented by various additional arguments.*"

The safety case is presented in the Preliminary Safety Report [12]. The postclosure safety assessment is presented in more detail in [13] and supporting technical reports.

3.2 Safety Strategy

Over 80% of the packaged waste volume is low-level waste. This decays within a few hundred years. However, some of the intermediate-level waste is hazardous for very long times. The safety strategy is to provide long-term isolation and containment through use of multiple barriers and passive systems, including in particular a stable geosphere.

The deep geologic repository provides the high-level safety functions of isolation and containment of the L&ILW. The site and design support these safety functions through a variety of safety relevant features or attributes, as summarized below.

Geology	- Multiple low-permeability bedrock formations enclose the DGR. - Predictable, horizontal geology with large lateral extent. - Stable deep diffusion-dominated groundwater system, even under glaciation. - Seismically quiet. - Geomechanically stable rock. - Low natural resource potential. - Low rock permeability limits the rate of repository resaturation. - Ordovician underpressures provide a convergent flow system. - Guelph and Salina A1 upper carbonate permeable formations can divert gas or solutes migrating upwards from repository via geosphere or shaft. - Chemical conditions limit contaminant mobility.
Layout	- DGR is located at 680 m depth - Shafts are placed in an islanded arrangement separate from waste panels. - Waste emplacement rooms are not backfilled, providing space for gas generated by the wastes. - Waste emplacement rooms are aligned with rock principal stress and have thick room pillars for mechanical robustness.
Shaft	- Concrete monolith at base of shafts provides long-term structural support of the shaft seals; it also helps delay water and gas flow. - The bentonite/sand mix is the primary shaft seal; it is a durable low-permeable material that can swell under DGR saline conditions. - The asphalt mix is a secondary shaft seal that provides an independent self-sealing barrier to transport. - The concrete bulkheads at the Guelph and Salina A1 levels isolate the bentonite from any flow in these units, and provide structural support for the overlying seals. - The shaft concrete liner and any highly damaged rock zone around the shafts are removed before the shaft seals are installed. - Site characterization boreholes are sealed when no longer needed.
Waste and packaging	- 80% of the waste package volume and 90% of the waste volume is LLW; its radioactivity decays within a few hundred years. - The majority of the very long-lived radioactivity is activated Nb-94 and Zr-93 within the corrosion-resistant Zircaloy retube components. - The most important radionuclides at closure are tritium and C-14 due to their early release as gas. Tritium decays within a few hundred years; C-14 decays in about 60,000 years, before the onset of glaciation at the site.

3.3 Safety Assessment Approach

Key components of the safety assessment context are summarized below.

Regulatory Requirements and Guidance:	Nuclear Safety and Control Act and associated regulations Canadian Nuclear Safety Commission regulatory guidance document G-320, "Assessing the Long Term Safety of Radioactive Waste Management" Canadian Environmental Assessment Agency and Canadian Nuclear Safety Commission guidelines for the preparation of the EIS for the DGR
Endpoints:	Radiation dose to humans Environmental concentrations of radionuclides and non-radioactive elements and chemical species Contaminant concentrations and fluxes in various spatial domains
Treatment of Uncertainties:	Consideration of a range of scenarios, from expected (likely) to "what if" (very unlikely) scenarios Use of conservatism in scenarios, models and data Use of a stylized approach for the representation of future human actions and biosphere evolution Use of a range of deterministic calculation cases to explore uncertainties in models and data; limited probabilistic assessment for a reference case condition
Timeframe:	1 million years baseline Encompassing the period over which most radioactivity in the waste has decayed and the maximum risk is expected to occur Some analyses extended beyond 1 million years to estimate the maximum impacts from some scenarios

3.4 System Description

A high-level description of the DGR system considered in the postclosure safety assessment is provided below.

Waste:	The total emplaced volume of low and intermediate level waste (L&ILW) is approximately 200,000 m^3, comprised of operational and refurbishment wastes from Ontario Power Generation (OPG) owned or operated nuclear reactors. The wastes are emplaced in a range of steel and concrete waste containers and overpacks. The total activity at closure is about 16,000 TBq. Key radionuclides in terms of total activity include H-3, C-14, Ni-63, Nb-94 and Zr-93. The waste generates about 2 kW of decay heat at time of closure.
Repository:	The repository is at a depth of around 680 m and comprises two shafts, a shaft and services area, access and return ventilation tunnels, and 31 waste emplacement rooms in two panels. The repository is not backfilled. At closure, a concrete monolith is emplaced at the base of the shafts and then the shafts are backfilled with a sequence of materials (bentonite/sand, asphalt, concrete and engineered fill).

Geological Setting:	The DGR is located in low permeability Ordovician argillaceous limestones, with 230 m of shales above and 160 m of limestones below. Significant underpressures exist in the Ordovician rocks, whereas overpressures exist in the Cambrian formation below the DGR. Above the Ordovician shales, there are 325 m of Silurian shales, dolostones and evaporites. The porewater in the Silurian and Ordovician sediments is highly saline (total dissolved solids of 150 to 350 g/L) and reducing with pH buffered by carbonate minerals. Above the Silurian sediments, there are 105 m of Devonian dolostones, the upper portions of which contain fresh, oxidizing groundwater that discharges to Lake Huron. Site investigations at the Bruce nuclear site have not found commercially viable mineral or hydrocarbon resources.
Surface Environment:	The present-day topography is relatively flat and includes streams, a wetland, and, at a distance of approximately 1 km, Lake Huron. The annual average temperature is about 8°C with an average precipitation rate of around 1.1 m/a. The region around the Bruce nuclear site is mainly used for agriculture, recreation and some residential development. Groundwater is used for municipal and domestic water in this region, while the lake provides water for larger communities. The lake is used for recreation and commercial fishing. A significant aboriginal traditional activity in the region is fishing in Lake Huron.

3.5 Scenarios

The future evolution of the DGR system was assessed through a Normal Evolution Scenario and four Disruptive Scenarios. The Normal Evolution Scenario describes the expected long-term evolution of the repository and site following closure, and the Disruptive Scenarios consider events that could lead to possible penetration of barriers and abnormal degradation and loss of containment. These Disruptive Scenarios are unlikely or "what if" cases that test the robustness of the DGR system. The uncertainties associated with the future evolution of the DGR system are assessed in part through these scenarios, and in part through sensitivity cases considered within each scenario. A brief description of each scenario is given below.

Normal Evolution Scenario: After closure, the repository will quickly become anaerobic. The repository will start to fill slowly with water seeping in from the shafts and the surrounding rocks. The slow anaerobic degradation of the waste packages will result in the generation of gases, especially CH_4. The assessment assumed that the waste materials and metal packages fully degrade or corrode, maximizing the generation of gases.

The repository will remain mostly unsaturated due to the low rock permeability and the gas pressure. This pressure will eventually equilibrate around the host rock steady-state hydraulic pressure of 7-9 MPa, similar to natural gas pressures within other sedimentary rocks, and much less than the 17 MPa lithostatic pressure.

As the wastes degrade, C-14 and tritium will be released mostly as gas. This was modelled as occurring relatively quickly, with limited losses by mineral or isotope exchange reactions with surrounding carbonate rock. Other contaminants will be released on contact with water, with no solubility limits credited.

The region around the Bruce nuclear site is tectonically stable. Large earthquakes are very unlikely. The host rock is strong, and small earthquakes will have little effect. The primary effect of large earthquakes will be to cause rockfall in the repository, which will continue until the rooms and tunnels have filled (a redistribution of the initial repository space, with the same total porosity volume). In the safety assessment, rockfall was assumed to occur quickly after closure and to cause failure of all packaging.

Over timescales of many thousands of years some contaminants may slowly migrate via the sealed shafts and geosphere into the shallow geosphere, and then into the surface environment. For dose assessment, it was assumed that a self-sufficient farming family is living directly on the repository site in the future, with a shallow groundwater well located downstream from the shafts to maximize uptake.

Over long timescales glaciation could return, with ice-sheets covering the site with a periodicity of around 100,000 to 120,000 years. This would result in significant changes in the surface environment and shallow geosphere. However, the deep geosphere would remain largely stagnant, as during past glaciations as evidenced by the groundwaters at repository depth. Glaciation would also not occur until after most of the C-14 had decayed, and any residual radioactivity was limited to groundwater transport.

On these timescales, the total residual radioactivity of the waste will have decayed to less than the low natural activity of the rock directly overlying the repository.

Disruptive ("what if") Scenarios:

Human Intrusion: This scenario considers the impact of inadvertent human intrusion into the repository via an exploration borehole at some time in the future. Humans are exposed to contaminated gas and drill core. It was assumed that contaminated drill mud is not contained and is spilled around the drill site. If the exploration borehole is further extended 150 m into the pressurized Cambrian formation and is not properly sealed, then contaminated water could be released to the shallow geosphere resulting in the subsequent exposure of people using the shallow groundwater.

Severe Shaft Seal Failure: This scenario considers the consequences of rapid degradation across the entire 500-m of shaft seals, and the increased degradation of the repository/shaft excavation damaged zones (EDZs).

Poorly Sealed Borehole: This scenario considers the consequences of a poorly sealed deep site characterization borehole within 100 m of the DGR, the nearest such borehole.

Vertical Fault: This scenario considers the hypothetical case of "what if" a transmissive vertical fault exists near the repository. The fault was assumed to extend from the Precambrian basement rock into the intermediate depth Silurian rocks. One fault was assumed at 500 m distance, at the edge of the area studied in detail in the site investigation program. An alternative hypothetic location, 100 m from the repository but within the characterized zone, was also considered.

3.6 Models, Data and Implementation

Data have primarily been taken from existing OPG waste characterization, DGR preliminary design, and Bruce nuclear site sub-surface and surface site information.

The models were implemented in three software codes.

- Assessment-level (system) models were implemented in AMBER 5.3, which is a compartment-model code that represents radioactive decay, package degradation, contaminant transport through the repository, geosphere and surface environment, and the associated impacts such as dose.

- Detailed groundwater flow and transport calculations were implemented in the 3-D finite-element/finite-difference code FRAC3DVS-OPG, the same code as used for DGR regional geosynthesis modelling.
- Detailed gas generation and transport calculations were implemented in T2GGM, a code that couples the Gas Generation Model (GGM) and TOUGH2. GGM is a project-specific code that models the generation of gas within the DGR due to corrosion and microbial degradation of the metals and organics present. TOUGH2 models the subsequent two-phase transport of gas through the repository and geosphere.

3.7 Results

Normal Evolution Scenario

The Normal Evolution Scenario Reference Case draws on the results of the site investigations and geosynthesis, and represents the site in the most detail. It includes the measured overpressure in the Cambrian sandstone below the DGR, and the measured underpressures and partial gas saturations in the Ordovician formations within which the DGR will be located. Analyses included evaluation of water inflow from rock and shafts, gas generation and build up within the repository, corrosion and rockfall processes that would degrade waste packages, groundwater and gas flow through repository, host rock and shaft seals, and impacts on people living above and around the repository. Variant calculation cases were also assessed to explore uncertainties associated with the Normal Evolution Scenario.

The key results for these cases are as follows.

- The full resaturation of the repository with water is gradual, taking more than 1 million years, due to the low permeability of the host rock and gas generation in the repository. The majority of the water seeps into the repository from the surrounding host rock rather than the shafts.
- Contaminants are contained within the repository and host rock, thereby limiting their release into the surface environment and their subsequent impacts. Reference Case calculations estimate that less than 0.1% of the initial waste activity is released into the geosphere around the repository, and much less is released into the shafts.
- Gases are contained within the repository and geosphere. The gas pressure is anticipated to equilibrate at 7-9 MPa, i.e., around or somewhat above the 7.4 MPa equilibrium hydrostatic pressure at the repository level, and well below the lithostatic pressure of about 17 MPa. The gas will be primarily methane in the long term.
- The low-permeability geosphere and shaft attenuate the release of contaminants, providing time for radioactive decay to decrease the radioactivity in the repository.
- The maximum calculated dose for all calculated cases is more than five orders of magnitude below the 0.3 mSv/a public dose criterion (Figure 1). Calculated doses within the shaded range on Figure 1 are negligible and the magnitude of the values within this area is illustrative. In general, peak doses to children and infants are within a factor of three of the adult dose.
- These results apply to a hypothetical family assumed to be living on the site in the future, and obtaining all of its food from the area. The potential dose would decrease rapidly with distance from the site. For example, the calculated dose to a "downstream" group

exposed via consumption of lake fish and water from Lake Huron are more than three orders of magnitude lower than the dose to the family living on the site.

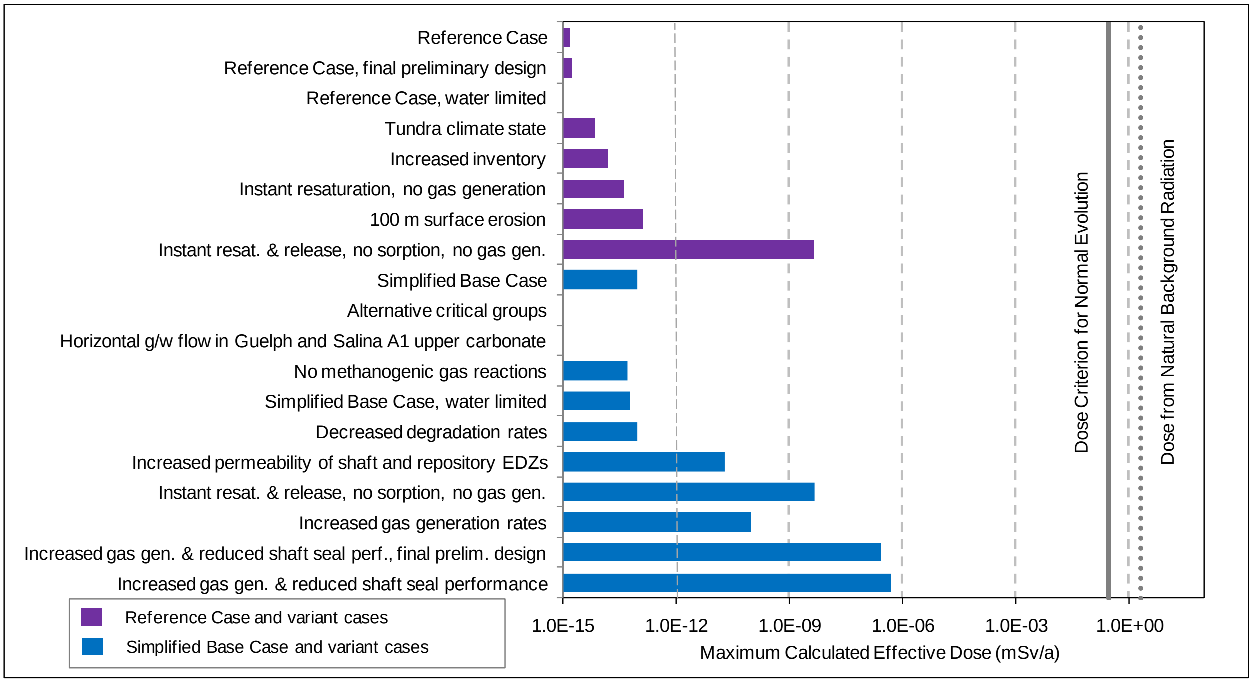

Figure 1. Normal Evolution Scenario: Maximum Calculated Doses for all Calculation Cases. All cases include steady Cambrian formation overpressure. Reference Case includes transient underpressures in Ordovician formations, while Simplified Base Case does not.

Disruptive Scenarios

A tiered approach is adopted for Disruptive Scenarios, recognizing the speculative nature of some scenarios. First, a dose criterion of 1 mSv/a is used for radiological exposure of humans under credible scenarios. Second, if calculated doses exceed 1 mSv/a for a scenario, the acceptability of results from that scenario is examined on a case-by-case basis taking into account the likelihood and nature of the exposure, conservatism and uncertainty in the assessment, and conservatism in the dose criterion. Where feasible, they are compared to a reference health risk of 10^{-5}/a.

Consistent with the Normal Evolution Scenario, a reference calculation was undertaken for each Disruptive Scenario. To avoid ambiguity with the Normal Evolution Scenario Reference Case, the reference calculation for each Disruptive Scenario is termed the Base Case calculation. In addition to the Base Case calculations, some variant calculations have been undertaken for each Disruptive Scenario.

The key results for these cases are summarized below and in Figure 2.

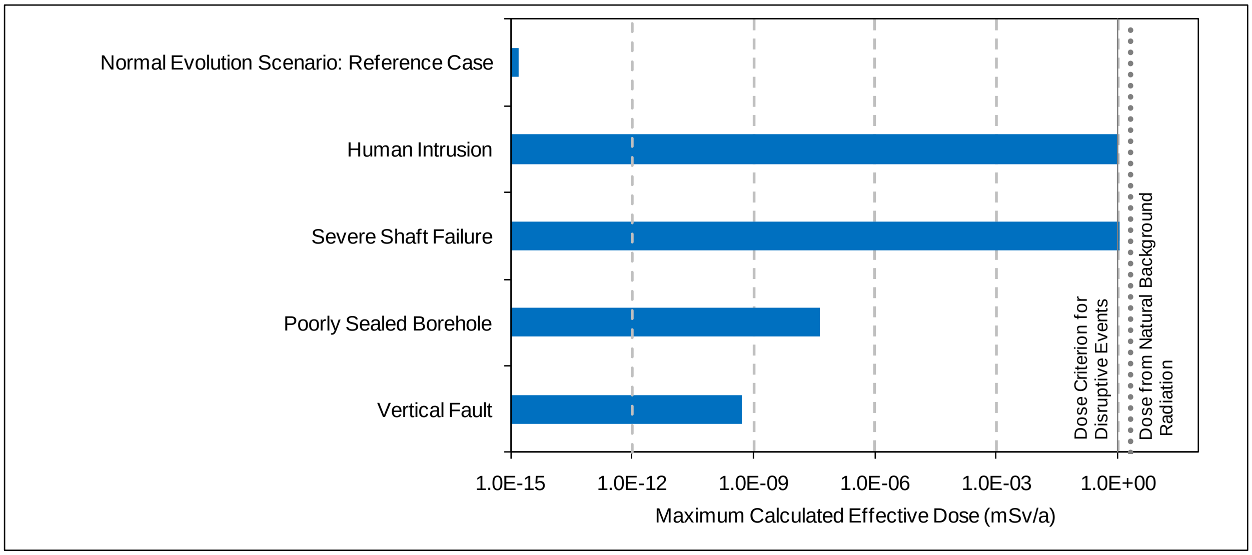

Figure 2. Disruptive Scenarios: Maximum Calculated Doses for Base Case Calculations

- For the *Human Intrusion Scenario*, if a borehole is drilled into the repository and gases and material from the repository are not appropriately contained, the calculated doses could be about 1 mSv for the drill crew and for a future person farming on the contaminated site for about 10,000 years after closure. The likelihood of drilling into the repository in any given year is very low due to the lack of mineral resources and the repository's small footprint and depth, and high contaminant releases are unlikely when following standard deep drilling practices. Thus, the risk of serious health effects is low, and much less than the reference health risk value of 10^{-5}/a.
- For the *Severe Shaft Seal Failure Scenario*, the maximum calculated doses are about 1 mSv/a, based on immediate failure of 500 m of low-permeability shaft seals (from about 10^{-11} m/s to 10^{-9} m/s hydraulic conductivity), reduced sorption in the shafts, increased degradation of shaft and repository EDZs, and assuming that a family is farming directly on top of the shafts (including a house located on the main shaft). The scenario is very unlikely. The risk from the severe shaft seal failure scenario is low.
- Calculated peak annual doses for the *Poorly Sealed Borehole Scenario* and for the *Vertical Fault Scenario* are much less than the dose criterion.
- Additional cases were evaluated to determine the conditions necessary for a disruptive scenario to result in larger impacts than those resulting from its base case. For the Human Intrusion Scenario, the borehole would have to be extended down to the Cambrian formation and then be poorly sealed, so that there is water flowing up the borehole, through the repository and into the shallow groundwater system. For Severe Shaft Seal Failure Scenario, the hydraulic conductivity of all the shaft seals would have to degrade by 4-5 orders of magnitude beyond the design basis to 10^{-7} m/s, about equivalent to fine silt and sand. In these cases, the peak doses to someone living on top of the repository site could be tens of mSv.
- The primary risk in the Disruptive Scenarios is from the release of bulk gas from the repository containing C-14. The potential impacts, therefore, decrease to well below the dose criterion after about 60,000 years due to C-14 decay. Since glaciation at the DGR

site is not likely to occur prior to then, there is little risk that glaciation will cause larger impacts for the Disruptive Scenarios.

Key Radionuclides

- Most radionuclides are retained within the repository or geosphere.
- H-3, although a significant contributor to the waste radioactivity at closure, is fully retained within the repository and host rock, where it decays.
- For scenarios that could result in releases of contaminants to the surface environment within about 60,000 years of closure, C-14 (mostly from ILW moderator resins) is the key radionuclide, together with Nb-94 (mostly from ILW pressure tubes) for human intrusion.
- For releases that occur at later times, Cl-36 (mostly from ILW pressure tubes), and I-129 (mostly from ILW Primary Heat Transport resins) become more important due to their longer half-life and their mobility.
- Nb-94 and Zr-93 are slowly released and mostly retained within the shafts and geosphere and so are not significant contributors to the calculated doses for groundwater releases.

Impacts on Non-human Biota and Non-radiological Impacts

Calculations have been undertaken to assess the impact of radionuclides on non-human biota and the impact of non-radioactive elements and chemical species on humans and the environment. The key results are as follows.

- For the Normal Evolution Scenario, concentrations of radionuclides and of non-radioactive contaminants in surface media are well below the relevant environmental protection criteria.
- For Disruptive Scenarios, impacts are also low. All non-radioactive contaminants and most radionuclides have calculated concentrations in surface media that are well below their screening concentration criteria for the base cases.
- However, there are some local exceedances of screening criteria for the Human Intrusion Scenario and the Severe Shaft Seal Failure Scenario. In particular, C-14 and Nb-94 could locally exceed soil criteria by a factor of 20 if the drilling debris from the repository were to be dumped on the surface at the site in the Human Intrusion Scenario. Also, C-14 could locally exceed the surface water screening criteria by a factor of 1.4 in the Severe Shaft Seal Failure Scenario.
- Since these higher concentrations are local, the screening criteria are conservative, and the scenarios are very unlikely, the risk to biota from these scenarios is low.

Implications on Design

- Calculations indicate that there is no benefit to be gained from backfilling the repository due to the significant containment already provided by the host geology and the shaft seals. Backfilling results in a higher gas pressure within the repository after closure due to a reduction in void volume.
- The calculations have emphasized the importance of the shaft seals in limiting contaminant fluxes in groundwater and gas from the repository. The damaged zone in the rock around the concrete monolith at the shaft base is a key pathway to the shafts.
- Some contaminants that do migrate up the shafts as gas or dissolved species can be laterally diverted into the higher permeability Silurian units (Guelph and Salina A1 upper

carbonate). The low-permeability shaft seals in the Silurian are effective in directing contaminant transport into these features.

Uncertainties

The long timescales under consideration mean that there are uncertainties about the way in which the system will evolve. These uncertainties have been treated in the assessment through: the assessment of a range of scenarios, models and data; the adoption of conservative scenarios, models and data; and the adoption of a stylized approach for the representation of future human actions and biosphere evolution. The key uncertainties in terms of their importance to potential impacts are as follows.

- **Gas pressure and repository saturation** are important in determining the release of radioactivity into repository water, and the potential for C-14 release through gas in the first 60,000 years. Therefore, the processes that control these parameters are important. They were approached in this safety assessment through use of a range of calculation cases to test the importance of uncertainties in those contributing processes.

- **Shaft seal and EDZ properties** and their evolution with time. Variant calculation cases for the Normal Evolution Scenario and the Severe Shaft Seal Failure Scenario calculations emphasize the importance of the shaft seals, particularly in the first 60,000 years following closure.

- **Glaciation effects.** Although geological evidence at the site indicates that the deep geosphere has not been affected by past glaciation events and that the deep groundwater system has remained stagnant, glaciation is expected to have a major effect on the surface and near-surface environment and it is not entirely predictable. It should, however, be noted that ice-sheet coverage of the site is likely to occur only after 60,000 to 100,000 years, at which point the primary remaining hazard will be long-lived radionuclides in groundwater rather than gaseous C-14. Calculations and geological evidence show that the deep groundwaters are stable and transport is diffusion-dominated, so dissolved contaminants will be contained in the deep geosphere with large safety margins.

- **Chemical reactions**. Under the highly saline conditions of the deep geosphere at the DGR site, several aspects of the chemistry are uncertain due to the limited database. In particular, this includes the sorption of contaminants on seal materials and host rocks, as well as mineral precipitation/dissolution reactions. Generally, conservative values have been adopted in this assessment.

The geosphere is clearly key to the DGR safety. In general, the attributes of the geosphere are sufficiently well known to support the safety assessment. However, some aspects are still uncertain, such as the cause of the over/underpressures. These geosphere uncertainties have been considered in this assessment through a range of scenarios, calculation cases and conservative parameter values. Although further resolution of these uncertainties is desirable to increase confidence in the safety assessment, they have not been found to be important to the conclusions of the assessment.

The DGR Geoscientific Verification Plan outlines plans to initiate tests of important processes and materials in the rock during DGR construction. Also, the shaft seal design will not be finalized until the decommissioning application several decades from now, and will take advantage of knowledge gained over the intervening period. While these tests plus further safety and geoscience modelling work will improve confidence in the assessment, the results presented here show that the DGR meets the postclosure safety criteria, that it provides isolation and containment of the wastes, and that the system safety is robust, i.e., the system will maintain its integrity and reliability under a range of conditions. Furthermore, the uncertainties should be interpreted in the context of the low calculated impacts; for example, calculated doses for all Normal Evolution Scenario variant cases are more than five orders of magnitude below the dose criterion.

3.8 Conclusions

The assessment calculations for the Normal Evolution Scenario indicate that the DGR system provides effective containment of the emplaced contaminants. Most radionuclides decay within the repository or the deep geosphere (Figure 3). The amount of contaminants reaching the surface is very small, such that the maximum calculated impacts for the Normal Evolution Scenario are much less than the public dose criterion of 0.3 mSv/a for all calculation cases. In addition, potential impacts of radionuclides on biota and non-radioactive contaminants on humans and non-human biota are well below the relevant criteria.

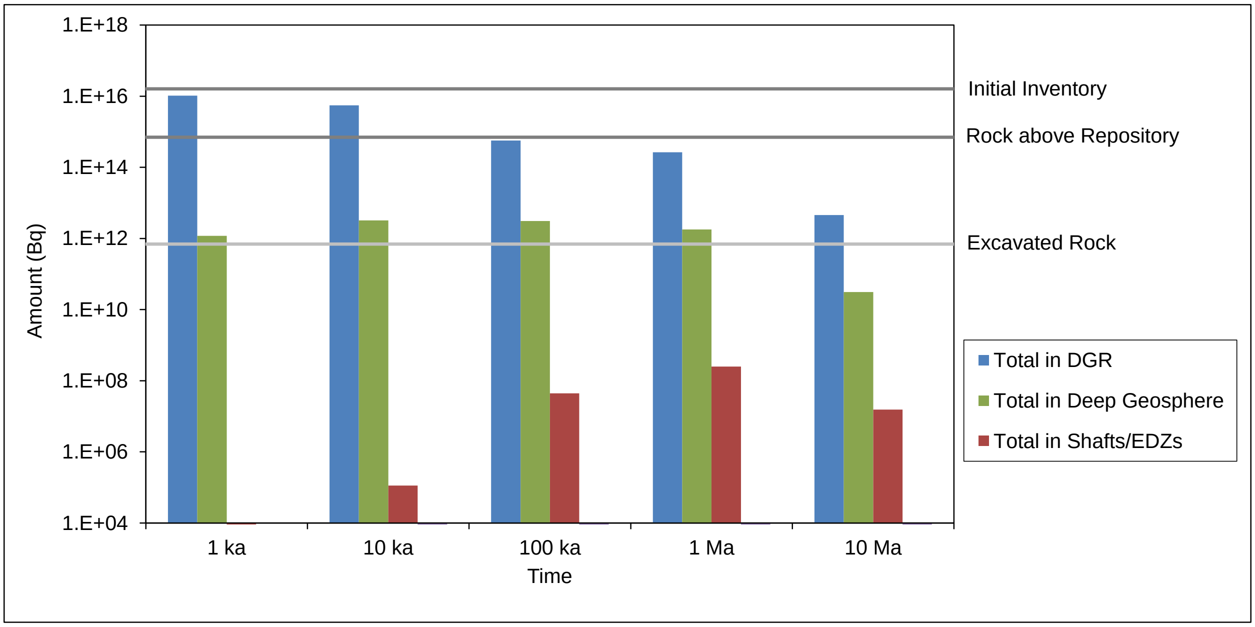

Figure 3. Distribution of Radioactivity in System at Different Times for the Normal Evolution Scenario Reference Case. The total natural radioactivity in the rock above the repository footprint and in the excavated rock volume are also shown.

The isolation afforded by the location and design of the DGR limits the likelihood of disruptive events potentially able to bypass the natural barriers to a small number of situations with very low probability. Even if these events were to occur, the analysis shows that the contaminants in the waste would continue to be contained effectively by the DGR system such that the risk criterion is met.

4. SUMMARY

Consistent with the EIS preparation guidelines and with the regulatory guide G-320, the safety assessment has evaluated the DGR's ability to perform in a manner that will protect human health and the environment from the emplaced waste during the operations and long-term, under both likely and unlikely scenarios. The arguments for DGR safety consist of multiple lines of evidence and provide confidence that:

- The DGR provides good long-term isolation and containment;
- The preclosure and postclosure safety criteria are met; all doses are below the regulatory limits and environmental impacts are below the acceptance criteria;
- The DGR system is robust - even under disruptive scenarios; and
- The DGR can be constructed, operated and decommissioned safely.

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