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THE THIRD CASE STUDY POSTCLOSURE SAFETY ASSESSMENT FOR A HYPOTHETICAL CANADIAN DEEP GEOLOGIC REPOSITORY

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ABSTRACT

The Third Case Study is a postclosure safety assessment of the deep geologic repository concept for used CANDU® fuel in the Canadian Shield. It incorporates advances in repository design concepts and in analysis methodology since the Environmental Impact Statement case studies presented in 1994 and 1996.

The reference container has an outer copper shell for corrosion protection, an inner steel vessel for structural support, and a capacity to hold 324 used fuel bundles. These containers are emplaced in a horizontal in-room configuration and surrounded by dense bentonite based clay seals. The hypothetical geosphere was developed using a geostatistical approach.

This paper presents an overview of the study. We conclude that the Third Case Study repository design and hypothetical site would meet international postclosure dose rate guidelines.

1. INTRODUCTION

One approach for the long-term management of used CANDU® fuel is a deep geologic repository located in a stable rock mass located in the Canadian Shield. Two Canadian postclosure safety assessments have been completed for hypothetical deep geologic repositories - the Environmental Impact Statement (EIS) study (Goodwin et al. 1994) and the Second Case Study (Goodwin et al. 1996). Studies have also been published for similar repository concepts in other countries, notably Sweden (SKB 1999) and Finland (Vieno and Nordman 1999).

The previous EIS study considered titanium alloy containers with 72-fuel-bundle capacity placed vertically into boreholes along the vault rooms, and assumed the repository was located in sparsely-fractured granitic rock with very low permeability. The Second Case Study considered 72-bundle copper containers placed horizontally within the vault rooms, and assumed the repository was located in granitic rock with substantially higher permeability.

The Third Case Study (TCS) evaluates an updated repository design and assumed site (Figure 1). The repository has sufficient capacity to hold all the used fuel from present Canadian nuclear power stations to the end of their planned life. The TCS uses a copper and steel container with 324-bundle capacity, placed horizontally within the vault rooms. The site is different from that assumed in the previous Canadian studies. The geologic setting is hypothetical, but believed to be representative of potential sites that could exist within the Canadian Shield. The TCS assumes the repository is located in granitic rock that is characterized by an intermediate permeability and a geostatistically-generated fracture network.

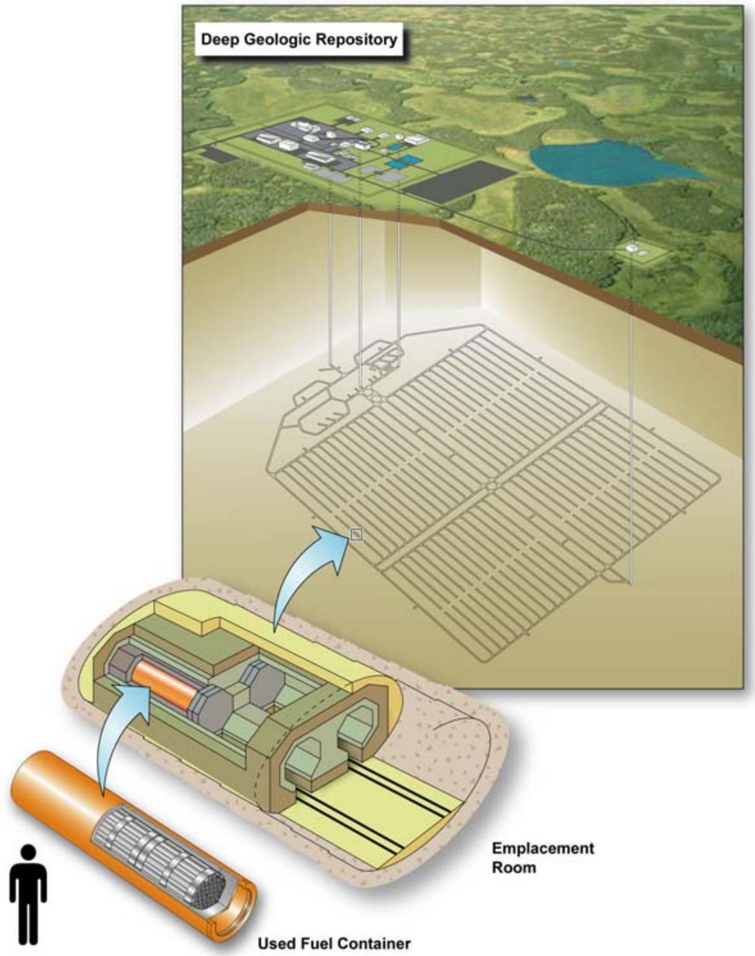

Figure 1: Illustration of the multi-barrier deep geologic repository concept considered in the Third Case Study. A human figure is shown next to the container for scale.

The main objectives of the Third Case Study are:

- to assess key aspects of the postclosure safety of a repository based on a current design concept, and
- to test and evaluate current safety assessment methods and tools.

The analyses are appropriate for the level of information that would typically be available for a candidate site during the site evaluation stage but prior to exploratory drilling. It focuses on three key scenarios that prior studies have identified as important aspects of postclosure safety. An assessment of a real candidate site would consider other scenarios and impacts. The results of this study provide a basic test of postclosure safety for this repository concept and hypothetical site, and a basis for future iterations in which progressively more topics can be addressed. It is not intended to be a full safety case.

The safety assessment methodology followed for the Third Case Study is consistent with that used in other recent international assessments, and in particular it follows the IAEA Integrated Safety Assessment Methodology (IAEA 2004). Additional details of the Third Case Study postclosure safety assessment are found in the supporting documents and references therein (Gierszewski et al. 2004, Garisto et al. 2004).

2. SYSTEM DESCRIPTION

The repository accommodates 3.6 million used CANDU® fuel bundles. The fuel bundles have an average burnup of 220 MWh/kgU. Previous Canadian studies assumed the fuel was emplaced 10 years after discharge, but present timelines for establishment of a deep geologic repository indicate that 30 years is realistic, and the reduced heat output simplifies the repository design.

The container design is based on a copper-shell outer corrosion barrier and an inner steel vessel for mechanical support. It is approximately 1.2 m diameter and 5.6 m long, and holds 324 bundles (Russell and Simmons 2003). It is similar to containers presently under test in Sweden and Finland.

The containers are emplaced horizontally in an "in-room" configuration, which is one of three configurations under consideration in the Canadian program. The containers are surrounded by pre-compacted blocks of buffer and dense backfill, and any gaps near the sides and top are filled with a light backfill (Figure 2). The buffer directly adjacent to the containers is compacted 100% bentonite in order to minimize the potential effects of microbial activity. Each room is sealed at the access tunnel end with a concrete plug.

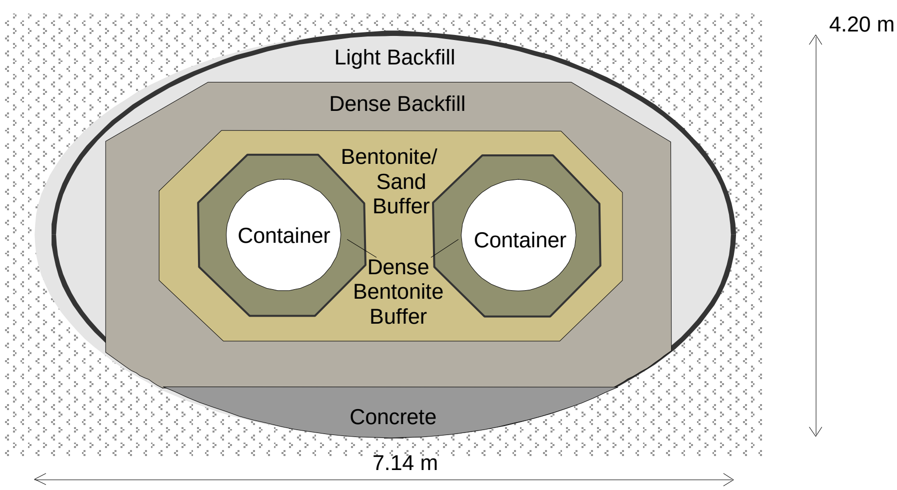

Figure 2: Illustration of cross-section through room showing the horizontal pair layout of the containers and the surrounding graded bentonite-based sealing materials.

The Third Case Study assumes that the repository is constructed in a hypothetical site in sparsely-fractured granitic rock of the Canadian Shield. Figure 3 illustrates the surface topography and hydrology for the hypothetical 10 km x 10 km watershed area in which the repository is located.

The repository is located at a depth of about 700 m below surface, at a location that allowed a square single-level layout between major fracture zones. It has a footprint of almost 2 km^2. The assumed fracture network for this site was generated based on Canadian Shield fracture statistics (Srivastava 2002). Figure 4 illustrates the fracture location and repository position at depth. For a real site, the fracture locations would not be known with certainty, especially at the beginning of the site evaluation process. The Third Case Study uses just one conceptual fracture model for the site, recognizing that the fracture uncertainty could be considered during a site evaluation by repeating the present analyses for a range of fracture networks that represent the model uncertainty.

The Third Case Study biosphere is a hypothetical site based on central Canadian Shield conditions. The topography is relatively flat, with a general slope from north to south. The granitic rock of the Canadian Shield extends close to surface throughout most of the site, with some sedimentary layers in the low-lying areas such as near lakes and rivers. Groundwater flow from the repository discharges to either a small Shield lake, a nearby river, or a nearby stream. In the assessment model, the nearest lake above the repository was conservatively assumed to be the focal point for the entire watershed, with all surface discharges accumulating at this point before leaving the local biosphere. We assume that there are no land uses, endangered ecosystems or mineral resources that would make this hypothetical site inappropriate for a repository.

The present climate is typical of a cool continental location. The surface ecosystem is temperate boreal. This is a relatively stable ecosystem for present climatic conditions. It is possible that global warming could cause changes to the climate over the next 1000 years. On a longer time scale (after 10,000 years), another glaciation cycle could begin with a period of around 120,000 years, but returning during interglacial periods to climate conditions similar to present-day. In the Third Case Study, only present day climate conditions are considered.

3. SCENARIO DEFINITION

The scenarios identified for analysis in the Third Case Study are:

- **Base Scenario**, in which the repository is built according to design, and the overall system behaves as expected.
- **Defective Container Scenario**, in which some containers are assumed to be emplaced with small undetected defects, resulting eventually in release of radionuclides into the groundwater.
- **Human Intrusion Scenario**, in which the engineered and natural barriers are bypassed by a borehole that is inadvertently drilled through a container, bringing used fuel material directly to the surface.

These scenarios are consistent with those identified as important in previous assessments. They are expected to provide a good test of the safety of the hypothetical Third Case Study. For a safety assessment of a real site, more scenarios would be analyzed.

4. MODELS, CODES AND DATA

The primary codes used in support of this safety assessment were as follows:

- **FRAC3DVS** (Version 5.10) **-** 3-D transient groundwater flow and transport model, used for vault and geosphere modelling,
- **SYVAC3-CC4** (Version SCC404) **-** Probabilistic safety assessment system model, including wasteform, container, vault, geosphere and biosphere.

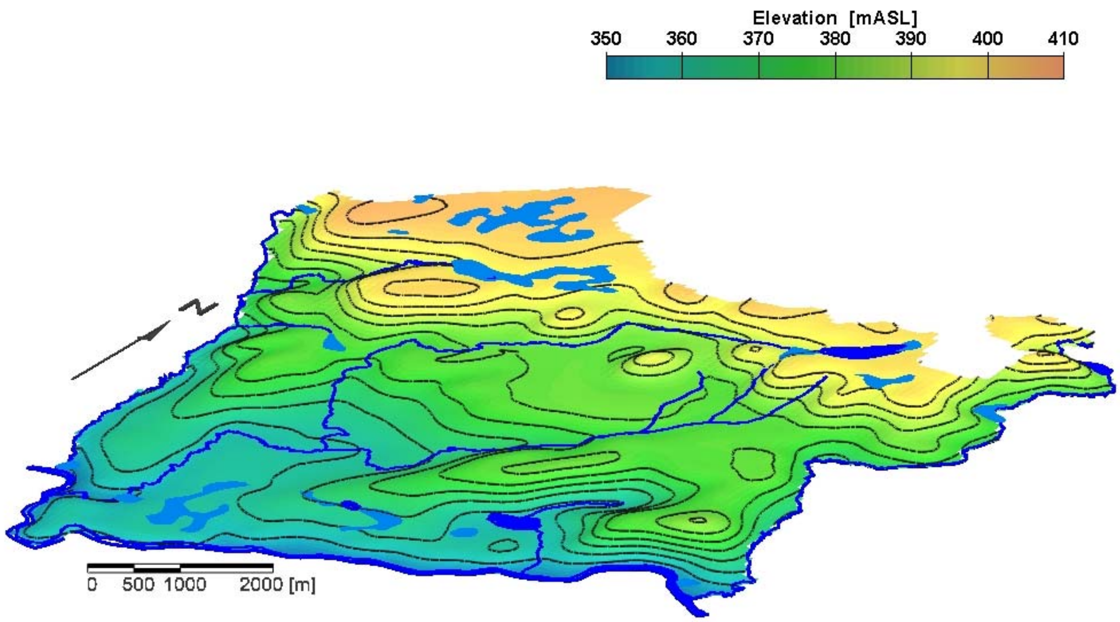

Figure 3: Surface topography and hydrology of the hypothetical 10 km x 10 km watershed containing the repository. Elevation is in units of mASL, metres Above Sea Level. Surface waters and wetlands are marked in blue.

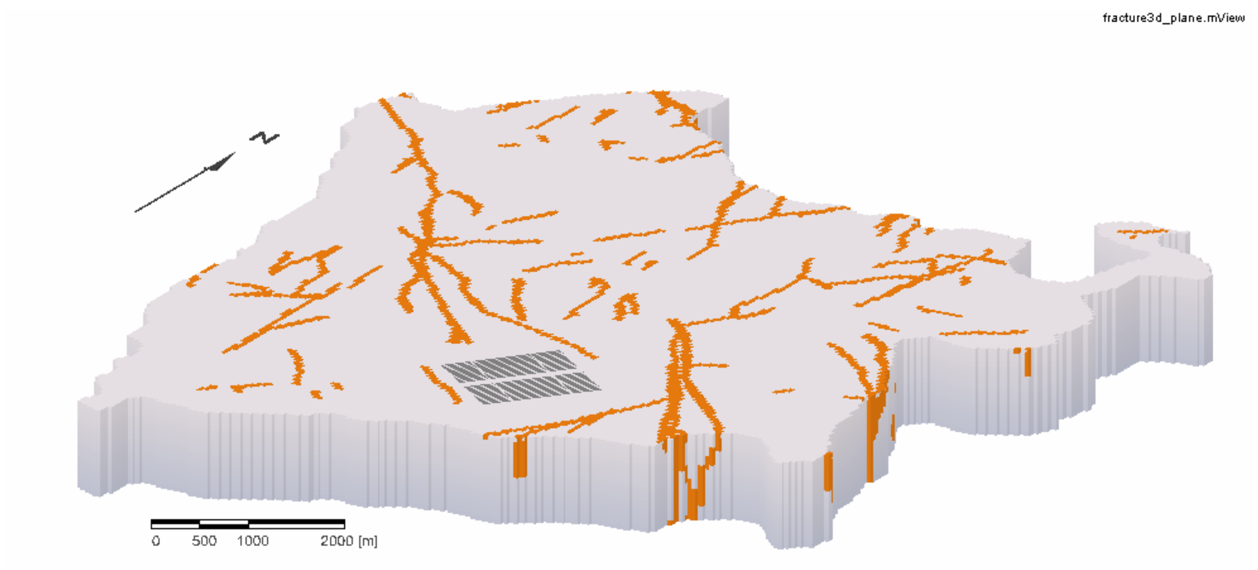

Figure 4: Cutaway view of rock mass under the watershed at the repository horizon of 660 m depth, showing the major fractures and repository location.

Some notable differences in the models and codes compared to previous Canadian studies are:

- Use of FRAC3DVS as the reference code for both vault and geoscience scale transport, in order to ensure a consistent representation of the site, including fracture system, for detailed transport analysis. FRAC3DVS is a current generation finite-element/finite-difference code.
- Revised analysis of the radionuclides present in used fuel based on a comprehensive treatment of impurities and using a current version of ORIGEN-S.
- Use of a Radionuclide Screening Model for explicit screening of the potential impact from all radionuclides.
- Explicit cross-verification of the FRAC3DVS and the SYVAC3-CC4 models with respect to vault and geosphere transport results.

A significant topic in this study was the explicit incorporation of a detailed groundwater flow and transport code into the safety assessment. FRAC3DVS provided the groundwater flow information, and was used for the reference transport calculations from vault through geosphere up to timescales of 1,000,000 years. SYVAC3-CC4 interfaced with FRAC3DVS by providing transport results from used fuel and container into the vault, and from geosphere to biosphere dose. Also, after being cross-verified with FRAC3DVS, the SYVAC3-CC4 system model was run in probabilistic mode, for times up to 10^7 years, and for full decay chains.

5. BASE SCENARIO

The Base Scenario describes what are thought to be reasonable expectations for the evolution of the Third Case Study repository (see also McMurry et al. 2003). In this Base Scenario, the various components of the repository perform to the specifications for which they were designed. In particular, the wastes are emplaced in thick-walled containers that have been carefully engineered to remain intact over timeframes in excess of 100,000 years. The containers are not breached, so water is unable to enter the containers. In the Base Scenario, therefore, there is no release and no transport of radionuclides from the containers.

6. CONTAINER DEFECT SCENARIO

6.1 Introduction

In the Container Defect Scenario, the repository is built to design specifications, except that it is assumed that some containers are emplaced with full penetration defects in the copper shell, due to, for example, undetected fabrication or installation flaws. These failed containers allow radionuclide release into the groundwater around the repository.

6.2 Screening Analysis

Used fuel can contain many different radionuclides at the time of discharge from the reactor. Most of these are present in very small quantities or have short half-lives. For groundwater transport analyses, a simple model called the Radionuclide Screening Model (RSM) was used to screen out unimportant nuclides. Potentially important radionuclides that warrant further consideration using more detailed models are listed in Table 1. Se-79 and Tc-99 were also retained for detailed analysis because they have historically been considered important in other postclosure safety assessments.

Table 1: Radionuclides Identified for Detailed Modeling[1]

I-129, Cl-36, Ca-41, C-14, Se-79, Tc-99
Nuclides of the 4n+1 actinide decay series: Pu-241 Am-241 Np-237 Pa-233 U-233 Th-229 Ra-225 Ac-225
Nuclides of the 4n+2 actinide decay series: U-238 Th-234 U-234 Th-230 Ra-226 Rn-222 Pb-210 Bi-210 Po-210

[1]All nuclides are from the UO_2 matrix.

6.3 Detailed transport modelling

Detailed steady-state groundwater flow modelling of the site and the subregional area around the site was carried out using FRAC3DVS. Detailed modelling of radionuclide transport in the vault and geosphere was also carried out using FRAC3DVS. However, FRAC3DVS does not include container or biosphere models. Therefore, the source term for the FRAC3DVS transport calculations was the nuclide release rate out of the container defect as calculated with the SYVAC3-CC4 system model. The main result from FRAC3DVS was the contaminant mass flow rate into the biosphere. The latter flow was calculated at three locations - the well, the lake and the river.

For the Reference Case calculations, two failed containers were assumed to occur in the emplacement room nearest the east edge of the repository, which is the location with shortest transit time to surface. Groundwater was conservatively assumed to contact the used fuel at 100 years. Iodine-129 was the first radionuclide to reach the surface. It does so predominantly through the well, as expected, given the conservative location of the well, with a smaller amount showing up in the lake and the river.

The radionuclide mass flows into the biosphere were used to calculate the dose rates to the critical group with the SYVAC3-CC4 biosphere model. The main contributor to dose was I-129, followed by Cl-36 (Figure 5). The peak dose rate of about 10^{-7} Sv/a is well below the average Canadian natural background dose rate and the ICRP 81 recommended dose rate constraint (ICRP 2000). Although we assumed that the defective containers were emplaced with defects and that groundwater contacted the used fuel 100 years later, the calculated time of peak dose rate is almost 500,000 years after disposal. This is due to the retention and delay characteristics of the engineered barriers and the geosphere.

6.4 System Modelling

In parallel with the transport modelling using FRAC3DVS, integrated modelling was conducted with SYVAC3-CC4. This system model includes the used fuel, container, vault, geosphere and biosphere.

The SYVAC3-CC4 geosphere is described using a network of one-dimensional flow tubes, which was derived from the FRAC3DVS groundwater flow modelling. Since SYVAC3-CC4 is based on a fixed groundwater flow pattern, it is not used to evaluate factors that could affect groundwater flow, such as uncertainty in geosphere permeability. (Instead, these topics were examined using FRAC3DVS.)
As a check, the SYVAC3-CC4 model results were compared with the FRAC3DVS results at the vault-geosphere interface and at the geosphere-biosphere interface. The results indicate that the two models are in reasonable agreement, with the SYVAC3-CC4 results somewhat more conservative.

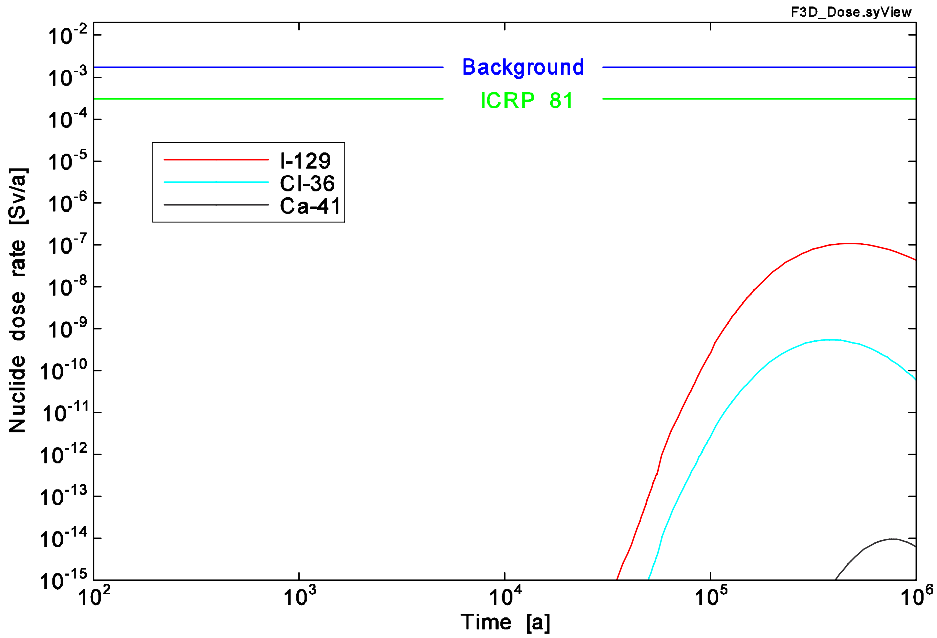

Figure 5: Dose rate impact for the Reference Case.

The SYVAC3-CC4 model was used to consider the following reference and "what if" cases:

- Best-estimate parameter values, with a self-sufficient farming household and well-water supply (this is the Reference Case);
- Defective barrier cases, in which various barriers are assumed to be less effective than designed (e.g., fuel dissolution rate is higher than expected);
- High solubility case, in which there is no radionuclide precipitation in the container;
- Low sorption case, in which radionuclides are not sorbed in the geosphere;
- Simultaneous failure of all containers at the minimum design lifetime of 100,000 years.

The results of these cases are described in the TCS Defective Container Scenario report (Garisto et al. 2004). Those cases that had the highest peak dose rates are shown in Figure 6. The calculated dose rates are all below the ICRP 81 recommended dose rate constraint. The one case in which the calculated peak dose rate approaches the ICRP 81 dose rate constraint is for the unlikely case of simultaneous failure of all containers.

6.5 Probabilistic Studies

In previous sections, the consequences from the Defective Container Scenario were assessed using specific cases. However, many of the input parameter values are uncertain or have a natural degree of variability. This means that they are more generally characterized by a range or distribution of values.

In order to systematically account for parameter uncertainty, the SYVAC3-CC4 system model was used in probabilistic mode. One important statistical result is the average dose rate, an estimate of the expected dose rate impact. Another result of interest is the 95th percentile dose rate, which is a measure of high dose rate tail.

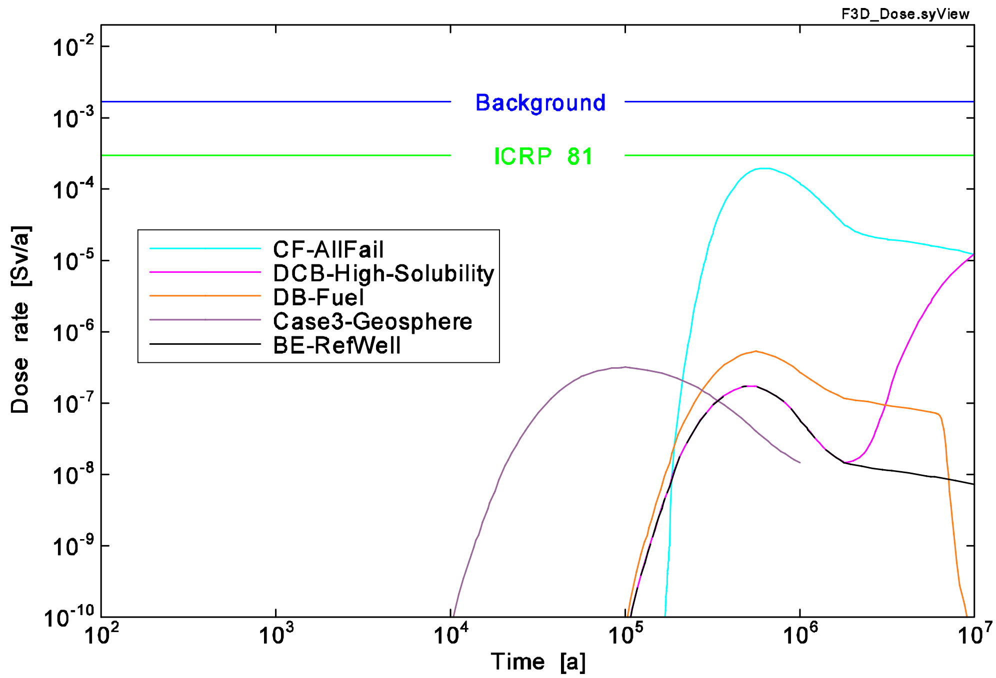

Figure 6: Dose rate results from selected sensitivity study cases. The cases shown had the largest increase in the peak total dose rate relative to the Reference Case (BE-RefWell). They include a 10-fold increase in the UO_2 dissolution rate (DB-Fuel); no precipitation for all elements (DCB-High-Solubility); all containers fail at 100,000 years (CF-AllFail); and a high permeability geosphere (Case3-Geosphere).

The key assumption of the Defective Container Scenario is that some containers have a defect at the time of emplacement. The probability of such a defect in any given container is considered to be random, ranging from 10^{-4} to 10^{-3} per container, with a best-estimate defect rate of $2x10^{-4}$ per container. The results from the 45,000 runs indicate that there are most likely 2 failed containers (the peak in the profile), and that on average there are 3.5 failed containers.

Figure 7 shows the histogram of peak total dose rates (the maximum dose rate summed over all nuclides, regardless of the time at which the maximum occurred) to the self-sufficient farmer critical group that used a well. The average peak total dose rate is $3.6x10^{-7}$ Sv/a. For comparison, the peak total dose rate was $1.7x10^{-7}$ Sv/a for the deterministic Reference Case analysis. The peak 95th percentile peak dose rate was $7x10^{-7}$ Sv/a. These values are in good agreement because the dose rates are dominated by I-129, and there is relatively low uncertainty in I-129 behaviour.

Figure 8 shows the individual nuclide contributions to the calculated dose rate to the critical group from the fission product probabilistic analysis results. The fission product contributions dominate up to 1,000,000 years. Contributions from the actinide chain nuclides do not appear until after 500,000 years. I-129 and Rn-222 are the largest contributors to the average dose rate from the fission products and actinides, respectively.

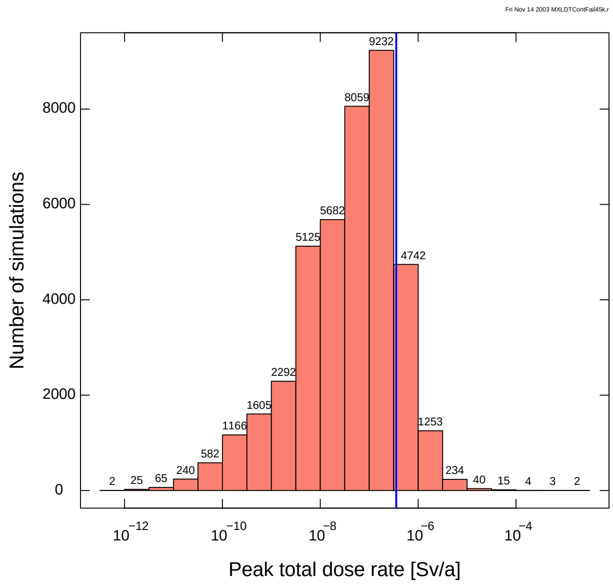

Figure 7: Distribution of peak total dose rates for simulations with container failures. The vertical blue line is the average peak dose rate of 3.6×10^{-7} Sv/a.

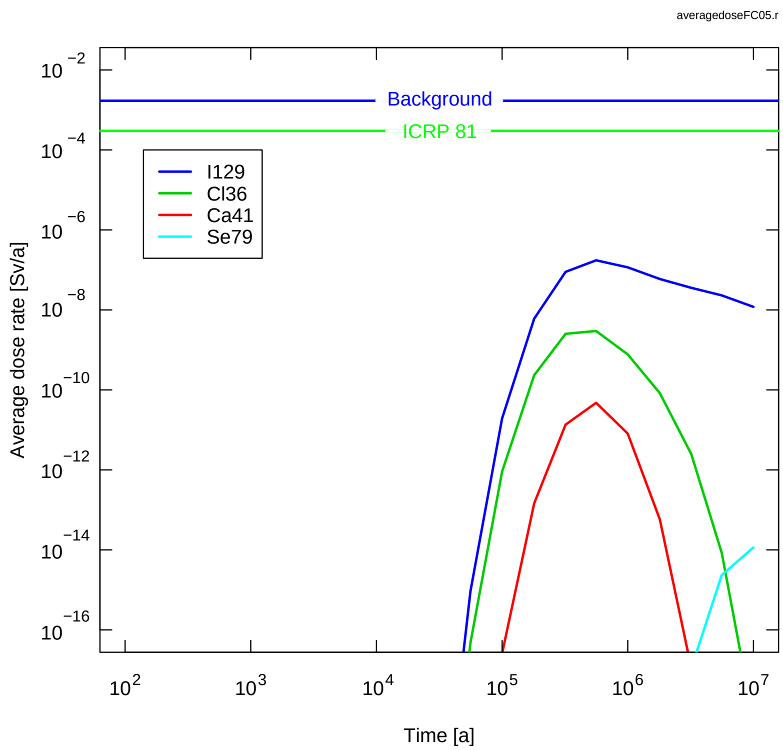

Figure 8: Calculated average dose rates from fission products from probabilistic analysis.

6.6 Complementary Safety Indicators

The dose rate to a critical group is the usual measure of safety of a nuclear facility. However, at the very long times considered in this study, the uncertainties in the calculated dose rates can be significant because of potential changes to the biosphere (such as glaciation), or changes to the characteristics of the critical group living near the repository. To deal with these concerns, we examined complementary safety indicators. Following the EC SPIN Project (Becker et al. 2002), we chose the following indicators: radiotoxicity concentration in the lake, and radiotoxicity flow from the geosphere. Figure 9 shows the calculated dose rate and complementary indicators, based on the results of the Reference Case. It is clear that the calculated values of all safety indicators fall well below their reference levels.

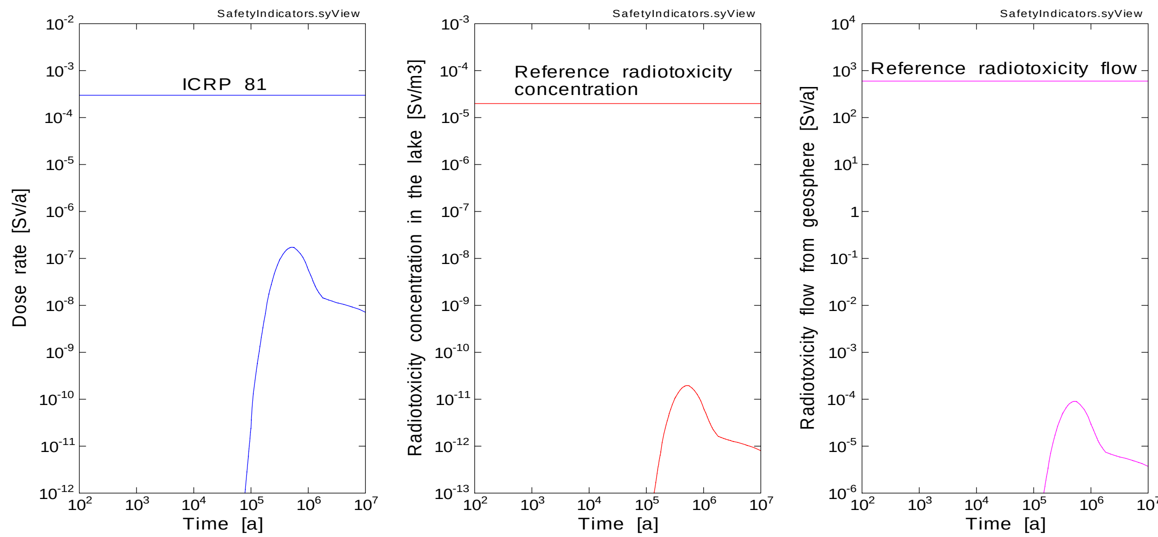

Figure 9: Comparison of three safety indicators. Reference values correspond to the ICRP 81 dose constraint and to natural radionuclide concentrations or flows in the Canadian Shield.

7. HUMAN INTRUSION SCENARIO

The repository is designed with a series of engineered and natural barriers so as to prevent or delay the release of radionuclides after repository closure without further human actions. It is expected that a record of the site will also be kept through both normal institutional records and societal memory, and by a durable surface marker at the site. The Human Intrusion Scenario considers the possibility that the records may be lost, and future humans may inadvertently bypass these barriers.

In order to qualitatively bound the potential exposure from human intrusion, we focussed on a scenario where a drilling crew unknowingly intercepts the container and brings used fuel debris to the surface. We considered four potential critical groups:

- the drill crew, exposed to contaminated drill slurry spread on the surface around the drill rig,
- a laboratory technician, exposed while examining a drill core section containing used fuel,
- a construction worker (e.g., building a house), exposed while working in soil that was contaminated by drill slurry, and
- a resident at the site, exposed by living near, and growing a garden in, soil contaminated by drill slurry.

The drill crew and core technician are assumed to be exposed before the debris is recognized as hazardous and do not take any precautions (e.g. do not wear face masks). The construction worker and resident are exposed after the drilling occurred, assuming that contaminated drill slurry was left at the site and not cleaned up. The model and parameter values generally follow Wuschke (1996).

The inadvertent human intrusion scenario assumes that all natural and engineered barriers are bypassed, and people are directly exposed to used fuel. In this case, it is possible for a few people to be exposed to relatively high doses (0.1 to 1 Sv) if intrusion occurs within 1,000 years following emplacement. This is a direct consequence of the "concentrate and contain" philosophy behind the deep geologic repository. However, the probability of these doses is very low, less than one-in-a-million. At a probability of around one-in-a-million, the maximum calculated dose or dose rate is about 50 mSv. This is an appreciable dose, but corresponds to the 1-year occupational dose limit for nuclear energy workers, for example. The potential dose continues to decrease with time as the used fuel decays. At times greater than one million years, the consequences of intrusion into the repository are similar to that of inadvertently intercepting natural uranium ores bodies.

In all these cases, the number of people who could receive these doses is small, and restricted to people who are intimately in contact with the used fuel debris. The highest calculated dose was for the core examination technician, because the technician is assumed to be exposed to undiluted used fuel dust as a result of cutting or grinding the core samples in preparation for their examination. The technician dose would drop significantly if they were to take even simple precautions such as wearing a dust mask.

The calculated impacts of human intrusion are all well below an annual risk of 10^{-6}.

8. SUMMARY AND CONCLUSIONS

The Third Case Study evaluated key aspects of the postclosure safety of a current container repository concept in a hypothetical site that was representative of the Canadian Shield.

In addition, this study incorporated several improvements to the analysis methodology, notably:

- use of current international methodologies, including in a formal FEP analysis;
- transport analyses use the same computer model as would be used for site characterization in order to fully capture the site conceptual model within the safety assessment;
- analysis objectively considers the full set of potential radionuclides;
- explicit treatment of various defective barrier and other "what if" scenarios;
- explicit treatment of the effect of uncertainties, including probabilistic analyses;
- presentation of results in terms of a range of scenario-specific consequences, rather than as an overall risk figure.

The impact of the repository was assessed in several ways. For the defective container scenario, in which radionuclides from the failed containers reach the surface through the groundwater, the calculated peak dose rates are:

- 1×10^{-7} Sv/a, using best-estimate input values (FRAC3DVS with SYVAC3-CC4),
- 2×10^{-7} Sv/a, using best-estimate input values (SYVAC3-CC4 only), and
- 4×10^{-7} Sv/a, the average from approx. 40,000 probabilistic simulations using SYVAC3-CC4.

The probabilistic analysis for this scenario also shows that 80% of the calculated peak dose rates fall between 10^{-11} and 10^{-6} Sv/a, and the 95th percentile dose rate is 7×10^{-7} Sv/a. These dose rates are well below the ICRP 81 dose rate constraint of 3×10^{-4} Sv/a.

In most simulations, I-129 dominates the radiological impact. In a small number of randomly sampled simulations, Rn-222 is the dominant dose rate contributor and calculated dose rates approach natural background (0.01% of the simulations). However, review of these high dose rate cases indicated that they were associated with unrealistically high uranium solubilities, and it is likely that the maximum Rn-222 dose rate is lower than calculated here.

The features of the repository and site prevent any release of radionuclides to the surface biosphere for several tens of thousands of years after disposal, even assuming some containers have full-penetration defects at the time of emplacement.

The calculated peak dose impacts occur at such long times in the future that the results are only indicative of the potential impact. Nonetheless, the overall conclusion is that the deep geologic repository design and hypothetical site considered in the Third Case Study provides effective isolation and retention of radionuclides. Almost all the radionuclides decay within the repository and adjacent geosphere before reaching the surface biosphere. Only a few radionuclides eventually reach the surface biosphere and their dose impact is much lower than the natural background dose rate and the internationally recommended ICRP 81 dose rate constraint.

Postclosure safety of the deep repository concept has now been illustrated for three possible combinations of engineering design and Canadian Shield sites. This increases confidence that a suitable site could be found within the Canadian Shield from a technical perspective.

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