Overview of a Postclosure Safety Assessment of a Canadian Used Fuel Repository in Sedimentary Rock

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The Nuclear Waste Management Organization (NWMO) is responsible for the implementation of Adaptive Phased Management (APM), the federally-approved plan for safe long-term management of Canada's used nuclear fuel. Under the APM plan, used nuclear fuel will ultimately be placed within a deep geological repository in a suitable rock formation.

A site selection process is currently underway to identify a safe site in an informed and willing host community. The process of site selection will take several years. As potentially suitable sites are identified with interested communities, detailed field studies and geoscientific site characterization activities will be conducted to assess whether the multi-barrier repository concept could be safely implemented to meet rigorous regulatory requirements.

At this early stage in the process, before specific sites have been identified for examination, it is useful to conduct generic studies to illustrate the long term performance and safety of the multi-barrier repository system within various geological settings.

This paper summarizes an illustrative case study of a conceptual multi-barrier design and postclosure safety of deep geological repository in a hypothetical sedimentary Michigan Basin setting[1]. The purpose of this postclosure safety assessment is to determine potential effects of the repository on the health and safety of persons and the environment from potential radiological and non-radiological hazards.

I. INTRODUCTION

The purpose of a postclosure safety assessment is to determine potential effects of the repository on the health and safety of persons and the environment. In the absence of a site, the illustrative postclosure safety assessment described here serves to illustrate the methodology, computer codes and analysis methods that will be applied in the future. Results are compared against acceptance criteria established for the protection of persons and the environment from potential radiological and non-radiological hazards.

The adopted approach is consistent with that outlined in CNSC Regulatory Guide G-320[2] *Assessing the Long Term Safety of Radioactive Waste Management[2]*.

NWMO postclosure safety assessments typically consider a one million year period or the duration of time until the maximum dose is reached. Due to the extremely low sedimentary rock hydraulic conductivities, the maximum dose is not reached within one million years and therefore the assessment timeframe is extended to ten million years to provide an indication of the dose response. Beyond ten million years other processes (such as plate tectonics) that are not considered in this assessment become significant.

II. WASTE FORM AND DESIGN CONCEPT

The reference waste form (See Figure 1) is a standard CANDU® 37-element fuel bundle with a burnup of 220 MWh/kgU and an average fuel power during operation of 455 kW. An unirradiated fuel bundle contains about 20 kg of natural uranium in the form of ceramic pellets. Each bundle is about 0.5m in length.

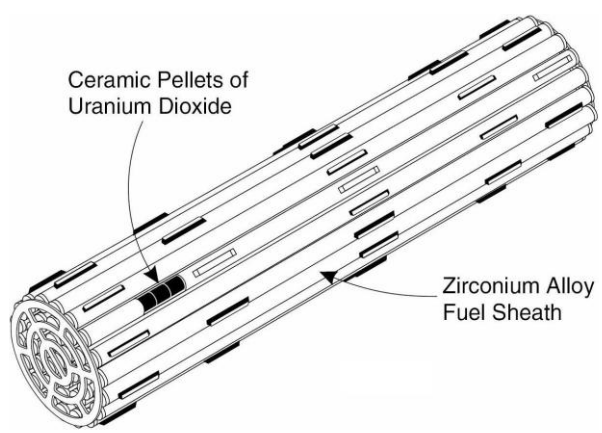

Fig. 1. Waste Form

The ceramic used fuel matrix is durable and dissolves slowly in water. The most important factor governing the rate of dissolution is the electrochemical potential of the groundwater saturating the repository. The groundwater is anticipated to maintain a reducing environment with any residual oxygen (from trapped air) available at the time of closure consumed by reactions with minerals in the enclosing engineered sealing materials and/or the copper and steel container itself. Microbial oxygen consumption would also help create reducing conditions in those locations in a repository where microbial activity is possible.

Despite the overall reducing environment, in the event of container failure, conditions immediately adjacent to the used fuel surface are likely to remain oxidizing due to radiolysis of groundwater that would eventually fill the container. Radiolysis would be caused by alpha, beta, and gamma radiation from the used fuel, at rates that decrease with time. Note that although used fuel dissolution experiments indicate that the dissolution rate decreases by several orders of magnitude in the presence of significant hydrogen gas as would be produced by corrosion of the steel container[3], this effect has been conservatively ignored. Figure 2 illustrates the fuel dissolution as a function of time[1].

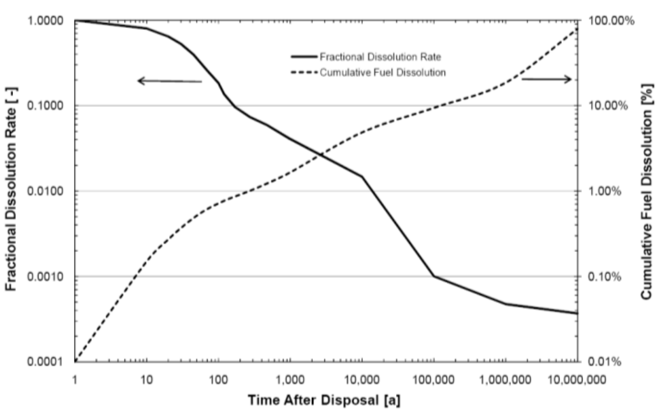

Fig. 2. Fuel Dissolution

I.A. Design Concept

In this illustrative case study, the reference design concept is similar to the KBS-3 repository method[4], with modifications to the container and internals as required to accommodate 360 used CANDU fuel bundles. The container is illustrated in Figure 3.

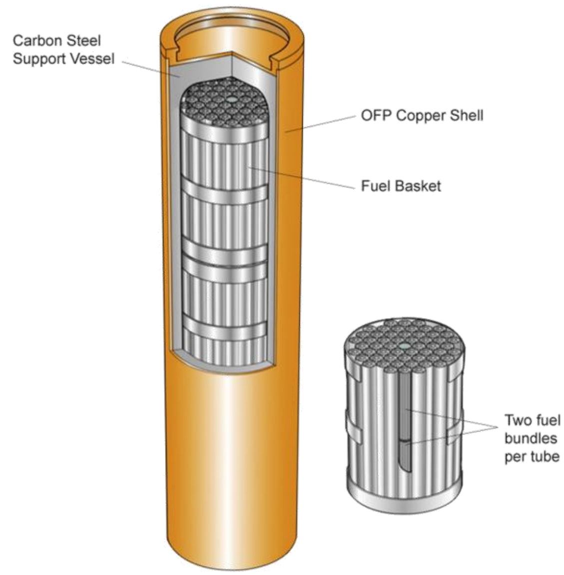

Fig. 3. Used Fuel Container

The container design consists of a copper outer vessel that encloses a steel inner vessel. The copper provides a corrosion barrier under deep geological conditions, while the steel vessel provides the strength required for the container to withstand the expected hydraulic and mechanical loads, including glaciation.

Figure 4 and 5 illustrate the layout of the placement rooms and the repository assumed in this study.

The conceptual repository contains a network of placement rooms for the base case inventory of 4.6 million used fuel bundles encapsulated in 12,800 used fuel containers. Each container is placed horizontally on a compacted bentonite pedestal with the remaining space backfilled with bentonite pellets.

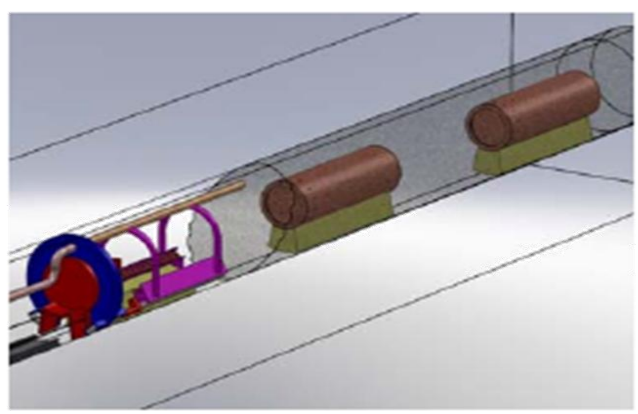

Fig. 4. Placement Room

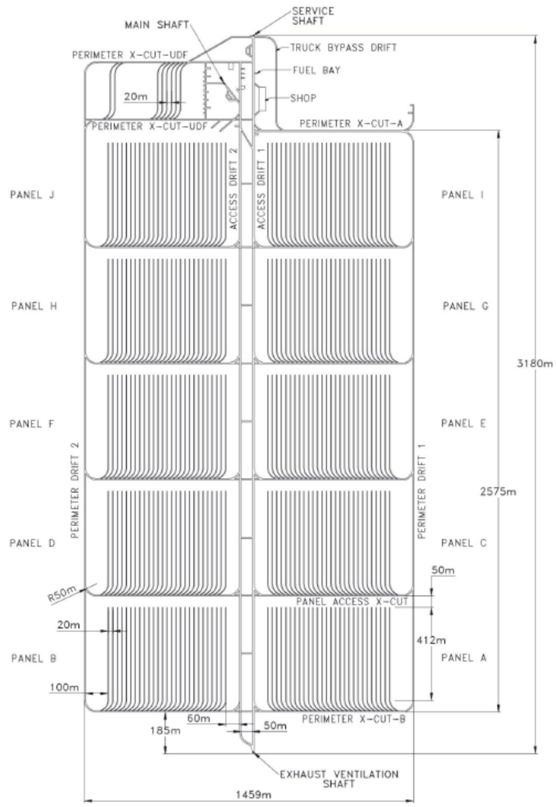

Fig. 5. Underground Layout

II. GEOSPHERE

The long-term safety and performance of a used fuel repository will rely, in part, on the surrounding geologic setting. The geosphere will provide a geomechanically and geochemically stable environment. Geomechanical stability enables safe excavation and placement of the containers and engineered barrier system, and isolates the containers from a wide range of future human and natural events. A stable geochemical and hydrogeologic environment supports container durability and minimizes radionuclide mobility. The ability of the geosphere to support these attributes will be dependent on site-specific conditions.

The hypothetical site represents one example of a possible sedimentary rock setting. A range of characteristics are described for alternative settings that are considered in the safety assessment to illustrate an approach to assess long-term safety and the functionality of various barrier systems. Although the site represents a hypothetical sedimentary basin site, the rock formation characteristics are consistent with reported values obtained from both regional and site-specific investigations for Ontario Power Generation's proposed Deep Geological Repository for Low and Intermediate Level Waste[5,6].

Figure 6 and Figure 7 shows the geological stratigraphy and the lithologies of the different geological formations, members, and units. The repository is placed in the Cobourg limestone formation at a depth of 500m below the surface and beneath the highly impermeable Georgian Bay shale layer. A domestic surface water supply well is conservatively placed such that it draws from the Guelph aquifer 219m below surface. The well is located such that it is in the most conservative location meaning it is able to intercept and capture the vast majority of any contaminants released from the repository.

The geosphere is continuous and relatively uniform, lacking the presence of permeable fractures or fault zones. The rock mass is assigned an effective hydraulic conductivity in accordance with properties for the different geological units assumed to be present. For rock layers below the Guelph aquifer the hydraulic conductivities are extremely low (between 10^{-14} m/s and 10^{-13} m/s). The Guelph aquifer has a hydraulic conductivity of $3x10^{-8}$ m/s, and the rock above the Guelph aquifer has a variety of high and low conductivity layers ranging from 10^{-14} m/s to 10^{-7} m/s. In general, contaminant transport in the hypothetical geosphere is diffusion dominated. Permeable aquifer layers exist closer to the surface in which advection is the dominant mechanism for contaminant transport.

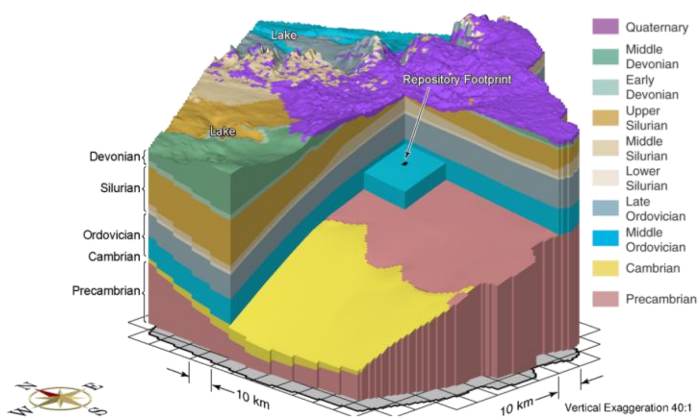

Fig. 6. Repository Site

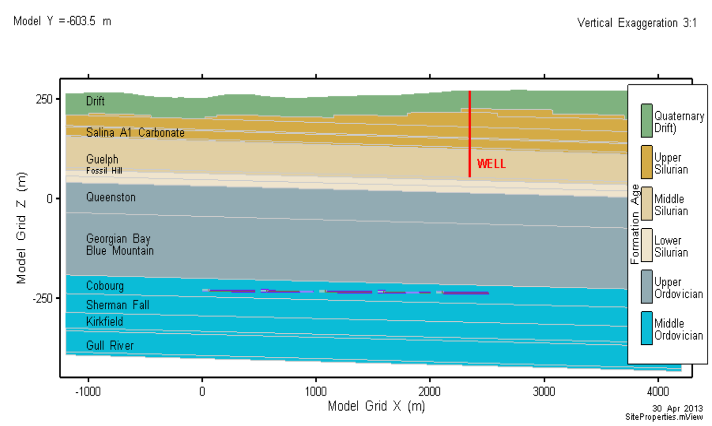

Fig. 7. Repository Site Cross Section

III. SCOPE OF THE ILLUSTRATIVE POSTCLOSURE SAFETY ASSESSMENT

Consistent with the specification of CNSC Guide G-320[2], the scope of work considers both Normal Evolution and Disruptive Scenarios. The Normal Evolution Scenario represents the normal (or expected) evolution of the site and facility, while Disruptive Scenarios examine the effects of unlikely events that might lead to penetration of barriers and abnormal degradation and loss of containment.

Results are measured against criteria for the radiological protection of persons, criteria for the protection of persons from hazardous substances, criteria for the radiological protection of the environment, and criteria for the protection of the environment from hazardous substances.

III.A. Scenario Identification and Description

Postclosure safety is assessed through consideration of potential future scenarios, where a scenario is postulated set of conditions or events. The purpose of scenario identification is to develop a comprehensive range of possible future evolutions against which the performance of the system can be assessed.

Scenarios of interest are identified through consideration of the various Features, Events, and Processes (FEPs) that could affect the repository system and its evolution. FEPs are categorized as either "external" or "internal", depending on whether they are outside or inside the spatial and temporal boundaries of the repository system. Repository and contaminant factors can be considered "internal" factors, whereas the "external" factors originate outside these boundaries. Hence, the repository and contaminant factors are referred to as Internal FEPs and the external factors are referred to as External FEPs.

The External FEPs provide the system with boundary conditions and include influences originating outside the repository system that might cause change. Included in this group are decisions related to repository design, operation and closure since these are outside the temporal boundary of the postclosure behavior of the repository system. If these external FEPs can significantly affect the evolution of the system and/or its safety functions of containment and isolation, they are considered scenario-generating FEPs[7] in the sense that whether or not they occur (or the extent to which they occur) could define a particular future scenario that should be considered.

The following sections describe the scenarios that were developed following the FEP review.

III.B. Normal Evolution Scenario

The postclosure safety assessment adopts scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or future site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions are adopted and documented to allow the impacts of uncertainties to be bounded.

The Normal Evolution Scenario is based on a reasonable extrapolation of the site and repository. It accounts for anticipated significant events, in particular glaciation. Significant features of the Reference Case of the Normal Evolution Scenario are:

- Waste form characteristics and conceptual repository design as outlined in Section 1.
- Hypothetical geosphere as outlined in Section 2.
- Three containers with undetected defects[1] (radius = 1mm) placed directly below the well (no evolution of the defect with time is considered and no other failures occur).
- Groundwater fills the defective containers 10,000 years after the containers are placed in the repository[8].
- Biosphere with a constant temperate climate.
- A self-sufficient farming family growing crops and raising livestock on the surface above the repository, who drink and irrigate with water from the well.
- The well is pumping at a rate of 1307 m^3/a. This is sufficient for drinking water and irrigation of household crops.
- A small amount (tens of metres) of surface erosion occurs in the first one million years.
- Input parameters that are represented by probability distributions are set to either the most probable value (when there is one) or to the median value otherwise.

The anticipated effect of glaciation, based on results of regional glaciation modelling studies, is described in the case study report[1].

Results are developed for one complementary radiological indicator.

Results are also generated to address the radiological protection of the environment, and the protection of persons and the environment from hazardous substances. A complementary indicator of safety for hazardous substances is also evaluated.

III.B.1. Sensitivity Studies

Recognizing that there are uncertainties associated with the future evolution of a repository, the assessment has varied a number of important parameters and assumptions, completed bounding assessments and developed a number of hypothetical "what-if" scenarios to explore the influence of parameter and scenario uncertainty in assessing long-term safety. Key parameters that could potentially affect long-terms safety are varied in deterministic sensitivity cases to understand the effect of uncertainties in these parameters. Some parameters are also pushed beyond the reasonable range of variations in bounding assessments. In these extreme cases, parameters are completely ignored by setting their values to zero or by removing physical limits.

The following deterministic sensitivity cases are examined:

- Fuel dissolution rate increased by a factor of 10,
- Container defect area increased by a factor of 10,
- Fuel instant release fraction set to 10% for all radionuclides,
- Rock hydraulic conductivity increased by a factor of 10,
- Excavation damage zone hydraulic conductivity increased by a factor of 10,
- Rock diffusivity increased by a factor of 10,
- Overpressure in the Shadow Lake formation, and
- Geosphere sorption decreased with coincident solubility limits in the container increased.

The following lists the extreme cases in which parameters were pushed beyond the reasonable range of variation:

- No sorption in the geosphere,
- No sorption in the near field, and
- No solubility limits

III.B.2. Probabilistic Analyses

A further understanding of uncertainties can be obtained through probabilistic modelling. For the probabilistic simulations, random sampling is used to simultaneously vary all input parameters for which probability distribution functions are available. The parameters varied include diffusion coefficients, sorption coefficients, the number and location of defective containers, the defect size, the size of the critical group and most of the biosphere parameters. A total of 120,000 simulations were examined to identify a 95^{th} percentile maximum dose rate.

III.C. Disruptive Scenarios

The FEPs review resulted in identification of the following Disruptive Scenarios:

- Inadvertent Human Intrusion,
- Shaft Seal Failure,
- Abandoned Repository,
- Poorly Sealed Borehole,
- Undetected Fault,
- Severe Erosion,
- All Containers Fail (a base case with failure at 60,000 years and a sensitivity case with failure occurring at 10,000 years), and
- Container Failure.

Not all scenarios were analysed in the illustrative case study. The key scenarios considered were "Inadvertent Human Intrusion", "Shaft Seal Failure" and All Containers Fail". Additional Disruptive Scenarios would be assessed as part of the safety case for a candidate site.

IV. METHODOLOGY OVERVIEW

The general approach for conducting the postclosure safety assessment is as follows.

1) Perform Radionuclide Screening

Used fuel contains many hundreds of radionuclides. Screening is performed to identify the potentially radiologically significant radionuclides so that subsequent work need only consider this group. In this study, 38 radionuclides are considered for the radiological hazard assessment, with these being a mix of long-lived fission products and actinides. Twenty-six elements are considered in the non-radiological hazard assessment.

2) Perform Detailed 3D Groundwater Flow and Radionuclide Transport Modelling

Detailed 3D steady-state hydrogeological modelling is performed with the FRAC3DVS-OPG code[9] to determine the groundwater flow field near the repository, FRAC3DVS-OPG is the reference groundwater flow and groundwater transport code used by the NWMO.

Detailed 3D radionuclide transport calculations (accounting for diffusive and advective processes) are performed for a small group of radionuclides (i.e. I-129, Cs-135, U-238 and U-234) that represent a range of low-sorption to high-sorption species. These calculations aid in understanding the transport behavior and provide data for subsequent use in SYVAC3-CC4 system modelling.

Dose consequences are not determined with FRAC3DVS-OPG results.

3) Perform System Modelling

SYVAC3-CC4[10] is a simple model used for radionuclide transport and the calculation of dose consequences, the code simulates the used fuel, container, repository, geosphere and biosphere, allowing feedback between these components. SYVAC3-CC4 executes very quickly (in comparison to FRAC3DVS-OPG) and is used to perform both deterministic and probabilistic calculations for all radionuclides and elements identified in the screening analysis.

The geosphere model used in SYVAC3-CC4 was intentionally developed to conservatively represent the sedimentary geosphere represented in the detailed FRAC3DVS-OPG model. To provide confidence in the resulting model, radionuclide transport calculations are performed for I-129, Cs-135, U-234 and U-238 and compared to similar results obtained from the more detailed FRAC3DVS-OPG model.

Dose consequences are calculated for a self-sufficient farming family growing crops and raising livestock on the surface above the repository. Internal and external exposure pathways are considered. Internal exposure pathways include drinking contaminated well water, eating contaminated crops and animals, and inhalation. External dose pathways include groundshine from contaminated soil and immersion in contaminated water. The total dose includes cumulative dose consequences from all screened in radionuclides and exposure pathways.

V. RESULTS

V.A. Normal Evolution Scenario

Figure 8 shows the results for the Reference Case Normal Evolution Scenario. Figure 9 compares the results of the Reference Case with its associated sensitivity cases.

The primary contributor to the public dose over the long term from the three assumed defective used fuel containers is I-129, a long-lived fission product that is non-sorbing in the geosphere. The calculated maximum dose rate for the Reference Case is about 150,000 times lower than the interim dose acceptance criterion of 0.3 mSv per year at the modelling cut-off time of ten million years. The long timeframe is due primarily to the fracture-free diffusion dominated sedimentary rock layers surrounding the repository. The shape of the curve is defined by the release of radionuclides into the Guelph layer from both the shaft and the rock layers. The shaft releases are low and appear first. The rock layer releases are greater and appear later. When the two are summed together, this results in the shape of the curve shown in Figure 8.

Pd-107 and Sm-147 are not usually identified as dose contributors in used fuel repository assessments, but show here at very low levels as they are long-lived and, in the absence of data, have been assumed to have no sorption and no solubility limits. Other fission products and actinides either decay away, or are released very slowly as the fuel dissolves and are thereafter sorbed in the engineered barriers and geosphere.

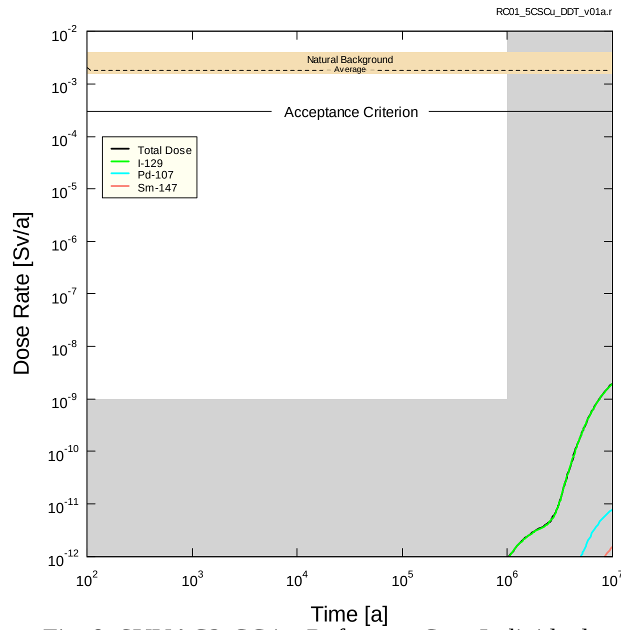

Fig. 8. SYVAC3-CC4 – Reference Case Individual Radionuclide Dose Rates

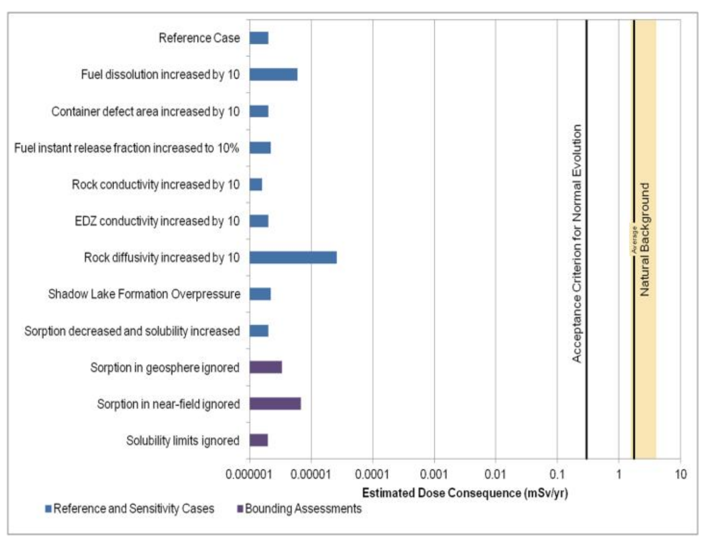

Fig. 9. Results from the Reference Case, Sensitivity Analysis, and Bounding Assessments.

The sensitivity analyses show that the effect on dose is small when key parameters are varied over credible ranges. The parameter with the most significant effect on dose is the rock diffusivity. Since the geosphere diffusivities are higher in this sensitivity case, I-129 (the dominant dose contributor) reaches its peak dose rate contribution within the 10 million year simulation time frame. The peak total dose rate occurs at $5.6x10^6$ years and reaches a value of $2.6x10^{-5}$ mSv/a. This is about 13-fold higher than for the Reference Case; however, as in the Reference Case, the maximum total dose rate is still well below the interim acceptance criterion and the average natural background dose rate.

For the non-radiological hazard, the results indicate that the large amounts of uranium in the repository do not pose a risk. Cu, Ag and Ni had the highest concentrations relative to criteria, but remain well below the interim acceptance levels.

Figure 10 and Figure 11 shows the results of the probabilistic assessment. The 95th percentile dose consequences are approximately 4,000 times below the interim dose rate acceptance criterion.

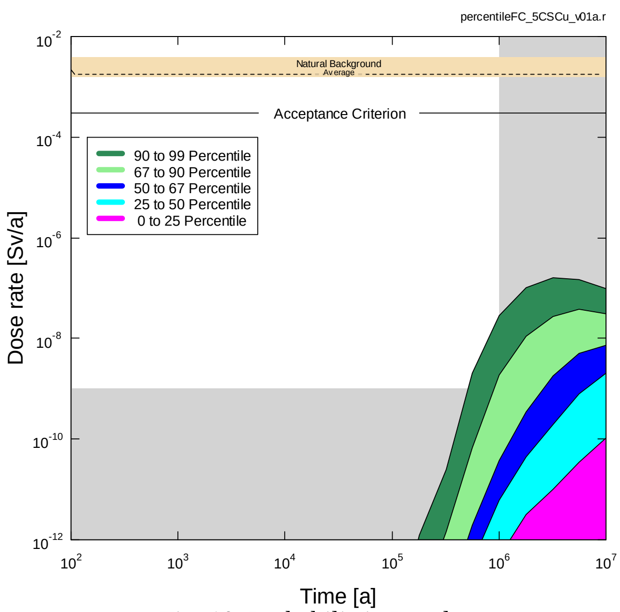

Fig. 10. Probabilistic Results

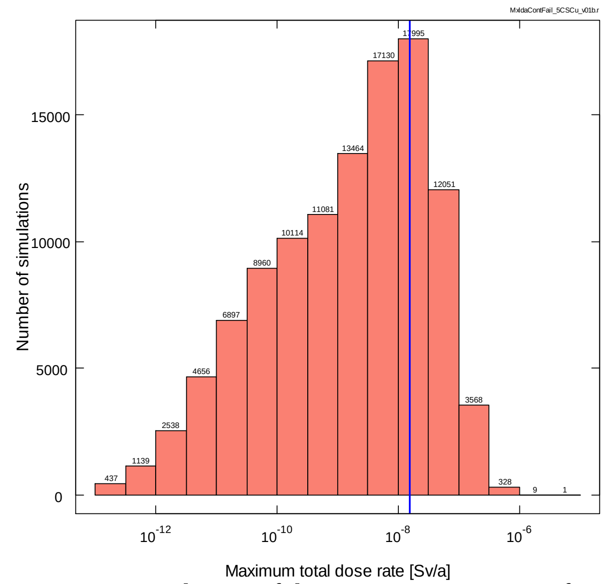

Fig. 11. Distribution of the Maximum Dose Rate for Simulations with at Least One Defective Container

V.B. Disruptive Scenarios

The results of the disruptive scenarios are discussed in detail in Ref. 11. For the cases considered (All Containers Fail, Human Intrusion, and Shaft Seal Failure) all radiological acceptance criteria are met with significant margins with the exception of Human Intrusion. All Inadvertent Human Intrusion is a special case that is recognized in G-320 as having a potential to exceed the regulatory dose limits; however, the likelihood of this occurring is very small and is estimated to be below the risk criterion of 10^{-5}/a for Disruptive Scenarios[11].

VI. Conclusions

The case study[1] describes a conceptual design for a deep geological repository in sedimentary rock and provides an illustrative postclosure safety assessment, which is structured, systematic and consistent with CNSC Guide G-320[2]. The assessment describes the repository system, systematically identifies scenarios, models and methods for evaluating safety, uses different assessment strategies, addresses uncertainty, and compares the results of the assessment with interim acceptance criteria.

The postclosure safety assessment shows, for the cases considered that all radiological and non-radiological interim acceptance criteria are met with substantial margins. This is consistent with previous assessments of a deep geological repository in Canada, as well as with safety assessment studies by other national radioactive waste management organizations.

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