FIFTH CASE STUDY: IDENTIFICATION AND ANALYSIS OF DISRUPTIVE SCENARIOS

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The Fifth Case Study is a postclosure safety assessment of a deep geologic repository for used CANDU fuel at a hypothetical sedimentary rock site in the Michigan Basin in Ontario. Postclosure safety is assessed through consideration of a set of potential future scenarios. Both Normal Evolution and Disruptive Scenarios are considered. In this paper, the methodology used to identify the disruptive scenarios for the Fifth Case Study is described. Then, the calculated radiological dose rates to humans and/or the I-129 release rates to a well for three disruptive scenarios are reported and compared to the Reference Case of the Normal Evolution Scenario. The robustness of the repository system is examined in light of these results.

I. INTRODUCTION

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. At this early stage in the process, before specific sites have been identified with interested communities, 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.

The Fifth Case Study (5CS) is a postclosure safety assessment of a deep geologic repository for used CANDU fuel at a hypothetical sedimentary rock site in the Michigan Basin in Ontario. It considers a repository for 4.6 million used fuel bundles, a used-fuel container holding 360 fuel bundles, in-room container placement, and a repository depth of 500 m.

The current study builds upon previous safety assessment studies, including the Third Case Study and Fourth Case Study.[1,2] The level of detail is consistent with the pre-project stage but not a full safety case. The Fifth Case Study postclosure safety assessment has been developed following regulatory guidance in CNSC G-320.[3]

Postclosure safety is assessed through consideration of a set of potential future scenarios, where a scenario is a postulated or assumed set of conditions or events. Both Normal Evolution and Disruptive Scenarios are considered.

The Normal Evolution Scenario is based on a reasonable extrapolation of present day site features and receptor lifestyle; and represents the normal (or expected) evolution of the site and facility, and consequently includes a few containers assumed to have undetected manufacturing defects leading to early releases of contaminants from the repository. Since glaciation is expected to occur in the future, the Normal Evolution Scenario includes a discussion of the effect of glaciation on calculated impacts.[4] Glacial erosion could also occur so the Normal Evolution Scenario considers that a small amount (tens of metres) of surface erosion occurs in the first one million years with 100 metres[4,5] adopted as a sensitivity case.

The Disruptive Scenarios are identified following the procedure described in the next section.

II. SCENARIO IDENTIFICATION

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 factors that could affect the repository system and its evolution.[6] These factors can be further categorized into Features, Events and Processes (FEPs) as shown in Table 1. FEPs are organized in a hierarchical structure with up to 4 levels. The finest discretization of the FEPs occurs at the lowest level.

FEPs can be characterized as either "external" or "internal", depending on whether they are outside or inside the spatial and temporal boundaries of the repository system domain, which here includes the repository, the geosphere and the affected biosphere. The "external" factors originate outside these boundaries; whereas the other factors in Table 1 can be considered as "internal" factors.

Table 1: FEPs Down to Level 2 (from Ref. 7)

FEP Number and Title	
1.	**EXTERNAL FACTORS**
1.1	Repository Issues
1.2	Geological Factors
1.3	Climatic Factors
1.4	Future Human Actions
1.5	Other External Factors
2.	**WASTE PACKAGE FACTORS**
2.1	Waste Package Characteristics
2.2	Waste Form Processes
2.3	Waste Container Processes
2.4	Contaminant Transport – Waste Package
3.	**REPOSITORY FACTORS**
3.1	Repository Characteristics
3.2	Repository Processes
3.3	Contaminant Transport – Repository
4.	**GEOSPHERE FACTORS**
4.1	Geosphere Characteristics
4.2	Geosphere Processes
4.3	Contaminant Transport - Geosphere
5.	**BIOSPHERE FACTORS**
5.1	Surface Environment
5.2	Human Behaviour
5.3	Contaminant Transport - Biosphere
5.4	Exposure Factors
6.	**CONTAMINANT FACTORS**
6.1	Contaminant Characteristics

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 behaviour of the repository system. If these External FEPs can significantly affect the evolution of the system and / or its safety functions of isolation and containment, they are considered scenario-generating FEPs in the sense that whether or not they occur (or the extent to which they occur or the form that they take) could define a particular future scenario that should be considered.

The External FEPs (see Ref. 5 and 7) were reviewed to identify those that are likely to occur and could potentially affect the repository and, therefore, should be included in the Normal Evolution Scenario. The repository is largely unaffected by many External FEPs, primarily due to its depth and associated geological characteristics. The main External FEPS that are likely to have a potential effect are:

- Placement of some containers with undetected defects;
- Glaciation and its effects;
- Earthquakes;
- Human influence on global climate; and
- Social and institutional developments leading to changes of land use at the repository site, and associated drilling, site development, etc.

The containers are robust and there are multiple inspection steps to ensure they are fabricated and placed correctly. However, with the large number of containers (12,778), it is possible that some containers could be placed in the repository with defects. Consequently, for the assessment of the Normal Evolution Scenario, it is assumed that some containers with undetected defects are present.

An important external influence is glaciation. Although glaciation is likely to cause major changes in the surface and near-surface environment, as discussed below, the repository itself is intentionally isolated from these changes by its depth. Glacial erosion at the hypothetical repository site, although slow, could progressively remove a fraction of the rock overlying the repository in the first one million years. Hence, glacial erosion is considered in the Normal Evolution Scenario; however, deep erosion is assumed not to be likely within this time frame for this hypothetical site and repository depth.

Finally, paleohydrogeologic simulations[4] indicate that glacial meltwaters will not reach the repository horizon due to the low hydraulic conductivity of the overlaying shales. Also, the glacial recharge penetrating below the shallow groundwater system (i.e., depths greater than 215 m) is not expected to be oxygenated or influence the redox conditions at the repository horizon. These simulations also show that the glacial perturbations did not materially change mass transport rates at the repository depth (i.e., diffusion remains the dominant transport mechanism). These characteristics of the repository site are used in the scenario identification.

Internal FEPs are important aids in defining the expected evolution of the repository. They assist in determining which features and processes are important to include in the conceptual model and related computer codes. The significant FEPs are accounted for in the description of the Normal Evolution Scenario. Internal FEPs are not usually scenario generating (i.e., their effect can be evaluated through different calculation cases for the Normal Evolution Scenario); however, for completeness, the potential for Internal FEPs to compromise the long term safety features were also considered in the identification of scenarios.[4,7]

The failure mechanisms identified in the FEPs review can be grouped into eight Disruptive Scenarios.[4,7] Since the long-term safety of the repository is based on the strength of the geosphere and engineered barriers (including the container and the shaft seals), the Disruptive Scenarios are typically based on circumstances in which these barriers might be significantly bypassed.

The following Disruptive Event Scenarios are identified as relevant to the hypothetical site and conceptual repository design for the Fifth Case Study:[4,7]

1. Inadvertent Human Intrusion,
2. All Containers Fail
3. Shaft Seal Failure,
4. Abandoned Repository,
5. Poorly Sealed Borehole,
6. Undetected Fault,
7. Severe Erosion, and
8. Container Failure.

Other potential Disruptive Scenarios were considered but ruled out on various grounds,[4] (e.g., no volcanic activity is anticipated in the area over the next one million years). Further confidence that an appropriate set of Disruptive Scenarios had been identified was obtained by reviewing the scenarios considered in assessments of deep repositories in other countries.[8,9,10] The results show that most assessments have identified a limited number of additional scenarios that consider the degradation / failure of engineered and natural barriers by natural processes (e.g., earthquakes, climate change) and human actions (e.g., drilling, poor quality control). Although there are some scenarios identified that are not considered in the current study, these are either not relevant to a Michigan Basin site (e.g., volcanic activity, sea-level rise, mining of resources) or have been included in the Normal Evolution Scenario (e.g., climate change, container failure).

Because of the limited scope of the current study, safety assessment calculations are done for only three disruptive scenarios: the Inadvertent Human Intrusion, All Containers Fail, and Shaft Seal Failure Scenarios. The safety assessment results for these three scenarios are described in this paper. The safety assessment results for the Normal Evolution Scenario are described in a companion paper.[11]

III. INADVERTENT HUMAN INTRUSION

The repository siting process will ensure that there are no known commercially viable natural resources at or below repository depth. Also, the repository panels have a small footprint (~6 km^2) and the repository is at a depth of 500 m. These factors limit the range of human activities that could directly affect the closed repository to a borehole unintentionally drilled into the repository as part of a future geological exploration program. Even this situation has a low probability of occurrence. Nevertheless, once controls on the use of the site are no longer effective, the possibility of inadvertent human intrusion by this method cannot be ruled out over long time scales.

The Inadvertent Human Intrusion Scenario considers the same evolution of the repository system as for the Normal Evolution Scenario with the only difference being the occurrence of human intrusion some time after institutional control of the site is no longer effective. In this scenario, an exploratory borehole is drilled through the geosphere and into the repository. The drill bit is assumed to intersect a used fuel container.

In an exploratory borehole, the investigators will most likely collect samples or conduct measurements at the repository level, which will readily identify any significant residual radioactivity (e.g., gamma logging is a standard borehole measurement). The investigators would then likely initiate appropriate precautions to prevent further exposure, including ensuring that any surface-released materials are appropriately disposed and that the borehole is sealed.

Thus, under normal drilling circumstances, there would be little impact. However, for conservatism, the Inadvertent Human Intrusion Scenario assumes that interception of the repository is not recognized and, therefore, no safety restrictions are imposed; and, the drill site is not managed according to current standards, and material from the borehole is released onto the surface.

The sequence of events leading to the Inadvertent Human Intrusion Scenario is as follows: (1) the repository records are lost; (2) there is drilling into the deep geosphere; and (3) the drilling breaches a used fuel container and used fuel is inadvertently brought to the surface.

This leads to exposure of the drill crew, exposed to contaminated drill slurry spread on the surface around the drill rig and to a core section containing used fuel, and a resident at the site, exposed by living nearby and growing food on soil contaminated by drill slurry. Similar exposure groups have been considered in recent inadvertent human intrusion safety assessments.[8,9,10]

The scope of the Fifth Case Study does not include the case in which the exploratory borehole is poorly sealed thereby resulting in a long-term pathway for contaminants to escape the repository. Such a case has been considered by SKB,[12] and this work shows the consequences are orders of magnitude less than the SKB maximum dose rate due to exposure to the used fuel brought to the surface during drilling.

III.A. Model and Assumptions

The radiological consequences are determined using HIMv2.0, a human intrusion computer model (see Ref. 13 for details and parameter values). HIMv2.0 models the acute dose to the drill crew at the time the material is brought to the surface and the annual chronic dose to residents who are assumed to live nearby and grow crops on the site after the intrusion has occurred.

In the Drill Crew exposure case, used fuel is brought to surface in the form of drill core and drill mud / slurry. Normal practice is for drill slurry to be contained at the site and ultimately be disposed of according to regulatory requirements. In this analysis, the drill slurry is conservatively assumed to be spilled around the drill rig without containment. The contaminated slurry would become mixed with surface material, as well as with subsequent drilled material. The waste is assumed to be uniformly mixed through a small near-surface volume of soil around the rig. The drill crew member handles the core sample containing used fuel for a short period of time, leading to an external exposure. The drill crew member is also exposed to the waste through groundshine, inhalation of contaminated dust and ingestion of contaminated soil from the mixed volume of near-surface material. The drill crew member does not wear a mask.

In the Resident exposure case, the waste brought up with the drill slurry and deposited on the surface around the drill rig is assumed to remain in place without remediation. It remains on the surface, subject only to radioactive decay and leaching (due to precipitation percolating through the soil). The resident lives around the contaminated site some time after the original intrusion, and grows some food on the contaminated soil. The resident is exposed to the contaminants through groundshine, dust inhalation and through ingestion of contaminated plants and soil. The area contaminated by drilling fluid would be small but have high contaminant concentrations, and therefore an allowance is made for the fraction of time that the resident is exposed to the contaminated site on an annual basis.

As a conservative estimate, the Resident case assumes that the exposure occurs in the first year after intrusion, before leaching has any significant effect on contaminant levels in the soil. Key assumptions in the calculations are:

- Institutional control is maintained for a minimum of 300 years after closure, at which point intrusion becomes possible;
- There is a minimum period of 70 years of extended monitoring and 25 years of decommissioning and closure following placement, which means the fuel is at least 425 years old at the earliest time of intrusion, assuming that 30-year old fuel is placed in the repository; and
- The drill intercepts a container in the repository and brings used fuel debris to the surface, either mixed with the drill slurry or as a section of intact drill core.

III.B. Results

Fig. 1 shows the acute dose to the Drill Crew and chronic annual dose to the Resident as a function of time after closure.

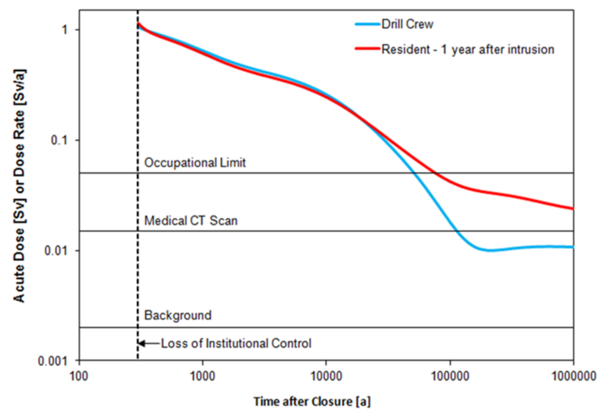

Fig. 1. Inadvertent Human Intrusion - Exposure as a Function of Intrusion Time

The exposure scenarios are stylized. They include all credible exposure pathways such that the overall dose estimate is credible, but not necessarily accurate. The results show:

- The maximum one-time dose to the Drill Crew is 1.06 Sv;
- The maximum annual chronic dose to the Resident in the first year after intrusion is 1.14 Sv;
- Doses decrease as a function of the assumed time of intrusion due to radioactive decay.

For the Drill Crew, ingestion and inhalation are the dominant exposure pathways for times less than 100,000 years, whereas groundshine dose dominates for longer times. For the Resident, ingestion and inhalation are also the dominant exposure pathways for times less than about 80,000 years; whereas groundshine and ingestion are the dominant exposure pathways for longer times. The dose for both groups tends to be dominated by Am-241 for the first 300 to 1000 years, by Pu-240 and Pu-239 from 10^3 to 10^5 years, and by the U-238 decay chain radionuclides for longer times. This is in contrast to the Normal Evolution Scenario in which actinides are slow to dissolve, sorb strongly in the repository and generally do not reach the surface.

For the Resident, the exposure could potentially occur any time after the used fuel is deposited on the surface, assuming the site is not remediated in the interim. Fig. 2 shows the dose to the Resident as a function of arrival time at the site, assuming the intrusion occurs at the earliest possible time after closure (i.e., 300 years).

The results show that leaching can cause a substantial reduction in dose at later times.

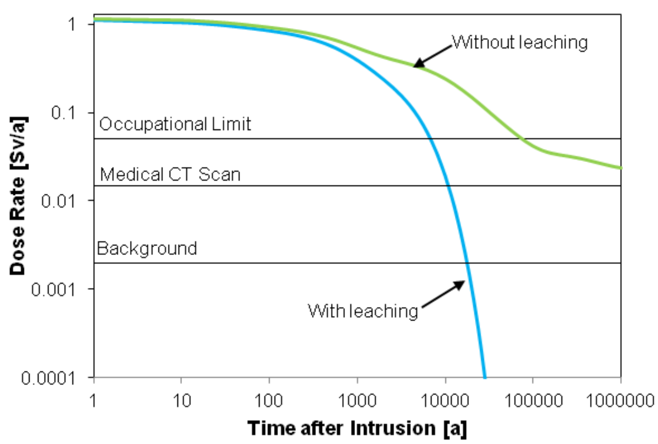

Fig. 2. Dose Rate to Resident as a Function of Arrival Times Assuming Intrusion Occurs 300 Years after Closure

To provide context for the dose rates, the annual risk to the Resident (R_R), the most exposed individual, was calculated using the equation:

$$R_R = Y \bullet H \bullet P$$

where Y = 0.057/Sv, the risk from fatal cancers or heritable effects per Sv of radiation exposure[14]; H is the highest calculated dose in the time period of concern; and P is the intrusion frequency.

The intrusion frequency was estimated using a simplistic approach in which only the frequency of drilling is considered. Specifically, given that the area around the repository has no significant mineral resources, a deep drilling frequency to resurvey or update the geological information of about once every 100 years is estimated. Assuming this surveys an area of 10 km × 10 km, this is a drilling frequency of 10^{-10} $m^{-2}a^{-1}$. Since the repository consists of 275 rooms, with each room having a projected area of 1030 m^2, the frequency of inadvertent human intrusion into a room can be estimated as 2.8×10^{-5} a^{-1}. This does not account for the container area being substantially less than the room area.

With H = 1.14 Sv and P = 2.8 x 10^{-5} a^{-1}, the annual risk to a Resident from an inadvertent human intrusion event is 1.8×10^{-6} a^{-1}. This is less than the risk target of 10^{-5}/a for disruptive scenarios selected for the 5CS.[4]

At long times, the cumulative probability of intrusion increases, but the consequences also decrease until eventually they are similar to those for inadvertent intrusion into a uranium ore body.

IV. ALL CONTAINERS FAIL

The long-lived used fuel containers are an important feature of the multi-barrier repository concept in this conceptual design. The reference copper containers are anticipated to last for a period of time in excess of one million years, based on their copper coating, sturdy mechanical design and favourable site attributes. Nevertheless, the All Containers Fail Scenario considers the hypothetical case in which all the containers fail early. Since the containers are durable and there is no identified mechanism to fail all containers, the base case considers failure at 60,000 years. This corresponds, for example, to the likely timeframe for an ice sheet to cover the site (see Ref. 2, Section 2), and it is possible that some unanticipated effect of the ice sheet might cause failure.

The sensitivity to earlier failure times is examined in a sensitivity case in which all containers are assumed to fail at 10,000 years.

The critical group and exposure pathways are the same as those considered in the Normal Evolution Scenario. In the Normal Evolution Scenario, the critical group is a self-sufficient farmer household growing crops and raising livestock on the surface above the repository. The critical group members spend all their lives in the local biosphere near the repository and obtain all their food, water, etc. from the local vicinity. Drinking and irrigation water for the critical group is obtained from a ~200 m deep well conservatively located in the Guelph Formation, a deep aquifer with somewhat saline water. The well pumping rate is sufficient for drinking water, domestic water uses, and irrigation of household crops.

The human exposure pathways include: ingestion of food (plants and animal products), water and soil; inhalation; groundshine; exposure to contaminated building materials; air immersion; and water immersion. The parameter values used in the calculation of the dose rates to the critical group are given in Ref. 15.

The surface biosphere has the characteristics of the Michigan Basin in Ontario. For the safety assessment calculations, a constant temperate climate is assumed. While the properties of the biosphere could vary with time due to, for example, glaciations; the assumption of a constant biosphere provides a convenient and clear measure of the potential impacts.

IV.A. Models and Assumptions

The dose assessment for the All Containers Fail Scenario is performed using the system model SYVAC3-CC4.[14] Groundwater flow rates are very low between the repository and the Guelph Formation (the well aquifer) so radionuclide transport is diffusion limited. All model parameters used in the All Containers Fail Scenario are identical to those in the Reference Case of the Normal Evolution Scenario except that:

- All 12,778 containers fail simultaneously;
- The radionuclide release model takes no credit for the presence of the container. As such, the release of radionuclides from the slowly dissolving fuel to the near field is limited only by the buffer properties; and
- The potential presence of a few containers with small initial defects is not included. This modelling simplification does not affect the peak dose rate.

IV.B. Results

Fig. 3 shows the dose rate for the base case in which all containers fail at 60,000 years. Also included for comparison is the dose rate for the Reference Case of the Normal Evolution Scenario. The maximum dose rate is 7.5×10^{-6} Sv/a, occurring at 10^7 years. The maximum is about 3750 times that of the Reference Case, but remains a factor of 130 below the dose acceptance criterion of 10^{-3} Sv/a.

Note that figures are shown with shading at times greater than 10^6 years to emphasize that these results are illustrative and included only to indicate maximum impacts. Shading for dose rates below 10^{-9} Sv/a indicates these values are negligible and are included to indicate trends.

Fig. 4 shows the dose contributions from the most significant radionuclides. As in the Reference Case, I-129 is the dominant contributor.

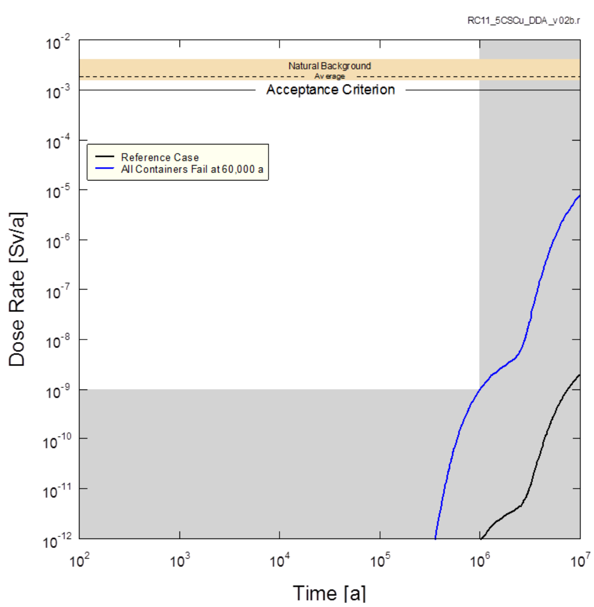

Fig. 3. All Containers Fail at 60,000 Years - Dose Rate

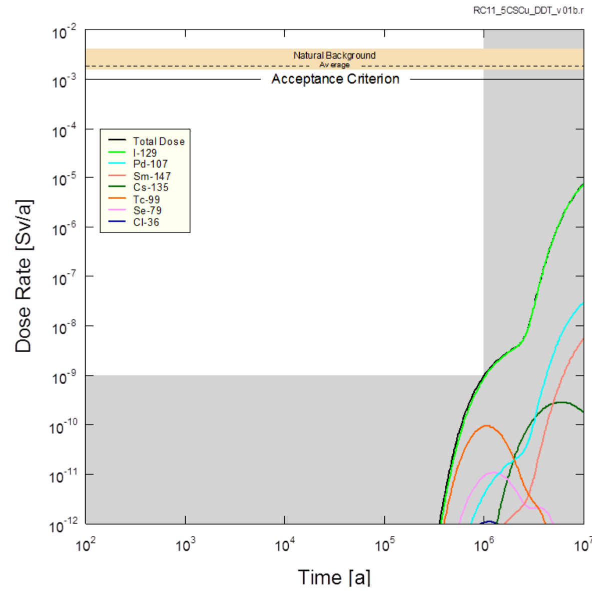

Fig. 4. All Containers Fail at 60,000 Years – Contributing Radionuclides

Fig. 5 compares the dose rate for the sensitivity case in which all containers fail at 10,000 years with results for the base case in which all containers fail at 60,000 years. The results are not substantially different, with a maximum dose rate of 8.4×10^{-6} Sv/a (or 1.1 times the base case value) occurring at 10^7 years. The increase in dose rate occurs as a result of less time being available for radioactive decay.

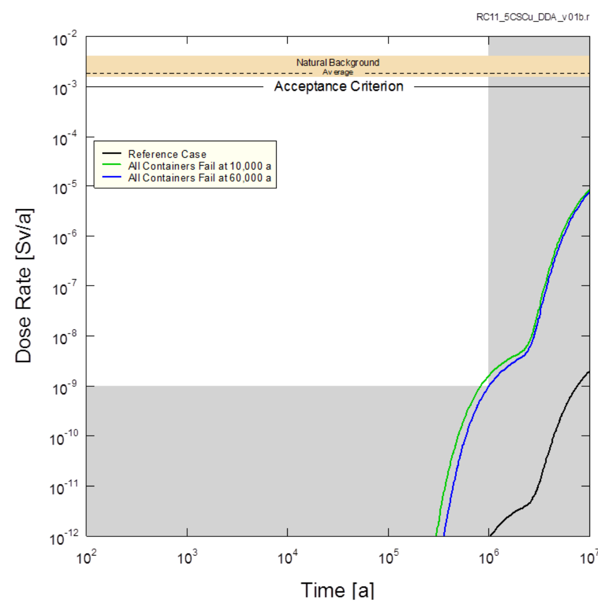

Fig. 5. Sensitivity Case- All Containers Fail at 10,000 Years - Dose Rate

V. SHAFT SEAL FAILURE

The three repository shafts (~8 m diameter) represent a potentially important pathway for contaminant release and therefore the repository design includes specific measures to provide good shaft seals (e.g., placement of shafts away from the waste panels and use of composite seals). The Normal Evolution Scenario considers the likely behaviour of the shaft seals and the repository / shaft excavation damage zones. The Shaft Seal Failure Scenario considers the same evolution of the repository system and the same exposure pathways as the Reference Case of the Normal Evolution Scenario except that rapid and extensive degradation of the shaft seals is assumed. For conservatism, it is assumed that this degradation occurs at the time of repository closure.

V.A. Model Assumptions

Analysis of the Shaft Seal Failure Scenario is performed using FRAC3DVS-OPG, a 3-dimensional groundwater flow and contaminant transport model.[14] This model is used in lieu of the SYVAC3-CC4 system model because the groundwater flow field in the repository and near-field geosphere could be affected by the degradation of the shaft seals and SYVAC3-CC4 does not model the groundwater flow field. Consequently, for this scenario, dose rates to the critical group are not calculated and the impact of this scenario is assessed by comparison of the I-129 mass flows to the well for this scenario with the corresponding values for the Normal Evolution Scenario. This is considered appropriate because I-129 is the dominant contributor to the total dose rate received by the critical group and the well is the dominant exposure pathway.

All model parameters are the same as in the Reference Case of the Normal Evolution Scenario, except that the hydraulic conductivity of all shaft seal materials is set to a high value. Two simulations have been performed: a base case in which the seal hydraulic conductivities are set to 1.0×10^{-9} m/s, about 2 order of magnitude higher than in the Normal Evolution Scenario, and an extreme case in which the hydraulic conductivities are set to 1.0×10^{-7} m/s. The locations of the defective containers and the well have not been changed. This implies that the analysis may not result in the most conservative consequence and therefore the results should be considered illustrative only. For a real candidate site, these locations would be varied to ensure the most conservative locations are selected.

V.B. Results

The results for I-129 transport to the well are shown in Fig. 6. Only the results for the extreme case are shown. The results show no perceptible difference from the Reference Case of the Normal Evolution Scenario. This is due to a combination of the distance of the defective containers to the shaft, the direction of groundwater flow, the low hydraulic conductivity of the host rock, and the effectiveness of the other intact seals.

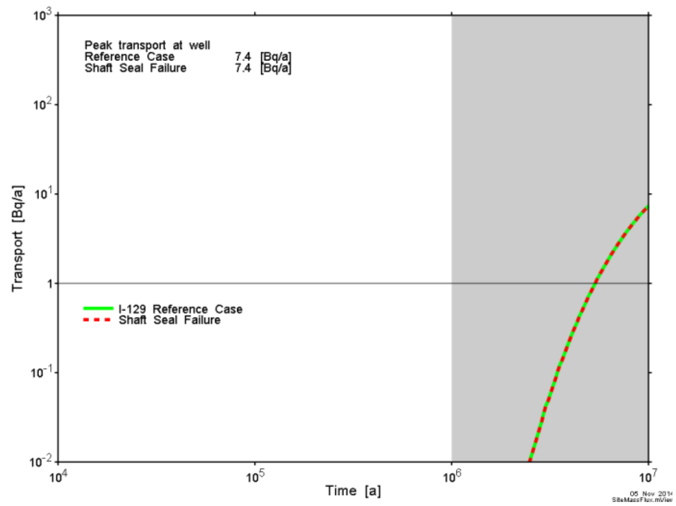

Fig. 6. I-129 Transport to the Well for Shaft Seal Failure Scenario.

VI. SUMMARY AND CONCLUSIONS

For the Inadvertent Human Intrusion Scenario, peak doses are approximately 1 Sv, mainly because intrusion bypasses all barriers and used fuel is brought to the surface. However, the risk of inadvertent intrusion is minimized by placing the used fuel deep underground in a location with no mineral resources. Based on simple estimates of deep drilling rates, the risk to a future Resident is estimated to be lower than a reference risk criterion of 10^{-5} per annum.

The All Containers Fail Scenario leads to calculated peak dose rates slightly below the criterion of 10^{-3} Sv/a for disruptive events (i.e., 5.8×10^{-4} Sv/a) for failure of all containers at 60,000 years and somewhat larger if failure occurs at 10,000 years. The probability of such a scenario is expected to be low because of the ability of the container to withstand both chemical and mechanical disturbances.

For the Shaft Seal Failure Scenario, the calculated dose rates are similar to those for the Reference Case of the Normal Evolution Scenario. This is in part because of the nature of the geosphere around the repository, and in part because of the assumed location of the three failed containers (i.e., the failed container location was selected to maximize radionuclide transport to the well under Normal Evolution).

Although the analyses are not as comprehensive as required for a licence application, these results indicate that this repository system is reasonably robust to disruptive scenarios. The results identify factors that would need to be considered in more detail in further assessments.

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