Assessment of Disruptive Scenarios of a Canadian Used Fuel Repository in Crystalline Rock

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Abstract

The NWMO has recently extended its modelling capabilities by performing simulations for four disruptive scenarios that, to date, have not yet been examined in detail. These scenarios complement those considered in an existing postclosure safety assessment for a conceptual geological repository located in a hypothetical crystalline rock formation. The four new disruptive scenarios are: Shaft Seal Failure, Undetected Fault, Open or Poorly Sealed Borehole and Open Borehole Due to Inadvertent Human Intrusion. All simulations are based on the FRAC3DVS-OPG [1] Site-Scale Model [2]. The Site-Scale Model includes a simplified representation of the full repository and a portion of the surrounding sub-regional flow system. All transport simulations are performed with only the radionuclide I-129. Transport rates to the surface and a domestic water supply well are compared to the Reference Case results from an earlier case study documented in Reference [2].

1. Introduction

A postclosure safety assessment of a conceptual deep geological repository for used CANDU fuel at a hypothetical crystalline rock site in the Canadian Shield is documented in Reference [2]. It considers a repository at a depth of approximately 500m in a crystalline rock geosphere containing a network of fractures. The repository holds 4.6 million used fuel bundles in roughly 12,800 durable steel and copper IV-25 containers. The containers are placed in an in-floor configuration and all placement rooms, tunnels and shafts in the repository are backfilled with engineered sealing materials containing swelling montmorillonite rich clay called Bentonite. Figure 1 shows the conceptual repository design.

The purpose of a postclosure safety assessment is to determine the potential effects of the repository on the health and safety of persons and the environment. A one million year baseline is adopted as the timescale of interest based on the time needed for the used fuel radioactivity to decay to essentially the same level as that in an equivalent amount of natural uranium. However, postclosure safety assessment simulations are typically extended to 10 million years due to the low transport properties of the rock and to ensure peak doses are captured.

The postclosure safety assessment has been developed following regulatory guidance in CNSC G-320 [3] and is assessed through consideration of a set of potential future scenarios, where a scenario is a postulated or assumed set of conditions or events. In this way, a comprehensive range of possible future evolutions are examined against which the performance of the system can be assessed. Both Normal Evolution and Disruptive Event Scenarios are considered.

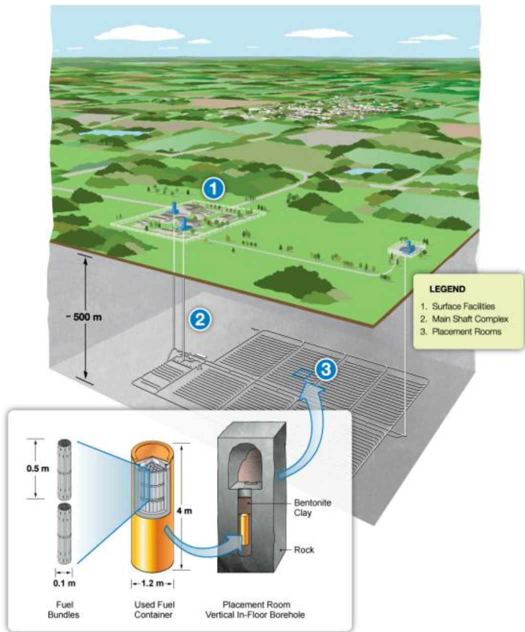

Figure 1: Conceptual Crystalline Rock Repository Design with IV-25 Containers

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. Since glaciation is expected to occur in the future, the Normal Evolution Scenario also includes a discussion of the effect of glaciation on calculated impacts [4]. The Reference Normal Evolution Scenario assumes the presence of a few containers with undetected manufacturing defects.

Disruptive Event Scenarios examine the effects of unlikely events that might lead to penetration of barriers, including the geosphere, and abnormal degradation and loss of containment. The disruptive scenarios of interest for the postclosure safety assessment in crystalline rock were identified following the procedure described in the next section.

2. 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. These factors can be further categorized into Features, Events and Processes (FEPs) which are discussed in detail in [5]. 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 those which originate inside these boundaries can be considered as "internal" factors.

The failure mechanism identified in the FEPs review [5] can be grouped into seven Disruptive Scenarios. Since the long-term safety of the repository is based on the strength of the geosphere and the engineered barriers (including the container and the shaft seals), the Disruptive Scenarios are typically based on circumstances in which these barriers might be significantly degraded or bypassed. The following Disruptive Event Scenarios have been identified as relevant to the hypothetical site and conceptual repository design:

1. Inadvertent Human Intrusion;
2. Open or Poorly Sealed Borehole;
3. Shaft Seal Failure;
4. Fracture Seal Failure;
5. Undetected Fracture or Fault;
6. Container Failure; and
7. All Containers Fail.

Disruptive Scenarios 1, 4, 6 and 7 were analyzed and documented in NWMO (2012). Scenario 3 was also analyzed in NWMO (2012) but in a simplistic manner and it has therefore been re-examined. The following Disruptive Scenarios are analyzed in this work:

1. Shaft Seal Failure;
2. Undetected Fault;
3. Open or Poorly Sealed Borehole; and
4. Open Borehole Due to Inadvertent Human Intrusion.

3. Reference Case Model Description

The Reference Case assumes three IV-25 containers are placed in the repository with small undetected manufacturing defects. Radionuclides are released from the defective containers once the repository has resaturated and the defective containers have filled with water (conservatively assumed to occur 100 years after closure). The defective containers are assumed to be placed in the location with the shortest transport time and the maximum radionuclide transport rate to a domestic water well. The water well is located in the position that maximizes uptake of the contaminant plume associated with the defective containers. The well pumps at a rate of 911 m^3/a, a rate sufficient to support the water demand of a self-sufficient farming family assumed to be living at the site. Doses to the self-sufficient farming family are dominated by I-129 and calculated using a variety of dose pathways. Reference [6] describes the Reference Case repository, geosphere material properties (e.g., porosity, permeability), radionuclide transport properties (e.g., sorption), and biosphere data. These same data are used in this assessment.

In this work, all Disruptive Scenario simulations were carried out using the finite-element, finite difference code FRAC3DVS-OPG [1] and are perturbations of the existing Reference Case Site-Scale Model documented in Reference [2]. The model domain contains a simplified representation of the full repository and a portion of the surrounding sub-regional flow system. Individual containers are not represented. The FRAC3DVS-OPG model domain consists of the repository footprint together with approximately 1500 m of surrounding geosphere that encompasses the repository influenced flow domain. Figure 2 shows the coordinate system and model boundaries. It also shows the projected particle tracks that illustrate the potential advective transport pathways for contaminants released from the repository. This information shows that the model domain includes all major discharge points. The primary discharges include the domestic water well, a river (shown below the repository in Figure 2), a lake (overlaying the bottom right corner of the repository in Figure 2) as well as wetlands near the repository location.

I-129 was the only radionuclide considered in the FRAC3DVS-OPG simulations as it was found to be the dominant dose contributor in all Normal Evolution and Disruptive Scenarios. This is because I-129 has a sizeable initial inventory, a non-zero instant release fraction, a very long half-life, is non-sorbing in the buffer, backfill and geosphere and has a radiological impact on humans.

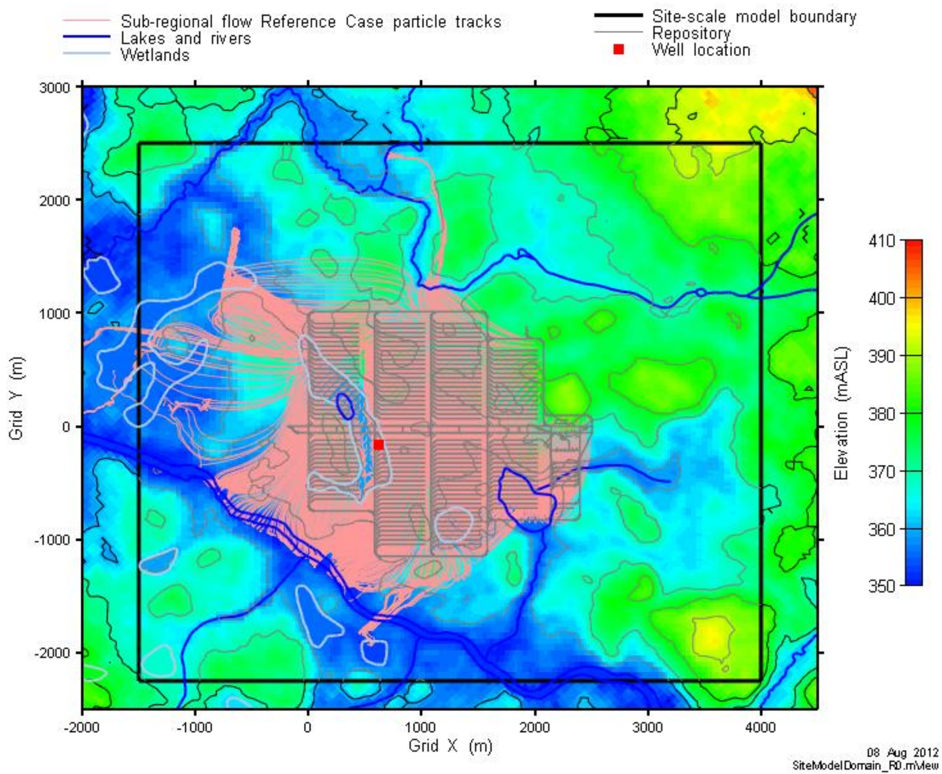

Figure 2: Site-Scale Model: Coordinate System and Domain Boundary

4. Shaft Seal Failure

The Shaft Seal Failure Disruptive Scenario simulations were run to determine the effects of degraded or failed shaft seals on the contaminant transport rates to the surface. In the conceptual repository, three shafts (main, service and ventilation) penetrate the geosphere. These shafts are placed away from the placement rooms and carefully sealed. The shaft seals consist of a low heat high performance concrete monolith at the base, a keyed in concrete bulkhead and a concrete capstone separated by layers of 70:30 bentonite clay:sand mix, and asphalt (Figure 3). The shafts are assumed to be surrounded by two regions of rock with increased transport properties that have been damaged by the shaft sinking process known as the inner and outer excavation damaged zone (EDZ).

The Shaft Seal Failure Scenario considers the possibility that the shaft seals are not fabricated or installed appropriately, or that the long-term performance of the shaft seals and shaft/repository Excavation Damage Zones (EDZ) is poor due to unexpected physical, chemical and/or biological processes. While either situation could result in an enhanced permeability pathway to the surface, both are very unlikely due to quality control measures that will be applied during shaft seal closure and due to the adoption of multiple durable material layers in the shaft.

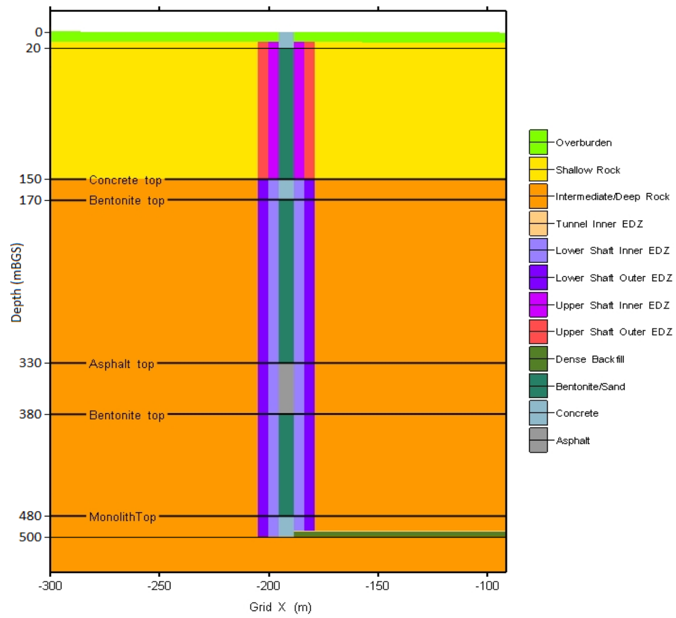

Figure 3: Ventilation Shaft Seal Design

4.1 Model Assumptions

The Shaft Seal Failure Disruptive Scenario focusses on a ventilation shaft, the shaft closest to the failed containers. A variety of Shaft Seal Failure cases were analyzed. The first case examined was the Base Case, which is identical in all aspects to the Reference Case described in Section 2 except that the domestic water well was relocated to be entirely within the ventilation shaft.

The first set of cases examined the effect of degradation in the individual shaft sealing materials. The Asphalt Seal Failure Case looks at the effect of increasing the hydraulic conductivity of the asphalt seal from 10^{-12} m/s to 10^{-9} m/s (10^{-9} m/s is roughly equivalent to sandstone) and the Concrete/Bentonite Failure Case examines the effect of increasing the hydraulic conductivity of the concrete and bentonite-sand seals from 10^{-10} m/s and 4.8×10^{-13} m/s respectively to 10^{-9} m/s.

A second set of cases examined the effect of degradation in all the shaft seal materials. In the Damaged Seals Case all the materials in the shaft are assumed to be degraded and are modelled as a single material with a conductivity of 10^{-9} m/s and a porosity equivalent to the bentonite-sand seal (0.411). The Extremely Damaged Seals Case takes this one step further and increases the hydraulic conductivity of the seals by an additional factor of 100 over the Damaged Seals Case to 10^{-7} m/s (10^{-7} m/s is roughly equivalent to fine sand).

The third set of cases examined the influence of increasing the EDZ permeability in the repository and the shaft (EDZ Failure Case) and the combined effect of the increased EDZ conductivity and degraded shaft materials (EDZ/Shaft Failure Case). The EDZ Failure Case assumes the EDZ permeabilities are 100 times greater than in the Reference Case and the EDZ/Shaft Failure Case assumes the EDZ permeabilities are 100 times greater than in the Reference Case. The shaft seals are modelled as a single material with a hydraulic conductivity of 10^{-7} m/s and a porosity of 0.411.

4.2 Results

Figure 4 shows the transport rate to surface discharge zones for all cases described in Section 4.1 together with the Reference Case described in Section 2 for comparison. Relative to the Reference Case all of the shaft failure cases have lower peak I-129 transport rates to the surface. The reason for this is that the fracture that contains the well in the Reference Case is closer to the failed containers than the ventilation (closest) shaft. Like the Reference Case, the overwhelming majority of the transport to the surface for all the shaft failure cases occurs through the well with almost no discharge to the river or other surface discharge locations.

Figure 4 shows the peak transport rates to the surface for the Base Case, the Asphalt Seal Failure Case, the Concrete/Bentonite Seal Failure Case, and the Damaged Seals Case all produce very similar results. The Extremely Damaged Seals Case is similar but with a slightly higher peak transport rate than the previously mentioned cases. The EDZ Failure and the EDZ/Shaft Seal Failure Cases allow relatively fast transport through the repository excavation damage zones to the shaft and as a result produce the highest I-129 peak transport rates of all the Shaft Seal Failure Scenarios. However, these results are still less than those associated with the Reference Case due to the shorter overall transport path in the Reference Case.

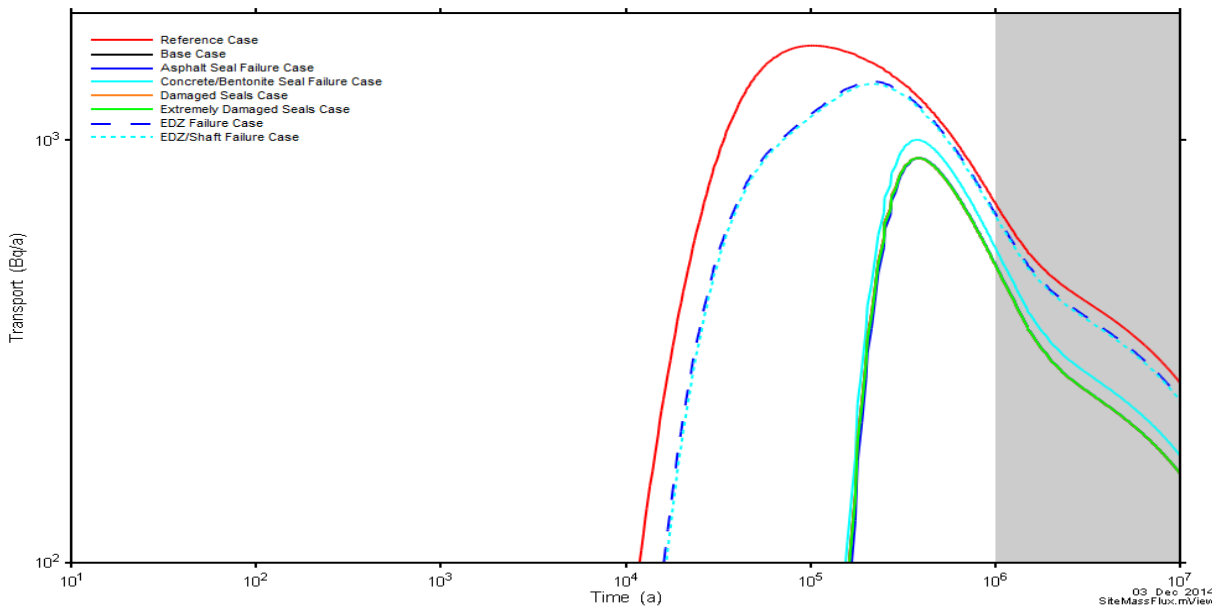

Figure 4: I-129 Well Transport Rate for All Shaft Seal Failure Sensitivity Cases

5. Undetected Fault

The Undetected Fault Disruptive Scenario assumes a vertical fault is located adjacent and parallel to the placement room containing the defective containers. The undetected fault through the repository footprint (see Figure 5) effectively bypasses the geosphere barrier and allows transport of radionuclides to the surface via the fault.

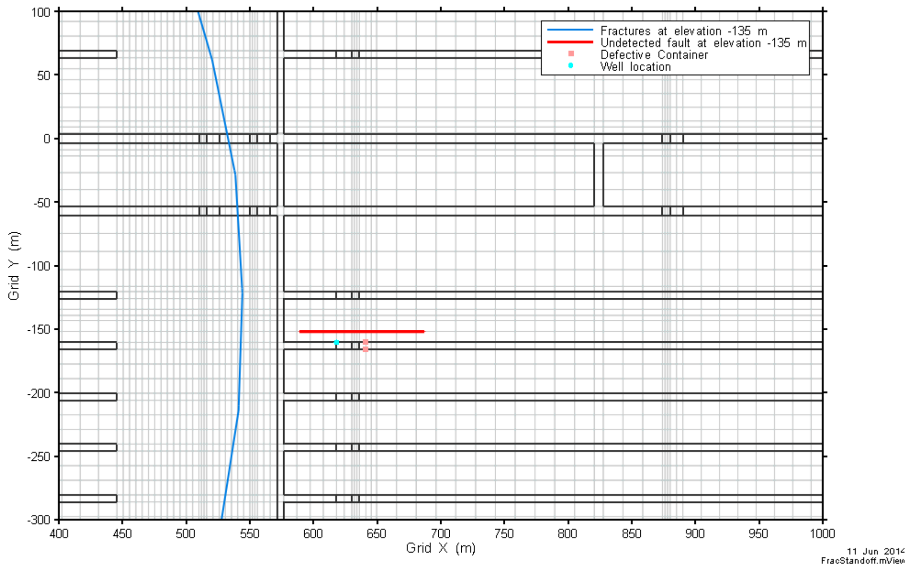

Figure 5: Undetected Fault Location

5.1 Model Assumptions

The undetected fault is defined as a vertical fault adjacent and parallel to the placement room containing the defective containers. The fault is located 10m from the placement room wall, and is 100m long, beginning 10m from the cross-cut drift wall and extending past the defective containers. Vertically the fault extends from 100m below the repository to the surface, with an elliptical shape increasing with elevation as is characteristic for vertical faults. The fault intersects the fracture containing the Reference Case well. As the Reference Case well is almost directly above the room containing the defective container, the Reference Case well is 10 m from the undetected fault.

Several Undetected Fault cases were simulated to investigate the effect of an undetected fault with a variety of transport properties and well locations. The first case investigated was the Base Case in which all the model parameters are identical to the Reference Case values. The fault was assigned the same transport properties as the other fractures present in the geosphere (hydraulic conductivity of 10^{-6} m/s and a porosity of 0.1).

The two sensitivity cases examined the effect of fault hydraulic conductivity. In the Low Conductivity Case the fault conductivity was reduced by a factor of 10 to 10^{-7} m/s and in the High Conductivity Case the fault conductivity was increased to 10^{-5} m/s. All other model parameters remained at the Reference Case values. Another sensitivity case studied the influence of the well location on the transport rate to the surface. In this case, known as the Fault Well Case, the well was relocated from its Reference Case location to a location intersecting the Undetected Fault as close to the failed containers as possible. The final sensitivity case, the Well/High Conductivity Case, examined the combined influence of the modified well location from the Fault Well Case and the increased fault conductivity from the High Conductivity Case.

5.2 Results

The undetected fault provides a transport pathway to the surface similar to the nearby fracture in the Reference Case. However, since the undetected fault is slightly closer to the failed containers than the Reference Case fracture, the peak transport rates for the undetected fault pathway occur roughly 30,000 years earlier. As in the Reference Case, the well is the primary discharge location, with very little mass reaching the other surface discharge locations in all variant cases except for those with increased hydraulic conductivity (i.e., High Conductivity and Well/High Conductivity Cases).

Figure 6 provides the total I-129 transport rate to the surface for the Undetected Fault Cases and the Reference Case described in Section 2. The peak I-129 transport rates are effectively the same between the Undetected Fault Cases and the Reference Case for most cases. Only the cases with increased hydraulic conductivity showed a slight increase in the peak transport rate to the surface. The cases with increased hydraulic conductivity are also unique in that a significant portion of the surface discharge is not captured by the well and is discharged into the river discharge. This is because the very high conductivity in the fault limits the influence of the well to the near-surface flow system and results in the well drawing in a significant quantity of fresh water.

Moving the well location to within the undetected fault has little effect on transport rates to the surface. This is not surprising given that the undetected fault intersects the same fracture where the well is located in the Reference Case. Lowering the conductivity in the undetected fault slowed the response to the well slightly and increased the transport time to the surface by roughly 7,500 years compared to the other Undetected Fault cases.

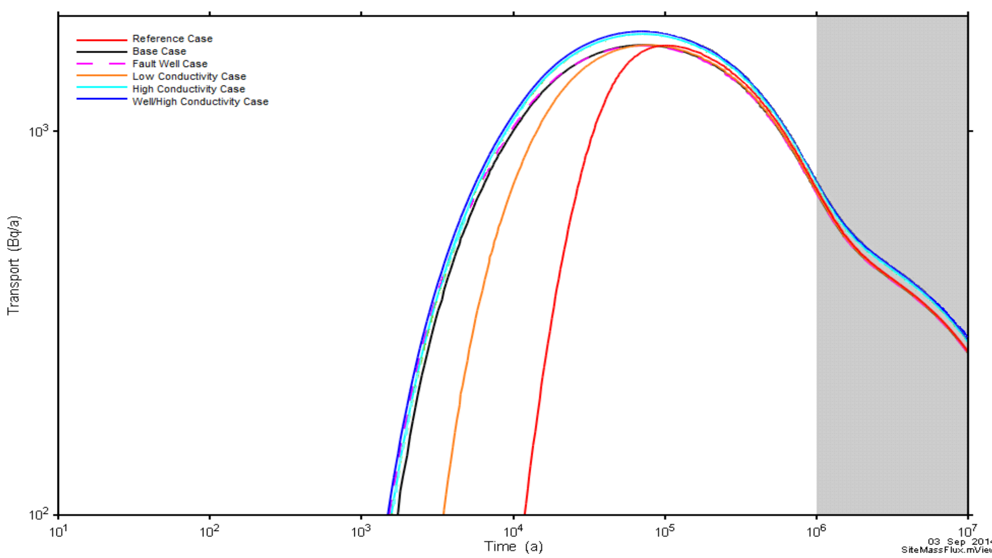

Figure 6: I-129 Total (Well and Surface Discharge) Transport Rate For all Undetected Fault Cases

6. Open or Poorly Sealed Borehole

In the Open or Poorly Sealed Borehole scenario, the impact of an undetected, improperly sealed or abandoned exploration borehole, site exploration borehole or site monitoring borehole is assessed. These boreholes are located in the vicinity of the repository and may penetrate to below repository depth. These boreholes will be sealed on completion of site investigation or monitoring activities so they will not have any effect on repository performance. However, if a deep borehole were not properly sealed or if the seal was to extensively degrade, then it could provide a small but relatively permeable pathway for the migration of contaminants. Such a situation is very unlikely due to the adoption of good engineering practice and quality control.

6.1 Model Assumptions

This scenario explores the effects of incompletely sealed or unsealed boreholes. Three unique boreholes case are examined:

1. Exploration Borehole Case;
2. Site Characterization Borehole Case; and
3. Monitoring Borehole Case.

The Exploration Borehole Case assumes a vertical borehole with a hydraulic conductivity of 10^{-4} m/s and a porosity of 0.25 that has been drilled next to the defective container to a depth of 500m (i.e., the elevation of the repository floor). The borehole is arbitrarily offset 10m from the wall of the placement room, similar to the Undetected Fault Case. The borehole intersects a fracture with connections to the Reference Case well. The water supply well is located at the Reference Case location.

The Site Characterization Borehole Case assumes a vertical borehole with a hydraulic conductivity of 10^{-4} m/s that is located within the repository footprint near the defective container and extends to repository depth. The borehole does not intersect a fracture and the discharge to the surface is assessed. The water supply well is located at the Reference Case location.

The Monitoring Borehole Case assumed an improperly sealed or abandoned site monitoring borehole with a hydraulic conductivity of 10^{-4} m/s located 50m outside the site footprint extending to repository depth. In this case the defective containers are conservatively relocated to the closest placement room location upgradient from the borehole. The water supply well is also conservatively relocated to intersect the same fracture as the monitoring borehole.

6.2 Results

Figure 7 provides the total transport rate to the surface for the various Open or Poorly Sealed Borehole cases. The only case with I-129 transport rates exceeding those of the Reference Case is the Exploration Borehole Case. This case resulted in earlier and slightly higher I-129 transport rates to the surface because the borehole was located closer to the failed containers than the fracture containing the well. The Site Characterization Borehole Case had no influence on the transport rates and results were identical to the Reference Case. The monitoring borehole transport rates were significantly lower than the Reference Case primarily because of the increased distance between of the failed containers to the well relative to the Reference Case.

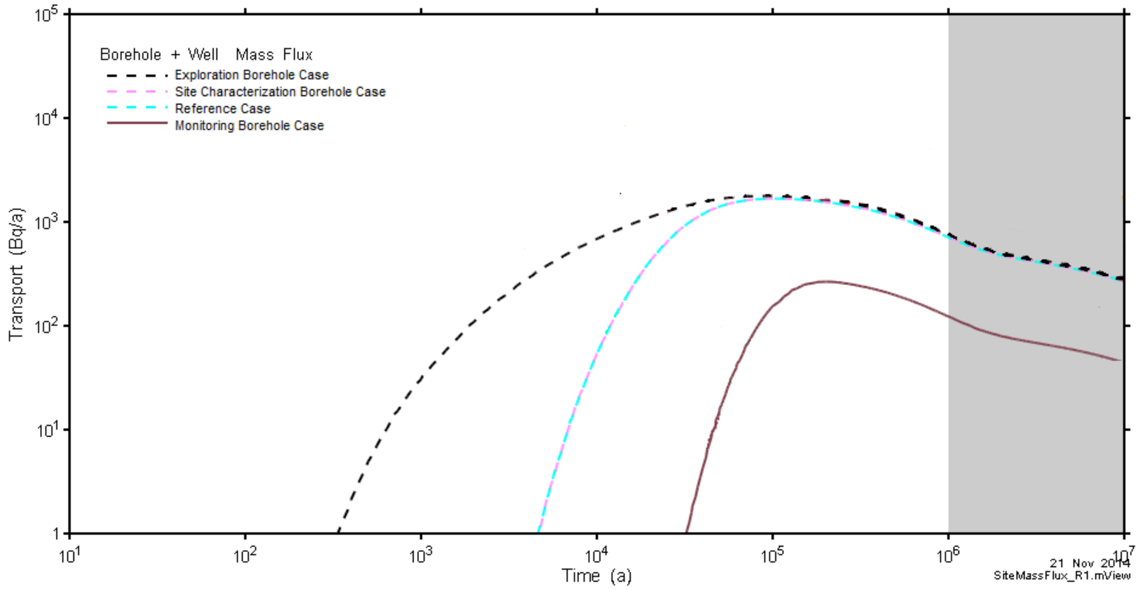

Figure 7: I-129 Total Transport Rate (Reference Case Well + Borehole) for Borehole Cases Compared with Reference Case Well

7. Open Borehole Due to Inadvertent Human Intrusion

The Inadvertent Human Intrusion scenario considers an exploration borehole drilled into the repository, intersecting a used fuel container, and subsequently abandoned without any sealing or attempt at closure. Human intrusion results in the immediate release of contaminants from the damaged container; the scenarios presented here are intended to bound possible transport and dose consequences.

The effects of bringing fuel directly to the surface are separately assessed [2] and not discussed here. This work only examines the consequences assuming the borehole is not sealed.

7.1 Model Assumptions

The open Human Intrusion Borehole is assumed to intersect both the container in the location of one of the Reference Case defective containers and the fracture containing the water supply well. The borehole is simulated as a well line element with 10^{-4} m/s hydraulic conductivity and a porosity of 0.25.

In this case, the borehole bypasses all geological and engineered barriers and intersects the container. Doses resulting from this scenario may have significant contributions from species other than I-129. As a result, transport modelling was performed using a fixed unit concentration source at the defective container location to assess the contaminant uptake by the well over the entire simulation time. A fixed unit concentration source facilitates the dose calculation through scaling the results of the fixed unit source to other radionuclides.

Two cases were simulated to assess the effects. The Base Case used the Reference Case well location and the Variant Case used the borehole as the water supply well.

7.2 Results

Figure 8 shows the well transport rates for the Base Case and the Variant Case compared to the Reference Case (using a fixed unit concentration source). The contaminant input for each case varies depending on the ability of the flow field to reduce concentrations near the fixed-concentration source. In the Reference Case and the Base Case, the well captures the vast majority of the source contaminant and there is essentially no transport to the other surface discharge locations. In the Variant Case, the well is also the dominant transport pathway to the surface; however, there is a non-negligible release to the other surface discharge locations.

In the Base Case, the open borehole provides a permeable pathway intersecting the fracture containing the well and greater transport occurs compared to the Variant Case. With the borehole acting as a well, the distribution of the well pumping rate along the whole length of the borehole and the lack of a well casing reduces the effect of the pumping on the flow field at depth. Consequently, some I-129 reaches other surface discharge locations. For the Variant Case, the transport rate to the well is almost the same as in the Reference Case and for the Base Case the transport rate to the well is approximately 3.5 times greater than for the Reference Case.

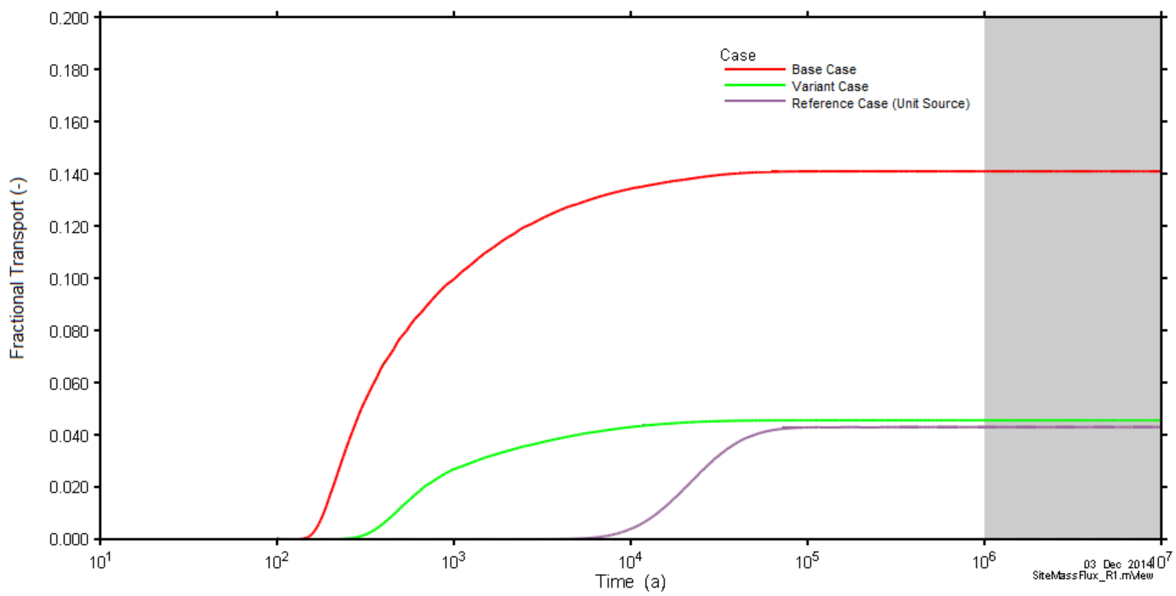

Figure 8: Open Human Intrusion Borehole Discharge Concentration

8. Conclusions

Four new Disruptive Scenarios in addition to those presented in [2] are assessed in this work:

1. Shaft Seal Failure;

2. Undetected Fault;
3. Open or Poorly Sealed Borehole; and
4. Open Borehole Due to Inadvertent Human Intrusion.

Many of the Disruptive Scenario cases emphasize the importance of a permeable feature near the location of the defective containers. In the Reference Case, this permeable feature is the vertical fracture containing the Reference Case well. If the disruptive scenario defined a permeable feature farther from the defective container than in the Reference Case fracture and well, such as in the Shaft Seal Failure Case, the resulting radionuclide transport rates would be lower than for the Reference Case. The Undetected Fault and Poorly or Open Borehole Cases (including Human Intrusion) added new permeable features closer to the defective containers than the Reference Case fracture and well which allowed for more rapid radionuclide transport to the surface discharge locations than in the Reference Case. The well was found to capture nearly all of the transport to the surface for most scenarios highlighting its importance. Only in cases where the permeable feature was assumed to have a high hydraulic conductivity were the other surface discharge zones found to have a significant contribution to the total transport to the surface.

In the future, the NWMO will continue to develop its scenario identification process as well as refine its models and approaches for the investigation of Disruptive Events as more site specific and repository design data becomes available.

9. References

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