Status Report on Generic Granite System Model Improvements

Fuel Cycle Research & Development

Prepared for
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Used Fuel Disposition
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Appendix E
FCT Document Cover Sheet

Name/Title of Deliverable/Milestone	LANL input to SNL L2 MS: Report describing the generic granite system model improvements (report entitled - " Status Report on Generic Granite System Model Improvements")
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This deliverable was prepared in accordance with Los Alamos National Laboratory
(Participant/National Laboratory Name)

QA program which meets the requirements of
☒ DOE Order 414.1 ☐ NQA-1-2000

This Deliverable was subjected to:

☐ Technical Review	☐ Peer Review
Technical Review (TR)	**Peer Review (PR)**
Review Documentation Provided	**Review Documentation Provided**
☐ Signed TR Report or,	☐ Signed PR Report or,
☐ Signed TR Concurrence Sheet or,	☐ Signed PR Concurrence Sheet or,
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USED FUEL DISPOSITION

STATUS REPORT ON GENERIC GRANITE SYSTEM MODEL IMPROVEMENTS

1. INTRODUCTION

This report discusses the model improvement and sensitivity analysis conducted for the granite Generic Disposal System Environment (GDSE) model described in UFD FY11 report [1]. The computer codes used for this study are: GoldSim (version 10.5) [2] and The Finite Element Heat and Mass Transfer (FEHM) code (version 3.0) [3, 4]. The report includes three main parts: 1) the improvement to the FY11 version of granite GDSE model for the safety case study; 2) improvement to the granite GDSE model by incorporating multiple fracture pathways; 3) sensitivity study of the impact of continental glaciation on radionuclide transport from the granite repository. Monte Carlo simulations with the combined near- and far-field transport models are performed, and the model input parameter sensitivities are evaluated. The dose rates for a subset of radionuclides that could be potentially important to repository performance are calculated. The analyses are conducted for undisturbed radionuclide release scenario.

2. MODEL DESCRIPTION

The granite GDSE model is composed of two major subsystems, the near field and the far field. The near field subsystem encompasses waste form and the EBS (Engineered Barrier System) and the interface with, and the adjacent portion of, the host rock; it includes:

- Repository layout and waste package (WP) configurations
- Radionuclide inventory and waste form degradation
- Solubility control and radionuclide release from waste panels
- Solubility control at the near-field and far-field interface

Current version of the model considered two radionuclide release scenarios:

- Disturbed - Human intrusion
- Undisturbed - Diffusion through bentonite buffer

The far-field component represents contaminant transport through the natural system from the near field host rock to 100s or 1000s of meters; it includes:

- Radionuclide decay and ingrowth
- Advection (RTD residence time distribution-based transport model to enable the study of potentially very heterogeneous domains)
- Matrix diffusion (GDPM generalized dual porosity model, diffusive exchange between flowing porosity and surrounding rock matrix)
- Sorption

The model assumes that the repository is located in a saturated, chemically-reducing environment below the water table. The repository is assumed to have a square footprint with 25 m spacing between emplacement tunnels and 6 m between waste packages. The options for the waste stream being considered are used nuclear fuel (UNF) and high-level radioactive waste (HLW). Types of HLW include DOE high-level radioactive waste (DHLW) and commercial high-level radioactive waste (CHLW) generated from hypothetical reprocessing of commercial UNF. The waste types included in this report are UNF and DHLW. The near-field model radionuclide inventory analysis was based on the detailed fuel cycle waste inventory analysis conducted for the UFD project [5]. The current version of the near-field model does not consider performance of waste package and Excavation Damage Zone (EDZ).

The FEHM code was coupled into the GoldSim system level model to represent the far field component [6]. The far-field component of the granite GDSE model consists of radionuclide decay and in-growth, advection, matrix diffusion, and sorption, all features that are implemented using FEHM's reactive transport modeling capability.

Two scenarios are considered for radionuclide release from granite GDSE: the disturbed case and the undisturbed case. The disturbed case represents a non-nominal process that provides a fast pathway for radionuclide release to the far-field from the GDSE, and is modeled with a stylized human intrusion. The undisturbed case releases radionuclides by a sequence of nominal processes that are expected to occur in a generic repository. Diffusion through bentonite buffer is considered as one potential undisturbed release scenario. For this report study, the undisturbed scenario is considered.

A hypothetical biosphere (the performance measure boundary) is assumed to be located 5 km from the repository edge. IAEA BIOMASS Example Reference Biosphere 1B (ERB1B) dose model is used to convert the output radionuclide concentrations in the ground water at the hypothetical drinking well location to an estimate of annual dose based on drinking well water consumption [7].

The system level generic granite GDSE model couples the near field and the far field components for performance assessment simulations. The granite GDSE model evaluates likely future outcomes by conducting Monte Carlo multi-realization probabilistic simulations with Latin Hypercube sampling. Sensitivity analyses are performed for probability distributions of uncertain parameters that may be important to a generic granite repository performance. The key model parameters are listed in Table 1. Other parameters and more detailed description of the granite GDSE model can be found in UFD FY11 report [1].

Table 1. Key assumption parameters

Parameter[1]	**Stochastic Parameter type**	**Base Case Value**	**Distribution Parameters**
UNF matrix degradation rate (1/yr)	Log-triangular	1.528×10^{-7}	1×10^{-8}, 1×10^{-7}, 1×10^{-6}

DHLW degradation rate (borosilicate glass) (1/yr)	Log-uniform	4.917×10^{-4}	3.4×10^{-6}, 3.4×10^{-3}
Porosity, inside waste package	Constant	0.175	N/A
Porosity, bed rock	Uniform	0.00525	Range: 0.0005-0.01
Waste package temperature (ºC)	Constant	25	N/A
Waste package size outer diameter (m)	Constant	0.863	N/A
Waste package size outer length (m)	Constant	5.096	N/A
Inventory Number of waste packages-UNF	Constant	140,000 MTU 32,154 WPs	N/A
Inventory Number of waste packages-DHLW	Constant	1,759 MT 5,003 WPs	N/A
Percent of total waste packages affected by canister failure and diffuse through bentonite buffer	Uniform	0.55%	Range: 0.1% - 1%
Portion of DHLW waste packages in above affected waste packages	Uniform	50%	Range: 0% – 100%
Water flow rate to fracture intersecting waste package in undisturbed scenario (m^3/yr/per WP)	Normal	$5.1\text{x}10^{-4}$	mean=5.1e^{-4}, stdv=0.2e^{-4}
Bentonite buffer thickness (m)	Constant	0.36	N/A
Bentonite density (kg/m^3)	Triangular	1562	1484, 1562, 1640
Bentonite porosity	Triangular	0.435	0.41, 0.435, 0.46
Fracture aperture (m)	Uniform	2.55e^{-4}	Range: 1e^{-4} - 5e^{-4}
Fracture spacing (m)	Constant	25	N/A
Solubility (mg/L) for C, Cl, Cs, I, Sr and Pb		unlimited	

[1] Parameters source: (Clayton et al. 2011 [1], Mariner et al. 2011 [8], SKB 2010 [9])

3. SAFETY CASE RERUN

This section discusses the improvement to the FY11 version of granite GDSE model for the safety case simulation. The UFD Granite GDSE Model was rerun with improved model and parameters selection for undisturbed radionuclide release scenario (diffusion through bentonite buffer). The waste type included in this simulation is used nuclear fuels (UNF).

In undisturbed scenario, radionuclides released from degrading waste form are transported away from the waste package by diffusion through the bentonite buffer; the advective transport through it is negligible [9]. Some waste packages directly intersect with fractures in the surrounding granite rock, and radionuclides released from these waste packages enter into the fractures for fast pathway transport. For those waste packages releasing radionuclides to the fractures, the model assumes that a fraction (0.1% to 1%) of the considered inventory is available for the advective transport in the fractures, and the fraction is sampled uniformly between the bounds. The small fraction of waste packages with potential release paths is consistent with detailed analyses from the SKB program [9].

There are several changes made for this calculation:

1) The model uses granite solubility from Sandia Report SAND2011-6203 Table 2-5 [8] for granite at 25°C.

2) The inventory use UNF only. The model calculates the radionuclide mass fluxes out of one waste package by following the transport through near field and far field, and then sums the doses for affected UNF packages at the end of transport pathway.

3) Far field flow rate was adjusted to be a more representative value (mean groundwater speed in the order magnitude of 1 m/year).

The radionuclide mass fluxes (converted to an annual dose) at the location of the hypothetical biosphere (5 km downstream from the repository boundary) are analyzed. The simulations are run for 1 million year with 100 Monte Carlo realizations. A subset of radionuclides is included in the calculations to evaluate different radionuclide transport processes. The results are shown in Figures 1 and 2. Mean annual doses for the highest dose rate species are shown in Figure 1. Sensitivity analyses of input parameters with respect to the uncertainties of ^{129}I annual dose (the key radionuclide contributed most to the final dose at hypothetical biosphere) are shown in Figures 2.

Figure 1 shows mean annual doses of individual radionuclides at the hypothetical biosphere location for undisturbed scenario, calculated from 100 realizations simulations. The ^{129}I mean annual dose (the highest dose turquoise color line in Figure 1) is the dominant contributor to the dose rate. The long half-life, high solubility, and weak sorption in the far field of ^{129}I contribute to its high mean dose. ^{36}Cl shows as the second highest mean annual dose species, followed by ^{79}Se and ^{226}Ra towards the end of the 1 million year simulation time period.

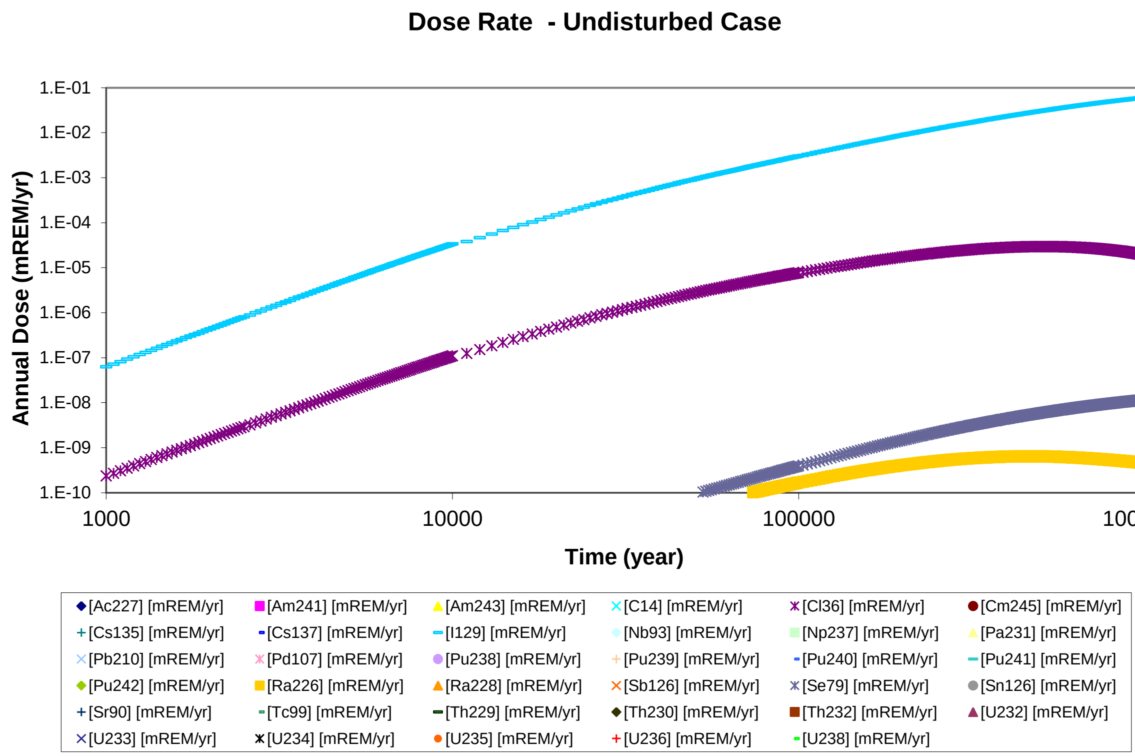


Figure 1. Safety case study undisturbed scenario: mean annual dose of 100 realizations for individual radionuclide species. The highest dose rate radionuclide species shown in the order from high to low are ^{129}I, ^{36}Cl, ^{79}Se, and ^{226}Ra.

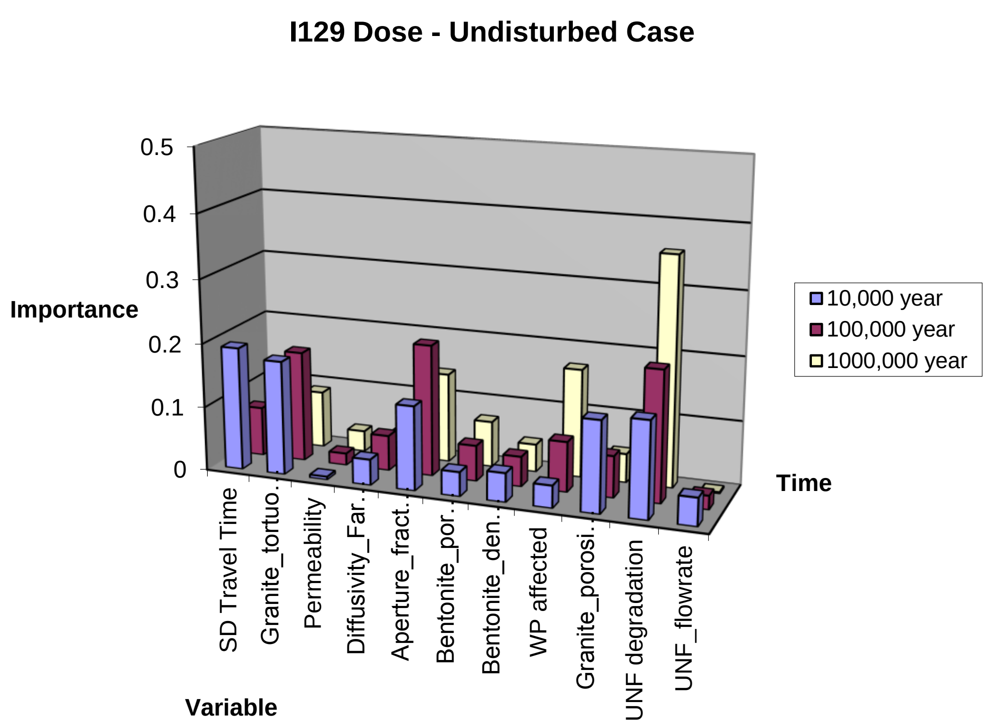
3.1 Sensitivity analysis

A benefit of probabilistic analysis of GDSE is that the relative importance of various uncertain processes can be examined through a statistical analysis of the Monte Carlo results. This analysis can guide future work planning to reduce uncertainties in the model analysis or in other ways improve the model. Figure 2 illustrated this process.

The annual doses are analyzed using a sensitivity analysis tool [10] provided as part of the GoldSim software. The importance analysis of the input variables to the results are statistical measures computed by analyzing multiple realizations of the model in which all of the stochastic variables are simultaneously sampled for each realization of a Monte Carlo simulation. The importance measure is a metric that varies between 0 and 1 representing the fraction of the result's variance that is explained by the variable. This measure is useful in identifying nonlinear, non-monotonic relationships between an input variable and the result (which conventional correlation coefficients may not reveal).

Important parameter uncertainties influencing the overall uncertainty in performance (as measured by the annual dose in this study) depends on the time frame of interest. Each relevant parameter is ranked in order of importance to the overall uncertainty with respect to the annual dose reached at 10^4, 10^5, and 10^6 years. The importance measures shown in Figure 2 are normalized for each time stage so that they can be compared among different time frame of interest.

Figure 2 shows sensitivity analysis of input parameters with respect to the uncertainties of ^{129}I annual dose at different time stage for undisturbed release scenario. It shows that uncertainty in the UNF degradation rate, fracture aperture, percent waste packages affected, granite bedrock porosity and tortuosity, and standard deviation of mean travel time all have relative strong influences on uncertainty in the ^{129}I annual dose. Among which the fracture aperture shows strong influence to ^{129}I annual dose throughout the entire one million year time frame. The UNF degradation rate has dominant influence to ^{129}I annual dose and its influence increases towards the end of simulation time period, while far field parameters such as standard deviation of travel time and granite bedrock porosity show deceasing influence towards the end of simulation. This shows that at lower UNF fractional degradation rate, for nonsorbing (in far field) radionuclide such as ^{129}I, the annual dose is controlled more by the uncertainties in the near field than by the uncertainty in the far-field transport.



NOTE: Larger values for a parameter denote that the uncertainties in that parameter have a larger influence on the overall uncertainty in the ^{129}I annual dose.

Figure 2. Sensitivity analysis of input parameters with respect to uncertainties for the ^{129}I annual dose at 5-km compliance boundary (safety case study undisturbed radionuclide release scenario).

4. MULTIPLE PATHWAYS

Due to computational challenges, repository performance assessments often employ representative waste packages with associated representative transport pathways instead of attempting to model transport from all waste packages. For example, all waste packages that occupy a specified region of a repository and have experienced certain conditions are typically lumped into a single representative package. Package-to-package variability and pathway-to-pathway variability within the far field are not represented by such an approach. Because of these considerations, the use of representative waste packages introduces significant uncertainties and potential biases in repository performance studies [11]. This section describes the improvement to the generic granite GDSE model by incorporating multiple fracture pathways to represent the transport from different waste type packages as a preliminary study for removing one source of systemic model uncertainty.

The waste types considered for this study are: 1) commercial used nuclear reactor fuels (UNF), and 2) existing DOE high-level radioactive waste (DHLW). The inventory parameters are listed in Table 1. Radionuclides releasing scenario is assumed to be undisturbed scenario (diffusion through bentonite buffer).

The model are developed with two far field transport pathways, each connected to different waste type package (one connected to UNF waste package, the other connected to DHLW waste package). The model calculates radionuclide mass flux out of each waste type package (UNF and DHLW, separately) by following the transport through near field and far field, and then sum the doses for affected UNF and DHLW packages at the end of transport pathway.

The radionuclide mean annual doses at the location of the hypothetical biosphere (5 km downstream from the repository boundary) are analyzed. The simulations are performed for 1 million year with 100 Monte Carlo realizations. A subset of radionuclides is included in the calculations to evaluate different radionuclide transport processes. The results are shown in Figures 3 and 4. Mean annual doses for the highest dose rate species are shown in Figure 3. Sensitivity analyses of input parameters with respect to the uncertainties of ^{129}I annual dose (the highest mean annual dose species) are shown in Figures 4.

Figure 3 shows mean annual doses of individual radionuclides at the hypothetical biosphere location for undisturbed scenario, calculated from 100 realizations simulations. The ^{129}I mean annual dose (the highest dose turquoise color line in Figure 3) is the dominant contributor to the dose rate. Again the long half-life, high solubility, and weak sorption in the far field of ^{129}I contribute to its high mean dose. ^{36}Cl shows as the second highest mean annual dose species, followed by ^{79}Se, ^{226}Ra and ^{135}Cs towards the end of the 1 million year simulation time period.

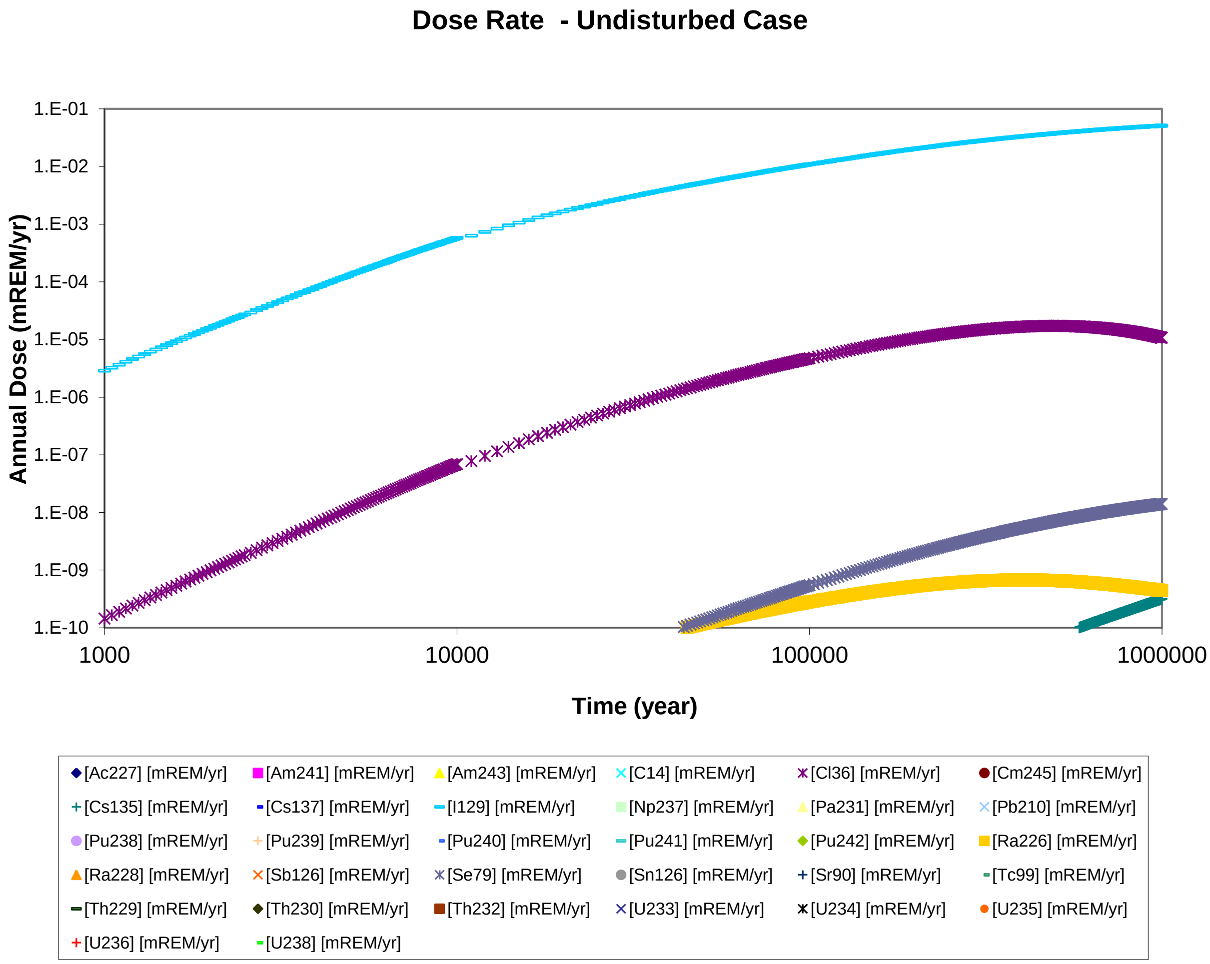


Figure 3. Multiple pathways undisturbed scenario: mean annual dose of 100 realizations for individual radionuclide species. The highest dose rate radionuclide species shown in the order from high to low are ^{129}I, ^{36}Cl, ^{79}Se, ^{226}Ra and ^{135}Cs.

Figure 4 shows sensitivity analysis of input parameters with respect to the uncertainties of ^{129}I annual dose at different time stage for undisturbed release scenario. It shows that the aperture of the fracture connected to the UNF waste package has dominant influence on ^{129}I annual dose throughout the 1 million year time frame. DOE HLW glass degradation rate shows strong influence at the earlier stage of simulation while the commercial UNF degradation rate shows strong influence toward the end of simulation. This indicates that due to the fast DHLW waste form degradation rate (about three orders of magnitude higher than UNF), the annual dose is controlled more by DHLW in near field and by UNF in far field. Far field parameter standard deviation of mean travel time has comparable influence as the granite tortuosity. The percent of waste packages affected shows relative strong influence towards the end of simulation time period with respect to uncertainty in the ^{129}I mean annual dose.

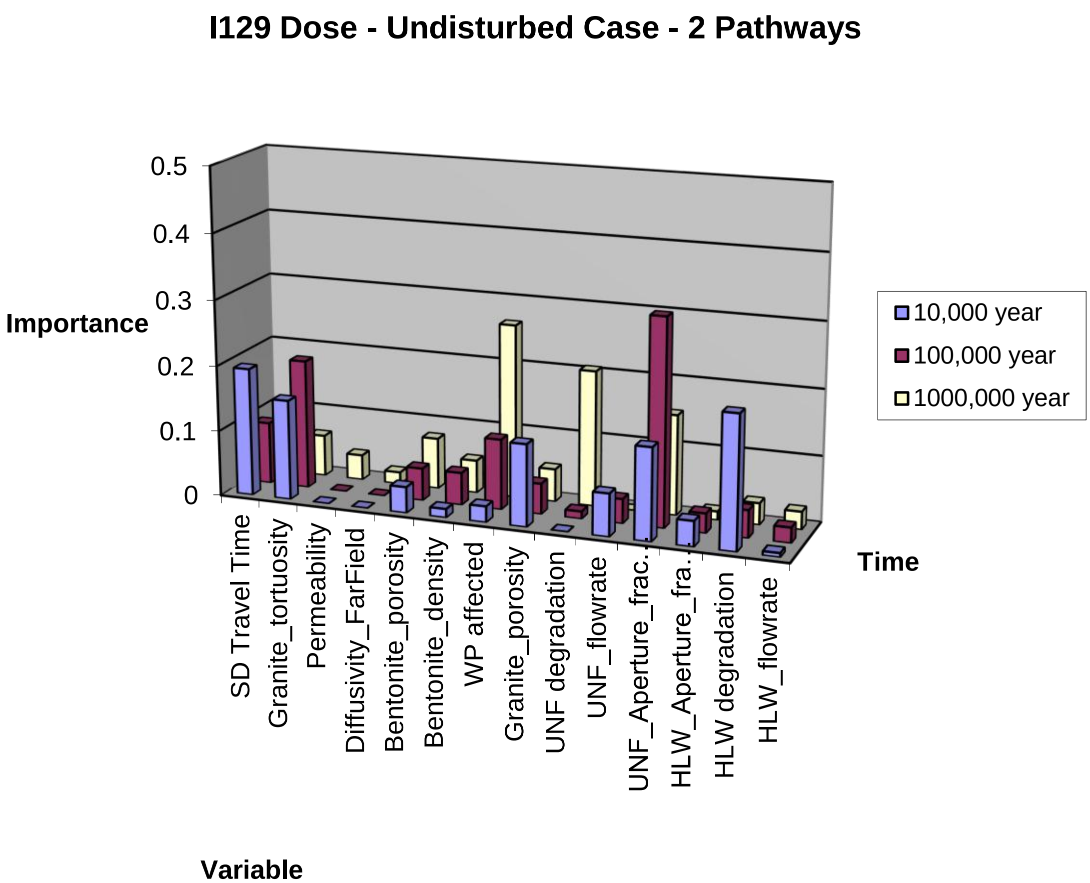


Figure 4. Sensitivity analysis of input parameters with respect to uncertainties for ^{129}I mean annual dose at 5-km compliance boundary (multiple pathways undisturbed radionuclide release scenario).

The above preliminary study results show the multiple pathways implementation includes the contribution from different waste type packages and pathways towards the final dose rate, therefore reduces the bias introduced by using single representative waste package with associated representative transport pathway.

5. GLACIAL IMPACT STUDY

This section discusses the sensitivity studies carried out addressing the effect of future glaciation events on the performance of a generic repository sited in granite environment. Glaciation has been identified in studies in Sweden, Finland and Canada as a potentially important process affecting repository performance. The sensitivity studies described in this section analyze the radionuclide transport consequences of groundwater flow velocity and chemistry changes associated with ice sheet approach and retreat.

Abstractions based on detailed flow modeling studies of SKB [9] are used. Based on those studies, large groundwater flow velocities are expected for brief periods as the ice front passes groundwater recharge points. Between these brief glacial flushing periods, the flow velocities are expected to be small compared with the temperate period velocities, because the ice sheet will block recharge. The abstraction considers the groundwater flow paths to be fixed and only consider changes in groundwater speed on the fixed pathways. Also the dose conversion factor is assumed not varying for different periods in the glacial cycle.

During the glacial flushing periods, oxygen rich water may be present over much of the transport pathways, which can reduce the sorption of redox-sensitive radionuclides. The equilibrium distribution coefficient (K_d) for uranium (U), thorium (Th), technetium (Tc), and neptunium (Np) will be reduced during the flushing periods to represent the decreased sorption. The abstractions are implemented by changing groundwater flow rates and K_d's in the granite GDSE model. The generic granite GDSE model is simplified for mapping to the Generic Performance Assessment Model (GPAM) model [1]. To be consistent with GPAM implementation, the model version used for this study is the simplified generic granite model with GoldSim contaminant transport pipe pathway replacing FEHM external pathway for the far field.

In addition to affecting the far-field performance through changes in groundwater flow and sorption characteristics, glaciation also has the potential to impact engineered barrier performance. Specifically, repeated exposure of bentonite buffer material to dilute glacial melt water can lead to loss of buffer material. The abstraction removes buffer material for a small fraction of waste packages to represent this process. The time at which buffer is lost is chosen from distributions based on results of detailed modeling studies of SKB [9].

The waste type considered for this study is used nuclear fuel (UNF) (Figures 7-15). Analysis is also performed for inventory including both UNF and DOE high-level radioactive waste (DHLW) (Figure 16). The inventory parameters are listed in Table 1. Radionuclides releasing scenario is assumed to be undisturbed scenario (diffusion through bentonite buffer).

5.1 Simplified one glacial cycle

For this study, a simplified cycle is used in place of the full details of the flow and chemical evolution during a glacial cycle. The simplified glacial cycle includes one temperate period, one periglacial period, one glacial period, one submerged period, and advancing before and retreating after glacial period in the 120 kyr cycle. The cycle repeats 8 times in the 1 million year assessment time period of interest. Table 2 lists the time periods for each flow change in the first 120 kyr cycle.

In the radionuclides transport calculations, the flow rates are scaled by the values in Figure 5 (flow scaling factor) to obtain corresponding values for different stages in the glacial cycle. Also sorption coefficient K_d values are adjusted to use oxidizing conditions values for the redox sensitive elements during ice front passages (i.e., during the time periods when flow scaling factors are 20 and 50, respectively).

Table 2. Duration of each climate period in the simplified 120 kyr glacial cycle

Climate Period	Time (kyrs after present)	Duration (kyrs)
Temperate	0 - 35	35
Periglacial	35 - 89	54
Advancing phase	89 – 90.8	1.8
Glacial	90.8 – 110.7	19.9
Retreating phase	110.7 - 111	0.3
Submerged	111 - 120	9

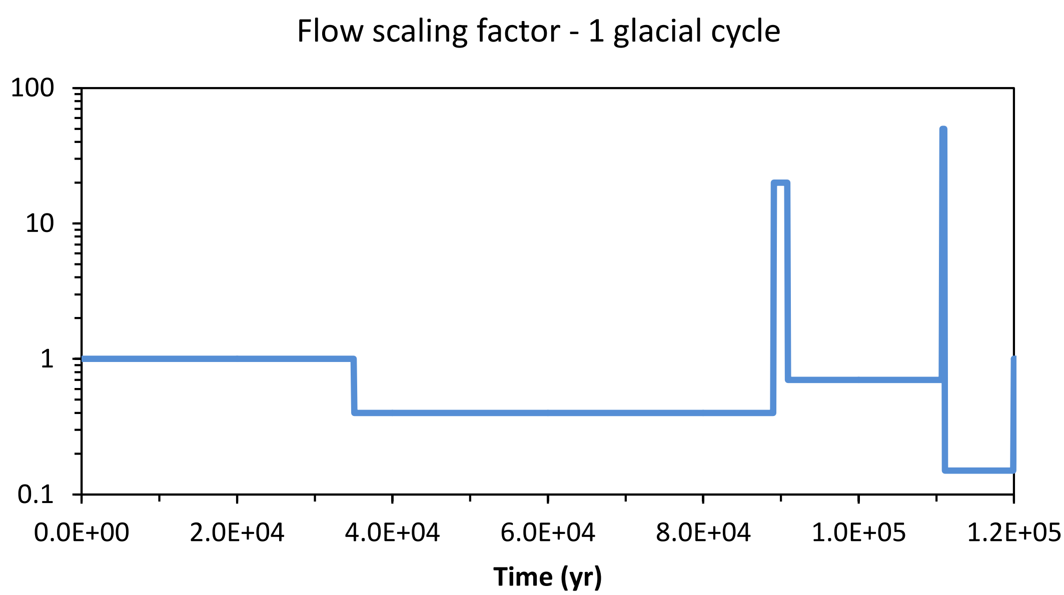


Figure 5. Flow scaling factors for one glacial cycle (of eight during 1 million years) for use in radionuclide transport simulations. The scaling factor is defined relative to the Darcy flux in the temperate period and is used to adjust flow rate and flow-related transport resistance.

Figures 6 and 7 show the groundwater speed and sorption coefficient K_d adjusted by the flow scaling factor and oxidizing condition, respectively, for use in radionuclide transport simulation. The dominant effects are that during the advancing and retreating flushing phases (i.e., during the time periods when flow scaling factors are 20 and 50), the groundwater velocities are large for brief periods during ice front passages, oxygen rich water may be present over much of the transport pathways, which can reduce the sorption of redox-sensitive radionuclides, such as ^{237}Np shown in Figure 7.

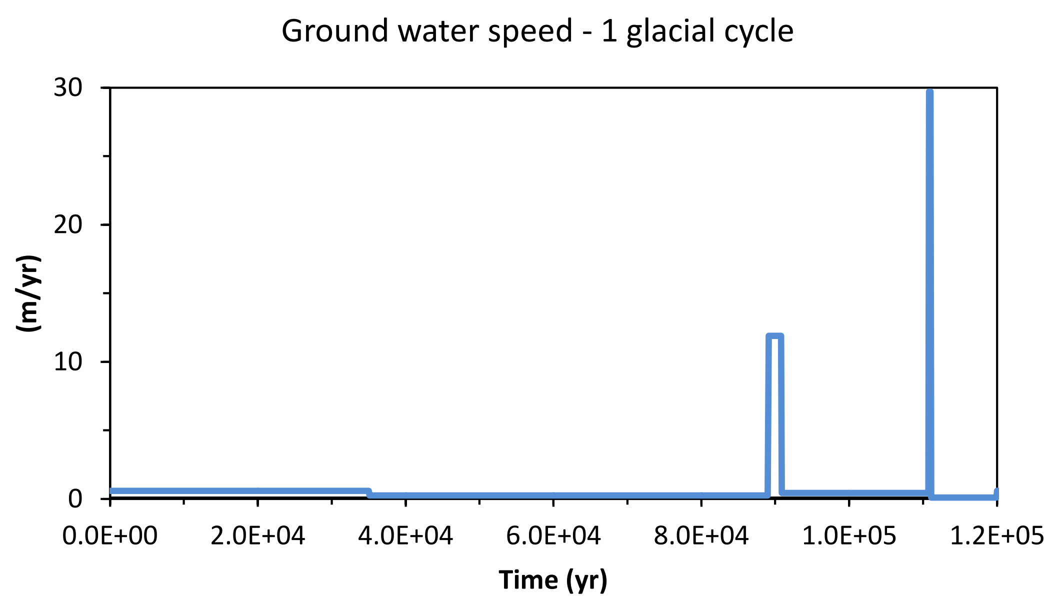


Figure 6**.** Groundwater speed adjusted by flow scaling factors during one glacial cycle for use in radionuclide transport simulations.

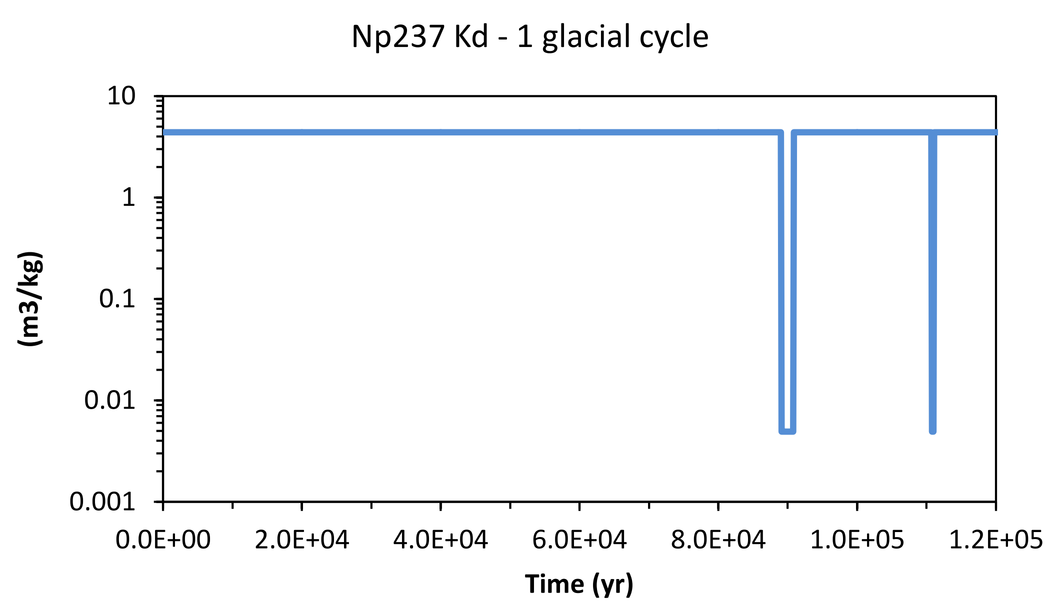


Figure 7. ^{237}Np sorption coefficient variation, affected by the oxidizing condition during the glacial flushing periods in one glacial cycle.

Figure 8 shows the highest mean annual dose species ^{129}I mass fluxes out of near field for one waste package during glacial cycle. It shows the small dip at 38 kyr when climate change from temperate period to the periglacial period, and abrupt increasing during the glacial flushing periods (advancing ~90 kyr and retreating ~110 kyr phases).

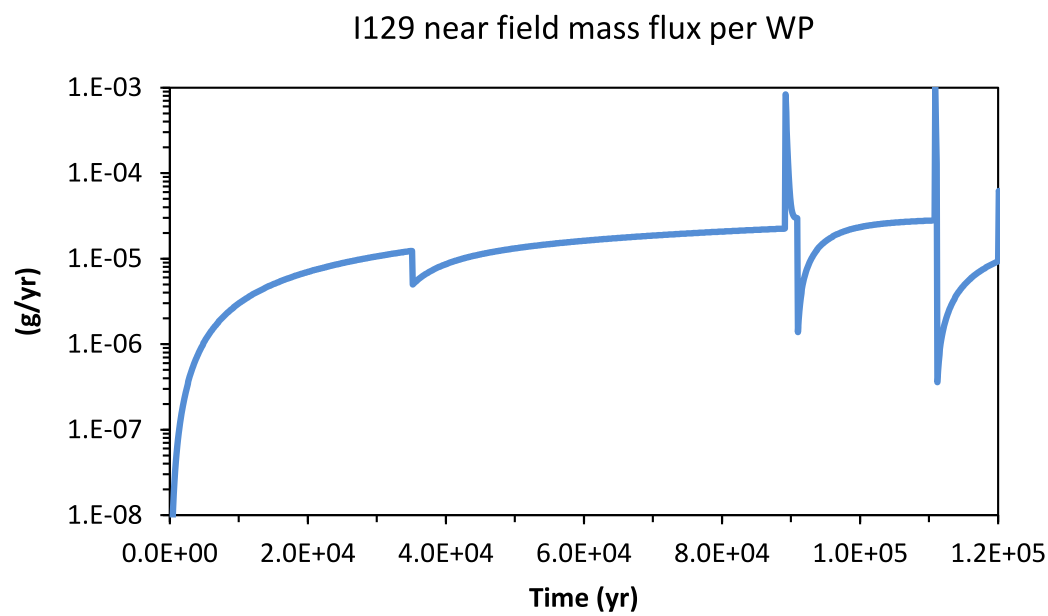


Figure 8. ^{129}I mass flux out of near field for varying climate condition (during one glacial cycle).

Figures 9 and 10 show the impact of chemical processes (here we focus on partitioning of nuclides between the aqueous and surface sorbed phases, represented by sorption coefficients K_d) variation during the glacial cycle. Figure 9 shows ^{237}Np mass flux per waste package out of near field in one glacial cycle assuming flow rate changes during ice front passages, but no sorption coefficient change. Figure 10 shows ^{237}Np mass flux per waste package out of near field in one glacial cycle assuming both flow rate and sorption coefficient change during ice front passages. The mass flux with both flow rate and sorption coefficient change (Figure 10) shows strong increasing during the advancing and retreating flushing periods due to the sorption coefficient change from under reducing condition to under oxidizing condition, which drastically decreases the K_d value for ^{237}Np from 4.38 m^3/kg to 0.0049 m^3/kg. Comparing to ^{129}I mass fluxes (Figure 8), ^{237}Np mass fluxes are much smaller by several orders of magnitude even with sorption reducing considered; its contribution to the total dose rate is very small.

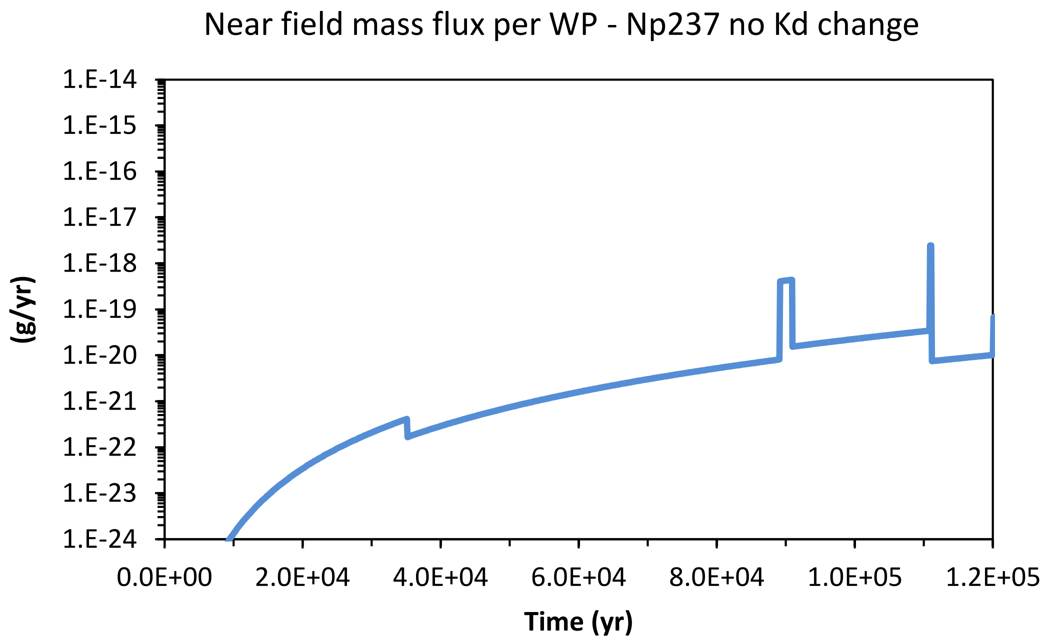


Figure 9. [237]Np mass flux out of near field during one glacial cycle (assume flow rate change, but no sorption coefficient K_d change).

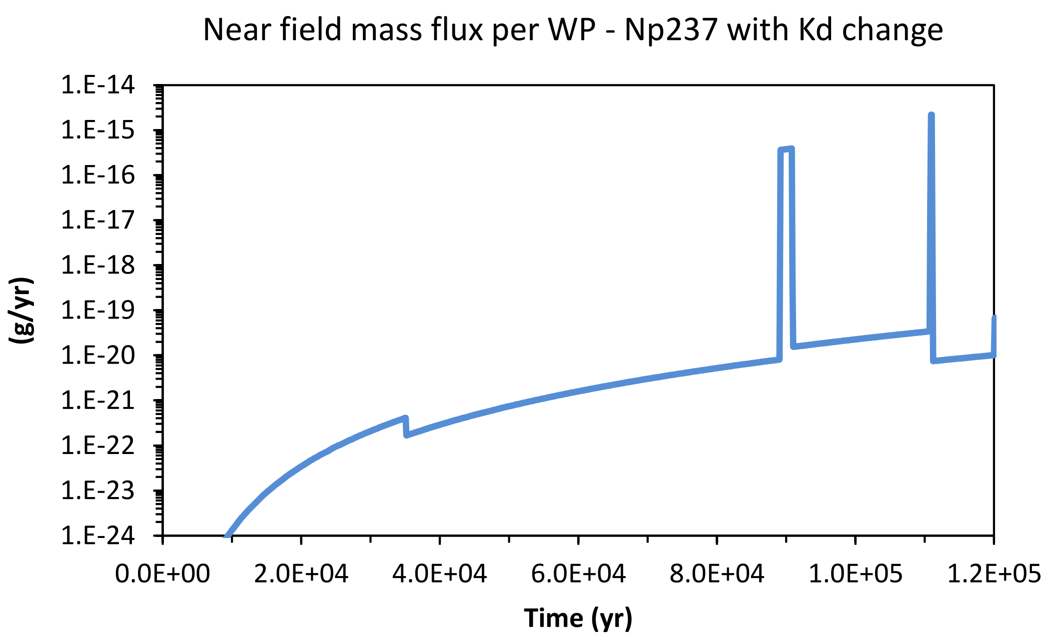


Figure 10. [237]Np mass flux out of near field during one glacial cycle (assume both flow rate change and sorption coefficient K_d change).

Figures 11a and 11b show far field highest dose species ^{129}I mean annual dose for one glacial cycle (Figure 11a) and temperate condition versus varying climate condition during one glacial cycle (120 kyr time period, Figure 11b). Figure 11a shows the abrupt increasing during the glacial flushing periods (advancing ~90 kyr and retreating ~110 kyr phases). Figure 11b shows the increased mean annual dose during the glacial period in comparison with temperate condition (i.e., neither flow rate nor K_d value changes).

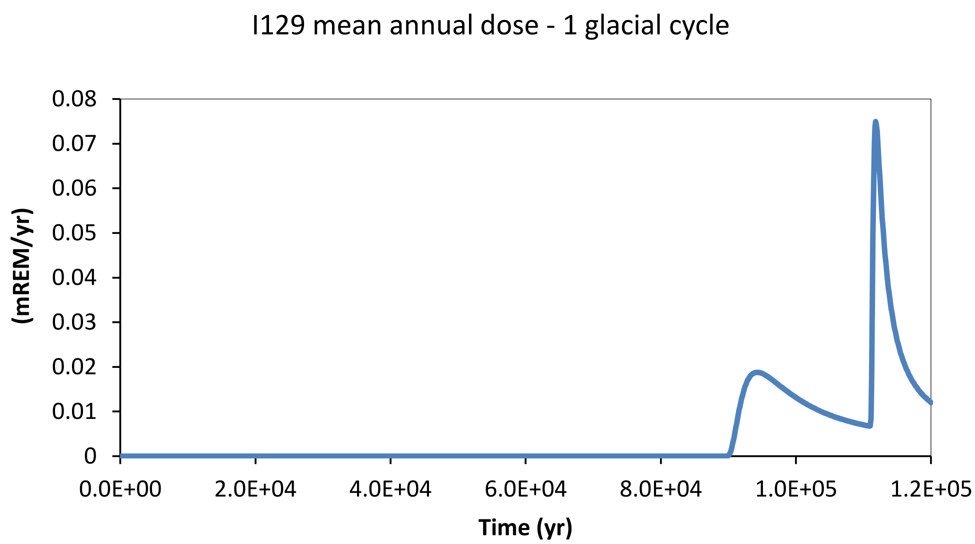


Figure 11a. ^{129}I Far-field mean annual dose for varying climate condition (during one glacial cycle).

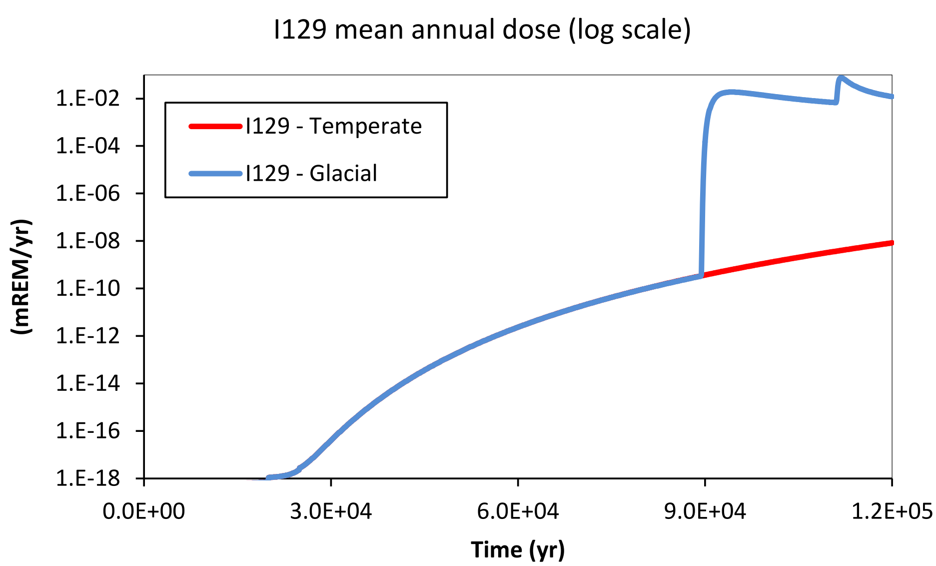


Figure 11b. ^{129}I Far-field mean annual dose for temperate condition versus varying climate condition (dose rates in log scale).

5.2 Simplified eight glacial cycles in one million year

Simulations are performed by repeating the simplified glacial cycle described above 8 times in the 1 million year assessment time period of interest. Figure 12 shows the flow scaling factor for eight glacial cycles during one million year time frame, with two prominent flushing phases for each cycle.

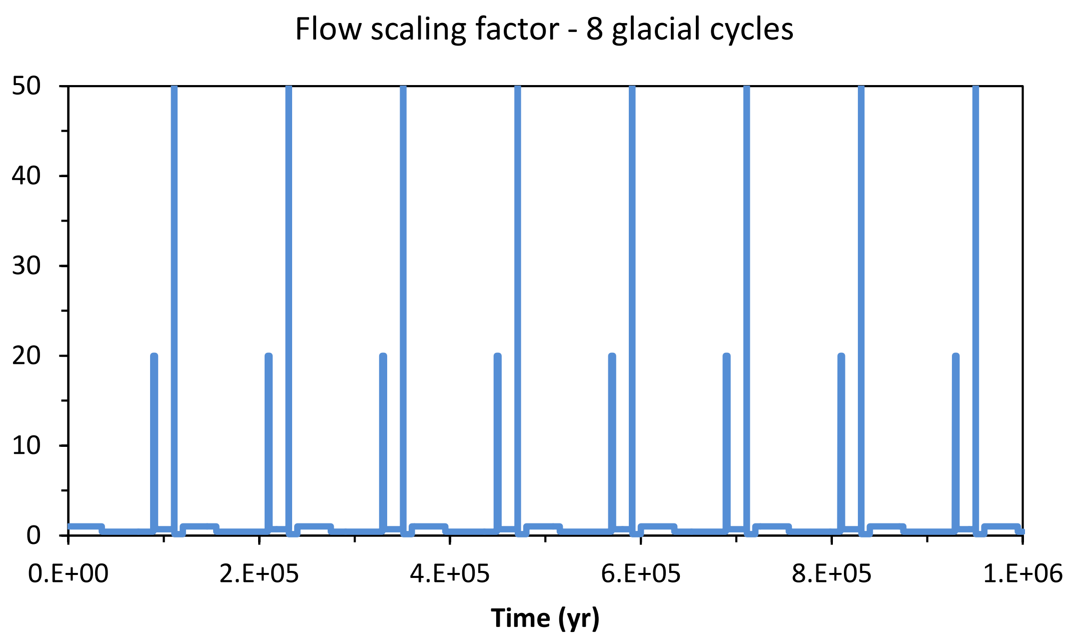


Figure 12. Flow scaling factors for eight glacial cycles (during 1 million years) for use in radionuclide transport simulations. The scaling factor is defined relative to the Darcy flux in the temperate period and is used to adjust flow rate and flow-related transport resistance.

Figure 13 shows far field highest dose species ^{129}I mean annual dose during one million year time frame for temperate condition (without flow rate and K_d value change) versus varying climate condition (eight glacial cycles). It shows the dose rate increasing sharply during each glacial flushing period (advancing and retreating phases) for eight cycles and the peak dose gradually increasing in the same trend as the temperate conditions.

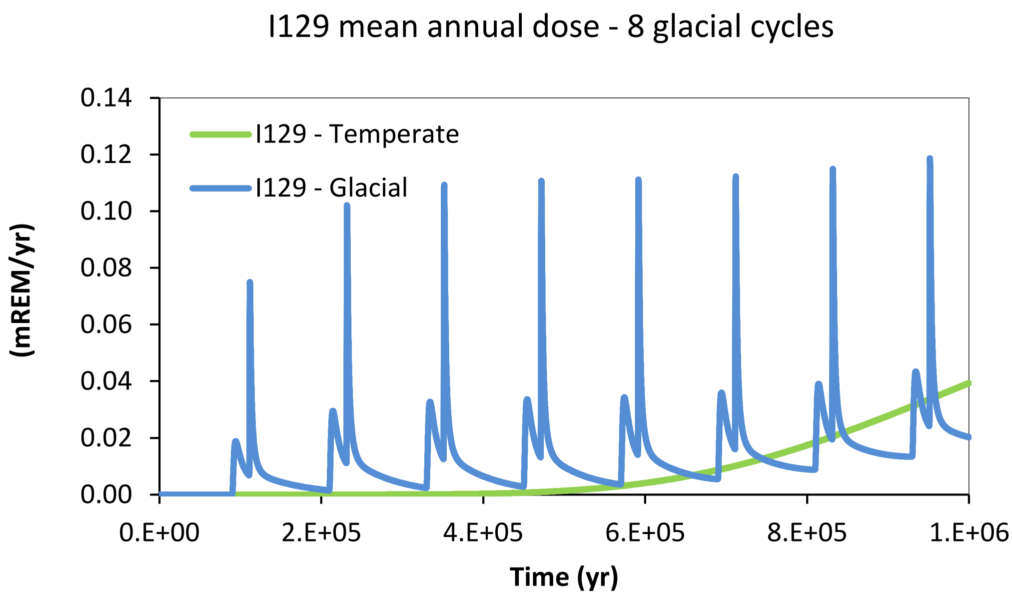


Figure 13. Far-field annual dose for temperate condition (i.e. without flow and K_d change, green curve) versus varying climate condition (during eight glacial cycles, blue curve), assuming no buffer failure.

Simulations are also performed to study the effect of losing buffer material due to repeated exposure of bentonite buffer material to dilute glacial melt water. Figures 14 and 15 show the ^{129}I far field mean annual dose for varying climate condition (with eight glacial cycles) with 20% and all affected waste packages buffer fail at 400 kyr, respectively.

Figure 14 shows about 20% increasing in peak dose rate during the glacial flushing period (advancing and retreating phases) for the first glacial cycle after buffer failure at 400 kyr, the next glacial cycle peak dose increasing not as much as the first one, and for all the subsequent cycles the peak dose gradually increasing in the same trend as the no buffer failure situation (Figure 13).

Figure 15 shows that with all the affected waste packages buffer failing, there is about 75% increasing in peak dose rate during the glacial flushing period for the first glacial cycle after buffer failure at 400 kyr. The next glacial cycle does not increase peak dose as much as the first one, but in all the remaining cycles the peak dose shows large increase in dose rate. The peak gradually increases in the same trend as shown in no buffer failure situation (Figure 13).

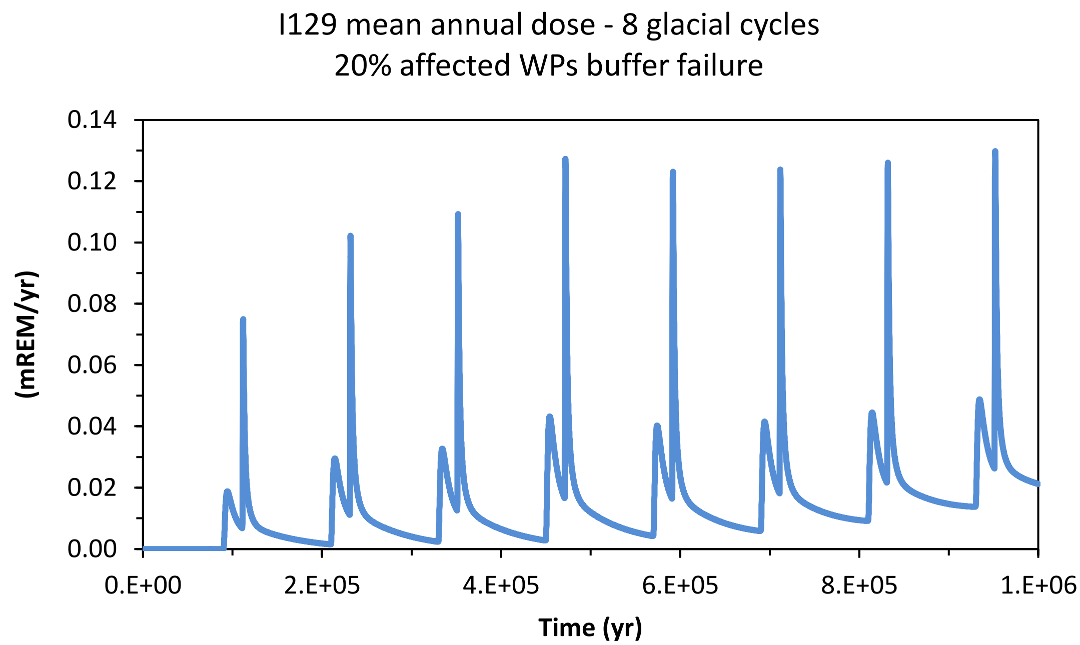


Figure 14. Far-field annual dose for varying climate condition (during eight glacial cycles) with 20% affected waste packages buffer failing at 400 kyr.

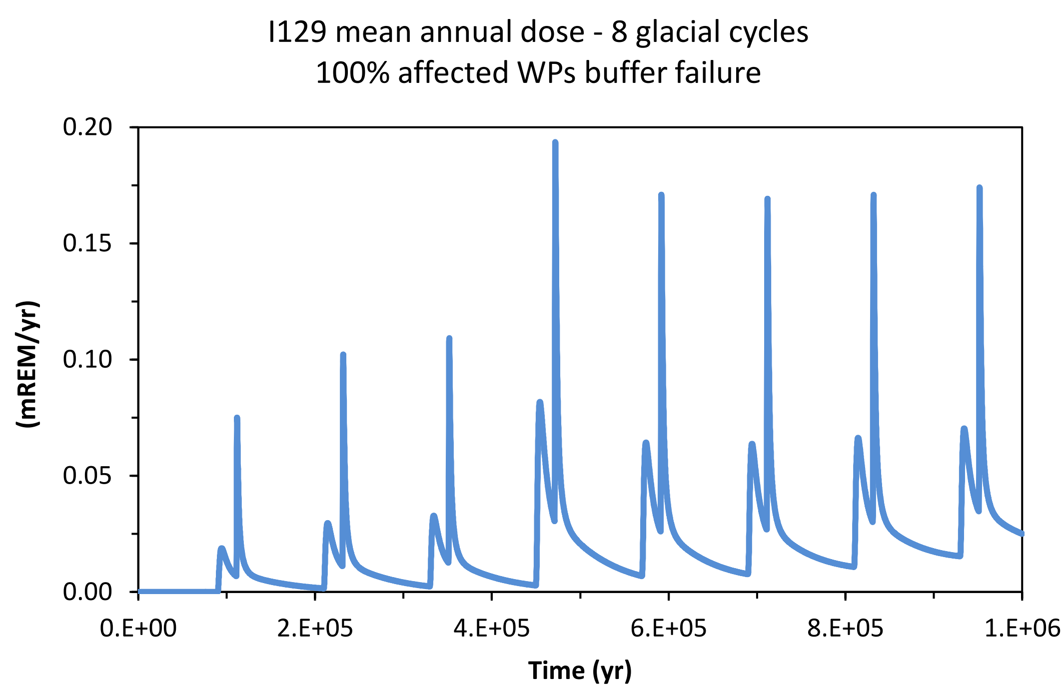


Figure 15. Far-field annual dose for varying climate condition (during eight glacial cycles) with 100% affected waste packages buffer failing at 400 kyr.

Additional analysis is performed for inventory that includes both UNF and DHLW. For this analysis, radionuclides out of UNF waste package and DHLW waste package are tracked separately in near field and far field using the multiple transport pathways described in section 4; the doses for affected UNF and DHLW packages are summed up at the end of transport pathway. The radionuclide mean annual doses at the location of the hypothetical biosphere (5 km downstream from the repository boundary) are analyzed.

Figure 16 shows far field highest dose species ^{129}I mean annual dose for varying climate condition (with eight glacial cycles) with 20% affected waste packages buffer fail at 400 kyr. The results show a large increase in dose rate during the first glacial flushing period, then the peak dose decreases for the following glacial cycles until after 400 kyr buffer failure kicks in, then the peak doses for all the subsequent cycles gradually increase in same trend as shown in no buffer failure situation (Figure 13). The early several glacial cycles' high peak doses are due to the very high DHLW degradation rates (three orders of magnitudes higher comparing to UNF degradation rate, see Table 1), which cause the large quantity of DHLW radionuclides release at early time period. Combined with glacial flushing large flow rate, the analysis shows DHLW contribute to the glacial cycle impact at early time stage while the slow releasing UNF contribute more to the later cumulating increasing dose rate for the one million year simulation time period.

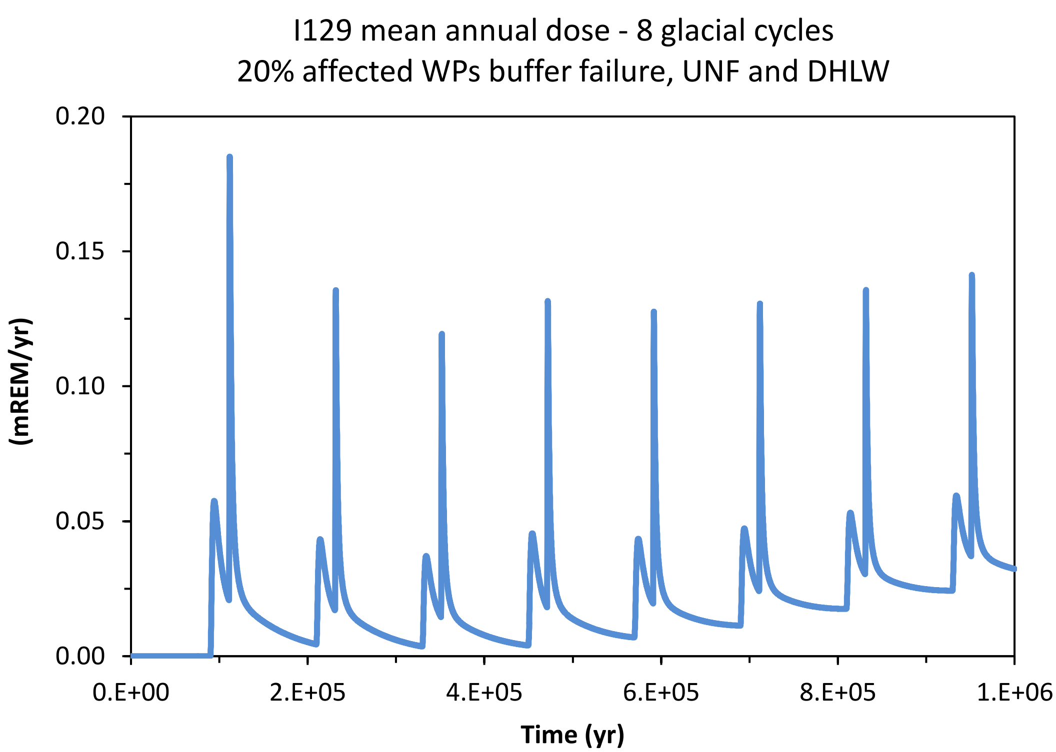


Figure 16. Far-field annual dose for varying climate condition (during eight glacial cycles) with 20% affected waste packages buffer failing at 400 kyr. Inventory includes both UNF and DHLW.

In summary, the glacial impact study carried out with unsteady flow caused by climate evolution and its influence on chemical processes and engineered barrier performance show that radionuclides transport are significantly influenced by the future glacial cycle. The total dose rates are influenced mostly by the flow rates change during the glacial flushing period. The sorption change only influences the redox-sensitive species, which are not the major contributors to the total dose rates. Potential engineered barrier failure due to repeated exposure of bentonite buffer material to dilute glacial melt water also affects the total dose rates with its influence magnitude determined by the fraction of waste packages affected and the time when buffer material is lost.

6. CONCLUDING REMARK

The granite GDSE model and the results presented in this report are preliminary and therefore not indicative of the performance of an actual geologic disposal environment or the potential radiation exposures that could occur in that environment. The parameter ranges and distributions are selected just for the purpose of demonstrating the granite GDSE model analysis; in an actual application, many of these parameters would be site-specific. Nevertheless, the study and analysis discussed can be used to identify the important processes (for example, flow pathway, sorption, and climate variation) that may affect repository performance.

Future work includes continual improvement of the existing model by incorporating more detailed physical, chemical and hydrological processes (such as: temperature variation, full representation of repository geometry); continual improvement of the granite GDSE model to enhance flexibility and integration to address technical issues with minimal changes; and performing comparative studies among the different disposal environments.

7. REFERENCES

1 Clayton, D., G. Freeze, T. Hadgu, E. Hardin, J. Lee, J. Prouty, R. Rogers, W. M. Nutt, J. Birkholzer, H.H. Liu, L. Zheng, and S. Chu, 2011, *Generic Disposal System Modeling: Fiscal Year 2011Progress Report*. FCRD-USED-2011-000184, SAND2011-5828 P. Sandia National Laboratories, Albuquerque, NM.

2 GoldSim Technology Group, 2010, *Users Guide, GoldSim Contaminant Transport Module*, Version 6.0, Issaquah, Washington, GoldSim Technology Group LLC.

3 G. A. Zyvoloski, B. A. Robinson, Z. V. Dash and L. L. Trease, 1997, “Summary of the models and methods for the FEHM application -A Finite-Element Heat- and Mass-Transfer Code”, *LA-13307-MS*, Los Alamos National Laboratory, Los Alamos, New Mexico.

4 G. A. Zyvoloski, 2007, “FEHM: A control volume finite element code for simulating subsurface multi-phase multi-fluid heat and mass transfer”, Los Alamos Unclassified Report *LA-UR-07-3359*.

5 J. T. Carter and A. J. Luptak, 2010, *Fuel Cycle Potential Waste Inventory for Disposition*, Fuel Cycle Research & Development, U.S. DOE, Report FCRR&D-USED-2010-000031 (January 2010).

6 S. Chu, E. Morris, W. Nutt, B. A. Robinson and Y. Wang, 2008, *Generic Repository Concept Analyses to Support the Establishment of Waste Form Performance Requirements – Fiscal Year 2008 Status*, GNEP-WAST-PMO-MI-DV-2008-000146 (September 30, 2008).

7 IAEA (International Atomic Energy Agency), 2003, *"Reference Biospheres" for Solid Radioactive Waste Disposal*, IAEA-BIOMASS-6 (July 2003).

8 Mariner, P. E., J. Lee, E. L. Hardin, F. D. Hansen, G. A. Freeze, A. S. Lord, B. Goldstein, and R. H. Price, 2011, *Granite Disposal of U.S. High-Level Radioactive Waste*. Sandia report SAND2011-6203, Sandia National Laboratories, Albuquerque, NM.

9 SKB (Swedish Nuclear Fuel and Waste Management Co.), 2010, *Radionuclide transport report for the safety assessment SR-Site*, Technical Report TR-10-50 (December 2010).

10 A. Saltelli and S. Tarantola, 2002, "On the relative importance of input factors in mathematical models: safety assessment for nuclear waste disposal", *J. Am. Sata. Ass.*, **97**, No. 459.

11 Y. Wang (editor), 2010, *Natural System Evaluation and Tool Development – Fiscal Year 2010 Progress Report*, Fuel Cycle Research & Development, U.S. DOE, (August 2010).