Assessment of the Chemical Hazard of a Canadian Used Fuel Repository with Copper Containers

M. Gobien*, F. Garisto, N. Hunt, and E. P. Kremer

Nuclear Waste Management Organization 6th Floor, 22 St. Clair Ave E, Toronto, M4T2S3, Canada
**Corresponding Author Email Address: mgobien@nwmo.ca (Mark Gobien)*

The Nuclear Waste Management Organization (NWMO) is responsible for the implementation of Adaptive Phased Management (APM); the federally-approved plan for the 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 host rock formation.

Several major case studies that examine the radiological safety implications of a conceptual repository have been completed, with each case study considering variations in repository design aspects and site characteristics. The two most recent studies consider a conceptual repository situated in the granitic host rock of the Canadian Shield and a conceptual repository situated in the southern Ontario portion of the sedimentary rock Michigan Basin.

The primary focus of these case studies has been to assess the radiological hazard; however, because the repository contains significant amounts of material that can also be chemically hazardous (e.g., Cu and U), the assessments also examined the associated non-radiological hazard.

This paper discusses the acceptance criteria, methodology, cases analyzed and results obtained in the chemical hazard analysis for the two case studies mentioned above. The results are further supported by defining and examining complementary indicators of safety on very long time frames.

I. BACKGROUND

The APM facility includes an underground repository for used CANDU fuel and a number of surface facilities designed to support the construction and operation of the repository. The primary function of the surface facilities is to receive used fuel that is shipped from reactor-site storage facilities, repackage it into durable long-lived used fuel containers and transfer the containers to the underground repository. The reference used fuel container is designed with a corrosion-resistant copper barrier and an inner supporting steel vessel to provide long-term containment of the fuel in the repository.

A repository site has not been selected, but the assumptions made for development of the site model reflect the properties of either crystalline rock found in the Canadian Shield or sedimentary rock found in the Michigan basin. The design for the crystalline and sedimentary rock repositories share many common elements. Two key safety concepts on which both repository designs are based are the multiple barrier system for containment of the fuel, and passive safety. In this case, passive safety means that once the operational phase is complete and the repository is backfilled and sealed, no further actions are needed to ensure its safety.

For the purpose of the crystalline and sedimentary rock assessments[1,2], the repositories are assumed to be constructed at a depth of 500 m. In both repositories the used fuel containers will be surrounded by engineered, clay-based sealing materials that will provide protection against mechanical, chemical and biological agents that could cause container damage. The function of the repository engineered barriers also includes creating both a chemical and physical environment that would limit the mobility of contaminants under the conditions of postulated scenarios that deviate from the expected, normal evolution of the repository.

The underground repositories consist of several panels holding roughly 12,800 used fuel containers (4.6 million used CANDU fuel bundles) in placement rooms, which are connected to the surface via a network of access tunnels and three vertical shafts. The layouts of the crystalline and sedimentary rock repositories vary slightly to account for geological features. The most notable difference between the two repository designs is the container placement. In the crystalline rock repository, containers are placed vertically in in-floor boreholes whereas in the sedimentary rock repository containers are placed horizontally in an in-room orientation. Fig. 1 and Fig. 2 Illustrate the two conceptual repository designs.

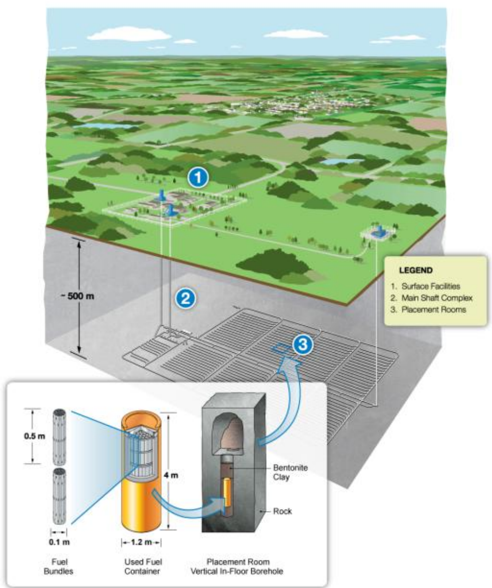


Fig. 1. Crystalline Rock Repository Design

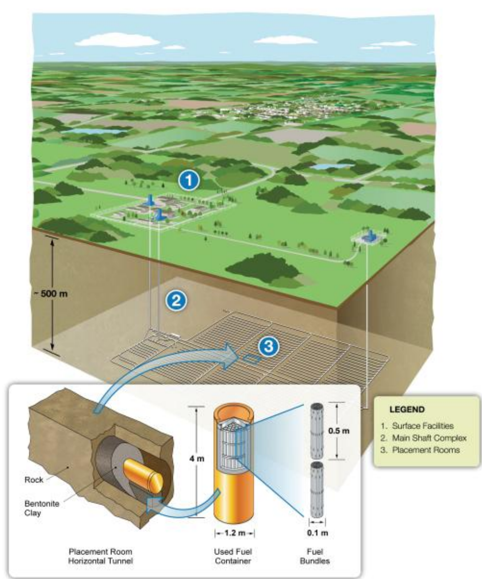


Fig. 2. Sedimentary Rock Repository Design

The emphasis of the crystalline and sedimentary rock repository postclosure safety assessments was on the calculation of the radiological consequences[1,2]. However, a repository contains a variety of other materials, some of which may be chemically toxic in large enough quantities. The majority of the chemically toxic species are contained in the used fuel; however, the repository also contains significant amounts of copper in the container corrosion barriers. The purpose of this paper is to present an assessment of the potential non-radiological hazard of a deep geologic repository in crystalline and sedimentary rock.

II. INTERIM ACCEPTANCE CRITERIA

For the protection of persons from hazardous substances, interim acceptance criteria, based on Canadian guideline values for concentrations in environmental media relevant to human health and environmental protection, have been defined.

The criteria are based on federal and provincial guideline concentrations for surface water, groundwater, soil, and sediment, and in particular on Canadian Council of the Environment[3,4,5,6] information. In cases where federal guidelines do not currently exist, Ontario Ministry of the Environment guidelines[7,8] and other comprehensive guidelines[9] data have been adopted as interim acceptance criteria. Depending on the actual repository site location, the applicable provincial guidelines would be used.

III. ASSESSMENT PROCEDURE

For this assessment the estimated environmental concentrations of contaminants are compared with the acceptance criteria. Additive effects are not considered in this stage.

III.A. Screening Assessment

At the time of discharge the used fuel contains a large number of elements from hydrogen to californium; however, only a small fraction of these could pose a non-radiological hazard to humans or to the environment. Thus, the subset of chemically elements of potential concern is identified via a screening analysis.

The screening analysis used the Radionuclide Screening Model (RSM)[10] which is a project-specific simple model. It models groundwater transport of contaminants (radionuclides or chemically hazardous species) from assumed defective used fuel containers in the repository to the biosphere. Through a conservative choice of input parameters, a large input set of contaminants can be screened so as to objectively identify those which should be considered for more detailed analysis. For the screening assessment, all chemically hazardous elements whose peak groundwater, surface water or soil concentration exceeds 10% of their associated interim accepted criterion were screened in.

Recognizing that there are uncertainties associated with the future evolution of a repository, the screening assessment includes a number of sensitivity cases in which a number of important parameters and assumptions are varied. The screening cases include a median case, a case with low sorption, a case with high solubility, a case with a high instant release fraction from the fuel, and an all containers fail case. The crystalline rock assessment also includes a "3 Sigma" case where all parameter values are set to their 3 sigma values in the conservative direction (i.e., low sorption, high solubility, high diffusion coefficients, etc.). The sedimentary rock assessment includes an additional sensitivity case in which the diffusion coefficients in the geosphere are increased. All model assumptions and data used in the crystalline and sedimentary rock screening analyses are described in Ref 11.

III.B. SYVAC3-CC4 Assessment

The subsets of species identified in the screening analysis are further analyzed with the detailed assessment model SYVAC3-CC4[12]. SYVAC3-CC4 is the reference system model developed for a deep geologic repository concept based on used fuel being placed in durable containers, surrounded by engineered barrier material and located deep underground.

The SYVAC3-CC4 wasteform and container model describes the failure of some containers through small defects, degradation of the used fuel by water, and contaminant release from the container via water. The repository model describes the movement of contaminants through engineered sealing materials, and an excavation damaged rock zone around the room. The geosphere model describes the movement of contaminants from the repository via groundwater, through both rock mass and fractures, to the surface environment. The biosphere model describes the concentration of contaminants in surface water, soils, atmosphere, vegetation and animals, and estimates the consequent radiological dose to a reference person and generic biota living near the repository. Peak element concentrations in water, air and soil are also calculated.

Unique SYVAC3-CC4 models were developed to represent the crystalline and sedimentary rock repositories. Many of the model parameters such as those describing the fuel wasteform are the same in the two models. Parameters describing the engineered sealing materials, geosphere and some biosphere parameters are site specific and intended to represent the features of either the crystalline or sedimentary rock sites.

Model assumptions, parameter values and justification are described in detail in Ref 13 and Ref 14 for the crystalline and sedimentary rock assessments respectively. Typically, the assessment models adopt scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research and/or future site investigation. Where there are high levels of uncertainty associated with processes and data, conservative assumptions are adopted and documented to allow the impacts of uncertainties to be bounded.

When assessing the chemical hazard of the crystalline and sedimentary repositories the following cases were analyzed with SYVAC3-CC4:

- Normal Evolution Scenario (Reference Case)
- Increased Geosphere Diffusivity (Sedimentary Sensitivity Case)
- No Solubility Limits (Crystalline Sensitivity Case)
- All Containers Fail (Disruptive Scenario)

If any predicted concentrations exceed criteria for the Normal Evolution Scenario, these contaminants are assessed further in a tiered approach with decreased conservatism in the models. If any concentrations exceed these criteria for Disruptive Scenarios, acceptability is judged on a case-by-case basis taking into account the likelihood and nature of the exposure, uncertainty in the assessment and conservatism in the criteria.

III.B.1. Normal Evolution Scenario

The Normal Evolution Scenario is based on a reasonable extrapolation of the site and repository. It accounts for anticipated significant events. Significant features of the Reference Case of the Normal Evolution Scenario for the crystalline and sedimentary rock assessment are:

- Three containers with undetected defects (radius = 1 mm) placed in the most conservative repository location.
- Groundwater fills the defective containers 100 years (crystalline case) or 10,000 years (sedimentary case) after the containers are placed in the repository, consistent with estimates of anticipated resaturation times.
- Biosphere with a constant temperate climate.
- A domestic water well pumping at a rate of 913 m^3/a (crystalline case) or 1307 m^3/a (sedimentary case).
- A self-sufficient farming family living on top of the repository who obtains all their drinking water and garden irrigation water from the well.
- Input parameters that are represented by probability distributions are set to either the most probable value (when there is one) or to the median value otherwise.

III.B.2. Sensitivity Cases

For the chemical hazard assessment the most impactful sensitivity cases from the radiological assessments were analyzed. This resulted in the sensitivity case with no solubility limits imposed on any species being analyzed for the crystalline rock assessment and the sensitivity case with the geosphere diffusion coefficient increased by a factor of ten being analyzed for the sedimentary rock assessment.

III.B.3. Disruptive Scenarios

The disruptive scenario analyzed for the chemical hazard assessment was the All Containers Fail Scenario. In this Disruptive Scenario all containers in the repository completely fail (no passive transport resistance due to the container) at 60,000 years for the crystalline rock assessment and 10,000 years for the sedimentary rock assessment.

III.C. FRAC3DVS-OPG Assessment

FRAC3DVS-OPG is the reference groundwater flow and transport code. This is a commercially available 3D finite-element / finite-difference code[15]. FRAC3DVS-OPG supports both equivalent porous medium and dual porosity representations of the geologic media. FRAC3DVS-OPG is primarily used to model the groundwater flow field in the geosphere and inform the development of the SYVAC3-CC4 geosphere model. FRAC3DVS-OPG is also used to model the transport of a limited set of radionuclides to validate the SYVAC3-CC4 model.

For the chemical toxicity analysis FRAC3DVS-OPG was also used to model the dissolution and transport of copper from the container corrosion barriers. In this assessment, a solubility-limited dissolution model is used to determine the rate of corrosion of the copper shell. In this model, the corrosion rate is controlled by the rate at which copper diffuses away from the container / sealing material interface.

The transport of copper away from the container is simulated by applying a constant concentration boundary condition of 1.4×10^{-4} mol/m^3 for the crystalline rock assessment and 2.6×10^{-1} mol/m^3 for the sedimentary rock assessment. The quoted concentrations correspond to the copper solubility limit in the crystalline and sedimentary groundwaters at repository depth.

The maximum total copper transported to the surface discharge locations (including the domestic water well) is estimated and the resulting concentration is compared against the interim acceptance criteria. The soil and sediment concentrations are also estimated and compared as well.

Chemical element impurities are also present in the copper. These impurities are also released as the copper dissolves. The copper impurities are transported with the copper. Element specific sorption coefficients in the engineered sealing materials and geosphere may produce some variation in the transport time and consequently the copper transport without sorption is used as a conservative surrogate for impurity transport.

IV. RESULTS

IV.A. Screening Results

For the crystalline rock assessment, the RSM screening analysis identified 16 elements of potential concern, where multiple isotopes of an element are considered as one element. In addition, Arsenic was added for historical reasons. Some of these screened in elements (e.g. Pb, Ag, and Te) are generated by radioactive decay of a parent. Consequently, to ensure that in-growth is properly accounted for, 21 additional nuclides and their decay chains are represented. These are shown in Table 1, with screened in species are highlighted in red.

Table 1: Screened in Hazardous Species for the Crystalline Rock Assessment.

Fuel Elements	As, Ce, Cd, Co, Cr, Eu, Hg, I, La, Nd, P, Pr, Y
Actinium Series	Pu-239 → U-235 → … → Pb
Thorium Series	Pu-240 → U-236 → … → Pb
Uranium Series	Pu-242 → U-238 → … → Pb
Misc.	Pd 107 → Ag, Sn-126 → Te

For the sedimentary rock assessment, the RSM screening analysis identified 26 elements of potential concern arising from the fuel, where multiple isotopes of an element (i.e., U, Pb, and Ba) are considered as one element. To ensure that ingrowth is properly accounted for, an additional 33 radionuclides are also included. The analysis also shows seven elements of potential concern arising from the Zircaloy sheath, to which an additional three parent radionuclides have been added to account for ingrowth. Table 2 shows the final list elements and parent species, with screened in species highlighted in red.

More potentially hazardous species were identified in the sedimentary rock assessment primarily due to conservative assumptions made as a result of limited site specific data. Data, specifically transport data (e.g., sorption coefficients, diffusion coefficients), applicable to the highly saline groundwater conditions present at repository depth are limited for the broad range of species considered in the screening assessment.

Table 1: Screened in Hazardous Species for the Sedimentary Rock Assessment.

Fuel Elements	Al, Cd, Ce, Co, Cr, Cu, Hg, La, Mo, Nd, Ni, P, Pr, Sb, Se, Sm, V, Y
Neptunium Series	Am-241 → …→ U-233 →…→ Bi
Uranium Series	Pu-242 → U-238 → Th-234 → U-234 → …→ Pb
Actinium Series	Pu-239 → U-235 → … → Pb
Thorium Series	Pu-240 → U-236 → … → Pb
Misc.	Sn-126 → Sb-126 → Te Sr-90 → Y-90 → Zr Cs-135 → Ba, Cs-137 → Ba Pd-107 → Ag, Sm-151 → Eu
Zircaloy Elements	Be, Cr, Cd, Sb, V
Zircaloy Chains	Pd-107 → Ag, Sr-90 → Y-90 → Zr

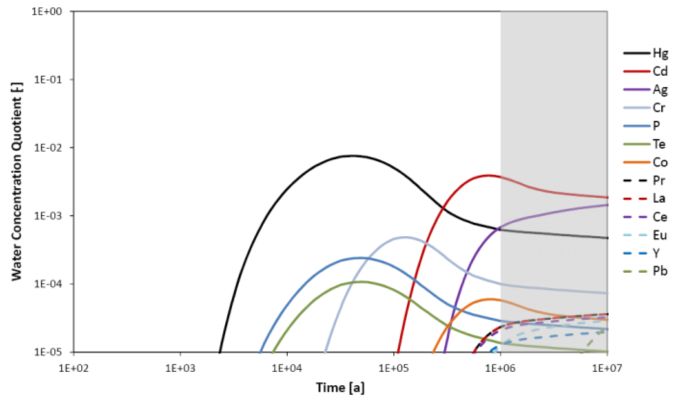
IV.B. SYVAC3-CC4 Results

IV.B.1. Crystalline Rock Repository

Figures 3, 4, and 5 show the Water Concentration Quotients as a function of time for the Reference Case, The No Solubility Limits Case and the All Containers Fail Case. Water Concentration Quotients are computed by taking the ratio of the maximum of the water concentrations (groundwater, surface water and well water) and dividing it by the minimum water acceptance criteria. Similarly, the Soil and Sediment Concentration Quotients are computed by dividing the Soil and Sediment concentration by the corresponding acceptance criteria.

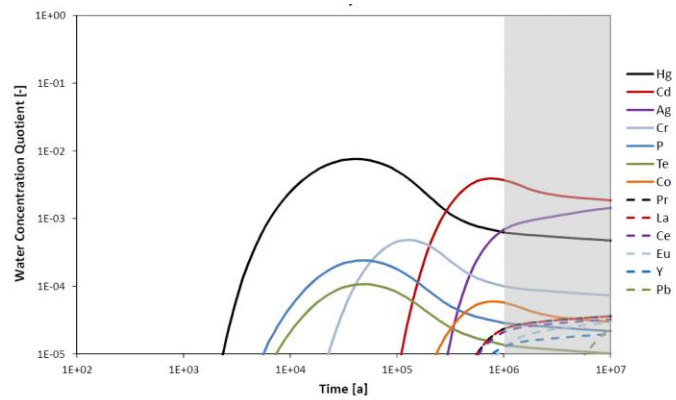
For the Reference Case the highest overall Concentration Quotient is 7.6×10^{-3} for Hg in water. The highest Concentration Quotient in the Soil is 5.8×10^{-5} for Cr. There is no discharge through the sediment layer in the SYVAC3-CC4 Reference Case simulation and therefore the concentration in that compartment is zero. All Concentration Quotients are well below 1.0, indicating that wide margins are available to the interim acceptance criteria.

The results of the No Solubility Limits Case are largely unchanged from the Reference Case because many species are not solubility limited. One exception is U which has increased in concentration by approximately 4.5 times in the water and by 44 times in the Soil at the end of a 10 million year simulation time but remains off-scale low in the figure. Despite the increases, all concentrations remain well below the interim acceptance criteria and no potential hazard exists.



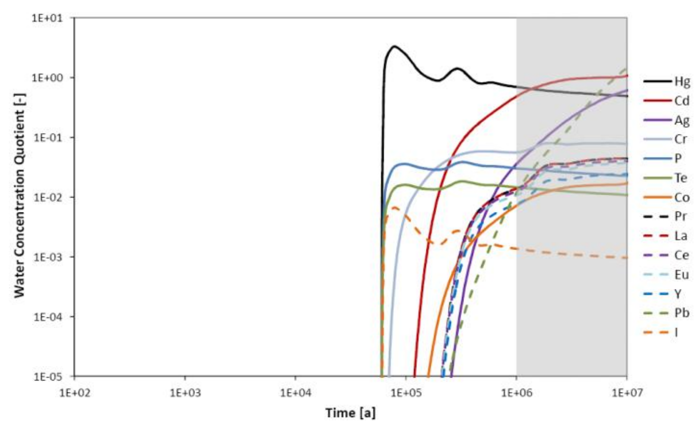
Note: results for As, I, Nd and U are off-scale low

Fig. 3. SYVAC3-CC4 – Water Concentration Quotients for the Reference Case



Note: results for As, I, Nd and U are off-scale low

Fig. 4. SYVAC3-CC4 – Water Concentration Quotients for the No Solubility Limits Case



Note: results for As, Nd and U are off scale low

Fig. 5. SYVAC3-CC4 – Water Concentration Quotients for the All Containers Fail Case

For the All Containers Fail Disruptive Scenario the Concentration Quotients are significantly higher than in the Reference Case (as expected due to the significantly increased source term), with Hg, Pb and Cd slightly exceeding the water criteria with Concentration Quotients of 3.3, 1.6 and 1.1 respectively. The peak Hg concentration occurs relatively early while the Cd and Pb values are still increasing at the end of the 10 million year simulation. Continuation of the simulation indicated peak values of 2.8 and 1.4 can be expected.

For the Soil and the Sediment criteria there are no exceedances and the highest Concentration Quotients are 9.0×10^{-3} for Cr and 1.7×10^{-1} for Pb in the Soil and Sediment respectively.

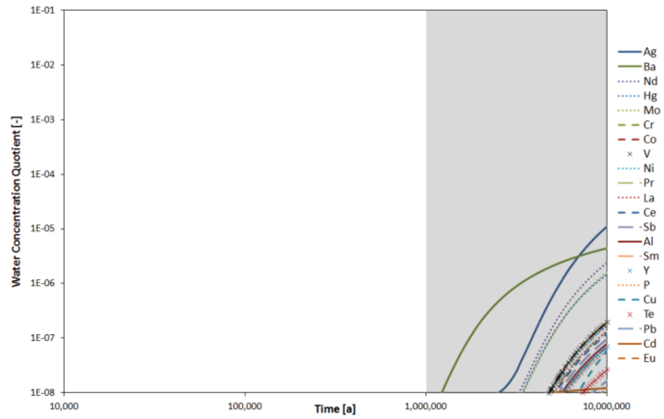
Although some species exceed criteria, the exceedances are judged acceptable on the basis that the amount of the exceedance is small and that the likelihood of the scenario is low. The acceptance criteria are intended to be conservative and the hazard is over-estimated. Considering the conservatisms in the model and the low likelihood of the scenario, it is concluded that the non-radiological hazard arising from this unlikely event is within acceptable risk bounds.

IV.B.2. Sedimentary Rock Repository

Figures 6, 7 and 8 show the Water Concentration Quotients as a function of time for the Reference Case, The No Solubility Limits Case and the All Containers Fail Case.

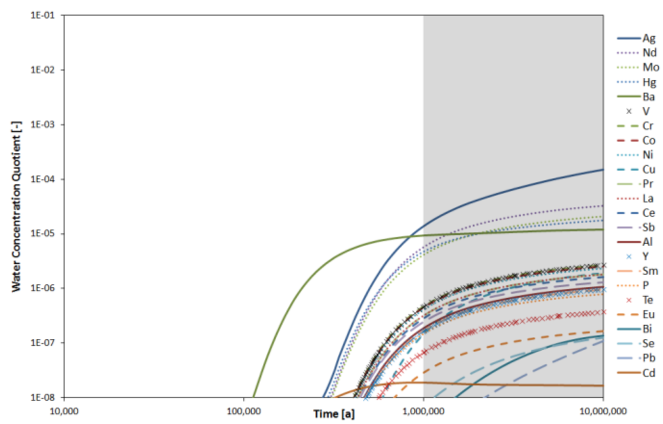
For the Reference Case the highest overall Concentration Quotient is 1.1×10^{-5} for Ag in water. The highest Concentration Quotient in the Soil is 1.6×10^{-5} for Ce and 8.0×10^{-5} for Ag in the Sediment. The results for the High Diffusion Case show Ag has the highest Water Concentration Quotient at 1.5×10^{-4}. The maximum Soil and Sediment Concentration Quotients are estimated to be 1.2×10^{-4} for Cr and 1.1×10^{-3} for Ag respectively. The results of the All Containers Fail Disruptive Scenario are a scalar increase in the results of the Reference Case by factor proportional to the increase in the number of assumed failed containers. The maximum Water, Soil and Sediment Concentration Quotients are estimated to be 4.8×10^{-2}, 5.0×10^{-2} and 3.4×10^{-1} for Ag, Cr, and Ag respectively.

Overall the Concentration Quotients were found to be below 1.0 for all species, pathways and cases considered in the sedimentary rock assessment. The sedimentary rock repository does not pose a significant non-radiological risk to people or the environment.



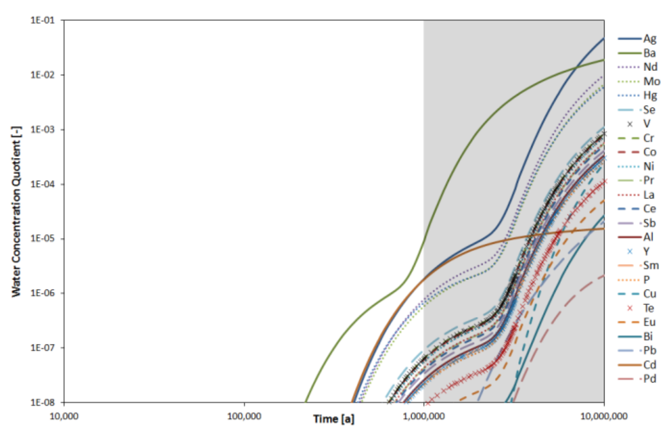
Note: results for Be, Cs, Sr, U, and Zr are off scale low

Fig. 6. SYVAC3-CC4 – Water Concentration Quotients for the Reference Case



Note: results for Be, Cs, Sr, U, and Zr are off scale low

Fig. 7. SYVAC3-CC4 – Water Concentration Quotients for the High Diffusion Case



Note: results for Be, Cs, Sr, U, and Zr are off scale low

Fig. 8. SYVAC3-CC4 – Water Concentration Quotients for the All Containers Fail Case

IV.C. FRAC3DVS-OPG Results

IV.C.1. Crystalline Rock Repository

Figure 9 shows the resulting copper concentration after 1 million years across the repository site.

To conservatively assess the Concentration Quotient, the maximum total flux to the surface (1.3×10^{-3} mol/a) is assumed to enter the well with the well pumping at a rate of 911 m^3/a. The resulting well water concentration is 1.4×10^{-6} mol/m^3 or 9.1×10^{-2} μg/L resulting in a maximum Water Concentration Quotient (using the maximum of the groundwater and surface water acceptance criteria) of 9.1×10^{-2}. The Concentration Quotients for Soil and Sediment are 5.3×10^{-4} and 2.1×10^{-3} respectively. All Concentration Quotients are well below 1.0 indicating wide margins are available to the acceptance criteria.

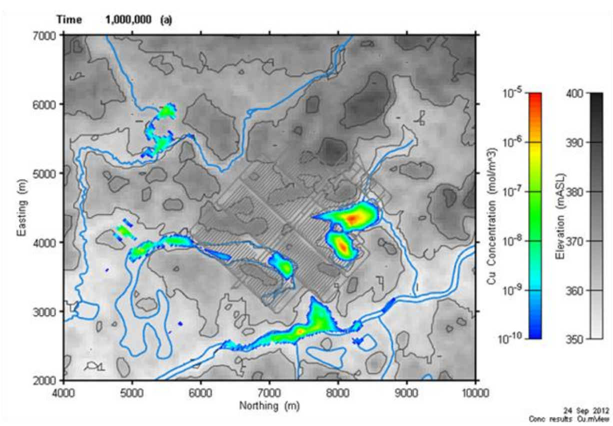


Fig. 9. FRAC3DVS-OPG – Copper Concentration over the Repository Site

IV.C.2. Sedimentary Rock Repository

Figure 10 shows the transport of copper through two subsurface parts of the sedimentary sequences (i.e., the Cobourg layer and the Georgian Bay layer) and the discharge to the surface as a function of time both with and without sorption.

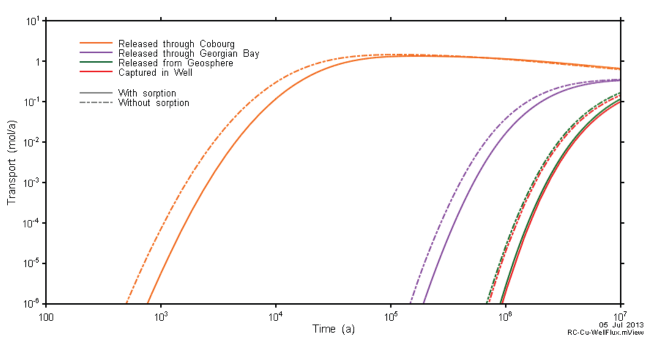


Fig. 10. FRAC3DVS-OPG – Copper Transport to the Surface both with and Without Sorption

To determine the Concentration Quotients, the maximum total copper transport to the surface (i.e., 0.10 mol/a with sorption and 0.14 mol/a without sorption) is assumed to enter the well, with the well pumping at the reference rate of 1307 m3/a. The resulting well water concentration (with sorption) is 7.65×10^{-5} mol/m^3 or 4.9 μg/L which is essentially equal to the groundwater acceptance criterion of 5μg/L. Because the well is the source of drinking water, a less conservative but appropriate comparison can also be made against the potable groundwater acceptance criterion of 69 μg/L. For this comparison, the Concentration Quotient is 0.07 indicating a wide margin to the acceptance criterion. The surface Water, Soil and Sediment Concentration Quotients were 0.1, 2.4×10^{-4}, and 1.1×10^{-2} respectively.

The primary reason the Cu Concentration Quotients are higher than the crystalline case is the increased copper solubility in the highly saline sedimentary geosphere. However, in either case the copper thickness is many times thicker than the amount removed by dissolution.

IV.C.3. Impurities in the Copper Corrosion Barrier

The hazard posed by the chemical element impurities present in the copper corrosion barrier was also assessed for both the crystalline and sedimentary rock repositories. Impurity levels in the copper varied from 1-100 ppm with phosphorous having the highest impurity level. The highest overall Concentration Quotient occurred for the sedimentary rock repository and was 4.0×10^{-4} for Ag in the groundwater and 1.2×10^{-4} for Hg in the surface water. All other Concentration Quotients were below these values. Thus, the impurities in the copper can be ruled out as a potential chemical hazard.

IV.D Complementary Indicators

Natural processes carry small amounts of naturally occurring chemical elements from within the geosphere to the surface. Reference values for natural chemical element transport fluxes to the biosphere can be obtained using the elemental composition of granitic Canadian Shield crystalline rocks and Michigan Basin Sedimentary formations and the erosion rate of the formation over long time periods.

The results of this calculation indicate that even under the conservative assumption of the All Containers Fail Scenario, the element fluxes to the biosphere are generally much smaller than the corresponding erosion fluxes. The ratio of the calculated peak element flux from erosion and the All Containers Fail Disruptive Scenario is largest for Te (with a value of 0.84) for the crystalline rock assessment and Bi (with a value of 3.0×10^{-4}) for the sedimentary rock assessment. This provides additional confidence that the repository will not have a significant effect on people or the environment.

V. CONCLUSIONS

The potential chemical hazard of a crystalline and sediment rock repository has been assessed. This paper discusses the acceptance criteria, methodology, cases analyzed and results obtained. In summary:

- A screening analysis identified 16 elements in the crystalline assessment and 26 elements in the sedimentary assessment that pose a potential chemical hazard.
- Water, Soil and Sediment Concentration Quotients estimated using SYVAC3-CC4 for the Reference Case and Sensitivity Case in the crystalline assessment were found to be well below 1.0 indicating environmental concentrations are well below the acceptance criteria.
- The All Containers Fail Disruptive Scenario has exceedances for Hg, Cd and Pb for the crystalline rock assessment but these are deemed to be with the acceptable bounds of risk given the conservative nature of the calculation and assumed scenario.
- All cases analyzed in the sedimentary assessment were found to have Concentration Quotients well below 1.0 indicating environmental concentrations are below the acceptance criteria.
- The FRAC3DVS-OPG assessment of the copper corrosion barrier indicates the copper and its impurities do not pose a significant chemical hazard.
- Complementary indicators provide added confidences that the effects of the repository on the health and safety of people and the environment are not significant.

Thus, it is concluded that the crystalline and sedimentary rock repositories will not pose a significant chemical hazard on long time frames.

REFERENCES

1. NWMO. 2012a. Used Fuel Repository Conceptual Design and Postclosure Safety Assessment in Crystalline Rock. Nuclear Waste Management Organization Technical Report NWMO TR-2012-16. Toronto, Canada.
2. NWMO. 2013. Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock. Nuclear Waste Management Organization Technical Report NWMO TR-2013-07. Toronto, Canada.
3. CCME. 2007a. Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health, Summary Tables. Canadian Council of Environment 2007 update. Access through website of the Canadian Environmental Quality Guidelines: http://st-ts.ccme.ca.
4. CCME. 2007b. Canadian Water Quality Guidelines for the Protection of Agricultural Water Uses, Summary Tables. Canadian Council of Environment 2007 update. Accessed through website of the Canadian Environmental Quality Guidelines: http://st-ts.ccme.ca/.
5. CCME. 2007c. Canadian Water Quality Guidelines for the Protection of Aquatic Life, Summary Tables. Canadian Council of Environment 2007 update. Accessed through website of the Canadian Environmental Quality Guidelines: http://st-ts.ccme.ca/.
6. CCME. 2002. Canadian Sediment Guidelines for the Protection of Aquatic Life, Summary Tables. Canadian Council of the Environment 2002 update. Accessed through website of the Canadian Environmental Quality Guidelines: http://st-ts.ccme.ca/.
7. MoE. 2001. Soil, Groundtware and Sediment Standards for Use under Part XV.1 of the Environmental Protection Act. Ontario Ministry of the Environment. Toronto, Canada.
8. MoEE. 1994. Water Management Policies Guidelines Provincial Water Quality Objectives of the Ministry of Environment and Energy. Toronto Canada.
9. ODEQ. 2001. Guidance for Exological Risk Assessments, Levels I, II, III and IV:P Level II Screening Level Values. Portland, USA.
10. Goodwin, B.W., P. Gierszewski and F. Garisto. 2001. Radionuclide Screening Model (RSM) Version 1.1 – Theory. Ontario Power Generation Report 06819-REP-01200-10045-R00. Toronto, Canada.
11. Gobien, M. and F. Garisto. 2012. Data for Radionuclide and Chemical Element Screening. Nuclear Waste Management Organization Technical Report NWMO TR-2012-11. Toronto, Canada
12. NWMO. 2012b. SYVAC3-CC4 Theory, version SCC409. Nuclear Waste Management Organization Technical Report NWMO TR-2012-22. Toronto, Canada.
13. Garisto, F., M. Gobien, E. Kremer and C. Medri. 2012. Fourth Case Study: Reference Data and Codes. Nuclear Waste Management Organization Technical Report. NWMO TR-2012-08. Toronto, Canada.
14. Gobien, M., F. Garisto and E. Kremer. 2013. Fifth Case Study: Reference Data and Codes. Nuclear Waste Management Organization Technical Report NWMO TR-2013-05. Toronto, Canada.
15. Therrien, R., R. G. McLaren, E. A. Sudicky, S.M. Panday and V. Guvanasen. 2010. FRAC3DVS-OPG: A Three-Dimensional Numerical Model Describing Subsurface Flow and Solute Transport. User`s Guide, Groundwater Simulations Group, University of Waterloo. Waterloo, Canada.