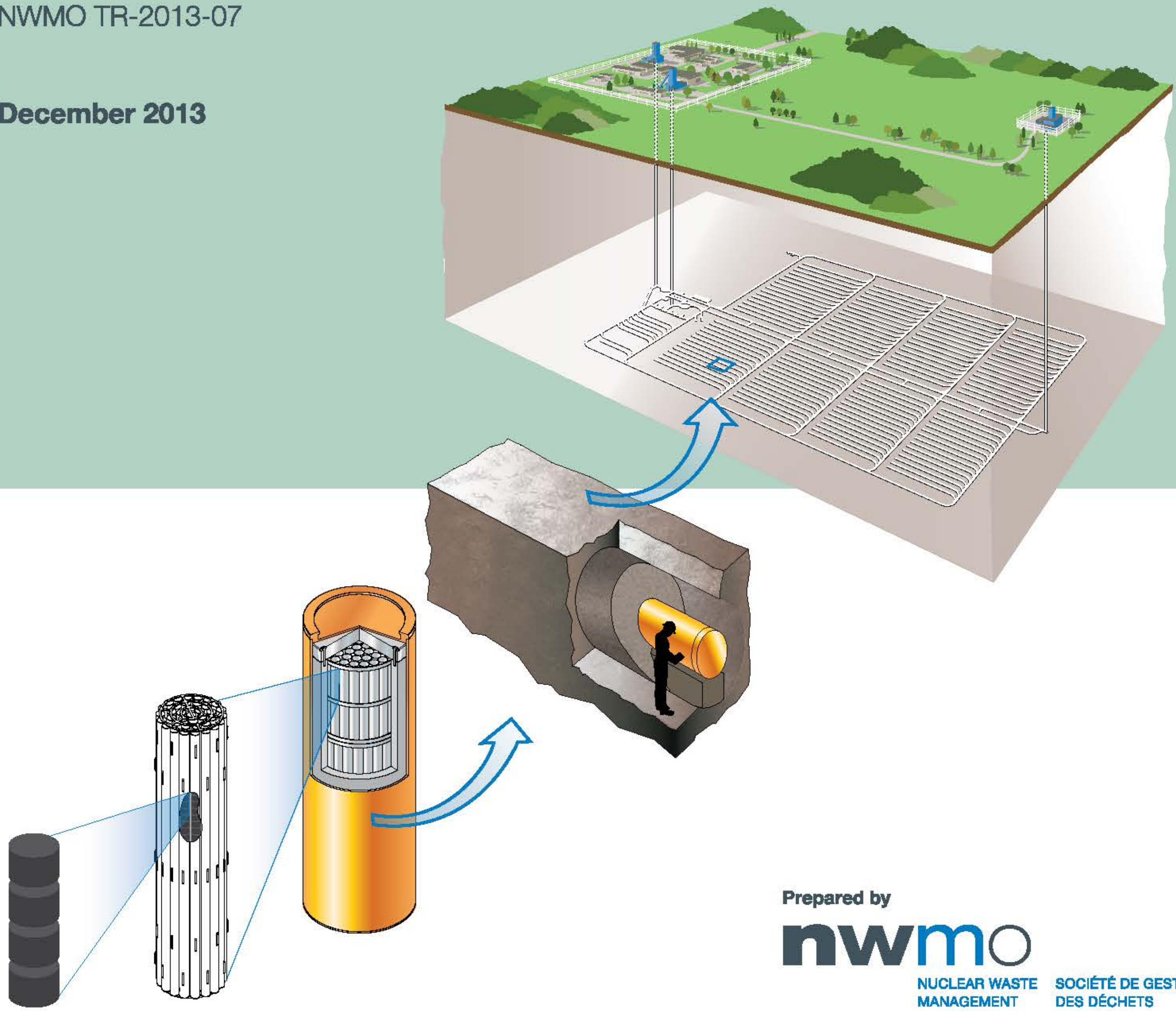
Adaptive Phased Management

Postclosure Safety Assessment of a Used Fuel Repository in Sedimentary Rock

Pre-Project Report

NWMO TR-2013-07

December 2013



Prepared by

NUCLEAR WASTE MANAGEMENT ORGANIZATION
SOCIÉTÉ DE GESTION DES DÉCHETS NUCLÉAIRES

Nuclear Waste Management Organization
22 St. Clair Avenue East, 6th Floor
Toronto, Ontario
M4T 2S3
Canada

Tel: 416-934-9814
Web: www.nwmo.ca

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EXECUTIVE SUMMARY

For decades Canadians have been using electricity generated by nuclear power reactors in Ontario, Quebec and New Brunswick. When used nuclear fuel is removed from a reactor, it is considered a waste product, is radioactive and requires careful management. Although its radioactivity decreases with time, chemical toxicity persists and the used fuel will remain a potential health risk for many hundreds of thousands of years. Canada's used nuclear fuel is now safely stored on an interim basis at licensed facilities located where it is produced.

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

The repository and its surroundings comprise a system that is designed to protect people and the environment through multiple barriers. These barriers include the ceramic used fuel, long-lived corrosion resistant containers, engineered sealing materials and the surrounding geosphere.

Safety is a priority for the implementation of the APM program. To support the focus on safety, the NWMO conducts a wide range of complementary activities, including research, design development, technology demonstration and safety assessment, which are necessary to assess the performance of the multi-barrier repository concept at timeframes relevant to illustrating long-term safety.

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

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

This report provides an illustrative case study of the current multi-barrier design and postclosure safety of a deep geological repository in a hypothetical sedimentary setting. The purpose of this case study is to present and illustrate a postclosure safety assessment methodology that demonstrates how Canadian Nuclear Safety Commission (CNSC) expectations are met, as documented in CNSC Guide G-320 on Assessing the Long Term Safety of Radioactive Waste Management. For a licence application for an actual candidate site, a full safety case would be prepared that would include the results of site-specific geoscience investigations, an associated deep geological repository design and a more comprehensive safety assessment than described in this document.

Geosphere

A hypothetical geosphere was derived, in part, from experience gained in the Canadian Nuclear Fuel Waste Management Program. It was developed for the purpose of this illustrative case study while the NWMO proceeds with the APM siting process and selection of a preferred site in an informed and willing host community. While the hypothetical site represents one example of a possible sedimentary rock setting in southern Ontario, other characteristics are considered in the safety assessment to illustrate an approach to assessing both long-term safety and the functionality of various barrier systems.

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

For the purposes of this illustrative assessment, the hypothetical geosphere is divided into three groundwater systems, which are assumed to have the following characteristics:

1. The shallow groundwater system, located between 0 and 215 m below ground surface, is predominately driven by local and sub-regional scale topographic changes. The average travel time for groundwater to recharge, and then subsequently discharge, in the shallow groundwater zone is typically less than 1000 years. The groundwater in the shallow groundwater zone is fresh and oxygen-rich with a low total dissolved solids concentration.
2. The intermediate groundwater system between 215 and 250 m below ground surface is a transition zone from fresh and oxygen-rich to more mineralized and chemically reducing with depth. At the hypothetical site, the shift from oxidizing to reducing conditions occurs within this system. In the intermediate groundwater system, larger domains of low permeability rock tend to decrease mass transport rates.
3. In contrast with the shallow and intermediate groundwater systems, the groundwater in the deep system below 250 m has a higher total dissolved solids concentration and fluid density, and is chemically reducing. The increased fluid density will influence both energy gradients within the groundwater regime and vertical upward movement of groundwater between the shallow/intermediate and deep groundwater zones.

Design Concept

The current conceptual design for sedimentary rock consists of a repository constructed at a depth of approximately 500 m below surface. This depth was arbitrarily selected for illustrative purposes only; at an actual site the repository depth would be selected based on site-specific attributes to enhance passive long-term safety and the presentation of a repository safety case. The host rock at 500 m at this hypothetical site is assumed to be a massive limestone formation overlain by a thick shale sequence that is suitable for construction and operation of a used fuel repository. The repository contains a network of horizontal tunnel placement rooms for the base case inventory of 4.6 million used fuel bundles encapsulated in about 12,800 long-lived used fuel containers. The container design consists of a copper outer vessel, or shell, that encloses a steel inner vessel. The outer copper shell provides effective resistance to container corrosion under deep geological conditions, while the inner steel vessel provides strength for the container to withstand expected hydraulic and mechanical loads, including earthquakes and glaciation. The report also describes observations on sedimentary rock considerations in other countries. A notable difference in this case study is with the copper-shell container design as opposed to the steel-only design primarily being considered in other countries. The design will be further refined and optimized for a licence application.

The used fuel container is supported by a highly compacted bentonite pedestal in its assigned position in the placement room. Bentonite pellets, placed by pneumatic methods, are used to fill all the remaining voids in the container placement room. Bentonite is a durable natural material that is expected to maintain its properties over the long term. Bentonite is a type of clay that swells on contact with water, resulting in its natural self-sealing property.

Postclosure Safety Assessment

The primary safety objective for the deep geological repository is the long-term containment and isolation of the used nuclear fuel. The safety of the repository would be based on a combination of the geology, engineered design, careful operations, and quality assurance processes including review and monitoring. Safety assessment provides a quantitative evaluation of the overall performance of the repository system and its impact on human health and on the environment. In this respect, it is able to identify features or processes that contribute to an understanding and confidence in long-term repository safety.

This illustrative case study focuses on long-term or postclosure safety. This is the period after the repository has been filled with used fuel containers, and has been sealed off and closed. Consistent with CNSC Guide G-320, the study identifies scenarios, models and methods for evaluating safety, with which to assess dose consequences and the influence of uncertainties. The results are compared against interim acceptance criteria for protecting persons and the environment.

The assessment does not try to predict the future, but instead examines the consequences for a range of scenarios, from likely to unlikely to “what if”. The likely scenarios are considered under the heading of “Normal Evolution Scenario.”

Normal Evolution Scenario

The normal evolution scenario presented in this report is based on a reasoned extrapolation of the reference case site and repository characteristics over time, consistent with the expectations of CNSC Guide G-320. The report describes why the used fuel copper containers are expected to remain intact over the timeframe of interest. For the purpose of the reference case normal evolution scenario, a small number of containers are assumed to be placed in the repository with undetected defects in the copper shell. Conservatively, these containers are assumed to be positioned within a placement room associated with the shortest travel time through the geosphere to the surface biosphere. The anticipated effects of glaciations on the assessment are also described.

The postclosure safety assessment adopts scientifically informed, physically realistic assumptions for processes and data that are understood and can be justified on the basis of the results of research. 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. Data from site investigations will further support the assumptions and be incorporated into future safety assessments.

For the reference case safety assessment, the primary contributor to the public dose over the long term from an assumed small number of defective used fuel containers is the instant release fraction of Iodine-129, a long-lived radionuclide in used fuel that is non-sorbing in the geosphere. The calculated maximum dose for the reference case is about 150,000 times lower than the interim dose acceptance criterion of 0.3 mSv per year for the normal evolution scenario and occurs at the modelling cut-off time of 10 million years after closure. This long timeframe is due, in part, to the combined performance of the repository barrier systems and the time required for Iodine-129 to reach the biosphere. The barrier systems include the long-lived containers, the integrity of the engineered sealing systems and the near-field rock surrounding the repository.

The radiological impact on non-human biota is discussed in the report and the assessment concludes that the effects are negligible for the normal evolution scenario.

The report also concludes that contaminant concentrations are below their associated interim acceptance criteria in the assessment for protecting persons and the environment from hazardous substances, such as copper and other elements released from the used fuel and the containers.

Sensitivity Analyses and Bounding Assessments

Recognizing that there are uncertainties associated with the future evolution of a repository, the NWMO has varied a number of important parameters and assumptions, completed bounding assessments and has developed a number of hypothetical “what-if” scenarios to explore the influence of parameter and scenario uncertainty in assessing long-term safety. This approach is consistent with CNSC Guide G-320 on the use of different assessment strategies.

Key parameters that could potentially affect long-term safety are varied in sensitivity cases to understand the impact of uncertainties in these parameters:

- An increase in fuel dissolution rate by a factor of 10;
- An increase of contaminant instant release fractions to 10%;
- An increase in rock mass and excavation damage zone hydraulic conductivities by a factor of 10;
- An increase in rock diffusivity by a factor of 10;
- A 158 m overpressure in the Shadow Lake Formation which is located at a depth of approximately 675 m at the hypothetical site;
- An increase in container degradation by increasing the assumed undetected container defect area by a factor of 10; and
- A decrease in geosphere sorption with a coincident increase in radionuclide solubility limits.

Some parameters are also pushed beyond the reasonable range of variations in bounding assessments. In these cases, parameters are completely ignored by setting their values to zero or by removing physical limits for the following:

- An increase in radionuclide solubility in groundwater by ignoring solubility limits;
- A decrease in radionuclide sorption in the geosphere by ignoring sorption; and
- A decrease in radionuclide sorption in the near field by ignoring sorption.

The results from the sensitivity analysis and the bounding assessments conducted as part of this illustrative case study are shown in Figure E1.

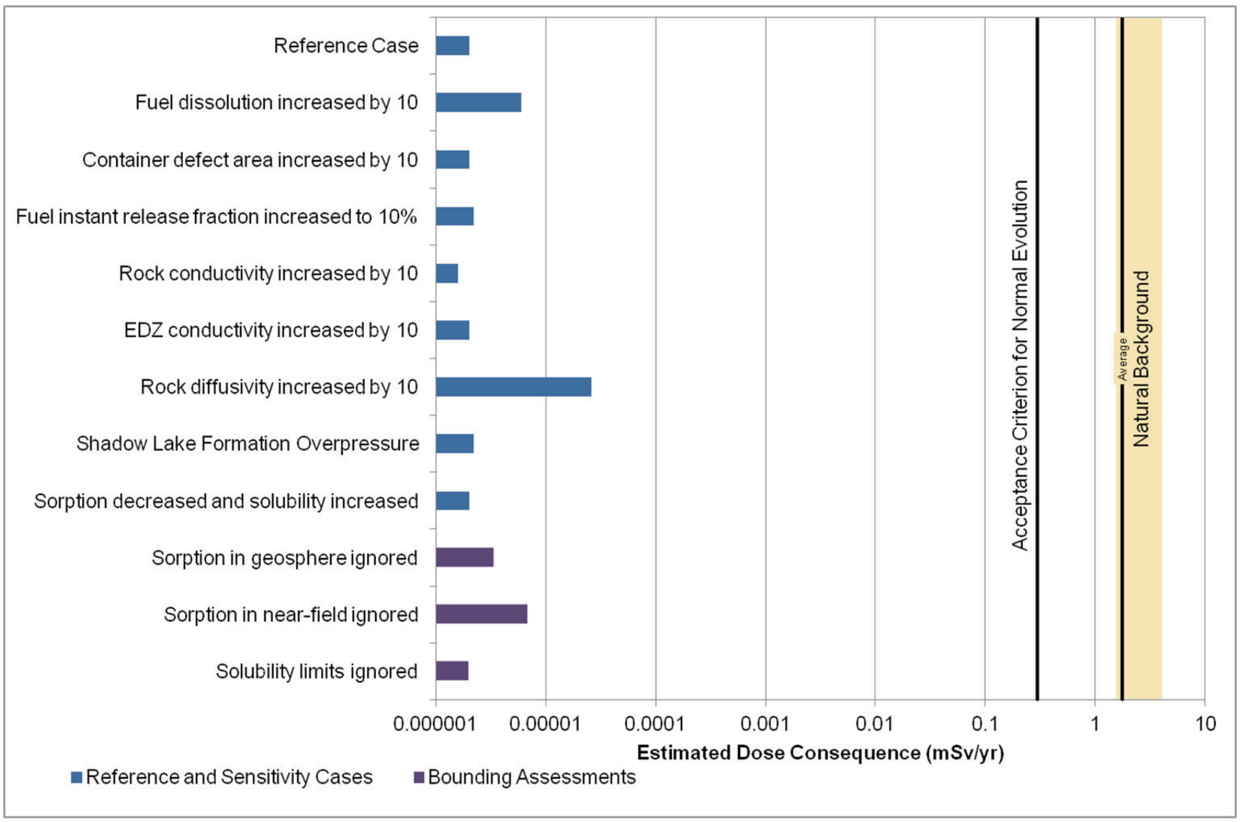

Figure E1: Results from Sensitivity Analysis and Bounding Assessments

The sensitivity analyses show that the impact on dose is small when key parameters are varied. As shown in Figure E1, the parameter with the most significant impact on dose is the rock diffusivity. The dose consequence when the rock diffusivity is increased by a factor of 10 is assessed to be 13 times greater than the reference case value.

The bounding assessments show a small impact on dose when sorption is ignored. When sorption is ignored in the near field, the dose consequence is assessed to be 3.4 times greater than in the reference case. When sorption is ignored in the geosphere, maximum dose is increased to 1.6 times the reference case value and occurs at same time (modelling cut-off time of 10 million years). No impact on dose was observed when radionuclide solubility limits are ignored (see Figure E1).

Recognizing the importance of processes such as used fuel dissolution and sorption as shown in this case study, NWMO maintains active research programs in these areas to continue to improve our understanding of these processes. Nevertheless, even if highly conservative assumptions are adopted where there is uncertainty, the maximum dose rate to a member of the public is still estimated to be orders of magnitude lower than the interim dose acceptance criterion of 0.3 mSv per year.

All the previous results were obtained through deterministic analyses. A further understanding of uncertainties can be obtained through probabilistic modelling. In the present illustrative case study, a probabilistic analysis was conducted on the contaminant release and transport parameters. A total of 120,000 simulations were examined to identify a 95th percentile peak dose rate. The peak dose consequence in this case is assessed to be 37 times greater than for the reference case. This remains 4,000 times below the interim dose acceptance criterion of 0.3 mSv per year.

Disruptive Scenarios

A number of disruptive or “what-if” scenarios are identified by examining possible failure mechanisms. These scenarios are assessed to evaluate the potential impact of major barrier failures on safety, in accordance with CNSC Guide G-320. The disruptive event scenarios considered in this illustrative case study include:

- All containers fail at 60,000 years;
- All containers fail at 10,000 years; and
- Failure of shaft seal.

The container failure scenarios (i.e., all containers fail at 60,000 years and a variation where all containers fail at 10,000 years) indicate a notable increase in the dose results. However, the maximum dose rates remain well below the interim dose acceptance criterion of 1 mSv per year for disruptive scenarios.

The results also reveal that there is low sensitivity of the peak dose rate to the assumed failure time of all used fuel containers in the reference case geosphere. This occurs primarily as the assumed container failure time is longer than the short-lived fission product decay time, meaning that fuel dissolution rates are greatly reduced due to the decay of the gamma and beta radiation fields. Furthermore, the failure times are much smaller than the contaminant transit times to the surface. The remaining actinides and most of the long-lived fission products are delayed principally by diffusion within the natural barrier of the enclosing rock mass so that the peak dose rate, which is dominated by the long-lived and non-sorbing Iodine-129, does not materially change.

The impact of gas generated in the repository is considered for the case where all the containers fail at 10,000 years. The largest potential for gas generation (from the corrosion of steel within the copper container) is examined for this scenario and the model shows that gas could travel upward to the permeable Guelph Formation where it will disperse and dilute laterally underground. However, to provide a bounding estimate, the gas-borne dose consequences are assessed using a set of extremely conservative assumptions to bound the potential dose consequences. A peak dose rate of 0.17 mSv per year is obtained when all the Carbon-14 is assumed to discharge into a house above the repository. This remains a factor of six below the 1 mSv per year interim dose acceptance criterion. For a more realistic case of failure of copper containers over longer times, the dose rates would be substantially lower. For example, if the copper fails on time scales associated with the next glaciation or later, the corresponding dose rates would be well below 0.001 mSv per year due to decay of Carbon-14.

The seal failure scenario has shown negligible effect on the predicted dose consequence in this study due to the distance between the containers with undetected defects and the shaft seal.

And finally, a stylized analysis was completed for inadvertent human intrusion. This scenario is a special case, as recognized in CNSC Guide G-320, since it circumvents all engineered and natural repository barriers. The results show that the potential dose to the drill crew, and to a site resident, from early intrusion, that exceeds the dose limit. However, the likelihood of this event occurring is very small due to placing the used fuel containers deep underground in a location with institutional controls in place for a period of time, no economically viable mineral resources, and no potable groundwater resources. Normal deep drilling practices (e.g., control of drilling fluids, use of gamma logging, etc.) will also tend to reduce consequences relative to those estimated here. Although the likelihood of human intrusion cannot be readily defined, it will be very low. The annual risk of health effects from human intrusion is estimated to be less than 1 in 100,000 per year.

Conclusion

This report provides an illustrative postclosure safety assessment of a deep geological repository in a hypothetical sedimentary rock setting. The objective is to provide a partial postclosure safety assessment that shows a structured and systematic approach that is consistent with expectations described in CNSC Guide G-320. The illustrative assessment includes a description of the repository system, systematically identifies scenarios, models and methods for evaluating safety, uses different assessment strategies, addresses uncertainty, and compares the results of the assessment with interim acceptance criteria. It indicates where additional analyses would be undertaken as part of a full safety case for an actual repository site.

The postclosure safety assessment shows, for the normal evolution scenario and associated sensitivity cases, that radiological and non-radiological interim acceptance criteria could be met during the repository’s postclosure period.

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