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A Prototype Performance Assessment Model for Generic Deep Borehole Repository for High-Level Nuclear Waste

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The U.S. is currently re-evaluating the policy on commercial used nuclear fuel (UNF) and high-level radioactive waste (HLW) management. As part of the Fuel Cycle Research and Development (FCRD) program supported by the U.S. DOE Office of Nuclear Energy, the Used Fuel Disposition (UFD) campaign has been studying generic disposal system environment (GDSE) concepts to support the development of a long-term strategy for geologic disposal of commercial UNF and HLW. The GDSE study focuses on the comparative analysis of different GDSE options, and a deep borehole repository is one of the options currently under study. The immediate goal of the generic deep borehole repository study is to develop the necessary modeling tools to evaluate and improve the understanding of the repository system response and processes relevant to long-term disposal of high-level nuclear waste in deep boreholes.

Deep boreholes have been proposed for many decades as an option for permanent disposal of high-level nuclear waste. This disposal concept is straightforward, and generally calls for drilling boreholes to a depth of approximately 5,000 m into crystalline basement rocks. Waste is placed in the lower 2,000 m of the hole, and the upper remaining portion (3,000 m) of the hole is sealed to provide effective isolation from the biosphere. The potential for excellent long-term performance has been recognized in many previous studies.

This paper presents a prototype performance assessment model for a generic deep borehole repository, developed using the same performance assessment methodology applied to mined geologic repositories for high-level nuclear waste. The paper also discusses the preliminary analysis results, emphasizing key attributes of a deep borehole repository that are potentially important to the long-term safe disposal of nuclear waste.

The deep borehole disposal performance assessment model consists of three components: 1) the waste-disposal zone, 2) the seal zone, and 3) the upper-borehole zone and aquifer. The waste-disposal zone contains 400 waste canisters in the lower 2,000 m of the 5,000 m long borehole. The seal zone consists of 1,000 m above the waste in which a series of low permeability seal materials are emplaced in the borehole. The upper-borehole and aquifer component consist of the upper 2,000 m of sealed borehole and the surrounding aquifer that serves as a potential source of groundwater for release to the biosphere. Groundwater flow in the disposal and seal zone is driven by thermal-hydrologic effects. Decay heat from the radioactive waste causes flow by thermal expansion and thermal buoyancy. Groundwater flow in the upper-borehole and

aquifer zone is driven by 3D radial flow to a hypothetical pumping well located above the waste-disposal and seal zones. Radionuclides that are released to the biosphere via pumping are contained in a representative volume of groundwater and radiological dose is calculated from the resulting radionuclide concentrations using a biosphere dose conversion factor.

Assumptions embodied in the performance assessment model include:

- Waste canister failure is assumed conservatively to occur immediately when the borehole is sealed.
- Waste form degradation and radionuclide release to groundwater are modeled using an annual fractional rate model.
- Radionuclide solubility limits representative of geochemically reducing conditions in brine are applied.
- Radionuclide transport processes include advection, dispersion, diffusion, sorption, decay, and in-growth.
- Radionuclide retardation is modeled using linear sorption coefficients representative of geochemically reducing conditions.
- Groundwater flow rates vary with depth and time in the waste-disposal and seal zones (derived from separate 3D thermal-hydrologic modeling).
- Groundwater flow rates are constant in the upper-borehole zone and surrounding aquifer, corresponding to continuous pumping from the hypothetical water supply well.
- Radionuclide releases to the biosphere are contained in groundwater pumped at a rate of 10,000 m^3/year.

The performance analysis studies to be presented in the paper take into account uncertainty in multiple aspects of the disposal concept, including host rock permeability, waste form degradation rate, radionuclide solubility, properties of the damaged zone surrounding the borehole, thermal-mechanical evolution of the system, and complete degradation of the borehole seals. Alternative design concepts included in preliminary evaluations include disposal of different waste types, commercial UNF and DOE high-level radioactive waste (DHLW) with varying thermal heat outputs. The numerical model is implemented with the GoldSim software code. Each performance assessment model analysis was run probabilistically, consisting of 100 realizations of uncertain parameters.

Estimates of releases from deep boreholes, and the annual radiation doses to hypothetical future humans associated with those releases, are extremely small. For the expected or base case values of permeability, radionuclide releases and dose rates at the surface are essentially zero. For the high-permeability case with fully degraded seals, the simulated releases and dose rates correspond to an acceptably small risk to human health. While much work needs to be done to validate the model assumptions, the analyses provide additional confirmation that deep borehole

emplacement may be a viable alternative to mined repositories for disposal of commercial UNF and HLW.

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