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Authors

Finsterle, S
Muller, RA
Baltzer, R
[et al.](#)

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NUMERICAL EVALUATION OF THERMAL EFFECTS FROM NUCLEAR WASTE DISPOSED IN HORIZONTAL DRILLHOLES

S. Finsterle¹, Richard A. Muller², Rod Baltzer², Joe Payer³, and James W. Rector⁴

¹ Finsterle GeoConsulting, 315 Vassar Ave, Kensington, California, 94708, stefan@finsterle-geoconsulting.com ² Deep Isolation, Inc., 2120 University Avenue, Ste. 623, Berkeley, California, 94704 ³ Corrosion Engineering, University of Akron, Whitby Hall 211, Akron Ohio, 44325 ⁴ Department of Civil and Environmental Engineering, University of California, 419 Davis Hall, Berkeley, California, 947200

We examine the temperature evolution near horizontal drillholes designed for the disposal of spent nuclear fuel and high-level radioactive waste. In this concept, directional drilling technology is used to complete a small-diameter, vertical access hole, which at the target depth gradually turns into a horizontal section dedicated for the end-to-end disposal of nuclear waste canisters in a suitable, low-permeable formation. Decay heat emanating from the waste leads to temperature increases within the drillhole and the surrounding host rock. Predicting the thermal evolution within the engineered and natural barrier systems is important, because high temperatures may lead to thermal stresses, alter material properties, or induce driving forces that affect the migration of radionuclides along the drillhole and in the near field of the repository. We present the results of numerical design calculations that examine the spatial and temporal evolution of temperature as a function of uncertain material properties and adjustable design parameters.

I. INTRODUCTION

Geologic repositories are considered to be a viable approach for solving the problem of permanent disposal of high-level radioactive waste (HLW) and spent nuclear fuel (SNF). In addition to centralized, mined repositories with various waste-deposition configurations, deep vertical boreholes into the basement rock have also been considered. We propose decentralized disposal of radioactive wastes in small-diameter drillholes that consist of (a) a vertical section to reach a deep, suitable host formation below confining layers, (b) a gradually curving section, and (c) a horizontal disposal section into which canisters containing waste capsules or SNF assemblies are emplaced end-to-end. The drillholes will be cased, backfilled, and sealed.

The density of waste canister placement and the properties of the engineered barrier components within the horizontal drillhole can be designed such that the temperatures remain below certain limits. Such limits may be imposed to ensure that high temperatures do not affect repository performance, and that this performance can be predicted with acceptably low uncertainty. For example, high temperatures tend to accelerate the kinetics of geochemical reactions, may lead to higher corrosion rates, induce

complex two-phase flow conditions, and trigger coupled thermal-mechanical effects, all of which making predictive modeling and performance assessment more challenging.

We present numerical design calculations that examine the thermal evolution for a wide range of material properties and waste emplacement densities. We report on the predicted maximum temperatures encountered at various locations within the drillhole repository during the thermal period (i.e., the first few hundred years after waste emplacement); however, we do not discuss whether these maximum temperatures are acceptable, as the determination of temperature limits is a complex technical and regulatory issue that is beyond the scope of this study.

The horizontal drillhole concept described above accommodates different waste forms, ranging from relatively small capsules containing cesium and strontium from the U.S. defense program, to SNF assemblies from boiling water reactors (BWR) and pressurized water reactors (PWR), to vitrified high-level radioactive waste. In this paper, we present the general approach of our design calculations, using canisters holding strontium capsules and SNF assemblies as illustrative examples.

II. MODEL DEVELOPMENT

The following design calculations are based on a numerical process model that represents the relevant features and processes in a simplified manner. Such simplification is justified given the intended use of the model, which is to examine maximum temperatures for a wide range of configurations and thermal material properties.

While coupled thermal-hydrological processes are considered in the simulations, thermal conduction is the dominant heat transfer mechanism given the low hydraulic permeability of the engineered materials and the host formation. The temperature dependence of thermal properties is ignored as such changes are small compared to the range of properties examined in this study.

Assuming that the disposal section of the drillhole repository is at a depth of approximately 1 km, the pore space is assumed to be fully liquid saturated and will remain so even under elevated temperature conditions, as the hydrostatic pressure at depth remains higher than the saturated vapor pressure for temperatures exceeding 300°C.

Given the concentric geometry of the waste, canister, backfill materials, casing, annulus, and host rock (see Fig. 1a), as well as the linear arrangement of waste canisters in a long, horizontal disposal hole leads to a symmetric configuration that can be exploited in the numerical model.

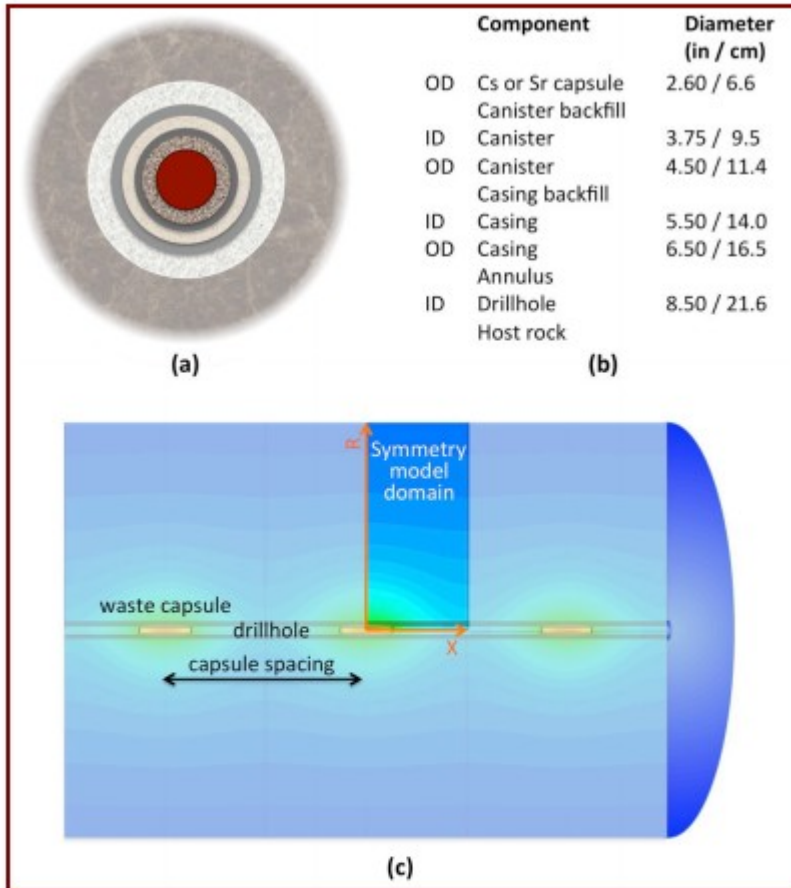


Fig. 1. (a) Cross-sectional schematic of components in a horizontal drillhole used for the disposal of heat-generating cesium or strontium capsules; (b) List of inner diameters (ID) and outer diameters (OD) of each component; (c) X-R cross section, showing symmetric model domain.

Here, we examine the temperature evolution in the immediate vicinity of the heat-generating radioactive waste; simulating a single waste package is thus sufficient for evaluating the impact of design decisions on temperature.

In a second set of simulations, spent nuclear fuel assemblies from a boiling water reactor are placed in a cylindrical canister, backfilled with quartz sand for stability and enhanced thermal conductivity. Canisters are pushed into the drillhole casing and backfilled with a bentonite slurry or other suitable material. The casing itself is centered and cemented into to horizontal drillhole.

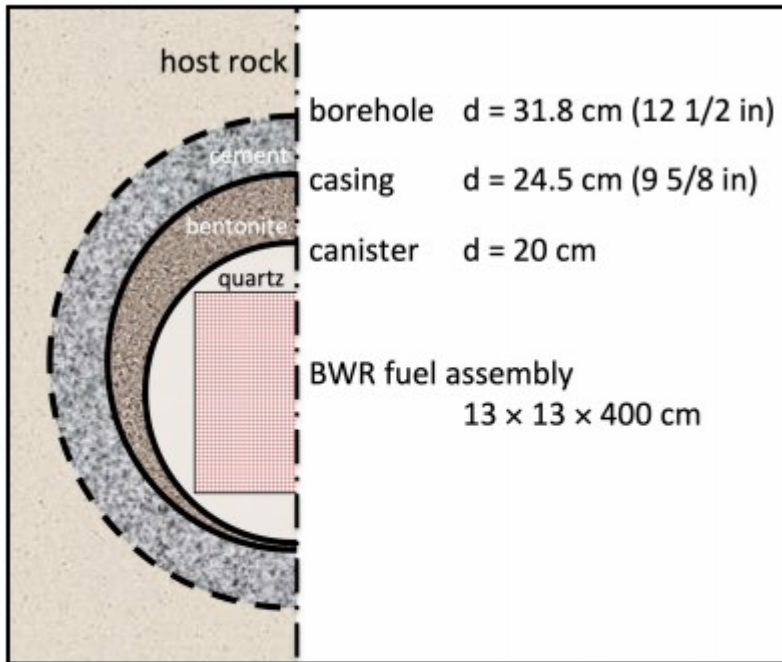


Fig. 2. Cross-sectional schematic of components in a horizontal drillhole used for the disposal of heat-generating spent nuclear fuel assembly from a boiling water reactor.

The simulations account for the time-dependent thermal output from the decaying radioactive waste and the (mainly conductive) heat transfer through the various containment shells (which include the canister, casing, and different backfill materials) into the host rock. The simulations are conducted with the TOUGH2 nonisothermal multi-phase flow and transport simulator¹, as implemented in the iTOUGH2 simulation-optimization framework.² In addition to predictive simulations of the temporal and spatial temperature distributions for reference configurations and base-case property sets, local and global sensitivity analyses as well as uncertainty propagation analyses were performed to examine the system response to changes in design parameters and uncertainties in thermal material properties.³

III. SIMULATION RESULTS

III.A. Temperature Control by Canister Spacing

Heat dissipation from cesium and strontium waste capsules emplaced end-to-end in a long horizontal disposal drillhole is predominantly cylindrical, with the expected fast temperature decline even at short distances from the drillhole axis. However, the maximum temperatures encountered within the drillhole may reach high values within a few years after waste emplacement, when radioactive decay is the highest. This maximum temperature is mainly

governed by the thermal conductivity of the host rock, as demonstrated by the detailed sensitivity analysis described below.

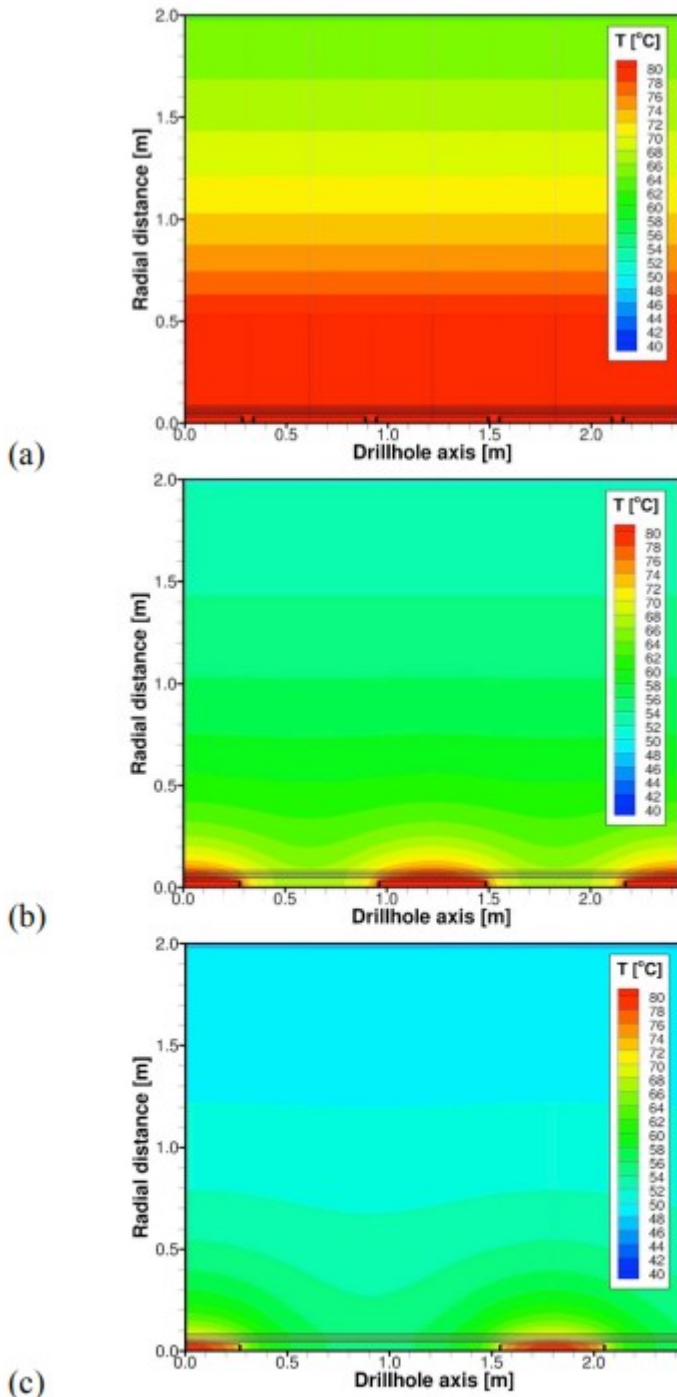


Fig. 3. Temperature distribution after 3 years for an initial heat release of 100 W per waste capsule with canister spacings of (a) 2 ft (0.61 m); (b) 4 ft (1.22 m); and (c) 6 ft (1.83 m).

The expected maximum temperatures within the drillhole and the adjacent host rock can readily be reduced by increasing the spacing between waste canisters, as heat dissipation transitions from a cylindrical (Fig. 3a) to a more spherical (Figs. 3b and 3c) regime.

Adjusting canister spacing in the horizontal drillhole concept to control maximum temperatures can readily be accomplished without undue reconfiguration of the emplacement technology. As demonstrated in Ref. 3, a short-duration heater test, which accounts for as-built and in-situ conditions, provides sufficient information about the local variability of thermal properties to guide waste emplacement. Once the effective thermal conductivity of the host rock has been determined by inverting temperature data collected during the in-situ heater test, a precalculated response surface can be used to select an appropriate canister spacing that avoids the risk of reaching excessive maximum temperatures at any point within the repository system. As an example, Fig. 4 shows such a response surface for the drillhole wall, which also reflects the maximum temperature the host rock would experience.

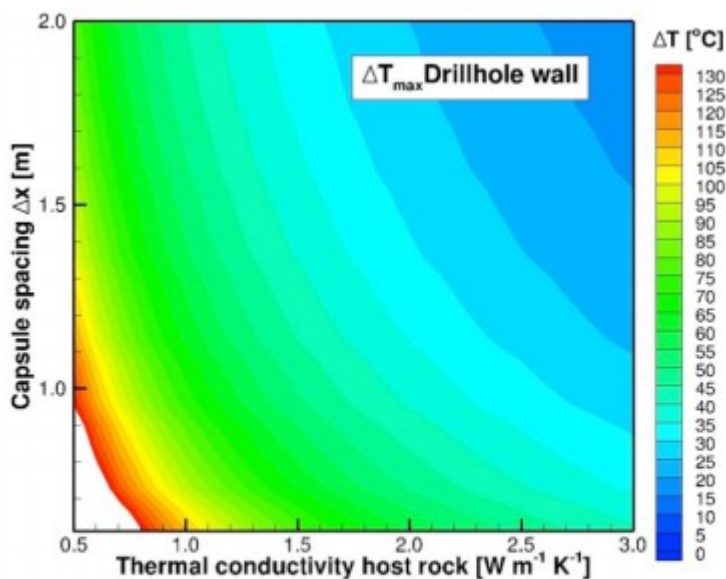


Fig. 4. Response surface of maximum temperature increase at the drillhole wall as a function of host-rock thermal conductivity and canister spacing for a 100 W initial heat output.

III.B. Temperature Evolution around BWR SNF Assemblies

A simulation of temperature evolution around a single SNF assembly is performed using the three-dimensional model depicted in Fig. 2. Vertical symmetry planes (i.e., no-heat-flow boundaries) were specified along the drillhole axis and perpendicular to the drillhole axis in the middle of the canister and at the center point between two canisters, which are spaced

with a separation distance of 1 m. A time-dependent heat output is specified, following the decaying total activity of the canister's inventory (see Fig. 5).

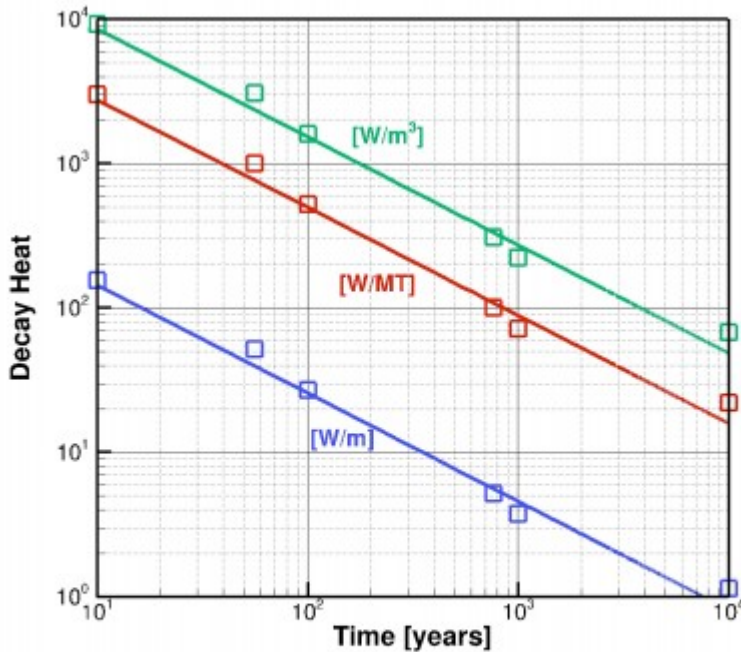


Fig. 5. Time-dependent release of decay heat (solid lines), approximately following scaled inventory activities (symbols) from Freeze et al. (2013)⁴.

The disposal section of the repository is assumed to be located in a shale formation with a porosity of 5%, a thermal conductivity of $1.4 \text{ W m}^{-1} \text{ K}^{-1}$, a specific heat of $835 \text{ J kg}^{-1} \text{ K}^{-1}$, and a grain density of 2650 kg m^{-3} , which results in a relatively low thermal diffusivity of approximately $6.3 \times 10^{-7} \text{ m}^2 \text{ s}^{-1}$.

Fig. 6 shows that given an initial temperature at the repository horizon of 50°C , heat generation leads to temperature increases reaching about 137°C within the waste itself, and about 123°C at the drillhole wall. At a radial distance of 5 m into the formation, the temperature is elevated by only about 22°C above its ambient value. No significant temperature perturbation is noticeable at a distance of 100 m.

Temperature maxima are reached after about 30 years, after which the decay of cesium and strontium, which dominate the early heat output, leads to a rapid cooling. The decay of transuranic radionuclides is mostly responsible for elevated temperatures for the remaining duration of the thermal period, which does not exceed 1000 years.

Fig. 7 shows that the spatial temperature distribution is essentially cylindrical, with only minor end effects noticeable in the backfilled spaced between individual canisters. The high thermal conductivities of the metal components in the drillhole, i.e., canister and casing, tend to homogenize

variabilities in heat output and backfill properties, leading to an axially more uniform heat release to the host formation.

The temperature perturbations shown in Figs. 6 and 7 must be assessed with respect to other factors affecting repository performance.

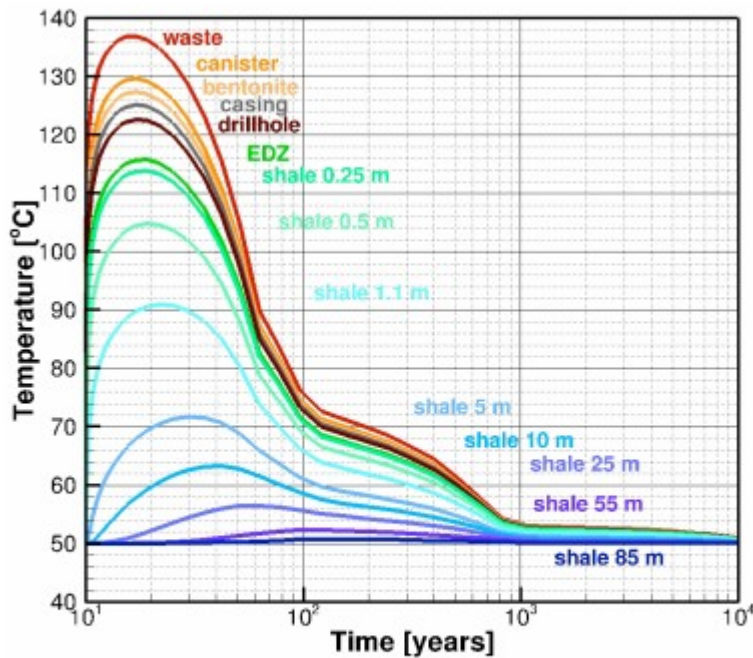


Fig. 6. Temperature evolution at select points within and outside of a drillhole segment containing a spent nuclear fuel assembly from a boiling water reactor.

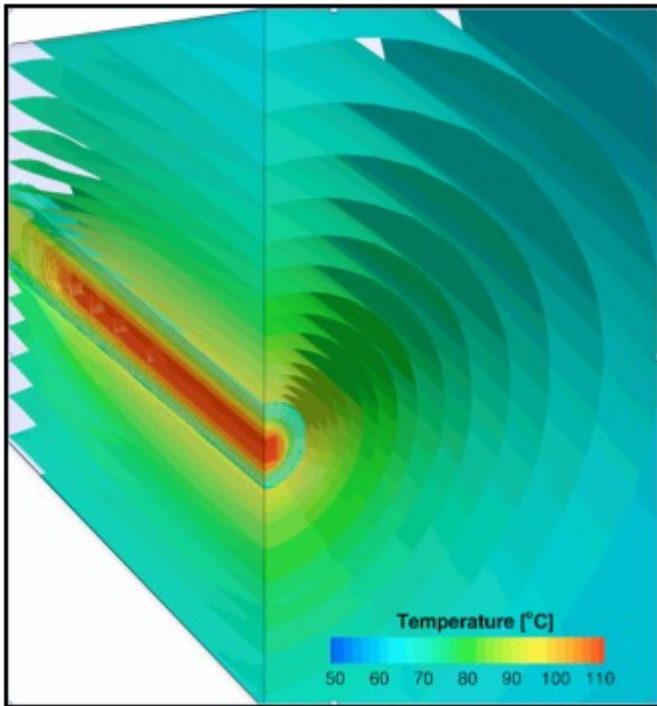


Fig. 7. Spatial temperature distribution around a spent nuclear fuel assembly disposed in a horizontal drillhole located in a shale formation.

Should the temperature maxima be unacceptable for any of the critical repository components, one (or a combination of) the following mitigation strategies could be considered:

- The spacing between canisters can be increased.
- The cool-down and storage times in surface facilities can be increased, i.e., older waste can be disposed of first.
- Canisters with hotter and cooler waste can be arranged in the drillhole in an alternating pattern.
- Backfill materials with different thermal diffusivities can be used to either increase heat dissipation (reducing temperatures for the components near the drillhole axis) or to insulate components away from the drillhole axis.
- A formation with higher thermal diffusivity can be selected as the host rock (note that the shale properties assumed in these simulations are chosen to be conservatively low).

IV. SUMMARY AND CONCLUDING REMARKS

We examined the dissipation of thermal energy from heat-generating nuclear-waste canisters disposed in deep horizontal drillholes. The maximum temperatures encountered by the various elements of the engineered barrier

system as well as the host rock need to be predicted with confidence as they may affect the properties, barrier function, integrity, and thus performance of the repository system.

The linear arrangement of waste canisters with relatively low energy density combined with a cylindrical or near-spherical heat dissipation regime reduces the risk of creating excessive temperature perturbations, both within the disposal section of the drillhole and the adjacent host rock. Despite heating due to radioactive decay, boiling of water at the canister surface, within the drillhole, and in the host rock is suppressed by the high hydrostatic pressure, making the prediction of the system behavior considerably less complex.

As conduction is the main heat transfer mechanism in a low-permeable repository, the thermal diffusivity of the host rock is the key parameter affecting temperature evolution. It is therefore important that thermal properties are determined with acceptably low estimation uncertainty. This is best accomplished by conducting a short-term heater test in the disposal section of the selected drillhole itself, making sure that scale-appropriate, process-specific, effective parameters under as-built and in-situ conditions are obtained (see Ref. 3 for more details).

Should the thermal diffusivity of the host rock be too low to effectively absorb or transport away the heat generated by the waste, minor adjustments during canister emplacement (i.e., increasing canister spacing; selecting appropriate backfill materials) can be made to control the maximum temperatures encountered by the repository during its projected life time. These adjustments do not amount to costly design changes or the need for a new performance assessment, as the changes will be done only within a well defined range of property values and adjustable design parameters, for which repository performance has been robustly evaluated in advance.

The physics-based simulations demonstrate that the proposed drillhole disposal strategy can be flexibly designed to ensure dissipation of the heat generated by decaying nuclear waste. Additional simulations for a wide variety of disposal configurations, waste forms, and material properties are underway to provide a basis for the inclusion of thermal effects into the performance assessment of a deep horizontal drillhole repository.

ACKNOWLEDGMENTS

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