Modeling Transient Thermal Conditions for Nuclear Waste in Deep Boreholes

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Previous deep borehole studies have focused on feasibility, providing proof-of-concept that a deep borehole repository can meet containment standards; but the basic design is not yet optimized. The thermal analysis presented in this paper provides insight into a design-to-performance approach, namely by modeling how changes in disposal depth, disposal zone rock type, disposal zone geometry, and initial heat load affect facility performance. As compared to a 5 km vertical deep borehole, a shallower borehole with multiple branches from a single vertical access shaft could cost less than a very deep vertical bore. This paper also considers heat transport from disposal in deep sedimentary rock in addition to disposal in granite. Borehole geometry changes, especially near-horizontal boreholes in sedimentary rock, can lead to longer disposal zone lengths and decrease the mechanical load on disposal canisters. The combination of shallower wells, rock types which require less effort to drill through, and the savings of a shared vertical access hole could considerably decrease facility construction costs. Cost savings could be redistributed among involved parties, which in turn may increase the likelihood of project success. Thermal transport analysis is also useful because it can provide insight into the physical processes relevant to the transport of radioisotopes in groundwater, including thermally-driven fluid flow and canister corrosion rates. Modeling the link between canister temperature and corrosion rates can inform better estimates of materials costs for canisters.

I. INTRODUCTION

Consideration of alternative methods of nuclear waste disposal has reignited interest in deep borehole storage. Technical reports from Sandia National Laboratory[1] and MIT[2] have found, on paper, that boreholes are capable of meeting radionuclide containment standards at a lower cost than a mined repository.

The next step towards improving existing designs for a deep borehole repository is to explore the relationship between depth of disposal, heat generation rate and isotope content of the disposed spent fuel, host rock formation, radionuclide release from the facility, and facility cost. The release of radionuclides can be linked to a handful of temperature-dependent factors, namely the corrosion of the cladding and disposal canister and the behavior of the groundwater surrounding the disposal zone.

II. DEVELOPING THE THERMAL TRANSPORT MODEL

A deep borehole facility could be constructed in a variety of locations and house a variety of spent nuclear fuel types. To better compare different possible disposal configurations it is helpful to examine a realistic set of fuel components and geologic conditions, as in the present paper.

II.A. Facility Geometry

The facility examined here has a single vertical access hole which curves to the horizontal direction at 1.25 km depth. Each of four access holes in a disposal field splits in a wishbone shape and ends in four horizontal disposal tubes. No assemblies are disposed in the tube until after its final split. Figure 1 shows the approximate shape of the splits. The heat generating region can be modeled as sixteen long parallel tubes, each of which is assumed to be separated by 20 meters.

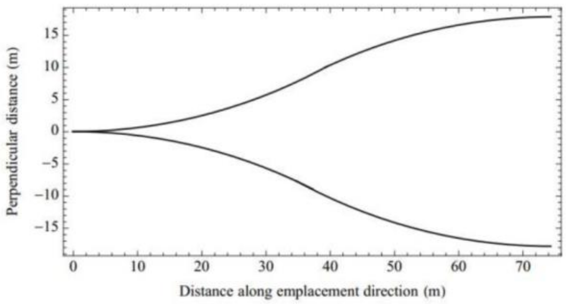

Figure 1. Example shape of the borehole access shaft splitting into two disposal zones.

The disposal tubes themselves are cased with an outside diameter of just under 35 cm. This accommodates a PWR assembly, canister, and gap between casing and canister to allow the canister to navigate the curves. Each assembly is separated by 10 cm.

II.B. Modeling the Heat Source

For fuel, the age and burnup of many core loads are available. By focusing on a core group of isotopes and using burnup to estimate isotopic content at discharge, it is possible to keep an approximate inventory of each isotope as spent fuel ages. The sum of all decay heat from each core isotope over time provides the heat per assembly. The, rectangular assemblies are approximated as cylinders with the same area and volumetric heat generation as the assembly. The isotopes included for decay heat estimates are Sr-90, Cs-137, Am-241, Am-243, and plutonium 238 through 242, with a linear heat generation rate of around 43 W/m. This linear heat generation rate is similar to the lower bound of other studies, representative of well-aged spent fuel.

II.C. Approximating the Properties of the Host Rock

The ambient temperature of the host rock varies by depth and region. It is assumed that a region is chosen that does not have abnormal subsurface activity which would cause major deviations from the standard thermocline. The average temperature at 1.25 km of depth is around 295K. For the bulk properties of the host rock, properties representative of a thick horizontal shale layer were chosen.

III. THERMAL TRANSPORT MODEL RESULTS

Figures 2 and 3 below demonstrate the temperature evolution of the canister temperature over the first 800 and the entire 10,000-year model window. The outermost borehole is denoted by the n=1 notation, whereas n=8 denotes the innermost two boreholes of the sixteen parallel tubes.

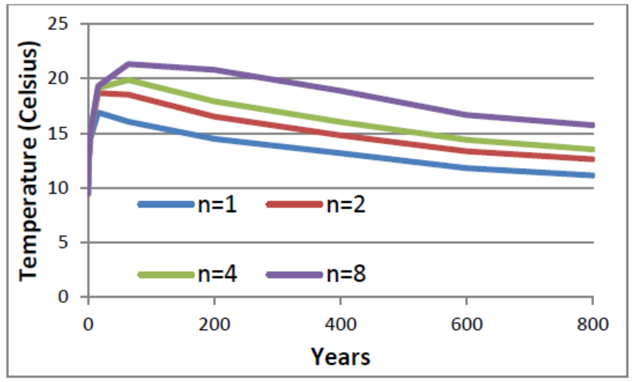

Fig. 2. Temperature increase of the fuel canister above background temperature for the first 800 years.

The profile makes a steep decline over the first 10,000 years, which is the required confinement time for U.S. repositories other than Yucca Mountain, encompassing over nine half-lives of Americium-241.

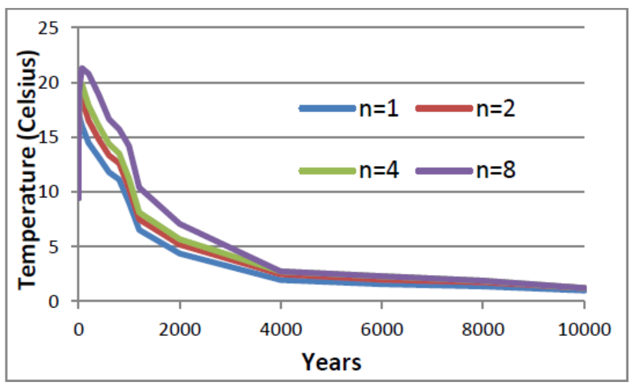

Fig. 3. Temperature increase of the fuel canister above background temperature over 10,000 years.

IV. DISCUSSION OF RESULTS

The primary metric for evaluating repository performance is radionuclide containment, encompassing both natural and engineered barriers. For a deep borehole system, engineered barriers are less important to radionuclide containment than for a mined repository, but it is nevertheless necessary to consider the behavior of fuel cladding and disposal canister to better model radionuclide release. The estimated temperature increases provide an initial framework under which design choices can be evaluated on their technical and economic merits. The release of radionuclides from the fuel pellets is assumed not to strongly correlate with temperature for the conditions considered here, but the breakdown of the initial barriers to release (fuel cladding and the canister) is temperature-dependent, as is evident from the type of formulation illustrated in Appendix A. Additionally, a steep horizontal temperature gradient can drive a convective instability, increasing the rate at which radioisotopes move away from the disposal zone. The relationships between depth of disposal, corrosion resistance of the canister material, and the heat generation rate of the canister-unit of fuel (whether an assembly or repacked assembly) are the primary drivers of cost-vs-containment analysis.

With the exception of a small fraction of assemblies containing leaking fuel rods which will likely require special canisters, all of the fuel disposed in the borehole has intact cladding. Corrosion rate estimates for zircalloy under reducing conditions at about the pre-emplacement ambient temperature range quite widely from 1 to 20 microns per thousand years.[3] The corrosion rate for low-carbon steel in similar conditions can range from 24 to 110 microns per year. Taking both rates into account at the geometric mean of the estimated ranges, each canister has mean breach time (shown in Appendix B) at which both the cladding and canister has been breached. After taking into account how the primary mobile isotope, I-129, leaches out of the exposed fuel pellet and into the groundwater (which is not discussed here), the corrosion rate determines the source term for groundwater contamination. Therefore, the choice of material, ranging from steel to more expensive but corrosion-resistant materials, can trade additional cost for slower corrosion. The horizontal nature of the disposal tubes in this model is relevant, as materials must bear a much lower mechanical load as compared to a single deeper vertical disposal zone, thus allowing a larger range of materials to be used for canister construction.[2]

V. CONCLUSIONS

The maximum canister temperature increase for well-aged spent fuel in shale is around 20°C. In the sample geometry with 20 meters between disposal zones, the interaction of heat from nearby tubes increases the temperature of interior wells 5°C more than the temperature of exterior wells. The temperature increase is enough to increase the corrosion rate of the canister and the cladding, but further research must be done on the subject to achieve more detailed results. Further analysis must be performed for repacked or damaged assemblies and for alternative fuel breach pathways like localized corrosion and material changes introduced to fuel cladding from the reactor environment. Finally, the larger question of how to design around or manage the possibility of disposal canisters becoming stuck during emplacement requires more analysis.

A. TWO REGION CYLINDRICAL HEAT TRANSPORT ANALYTICAL SOLUTION

Borrowing from Amos,[4] the Green's function solution for an infinite cylinder is

$$T_1 = T_0 \int_0^\infty dx \frac{J_1(b_f) J_0(b_r)\left(e^{-x^2\tau} - e^{-\tau}\right)}{(e_1^2+e_2^2) b (1-x^2)} \quad (1)$$

$$T_2 = \kappa T_0 \int_0^\infty dx \frac{J_1(b_f)\left(e_1 J_0(b_r) - e_2 Y_0(b_r)\right)\left(e^{-x^2\tau} - e^{-\tau}\right)}{(e_1^2+e_2^2) b (1-x^2)} \quad (2)$$

Where e_1, e_2, and T_0 are defined as:

$$e_1 = \left(\frac{\pi}{2}\right)\left(-J_0(b)Y_1(\kappa b) + \kappa\left(\frac{k_1}{k_2}\right)J_1(b)Y_0(\kappa b)\right) \quad (3)$$

$$e_2 = \left(\frac{\pi}{2}\right)\left(-J_0(b)J_1(\kappa b) + \kappa\left(\frac{k_1}{k_2}\right)J_1(b)Y_0(\kappa b)\right) \quad (4)$$

$$T_0 = \left(\frac{4 q_0 \alpha_j d}{\lambda r^2}\right)\left(\frac{\alpha_2}{k_2}\right) \quad (5)$$

And $\tau = \lambda t$, $b = x/c_0$, $b_f = b a_f / a_c$, $b_r = br/a_c$, and $c_0 = \frac{\sqrt{\alpha_1 \lambda}}{a_c}$.

Here a_f is the outer radius of the canister, a_c is the inner radius of the canister *d* is the number of seconds in a year.

B. CORROSION AND BREACH FRACTION

Where w_{Zr} is the thickness of zirconium cladding (0.00057 meter), z_1 is 7.77x10-6/yr, z_2 is 2231.7K, T_K is the temperature in Kelvin, and t_1 is the time in years until the canister will breach, the mean breach time t_{Zr} for the clad is the solution to:

$$w_{Zr} = \int_{t_1}^{t_{Zr}} z_1 e^{-z_2/T_K(t)} dt$$

The probability, then, of a given assembly's cladding failing as a function of time *t* is:

$$p_{Zr} = \left(\sigma_{Zr}\sqrt{2\pi}\right)^{-1} e^{-(t_{Zr}-t_1-t)^2/2\sigma_{Zr}^2}$$

σ_{Zr} is set so that the initial damage fraction of rods (f_{Zr}) is 0.02 and is expressed as:

$$\sigma_{zr} = -InverseErf[2f_{Zr} - 1]t_{Zr}$$

The time is takes for the canister to breach is t_{ZFer}, which is the solution to:

$$w_{Fe} = \int_0^{t_{Fe}} b_1 e^{-b_2/T_K(t)} dt$$

Where b_1 is 27.7/yr and b_2 is 2254 K. Unlike for the cladding, it is expected that none of the canisters will be emplaced with damage, so the probability of an individual canister breaching at time t is:

$$p_{Fe} = \left(\sigma_{Fe}\sqrt{2\pi}\right)^{-1} e^{-(t_{Fe}-t)^2/2\sigma_{Fe}^2}$$

Where σ_{Fe} is:

$$\sigma_{Fe} = -InverseErf[2f_{Fe} - 1]t_{Fe}/\sqrt{2}$$

Combining all factors, the fraction of all fuel rods that are leaking at time t can be approximated as:

$$f_{leak} = (0.5 - 0.5Erf[t - t_{Fe}])\left(0.5 - 0.5Erf\left[t - t_{zr} - t_{fe}\right]\right)$$

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