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Drift Emplaced Waste Package Thermal Response

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ABSTRACT

Thermal calculations of the effects of radioactive waste decay heat on the potential repository at Yucca Mountain, Nevada have been conducted by the Yucca Mountain Site Characterization Project (YMP) at Lawrence Livermore National Laboratory (LLNL) in conjunction with the B&W Fuel Company. For a number of waste package spacings, these 3D transient calculations use the TOPAZ3D code to predict drift wall temperatures to 10,000 years following emplacement. Systematic temperature variation occurs as a function of fuel age at emplacement and Areal Mass Loading (AML) during the first few centuries after emplacement. After about 1000 years, emplacement age is not a strong driver on rock temperature; AML has a larger impact. High AMLs occur when large waste packages are emplaced end-to-end in drifts. Drift emplacement of equivalent packages results in lower rock temperatures than borehole emplacement. For an emplacement scheme with 50% of the drift length occupied by packages, an AML of 138 MTU/acre is about three times higher than the Site Characterization Plan-Conceptual Design (SCP-CD) value. With this higher AML (requiring only 1/3 of the SCP-CD repository footprint), peak drift wall temperatures do not exceed 160°C, but rock temperatures exceed the boiling point of water for about 3000 years. These TOPAZ3D results have been compared with reasonable agreement with two other computer codes.

MODEL DESCRIPTION

The 3D transient finite element heat transfer code, TOPAZ3D¹, was used to calculate the thermal distributions in a high level waste repository. The repository is modeled as homogeneous tuff with constant isothermal boundary conditions at the ground surface and at the water table. The dry thermal conductivity of the tuff is taken as 2.1 W/m K (reference 2). Adiabatic conditions are used at the symmetry planes between drifts and at the repeat points along drifts. This is equivalent to assuming an infinite number of infinitely long drifts. The initial temperature was 27°C (80°F) in the rock. The boundary temperatures are 32°C (90°F) at the water table 213 m (700 ft) below the repository horizon and 24°C (76°F) at the surface 305 m (1000 ft) above the repository horizon. The repository drifts are 7.9 m (26 ft) in diameter and spaced 26 m (85 ft) center to center, giving an extraction ratio of 30%. Each waste package may include up to 21 pressurized water reactor (PWR) spent fuel assemblies with burnup equal to 33 GWd/MTU. While these waste packages are considerably larger than the SCP-CD waste packages, they are not beyond the operational size limit set by drift size and waste package weight limits. Figure 1 is an artist's view of a drift emplaced repository.

The heat source is taken as spatially uniform from the waste package surfaces and with the appropriate temporal form^{3,4}. For ease of zoning, each waste package is modeled with a diamond cross section and volume equal to a cylindrical

package. The bottom point of the modeled waste packages touches the compacted tuff drift floor. Seventy-five years after emplacement, 65% of the remaining space is backfilled. The model symmetry precludes axial convection within the drifts because only one section of a drift is analyzed. Combined heat transfer modes (including conduction, free convection, and radiation) between the waste package and drift walls are modeled. The free convection in the drift uses equations taken from Holman⁵ (concentric cylinder initially and upward facing plate after backfilling). The surface emissivities used for radiative heat transfer are 0.6 for the waste packages and 0.75 for the drift walls and floor. Because radiation is a non-linear function of temperature gradient, the combined-mode, temperature-dependent, effective thermal conductivity ranges from 4.0 to 8.3 W/m·K (1678 to 3521 Btu/yr·in·R) between 60 and 171°C before backfill and from 4.1 to 8.0 W/m·K (1716 to 3374 Btu/yr·in·R) after backfill.

Evaporation, condensation, and water vapor movement are not modeled in these calculations. Recent V-TOUGH calculations by Tom Buscheck⁶ include these processes.

For these calculations, the spent fuel age and repository Areal Mass Loading (AML in metric tons uranium per acre - MTU/acre) are varied. Fuel ages of 10, 20, 30, and 60 years are considered. AMLs are varied by changing the spacing of the waste packages along the drift axis and by varying the number of PWR assemblies in each waste package. Waste package spacings of 5.5 m (18 ft), 11 m (36 ft), and 22 m (72 ft) are considered; the smallest spacing has the packages lined up end to end with only a small gap between them. It was assumed that the waste packages were emplaced simultaneously, but for two analyses, they were emplaced in two batches with 30 and 50 years between batches.

The output variables of interest are the temperature histories at several locations. In addition, the peak drift wall temperatures and occurrence times are recorded, as are the durations for which the drift walls remain above 97°C.

AREAL POWER DENSITY, EMPLACEMENT AGE, AND AREAL MASS LOADING

It has been the practice to characterize repository heating by the APD (kW/acre) and age at emplacement. Because the APD changes fairly quickly during the first century after spent fuel is removed from the reactor, citing an APD without citing the age is not appropriate. For example, suppose a repository and waste package are designed for 21 PWR assemblies per package and emplacement at 60 years age. If the same drift and package spacing and peak temperature limits are used and the same initial APD is required, only 8 assemblies are permitted in each waste package if the emplacement occurs at 10 years age. The repository footprint must increase or the repository capacity must decrease to compensate for the smaller packages.

The age at emplacement influences the peak temperatures, which occur within a few decades to a few centuries, depending on the emplacement geometry and APD. Peak temperature is sensitive to thermal power output (APD) which is a strong function of fuel age.

The duration above 97°C is sensitive to the total energy deposited, which is not sensitive to fuel age. The Areal Mass Loading variable (AML), combines the age

and initial APD variations into a single independent variable which is appropriate for long term results such as duration above the boiling point.

The sensitivity of peak drift wall temperature and duration to AML, APD, and age are summarized by Figure 2 which plots peak temperature vs. AML with age as a parameter. Several APD points are labeled, and the duration is noted for three points. The highest AML points are for the 21 PWR assembly waste packages with only small gaps between them; the peak drift wall temperature ranges from about 260°C to 400°C for this AML (depending on the age at emplacement), and only about 7200 waste packages and 245 acres are required to dispose of the 70,000 metric tons specified in the Nuclear Waste Policy Act. The lowest AML points are for the same waste package configuration, but with only one PWR assembly per package; the peak drift wall temperature ranges from 30 to 50°C for this AML, but over 150,000 waste packages and 5100 acres (about three times the SCP-CD footprint) are required to dispose of 70,000 metric tons. The SCP-CD areal power density of 57 kW/acre is shown for emplacement ages of 10 years (the SCP-CD value), 30 years (a more realistic value), and 60 years (a value that uses aging to improve repository performance). The AML varies by about a factor of three for these three ages, and the peak temperature is fairly constant (110 to 135°C). Peak temperature is more sensitive to APD than to AML. However, the duration above the boiling point varies over a much larger range for these cases, 1000 to 5000 years; this duration is more sensitive to AML than to APD.

EMPLACEMENT MODE

Drift emplacement is often associated with larger waste packages and higher radioactive decay heat levels. However, drift emplacement more effectively removes heat from the waste packages because the radiation heat transfer to the large area drift wall is very effective. The larger surface area of drifts compared to boreholes spreads the heat and reduces the rock surface temperature. Figure 3 shows the peak rock temperature as a function of time for drift and borehole emplaced waste packages with an AML of 69 MTU/acre, an APD of 80 kW/acre, and an emplacement age of 10 years; this loading is about 40% higher than the SCP-CD loading. The borehole emplacement mode heats the rock surface faster than the drift mode, with the peaks occurring at about 20 years and 100 years respectively. The borehole emplacement rock surface also reaches higher temperatures, above 215°C, than does the drift emplacement walls (about 125°C).

THE FIRST 1000 YEARS

Figure 4 shows the temperature histories for twelve runs. Each history plots the hottest drift wall temperature at selected times from the more detailed output files. Additional detail exists in these files about the spatial and temporal temperature distributions. For example, a decrease (about 10°C) in drift wall temperature occurs for 10 to 15 years after backfill is emplaced, because the backfill requires time to heat to the levels needed to transfer heat to the drift wall. Also, the variation between drift wall temperatures directly opposite the waste package and areas between the packages is not large (~5°C).

The histories are in three groups, for AMLs of 276, 138, and 69 MTU/acre, corresponding to spacings of 5.5 m (18 ft), 11 m (36 ft), and 22 m (72 ft) for 21 PWR assembly waste packages. For each group, four emplacement ages are plotted.

Several trends are evident from these curves. The temperature rise above the initial temperature is roughly proportional to the AML. The time of highest drift wall temperature ranges from 60 years to 600 years, with younger fuel causing earlier peaking of the temperature. The peak temperature is also higher for the younger fuel.

FROM 1000 UNTIL 10,000 YEARS

Although the temperature histories shown in Figure 4 were calculated to 10,000 years, only the first 1000 years are shown because the time dependence of the heat source beyond 1000 years was not accurate; the heat source was assumed to be zero at 10,000 years. Figure 5 shows the heat source temporal dependence used in the original calculations⁴ and the revised source³ used in the subsequent calculations. It should be noted that when the source was changed to properly represent the temporal dependence beyond 1000 years, the levels of the source during the first 1000 years were slightly reduced. Because of this adjustment, the temperature history curves from the two sets of calculations are not identical.

The temperature history for the 276 MTU/acre case is shown in Figure 6. This case corresponds to 314 kW/acre for the emplacement age of 10 years. The waste packages each contain 21 PWR spent fuel assemblies with almost no gap between packages (5.5 m or 18 ft center to center spacing). The curve crosses the nominal ambient boiling point at about 8500 years.

The nominal boiling point may be changed by local pressurization or by chemical effects. Further, the semilog plotting technique makes the temperature history appear to be steeper than it actually is. These curves in Figure 5 are quite shallow when plotted on a linear scale, and small changes in key variables can shift the point at which the temperature falls below the boiling point. For example, the change in heat temporal dependence reduced the duration above the boiling point from 6000 to 3000 years in one case. These calculations are applicable to show sensitivity to the independent variables, but they should not be used to determine absolute design points without normalization to actual field data.

SIMULTANEOUS VS. STAGGERED EMPLACEMENT

Waste would not be simultaneously emplaced in an actual repository, but that scenario is much easier to model than actual emplacement scenarios. To determine the impact of gradual emplacement, three cases were run using an AML of 138 MTU/acre (21 PWR assemblies per package, 36 ft package spacing). In one case, all packages were emplaced at 30 years age. In a second case, alternating packages were emplaced at 10 and 60 years age, and in a third case, alternating packages were emplaced at 30 and 60 years age. The temperature histories are shown in Figure 7. The variation is largest during the first few centuries and not very significant after 2000 years. The 10/60 case is hotter than the 30 year age case because the heat source decays more between 10 and 30 years than it does between 30 and 60 years. The 30/60 case is coldest because half of the fuel does not add heat to the rock for 30 years. Although the effect is not large, it may have significance in determining appropriate repository operating and emplacement strategies.

COMPARISON WITH OTHER COMPUTER CODES

Two other YMP groups have conducted temperature history calculations. Eric Rider at Sandia National Laboratories uses several codes that account for detailed repository geometries and emplacement strategies. He furnished the results of one run⁷ of the COYOTE-2D code at 100 kW/acre, 30 year fuel age at emplacement, and a homogeneous tuff thermal conductivity of 2.1 W/m K.

Tom Buscheck at LLNL uses the V-TOUGH code to account for property variation with temperature and stratigraphy, phase change, and mass transfer in addition to heat transfer⁶. He furnished the results of one run at 114 kW/acre, 30 year fuel age, and the same homogeneous thermal conductivity used by Rider of SNL and in this analysis.

The results from the three codes are compared in Figure 8. Buscheck's temperatures were reduced by 14% to normalize them to the same APD as the other two runs. The temperature variations are not large, particularly after a few hundred years. Much of the variation can be explained from the differing heat source geometry and physical phenomena modeled in the various codes.

SUMMARY

A series of thermal calculations modeled the variation of drift wall temperature for a variety of thermal loads and emplacement scenarios. Systematic temperature variation occurs during the first few centuries as a function of emplacement age and Areal Mass Loading. Peak temperature depends on both emplacement age and AML. Duration above the nominal boiling point depends only on the AML for the ages investigated. Drift emplacement results in lower rock temperatures than borehole emplacement of equivalent packages. For drift emplacement with 50% of the drift length occupied by 21 PWR assembly waste packages, the AML is about three times as high as the SCP-CD value, requiring only 1/3 of the repository footprint. For that loading, the peak drift wall temperatures do not exceed 160°C, and the duration above the boiling point is about 3000 years. These results are in reasonable agreement with those from two other computer codes. During the advanced conceptual design phase, additional calculations will be performed to further determine the repository rock and internal waste package temperatures.

Figure Captions

Figure 1. An artist's conception of a drift emplaced repository. This layout corresponds to about 140 MTU/acre (21 PWR assemblies per waste package). A compatible Defense High Level Waste Package with four glass logs is also shown. Key design decisions on waste package size, transporter propulsion method, and remote vs. manned transporter operation will be made late in advanced conceptual design.

Figure 2. The dependence of peak drift wall temperature on areal mass loading, areal power density, and age at emplacement. Peak temperature is sensitive to all three variables while duration above the boiling point is sensitive to AML.

Figure 3. The dependence of peak rock temperature on emplacement mode for an AML of 69 MTU/acre, APD of 80 kW/acre, and emplacement age of 10 years. Borehole emplacement heats the rock surface faster and to much higher temperatures than does drift emplacement.

Figure 4. The dependence of drift wall temperature history on AML and emplacement age. The three spacings correspond to 276, 138, and 69 MTU/acre.

Figure 5. The temporal dependence of the heat source (per Metric Ton of Uranium) in the original and updated calculations. The burnup was 33 GWd/MTU for those curves, and only the portion beyond 30 years is shown, although the curves do extend to earlier times.

Figure 6. The temperature history for the 276 MTU/acre case. The duration above the boiling point is about 8500 years.

Figure 7. Temperature histories for 138 MTU/acre with three emplacement scenarios. The highest temperatures are for the case where alternate packages are emplaced at 10 and 60 years age. The nominal case is for all packages emplaced at 30 years. The lowest temperatures are for the case where alternate packages are emplaced at 30 and 60 years age.

Figure 8. Temperature histories for 100 kW/acre and 30 year old fuel (about 140 MTU/acre) as calculated by TOPAZ3D (this work), COYOTE-2D at SNL, and V-TOUGH at LLNL.

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Cutaway of a drift showing coning waste packages

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Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

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