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ABSTRACT

A repository heat transfer analysis has been performed by the Pacific Northwest Laboratory (PNL) for the U.S. Department of Energy's Performance Assessment Scientific Support Program. The objective of this study was to evaluate the near-field thermal environmental conditions for a spent fuel repository system. A spent fuel logistics analysis was performed using a waste management system simulation model, WASTES-II, to evaluate the thermal characteristics of spent fuel received at the repository. A repository-scale thermal analysis was performed using a finite difference heat transfer code, TEMPEST, to evaluate the near-field host rock temperatures. The calculated temporal and spatial distributions of near-field host rock temperatures provide input to the repository source term model in evaluations of engineered barrier system performance.

INTRODUCTION

The U.S. Department of Energy's (DOE) Office of Civilian Radioactive Waste Management (OCRWM) is developing a performance assessment strategy for demonstrating compliance with the Nuclear Regulatory Commission's (NRC) regulatory requirements (10 CFR 60) for the geologic repository waste isolation system. One aspect of this strategy is the development of the Analytical REpository Source Term (AREST) computer model (Liebetrau et al. 1987), which evaluates the radionuclide containment and release rate performance of the engineered barrier system. AREST model evaluations are based on several input parameters which describe the time-dependent behavior and spatial distribution of near-field environment conditions throughout the repository underground facility. In this study, the near-field host rock temperatures are evaluated for the current conceptual design of a spent fuel repository system.

PURPOSE

The purpose of this study is to evaluate the impact of waste management system design strategies on the near-field thermal performance of the geologic isolation system. An important aspect of this analysis is the repository waste packaging and emplacement design strategies being developed to accommodate spent fuel receipts with variable age and heat generation rate characteristics. Until recently, conceptual design information had been based on a single reference light water reactor spent fuel description, 10-years-old and nominal exposure (i.e., burnup) levels. As a result, previous AREST thermal model evaluations were based on a constant waste loading assumption for the repository underground facility. The objective of this study is to improve the inputs for the AREST model by evaluating the thermal performance of a proposed waste emplacement strategy identified for a conceptual spent fuel repository designed for a candidate site in tuff (MacDougall et al. 1987).

TECHNICAL APPROACH

The technical approach for this study involves a series of computational modeling steps in support of AREST model evaluations of engineered barrier system performance. AREST is a systems-level model and requires support from a more rigorous set of process-specific (i.e., support) codes. The support codes are used to characterize the environmental conditions throughout the engineered barrier system as they are influenced by site-specific design and environmental variables. This modular approach for developing the input parameters allows for the results of state-of-the-art environmental process models to be interfaced directly with the systems-level performance assessment analyses.

In this study, an approach for estimating near-field host rock temperatures is described which takes into consideration the influence of spent fuel receipt characteristics and a waste emplacement design strategy. A spent fuel logistics model is first used to evaluate the age and heat generation rate characteristics of repository receipts. A repository-scale thermal model is then used to evaluate the temporal and spatial distributions for near-field host rock temperatures. This information is used in subsequent AREST model evaluations of engineered barrier system containment and controlled release performance. A description of the spent fuel logistics and repository-scale thermal models used in this study is given in the following sections.

Spent Fuel Logistics Model Description

The WASTE-II (WAste Systems Transportation and Economic Simulation - Version II) spent fuel logistics model (Shay and Buxbaum 1986) was used to evaluate the thermal characteristics of repository receipts. WASTES-II was developed at PNL for use in spent fuel waste management system costs and logistics analyses. The model simulates a user-defined system of nuclear spent fuel generation, transportation, storage and final disposal. The number of each type of facility, their locations and capacities, and priorities for spent fuel transfers are all specified by the user. PNL's spent fuel database (Heeb 1987) is used to provide WASTES-II with reactor-specific discharge information based on the 1986 Energy Information Administration's lower reference nuclear growth projection.

WASTES-II maintains the age and exposure of each discharged batch of assemblies throughout the simulation and calculates the heat generation rate of spent fuel received at each facility on a annual basis. Figure 1 depicts the heat generation rate data used in WASTES-II model evaluations for pressurized water reactor (PWR) spent fuel at exposure levels ranging from 10,000 to 40,000 MWd/MTU and decay times from 1 to 50 years after discharge.

The key parameters used in this analysis are the waste acceptance rate schedule and the selection criterion for spent fuel shipped to the geologic repository. The waste acceptance schedule used in this study is the same as the authorized waste management system described in the DOE Mission Plan Amendment (DOE 1987). The first repository begins receiving spent fuel in 2003 with a maximum receipt rate capacity of 3000 MTU per year and a total capacity of 62,000 MTU. For this analysis, spent fuel is assumed to be shipped to the repository on a strictly oldest-first selection criterion.

Repository-Scale Thermal Model Description

The TEMPEST (Transient Energy, Momentum, and Pressure Equation Solution in Three Dimensions) finite-difference hydrothermal code (Eyler et al. 1983)

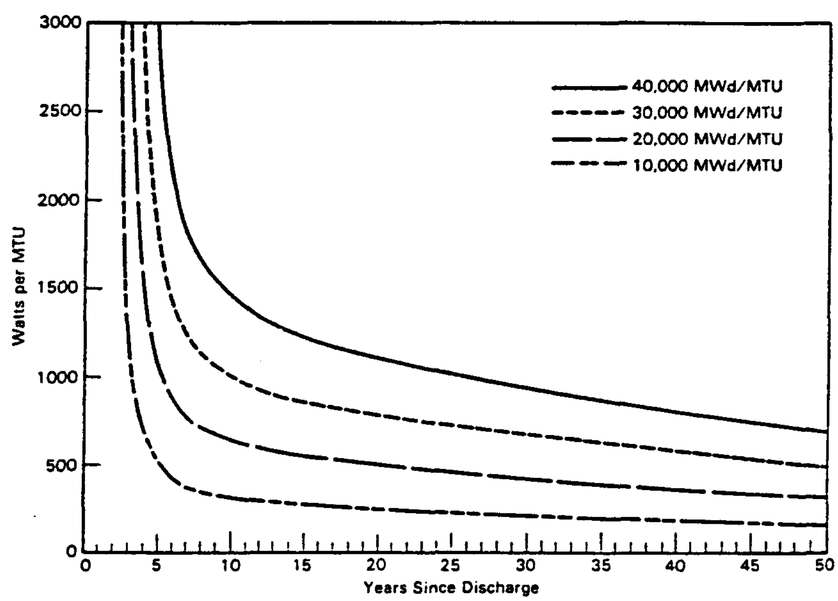

FIGURE 1. PWR Spent Fuel Heat Generation Rate Data Used in WASTES-II Model Evaluations

was used to evaluate near-field host rock temperatures for the geologic repository system. TEMPEST was developed at PNL to analyze a rather broad range of coupled fluid dynamics and heat transfer problems in nuclear reactor systems. Because TEMPEST has been constructed with reasonable generality, it has considerable application outside the intended reactor design applications. This study makes use of the transient, three-dimensional heat conduction capabilities of TEMPEST.

The conceptual design of the repository underground facility is shown in Figure 2. As indicated by the spent fuel panels, the underground facility is loaded in a clockwise pattern beginning at the exploratory shaft test location. The conceptual design is based on a reference spent fuel description, 10-years-old and nominal burnup levels (MacDougall et al. 1987). Several studies have shown that spent fuel age and exposure variations have an important impact on the underground facility design and thermal performance of the

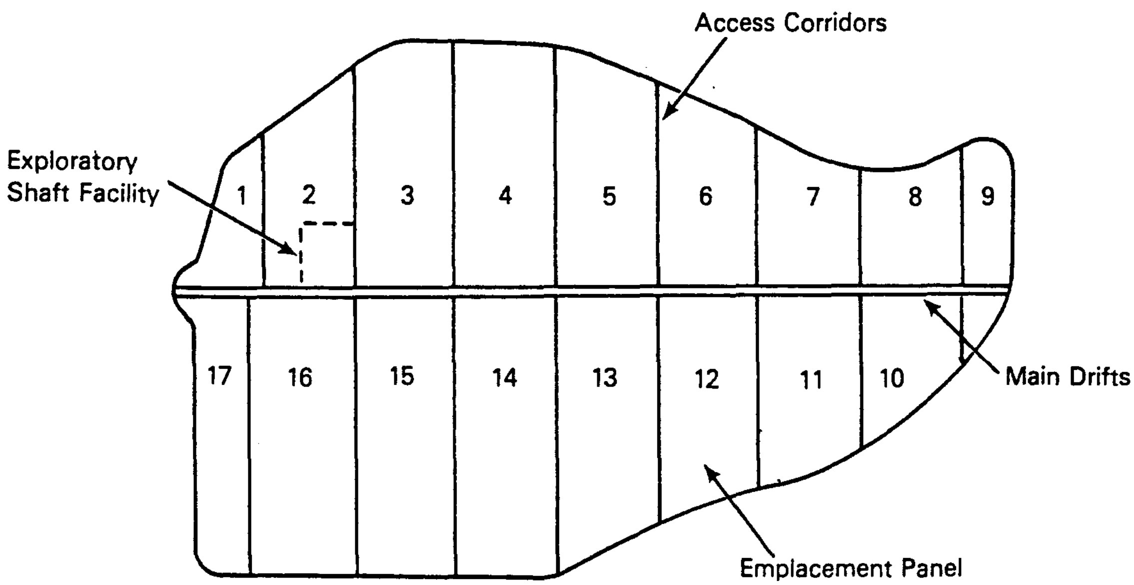

FIGURE 2. Repository Underground Facility Description - Plan View (MacDougall et al. 1987)

repository system (Wang 1983; O'Brien 1984; Dippold 1984). In this study, it is assumed that the repository area thermal load at the time of emplacement (i.e., waste emplacement density) is adjusted on an annual basis to accommodate spent fuel receipts with variable age and exposure characteristics.

The waste emplacement density of the underground facility is based on maintaining a constant areal energy deposition during the initial 1000-year containment period. This waste emplacement strategy is designed to maintain temperatures and surface uplift at or below their respective limits during the long-term isolation period. The following procedure was used to determine the effect of spent fuel age and burnup on the allowable repository area thermal load.

An exponential equation used to describe the unit heat generation rate given by

$$Q(t,b) = \sum_{i} A_i \cdot e^{[-B_i \cdot (t-1)]} \qquad \text{(Eq.1)}$$

where, $Q(t,b)$ = heat generation rate (W/MTU), t = age (years), b = burnup level (MWd/MTU), and Ai,Bi are the decay heat coefficients for the dominant group (i) of heat-producing isotopes. The coefficients for this equation are provided in Table 1 for nominal (32,700 MWd/MTU) and extended (50,000 MWd/MTU) burnup PWR spent fuel (Dippold 1984).

TABLE 1. Coefficients for PWR Spent Fuel Heat Generation Rate Equation

Burnup Level = 32,700 MWd/MTU			Burnup Level = 50,000 MWd/MTU		
i=	Ai=	Bi=	i=	Ai=	Bi=
1	130	0.001604	1	210	0.001604
2	30	0.000106	2	34	0.000106
3	80	0.007900	3	200	0.007900
4	920	0.023417	4	1400	0.023417
5	35	0.038274	5	130	0.038274
6	20	0.084530	6	100	0.084530
7	800	0.336152	7	2300	0.336152
8	1500	0.462098	8	3000	0.693147
9	2250	0.693147	9	4000	0.96
10	3875	1.25	10	940	2.2

Integrating Equation 1 over the initial 1000 years of waste isolation provides the unit energy deposition term given by

$$\int_t^{1000+t} Q(t,b)dt = E(t,b) = \sum_i \frac{A_i}{B_i} \cdot \{e^{[-B_i \cdot (t-1)]} - e^{[-B_i \cdot (999+t)]}\} \qquad \text{(Eq.2)}$$

where, E(t,b) = energy deposition (watt-years/MTU). The heat generation rate and cumulative energy terms can then be evaluated for the coefficients of the reference spent fuel description. The relationship for maintaining the same energy deposited per unit repository area keyed to the area thermal load at the time of waste emplacement is represented by

$$\frac{A(t,b) \cdot E(t,b)}{Q(t,b)} = \frac{A(ref) \cdot E(ref)}{Q(ref)} \qquad \text{(Eq.3)}$$

where, A(t,b) = repository area thermal load (watts/m^2) at emplacement. The allowable repository area thermal load at emplacement for each spent fuel type is derived by rearranging Equation 3 to provide the following equation:

$$A(t,b) = \frac{A(ref) \cdot Q(t,b) \cdot E(ref)}{Q(ref) \cdot E(t,b)} \quad \text{(Eq.4)}$$

and the repository area mass load for each spent fuel type is given by

$$M(t,b) = \frac{A(t,b)}{Q(t,b)} \quad \text{(Eq.5)}$$

where, $M(t,b)$ = repository area mass load (MTU/m^2).

Figure 3 provides the repository area thermal and mass load as a function of age at emplacement and burnup level relative to the reference PWR spent fuel description. The repository area thermal load is shown to be sensitive to age and relatively insensitive to burnup, whereas area mass

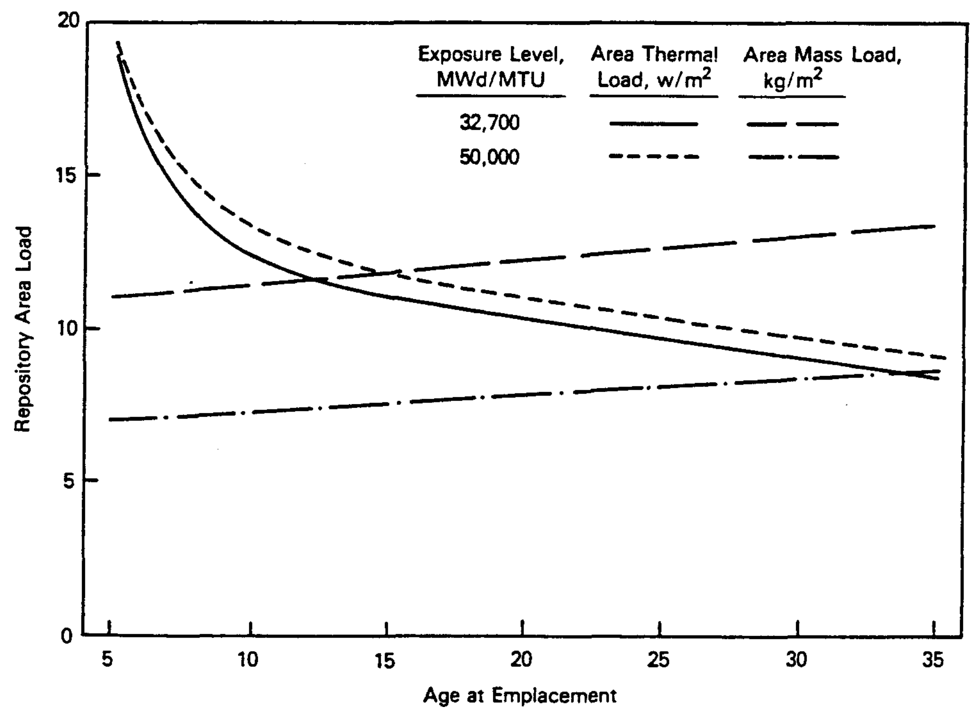

FIGURE 3. Repository Area Thermal and Mass Load as a Function of Spent Fuel Age and Exposure Level - Based on Maintaining Constant 1,000-Year Energy Deposition

load is sensitive to burnup and relatively insensitive to age at emplacement. As a result, the expression for nominal-burnup (32,700 MWd/MTU) spent fuel can be used as a close approximation to determine the allowable repository area thermal load as a function of spent fuel age at emplacement. The equivalent area mass load is then determined from the initial heat generation rate.

Table 2 provides the average annual spent fuel receipt characteristics from the spent fuel logistics analysis and the corresponding repository waste

TABLE 2. Repository Receipt Characteristics and Waste Emplacement Design Parameters Used in Repository-Scale Thermal Model[(a)]

		Average Receipt Characteristics			Allowable Area	
Year	Receipt Rate, MTU	Age, Yrs	Burnup, GWd/MTU	Heat, kW/MTU	Thermal Load, W/m^2	Mass Load, kg/m^2
2003	400	32.2	13	0.32	8.57	26.78
2004	400	31.1	19	0.41	8.69	21.20
2005	400	31.0	15	0.32	8.70	27.19
2006	900	30.9	18	0.39	8.71	22.33
2007	1800	30.2	23	0.49	8.78	17.92
2008	3000	29.0	26	0.58	8.91	15.36
2009	3000	27.4	28	0.66	9.09	13.77
2010	3000	26.0	29	0.69	9.24	13.39
2011	3000	24.9	28	0.68	9.37	13.78
2012	3000	24.0	31	0.77	9.48	12.31
2013	3000	23.4	33	0.83	9.55	11.51
2014	3000	22.8	34	0.88	9.62	10.93
2015	3000	22.4	36	0.95	9.67	10.18
2016	3000	21.8	38	1.01	9.74	9.64
2017	3000	21.3	39	1.04	9.80	9.42
2018	3000	20.6	39	1.07	9.89	9.24
2019	3000	20.0	40	1.11	9.97	8.98
2020	3000	19.4	40	1.12	10.05	8.97
2021	3000	19.0	40	1.14	10.10	8.86
2022	3000	18.3	40	1.15	10.19	8.86
2023	3000	17.7	40	1.15	10.28	8.94
2024	3000	17.3	40	1.16	10.34	8.91
2025	3000	16.7	39	1.16	10.42	8.98
2026	3000	16.4	38	1.14	10.47	9.18
2027	1100	16.0	38	1.14	10.52	9.93

(a) For a constant area energy deposition design strategy.

emplacement design parameters. As described in the previous section, the WASTES-II model was used to determine the average age and heat generation rate of spent fuel receipts on an annual basis. The repository waste emplacement design parameters were used to develop a three-dimensional, finite difference grid of the repository underground facility.

Figure 4 depicts the plan view of the repository-scale thermal model. The underground facility is represented by a finite heat generating source region in a semi-infinite tuff medium. A heat generating source region was specified for each year of spent fuel emplacement operations. The shaft pillars and access corridors are not simulated in the model. A reflecting boundary condition was applied at the horizontal plane of symmetry at the repository elevation. The remaining adiabatic boundaries were specified at

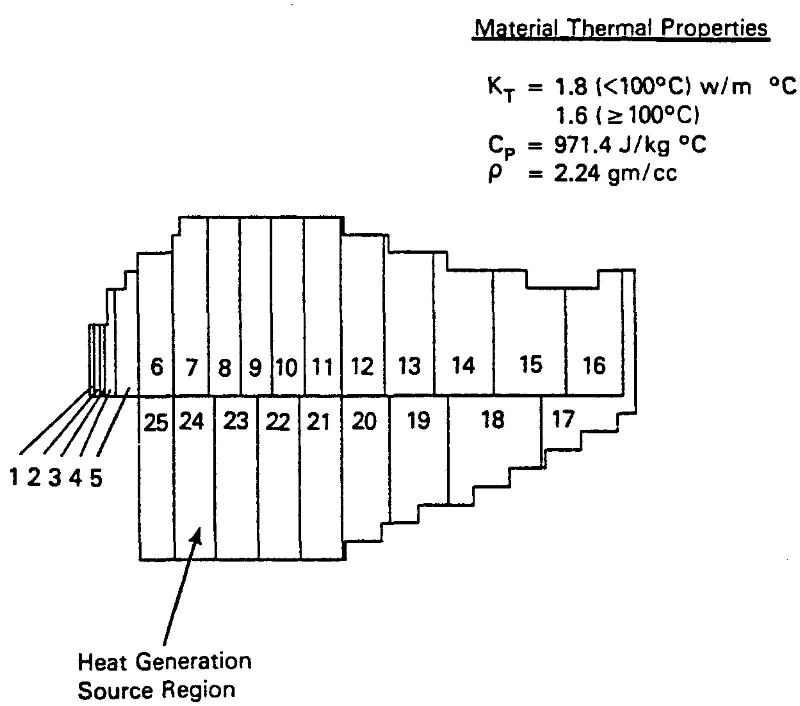

FIGURE 4. Repository-Scale Thermal Model Description - Plan View

distances sufficiently large to not influence the near-field host rock temperatures throughout the 10,000-year isolation period.

RESULTS

As indicated in Table 2, the average age of spent fuel received at the repository decreases with time as the backlog of older spent fuel is depleted under the oldest-first acceptance scenario. The average heat generation rate increases with time due to the combined effect of decreasing age and increasing burnup levels. The allowable repository area thermal load increases and the allowable area mass load decreases with time, assuming a constant energy deposition waste emplacement design strategy.

The results of the repository-scale thermal analysis are shown in Figures 5 through 10 in the form of isotherm plots for selected times between 100 and 10,000 years. At 30 to 100 years, the near-field host rock temperatures are influenced by the initial repository area thermal loads. At 300 to 1000 years, the temperatures are uniformly distributed except near the

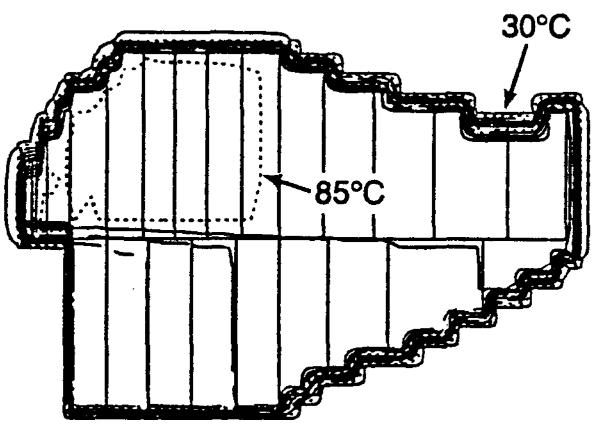

FIGURE 5. Near-Field Host Rock Temperature Results at the Repository Midplane - 5°C Isotherms at 30 Years

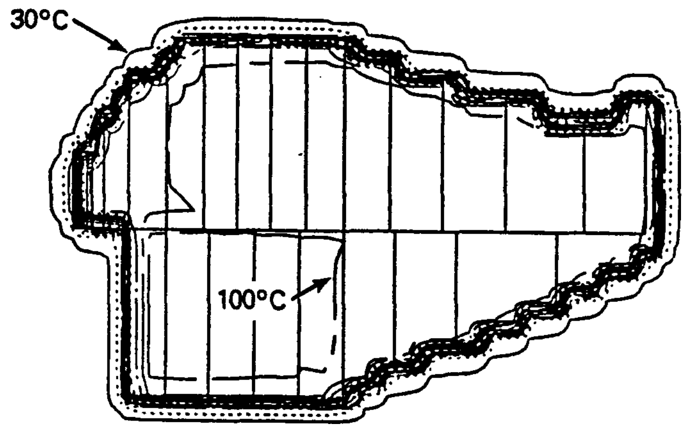

FIGURE 6. Near-Field Host Rock Temperature Results at the Repository Midplane - 5°C Isotherms at 100 Years

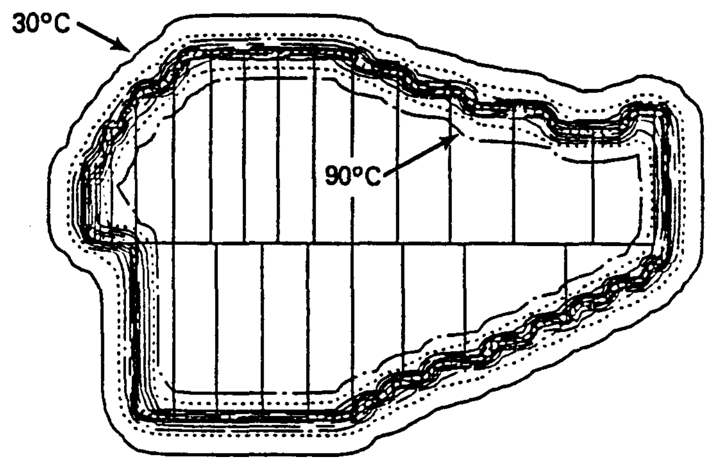

FIGURE 7. Near-Field Host Rock Temperature Results at the Repository Midplane - 5°C Isotherms at 300 Years

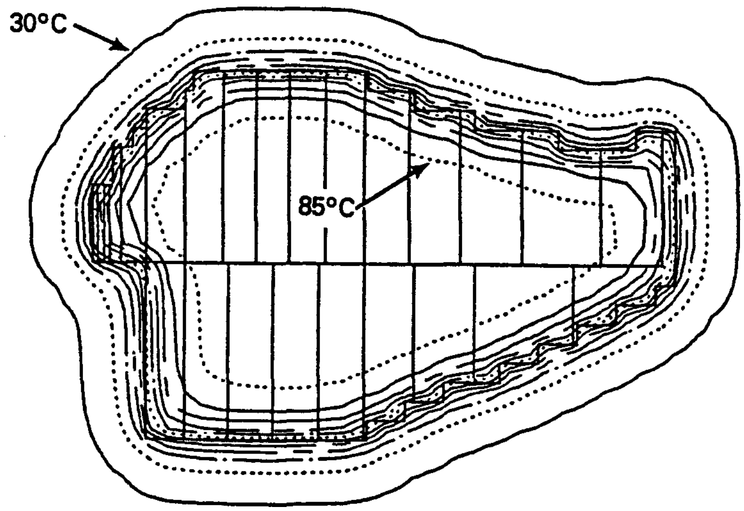

FIGURE 8. Near-Field Host Rock Temperature Results at the Repository Midplane - 5°C Isotherms at 1,000 Years

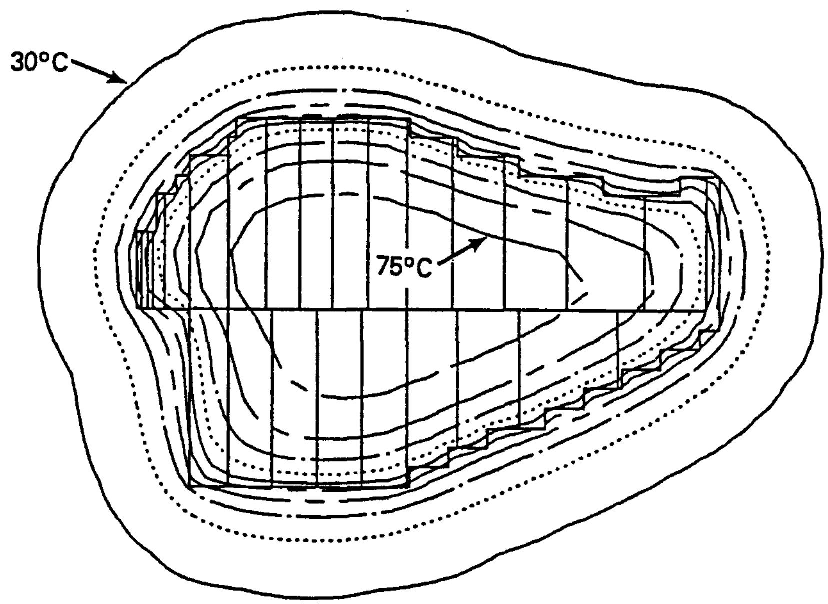

FIGURE 9. Near-Field Host Rock Temperature Results at the Repository Midplane - 5°C Isotherms at 3,000 Years

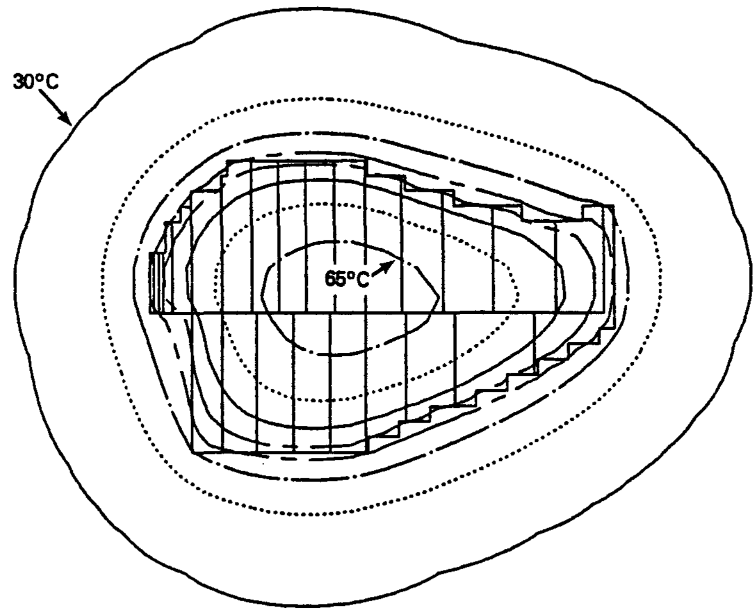

FIGURE 10. Near-Field Host Rock Temperature Results at the Repository Midplane - 5°C Isotherms at 10,000 Years

outside edges of the repository. At 3,000 to 10,000 years, edge effects are shown to have a more significant impact on the near-field distributions of host rock temperatures.

CONCLUSIONS AND RECOMMENDATIONS

The results of this study provide estimates of the temporal and spatial distributions of near-field host rock temperatures based on a constant areal energy deposition over 1000 years. This information provides a boundary condition for thermally coupled process models of very near-field waste package environmental conditions. Repository and waste package scale model results can then be used in support of AREST model evaluations of engineered barrier system performance.

To further improve the input to AREST model evaluations, it is recommended that the spent fuel logistics and repository thermal model analyses be revised for alternative waste management system and emplacement design strategies as they become available.

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