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Groundwater Removal Near Heat Dissipating Waste Packages in a Geologic Repository

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ABSTRACT

The thermohydrologic environment of heat-dissipating nuclear waste packages in a subsurface repository is affected by ventilation of the facility prior to permanent closure. Heat dissipated by the waste will raise the temperature of host rock and vaporize groundwater. Ventilation will remove some heat and water vapor from the subsurface, creating a desiccated region surrounding the waste packages. The resulting hot, dry environment will tend to favorably extend the containment time of the waste. This work evaluates the transient temperature field near emplacement drifts and predicts the extent of rock dryout and removal of groundwater. For two hypothetical ventilation schemes with 30-yr-old fuel and

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repository loading of 40 metric tons of uranium (MTU) per acre, about 4.5 m of rock surrounding the drifts are predicted to be dried during the pre-closure period.

Nomenclature

c_a = specific heat of ventilation air, J/(kg-K)

D_d = drift diameter, m

L_{wp} = length of a single waste package, m

L_{rep} = total length of the repository drifts, m

h_{fg} = heat of vaporization of water, J/kg

$\dot{m}_a$ = mass flow rate of ventilation air, kg/s

$\dot{m}_v''$ = vapor flux into the drift at the drift wall, kg/(m^2-s)

N_{wp} = total number of waste packages in the repository

q_w'' = heat flux applied to the wall, W/m^2

$Q(t)$ = thermal output of a single waste package, W

r = location of dryout front from drift wall, m

$T_{a,o}$ = exit temperature of ventilation air, K

$T_{a,i}$ = inlet temperature of ventilation air, K

x_v = mass fraction of vapor in the gas

η = diffusion-induced advection enhancement factor

$\bar{\rho}$ = average density of the humid air, kg/m^3

ϕ = porosity

τ = tortuosity

INTRODUCTION

The movement of groundwater and/or volatile substances in a hydrothermal system is of interest in a number of application areas such as hazardous waste cleanup (Ho and Udell, 1995) and geologic disposal of radioactive waste (Danko and Mousset-Jones, 1993; Manteufel et al., 1995). In many cases, a heat source is placed in a porous media which raises the subsurface temperature. In hazardous waste cleanup, the heat source may be part of a remediation strategy and for disposal of nuclear waste the heat may be a natural consequence of the waste. Frequently, a natural (in the case of nuclear waste disposal) or forced (in the case of hazardous waste cleanup) gaseous convection system is established. The elevated temperatures vaporize the fluid and encourages vapor flow to regions where convection removes it from the subsurface media. The media surrounding the heat source is thus desiccated. Although for different reasons, the desiccation of subsurface media is of interest in both remediation and disposal of hazardous waste.

One problem associated with removal of a volatile substance is the accurate prediction of the rate of fluid removal as well as the extent of removal. Frequently, the liquid is immobile due to the low permeability of the medium. In this case, the most effective removal mechanism is vaporization coupled with purging. Gas flow induced by soil pumping or venting, however, leads to flow isolated to only small regions of the geologic media. Pore- and field-scale heterogeneities are almost always present in the medium and are the source of preferential flow paths. The volatile fluid is often located throughout the media. After vaporization, the transport of the vapor is a combination of diffusion and advection.

Diffusion dominates transport in the stagnant regions of the media while advection dominates in the flow channels. Frequently mass transfer is limited by diffusion of the vapor (Ho and Udell, 1995; Manteufel et al., 1995). If the media temperature exceeds the boiling point temperature of the fluid, then pressure driven vapor flow occurs.

In the United States nuclear high-level waste (HLW) repository program, current plans call for the construction of a mined underground facility (TRW, 1993, 1994). The facility is proposed for Yucca Mountain (YM), Nevada which is located in a semi-arid environment. The proposed repository is designed to accommodate 70,000 metric tons of uranium (MTU) waste which is primarily spent nuclear fuel (63,000 MTU) from commercial nuclear reactors used to generate electricity. The waste is expected to be placed in packages with the largest containing up to 10 MTU. Hence at least 6,300 waste packages will need disposal. The packages will be located in mined drifts at least 4.3 m in diameter, the smallest diameter currently being considered (TRW, 1994). Proposed packages are about 1.8 m in diameter and about 5.6 m in length. The distance between packages along a drift and the distance between parallel drifts are design variables. Figure 1 shows a plan view of a section of the proposed repository highlighting the waste package and drift spacing.

A number of analyses have addressed the parameters that affect the thermohydrologic environment of packages (Pruess et al., 1984; Buscheck and Nitao, 1993). In most studies, however, the removal of either heat or groundwater by ventilation of the underground facility has been ignored—in part, because the facility was originally to be constructed, loaded, and closed within a relatively short time period. Recently however, plans call for an extended time period of observation up to 150 yr during which the facility will remain open (TRW, 1993). Given such a long time frame, it now appears feasible that ventilation of the facility may remove some heat and groundwater. Removal of heat will reduce the peak waste package temperature and removal of groundwater will create a drier less corrosive environment. This analysis addresses the effects of hypothetical ventilation schemes on temperature reduction and groundwater removal. Improved estimates of waste package environments are needed in total system performance assessment (NRC, 1995; TRW, 1995).

MODEL GEOMETRY

The proposed repository horizon is located in the vadose zone about almost 350 m below the ground surface and 250 m above the water table at YM. The hydrostratigraphy can be characterized by seven distinct layers of rock. In this work, a coarse mountain-scale model was used to predict the evolution of the large-scale temperature field from the ground surface to the water table. The large-scale model was used to provide boundary conditions to a smaller and more refined drift-scale model. The mountain-scale thermal properties were taken from Appendix C of Wilson et al. (1994) which are from DOE (1993).

Figure 2 depicts the drift-scale model used in this work. The model contains 8340 linear hexahedral elements and 10,021 nodes. The drift has a 4.3 m diameter. The model extends 20 m above and 20 m below the center of the drift. All of the geophysical media in this region is of the Topopah Spring welded thermohydrologic unit which has an assigned thermal conductivity of 2.1 W/(m-C), density of 2200 kg/m^3, and specific heat of 930 J/(kg-K) (DOE, 1993). The drift-scale model corresponds to the unit cell drawn in Fig. 1.

There are two main repository design variables that control the density and affect the thermohydrologic environment of waste packages—waste package and drift spacing. Three different spacings are shown in Fig. 1 and these change the shape of the mesh in Fig. 2. Three different areal mass loadings (AMLs) are considered in this work: 20, 40, and 80 MTU/acre. They are achieved by having either 20, 30, or 40 m for waste package spacing and either 25, 35, or 50 m for drift spacing, respectively. The AMLs represent low, medium, and high heat loading strategies currently being considered (TRW, 1995).

The temperature of the top and bottom surfaces of the modeled volume is controlled as a function of time (as determined from the mountain-scale model). A heat flux [W/m^2] is applied to the drift wall for the first 3 m length of drift in only one end of the modeled volume. This is consistent with the approximately 6 m waste package length and the unit cell shown in Fig. 1. The heat is concentrated to simulate heat dissipating from a single waste package. By concentrating the heat flux to the drift wall over the length of the waste package, the maximum drift wall temperature and maximum axial wall temperature variation are conservatively predicted. Current repository designs have a limit of 200 °C on the drift wall temperature (TRW, 1993; 1994).

HEAT TRANSFER

Figure 3 provides the maximum drift wall temperature for times to 10,000 yr. The temperatures have been calculated using a commercially available software package, ABAQUS (1995). In total, nine different cases were considered consisting of a matrix of three AMLs and three ages of waste. The age of waste is measured as time from discharge from the reactor. In many earlier studies, the spent fuel was assumed to be 10 yr old. More recent estimates show the average age of waste to be at least 20 yr at time of emplacement (TRW, 1994). A minimum age appears to be about 20 yr with a maximum age of 50 yr. Thermal output of a waste package is about 10.0, 7.8, 6.5, and 4.7 kW for 10, 20, 30, and 50-yr-old fuel (based on data from Appendix 1C DOE, 1987). Thermal output decays with time. For example, the thermal output of 25-yr-old fuel is 70 percent that of 10-yr-old fuel. Similarly, 50-yr-old fuel has 47 percent of the thermal output of 10-yr-old fuel. A number of repository strategies have been proposed to load older fuel in a high spatial density in the repository to have a strong thermal effect. The ages and AMLs considered in Fig. 3 represent a spectrum of conditions.

Figure 3 also gives the time and magnitude of the peak drift wall temperature. Based on the application of the localized heat flux, the peak wall temperature is conservative. Although predictions are conservatively high, all are well below the 200 °C design limit (TRW, 1994). The highest peak wall temperature is 162 °C at 21 yr for 20-yr-old fuel in a repository with an 80 MTU/acre AML.

A number of trends can be observed in Fig. 3. The lowest AML tends to yield the lowest peak temperatures (which is not surprising) and at the earliest times (somewhat surprising). The 20 MTU/acre AML attains a peak temperature within 5 yr for all ages of waste. In contrast, the 80 MTU/acre AML attains higher temperatures at later times. Another observation is that the lower AMLs have more distinct peak temperature. For 20 MTU/acre case, the maximum drift wall temperature decreases significantly below the peak within the first 80 to 100 yr. In contrast, the higher AML (80 MTU/acre) has a less distinct peak. For the case of 50-yr-old fuel in a 80 MTU/acre AML, the maximum drift wall temperature attains and maintains above boiling conditions for a few thousand years.

The axial temperature variation down the drift wall is presented in Fig. 4. The temperature is highest at the left end where the waste package resides and heat applied. In all the models, heat is applied to the first 3 m of drift wall. The axial temperature variation is greatest for the lowest AML which has the longest spacing between waste packages. The highest AML has the smallest axial temperature variation. The axial variation is also greatest at earlier times. All of these simulations assume there is no removal of heat or groundwater from the repository. Because above boiling conditions can be achieved, it was considered important to estimate the effects on ventilation on the removal of heat and moisture.

VENTILATION

During construction and operation of the repository, ventilation will be used to provide fresh air to workers. The current designs call for a minimum ventilation capacity of 125 m^3/s of air for normal operations and a maximum of nearly 600 m^3/s for cooling if needed (TRW, 1994). Ventilation will remove both heat and moisture. Most ventilation codes (Laage et al., 1994; MVS, 1986) have been developed for wetter conditions than expected in the proposed HLW repository. The liquid is frequently assumed to be available in damp areas on the drift wall from which it vaporized. In the proposed HLW repository, the potential for removal is large and the permeability relatively low, hence liquid will be comparatively immobile. In this work, the heat is applied as a flux to the drift wall. The flux is based on three terms. The first is the waste package thermal output divided by the wall area. The second and third account for the removal of sensible heat by ventilation air and removal of latent heat by vaporized groundwater.

$$q_w'' = \frac{Q(t)}{\pi D_p \, L_{wp}} - \frac{\dot{m}_a c_a (T_{a,o} - T_{s,i})}{\pi \, D_P \, L_{wp} \, N_{wp}} - \frac{\dot{m}_v'' \, h_{fg} \, L_{rep}}{L_{wp} \, L_{wp}} \quad (1)$$

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where q_w'' is the heat flux applied to the wall, $Q(t)$ is the thermal output of a single waste package which is assumed to contain 10 MTU of waste, D_d is the drift diameter, L_{wp} is the length of a single waste package, $\dot{m}_a$ = mass flow rate of ventilation air, c_a = specific heat of ventilation air, $T_{a,o}$ is the exit temperature of ventilation air, $T_{a,i}$ is the inlet temperature of the ventilation air, N_{wp} is the total number of waste packages in the repository, $\dot{m}_v''$ is the vapor flux into the drift at the drift wall, h_{fg} is the heat of vaporization of water, and L_{rep} is the total length of the repository.

Figure 5 shows three heat fluxes considered, one without ventilation and two with ventilation. The reference case (first scheme) is based on no removal of heat by ventilation. For no ventilation, $\dot{m}_a = 0$ and $\dot{m}_v'' = 0$ in Eq. (1). The other two cases evaluate potential effects of ventilation. Scheme B is based on a constant ventilation flow rate of $\dot{m}_a$ = 125 kg/s and an average temperature increase of $T_{a,o} - T_{a,i} = 50\ °C$. In addition, thermal energy is removed by vapor transport. A hypothetical model adopted here is $\dot{m}_v = 0.01 e^{-t/20yr}$ kg/(m^{2}s) based on drying up to 5 m of media surrounding the drift. This model is estimated to conservatively over predict the extend of drying which was estimated to be 3 to 4 m in earlier work (Manteufel et al., 1995). By over estimating moisture removal, the heat removed will be over estimated, energy transferred into the rock will be underestimated, and maximum rock temperatures will be underestimated. Higher temperatures lead to increased vaporization of groundwater and more rock dryout. The third scheme (C) is based on applying a greater quantity of ventilation initially, but decreasing the ventilation steadily over the 150-yr operations time period. A linear decreasing ramp function was applied. Although the last two schemes have some physical basis, they were assumed to investigate the potential effect of ventilation on heat and moisture removal. These three

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schemes are applied to the 40 MTU/acre AML which is the intermediate thermal loading, assuming 30-yr-old fuel.

The maximum drift wall temperature for the three schemes is plotted out to 10,000 yr in Fig. 6. The maximum wall temperature is always located at the model axial distance of 0 m which is in the middle of the heat flux zone. Both ventilation cases have a strong effect on the wall temperature to 150 years. Without ventilation, the peak drift wall temperature is 120 °C at 10 yr. With ventilation, the temperature is lower by 33 °C (87 °C) at 14 yr or by 42 °C (78 °C) at 147 yr. Both ventilation schemes tend to moderate the wall temperature over time so there is less of a rapid increase and decrease. Scheme C gives the most steady temperature profile with the maximum wall temperature maintained about 75 °C for at least the first 200 yr. The long term effects are less significant between schemes. After 1,000 yr, the wall temperatures are within 10 °C for all schemes and this difference continues to diminish with time.

A model was developed and applied to predict the rate and extent of rock dryout. It is based on immobile groundwater locally vaporized. The vapor and groundwater in the pores are in local thermodynamic equilibrium such that the local vapor pressure is controlled by the local temperature, assuming negligible vapor pressure lowering due to large capillary forces. After being vaporized, the water vapor diffuses through the air in the porous media toward the drier ventilated drift. Dryout proceeds as if a vaporization front penetrates the media. The vapor mass fraction from the vapor front to the drift wall is essentially linear, except for the cylindrical nature of the problem. Because the drift is ventilated, air in the drift is relatively dry and the vapor mass fraction is negligible compared to that at the vaporization front. The diffusive vapor flux is modeled as

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$$\dot{m}_v'' = \frac{\eta \bar{\rho} \tau \phi D_v \, s_v(r)}{\frac{D_d}{2} \ln\left(\frac{2r - D_d}{D_d}\right)} \tag{2}$$

where η is the advective enhancement factor that accounts for diffusion induced flow, $\bar{\rho}$ is the average density of the humid air, τ is the tortuosity of the media (assumed to be 2/3, p. 296 of Marshall and Holmes, 1988), ϕ is the porosity of the media (=0.1), $x_v(r)$ is the mass fraction of vapor in the gas at the dryout front, and r is the location of the dryout front from the drift wall into the media. The advective enhancement factor is defined as

$$\eta = \frac{P_t}{P_t - P_v} \tag{3}$$

where the total gas pressure at the unsaturated repository horizon is about 90.5 kPa corresponding to a boiling point temperature of $T_b = 97\ ^\circ C$. Above the boiling point temperature, the gas is modelled to consist of only vapor, so that Eq. (3) is only valid for below boiling conditions. A number of accurate correlations for the vapor pressure for water as a function of temperature exist (Appendix A of Reid et al., 1987).

The vapor diffusion coefficient is temperature dependent (from p. 531 of Lienhard, 1987)

$$D_v = D_{v,o}\left(\frac{T}{T_o}\right)^{3/2} \tag{4}$$

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where $D_{v,o}$=26.0 $10^{-6}m^2/s$ and T_0=298K. The mass fraction of vapor at the dryout front is $x_v(r)=\rho_v/(\rho_v+\rho_a)$. If the temperature of the dryout front equals or exceeds the boiling point, then $x_v(r)=1$. The air and vapor densities are based on the ideal gas law. The partial pressure of vapor equals the saturation vapor pressure assuming local thermodynamic equilibrium between the liquid and vapor. The partial pressure of air is the total pressure minus the vapor pressure. Equation (2) was used to predict groundwater removal from the host rock and into the ventilated drifts. Once in the drifts, ventilation readily removes the vapor from the underground facility.

Figure 7 predicts radial rock dryout depth for the two ventilated schemes. Both schemes predict nearly the same dryout. The dryout curves appear to have the characteristic diffusion-limited scaling of the square root of time for the position of the vaporization front. This implies the vapor mass flux into the drift scales as the inverse of the square root of time. Over 150 yr, the extent of dryout predicted is about 4.5 m. Comparing Figs. 6 and 7, it is noted the rate of dryout is highly dependent on temperature. Initially, scheme B generates higher wall temperatures and thus has a higher rate of dryout. After about 70 yr, however, scheme C has a higher wall temperature and a higher rate of dryout.

These results suggest that ventilation can be optimized to attain higher rates of groundwater removal and increased extent of rock dryout. An optimal scheme will initially have low ventilation flowrates so that minimal heat is removed. This will raise the temperature of the underground facility as rapidly as possible. As rock temperature elevates, groundwater will be vaporized. The flowrate can be increased to the extent necessary to maintain dry drift conditions. Because the vapor flow will scale roughly as inverse of the square root of time, the necessary ventilation flow rate will be greatest initially

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(5 to 10 yr) and will decrease with time. The ventilation will then remove the maximum amount of groundwater.

CONCLUSIONS

A 3-dimensional drift-scale model was developed and applied to predict the evolving underground temperature field near heat dissipating HLW packages. The model was applied to three AMLs (20, 40, and 80 MTU/acre) with 10 MTU per package and three ages of waste (20, 30, 50 yr from reactor). The results show the peak wall temperature is strongly affected by AML (higher AML produces higher temperatures) and age of the waste (older waste produces lower temperatures). The effects of age of the waste, however, are more transient and diminish within a few hundred years. For the 20 MTU/acre AML, peak wall temperature is 134 °C at 3 yr for 20-yr-old fuel and 92 °C at 5 yr for 50-yr-old fuel. The effects of AML are much more persistent. At 2,000 yr, the drift wall temperature is 45 °C for 20 MTU/acre, 65 °C for 40 MTU/acre, and 105 °C for 80 MTU/acre.

The effects of ventilation were investigated for the 40 MTU/acre AML with 30-yr-old fuel. It was observed that ventilation during the first 150 yr readily moderates underground temperatures. For two hypothetical yet plausible ventilation schemes considered, the maximum drift wall temperature was 87 °C at 14 yr and 78 °C at 147 yr, compared with 120 °C at 10 yr without ventilation. Ventilation provides a removal mechanism for water vapor. Because vapor removal is diffusion-controlled, the extent of radial dryout scales roughly as the square root of time. The extent of rock dryout was about 4.5 m over 150 yr for both cases. This work suggests an optimal ventilation scheme where only a minimal ventilation flowrate is applied to maintain dry drifts conditions, yet allowing the highest underground temperatures possible.

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REFERENCES

ABAQUS, 1995, "Theory and User Manuals," Pawtucket, RI: Hibbitt, Karlsson & Sorensen.

Buscheck T.A., and Nitao, J.J., 1993, "Repository-Heat-Driven Hydrothermal Flow at Yucca Mountain, Part I: Modeling and Analysis," *Nuclear Technology,* Vol. 104, pp. 418–448.

Danko, G., and Mousset-Jones, P., 1993., "Coupled Heat and Moisture Transport Model for Underground Climate Prediction," *Proceedings, International High-Level Radioactive Waste Management Conference,* American Nuclear Society, LaGrange Park, IL, pp 790–798.

DOE (U.S. Department of Energy), 1987, "Characteristics of Spent Fuel, High-Level Waste, and Other Radioactive Wastes Which May Require Long-Term Isolation," DOE/RW-0184 Vol. 2, DOE, Washington, DC.

DOE (U.S. Department of Energy), 1993, "Yucca Mountain Project Reference Information DataBase," YMP/93-02 Rev. 3, DOE, Las Vegas, NV.

Ho, C.K. and Udell, K.S., 1995, "Mass Transfer Limited Drying of Porous Media Containing an Immobile Binary Liquid Mixture," *International Journal of Heat and Mass Transfer,* Vol. 38(2), pp. 339–350.

Laage, L.W., Greuer, R.E., and Pomroy, W.H., 1994, "MFIRE Mine Fire and Ventilation Simulators, Users Manual," U.S. Bureau of Mines, Minneapolis, MN.

Lienhard, J.H., 1987, *A Heat Transfer Textbook* (2nd ed), Prentice-Hall, New Jersey.

Marshall T.J., and Holmes, J.W., 1988, *Soil Physics* (2nd ed), Cambridge University Press, Cambridge, United Kingdom.

Manteufel, R.D., Castellaw, H.M., and Stothoff, S.A., 1995, "Microslab Model for Diffusion-Controlled Drying of a Fractured Porous Media," *Proceedings, National Heat Transfer Conference,* HTD-309 Vol. 7, ASME, New York, pp. 31–40.

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MVS (Mine Ventilation Services), 1986, "CLIMSIM Climatic Simulation Program, User's Manual," MVS, Lafayette, CA.

NRC (U.S. Nuclear Regulatory Commission), 1995, "Phase 2 Demonstration of the NRC's Capability to Conduct a Performance Assessment for a High-Level Waste Repository," NUREG-1464. NRC, Washington, DC.

Pruess, K., Tsang, Y.W., and Wang, J.S.Y., 1984, "Numerical Studies of Fluid and Heat Flow Near High-Level Nuclear Waste Packages Emplaced in Partially Saturated Fractured Tuff," LBL-18552, Lawrence Berkeley Laboratory, Berkeley, CA.

Reid, R.C., Prausnitz, J.M., and Poling, B.E., 1987, *The Properties of Gases and Liquids* (4th ed), McGraw-Hill, New York.

TRW (Environmental Safety Systems), 1993, "FY93 Thermal Loading Systems Study Final Report," B00000000-01717-57-5-00013 Rev. 01, TRW, Las Vegas, NV.

TRW (Environmental Safety Systems), 1994, "Initial Summary Report for Repository/Waste Package Advanced Conceptual Design," B00000000-0-5705-00015, Rev. 00, TRW, Las Vegas, NV.

TRW (Environmental Safety Systems), 1995, "Total System Performance Assessment 1995: An Evaluation of the Potential Yucca Mountain Repository," B00000000-01717-2200-00136, Rev. 01, TRW, Las Vegas, NV.

Wilson, M.L., Gauthier, J.H., Barnard, R.W., Barr, G.E., Dockery, H.A, Dunn, E., Eaton, R.R., Guerin, D. C., Lu, N., Martinez, M.J., Nilson, R., Rautman, C.A., Robey, T.H., Ross, B., Ryder, E.E., Schenker, A.R., Shannon, S.A., Skinner, L.H., Haley, W.G., Gansemer, J.D., Lewis, L.C., Lamont, A.D., Triay, I.R., Meijer, A., and Morris, D.E., 1994, "Total-System Performance Assessment for Yucca Mountain—SNL Second Iteration (TSPA-93)," SAND93-2675, Sandia National Laboratory, Albuquerque, NM.

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Table 1 Summary of Peak Drift Wall Temperatures

Areal Mass Loading			
Age of Fuel (yr)	20 MTU/acre	40 MTU/acre	80 MTU/acre
20	134 °C @ 3 yr	138 °C @ 8 yr	162 °C @ 21 yr
30	116 °C @ 4 yr	120 °C @ 10 yr	145 °C @ 26 yr
50	92 °C @ 5 yr	95 °C @ 14 yr	119 °C @ 53 yr

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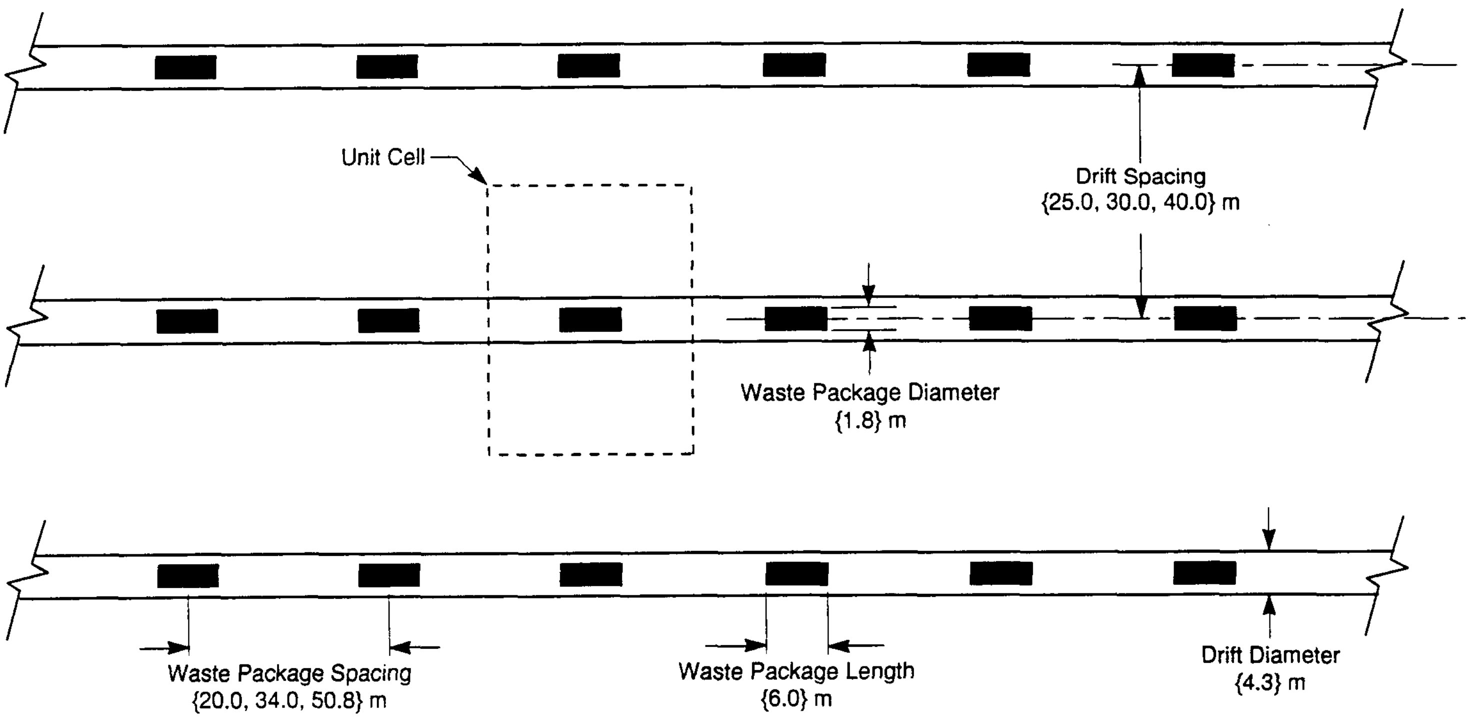

FIGURE 1 PLAN VIEW OF REPOSITORY

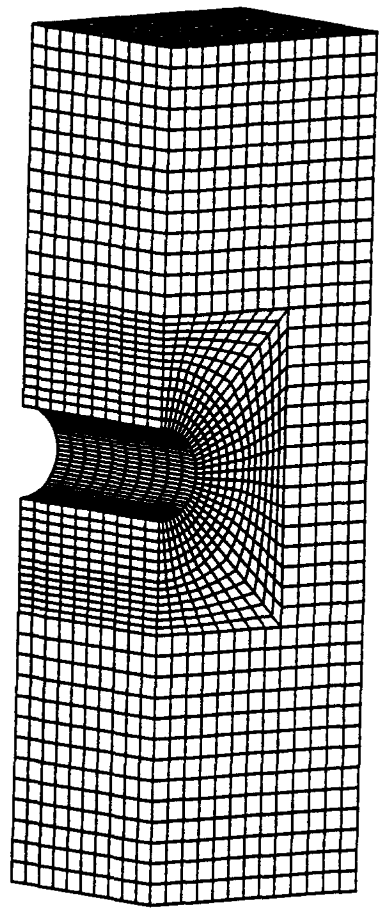

FIGURE 2 3D MODEL WITH DRIFT

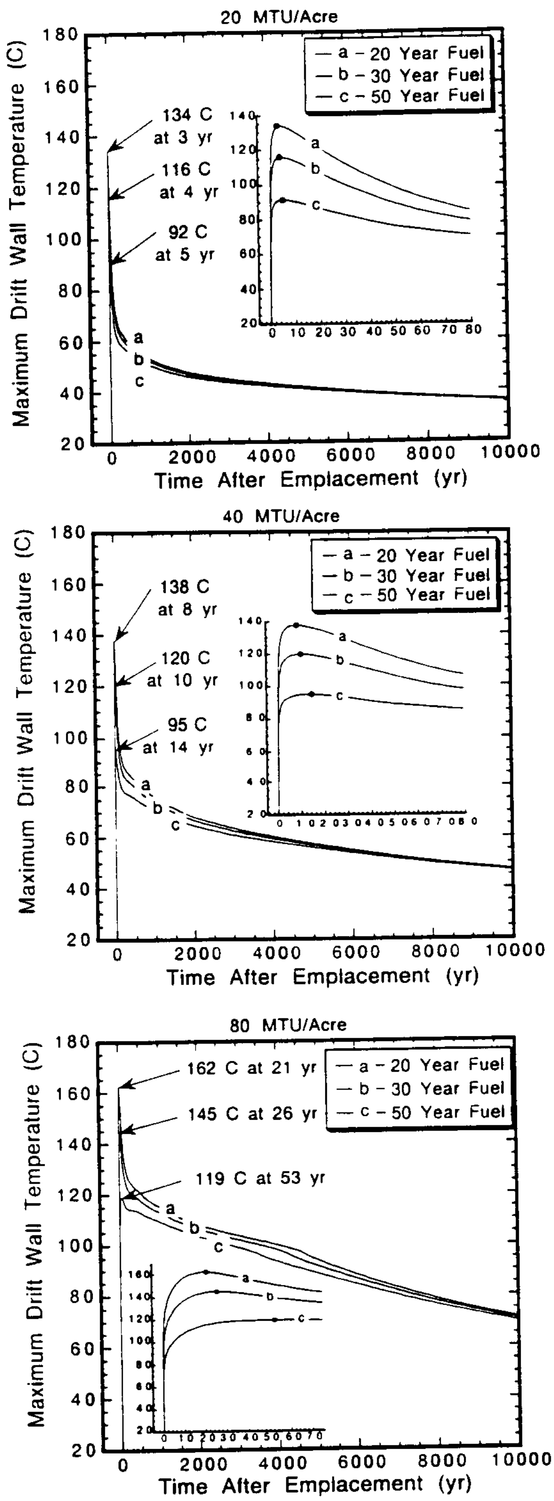

FIGURE 3 MAXIMUM DRIFT WALL TEMPERATURE FOR 20, 40, AND 80 MTU/ACRE AREAL MASS LOADINGS

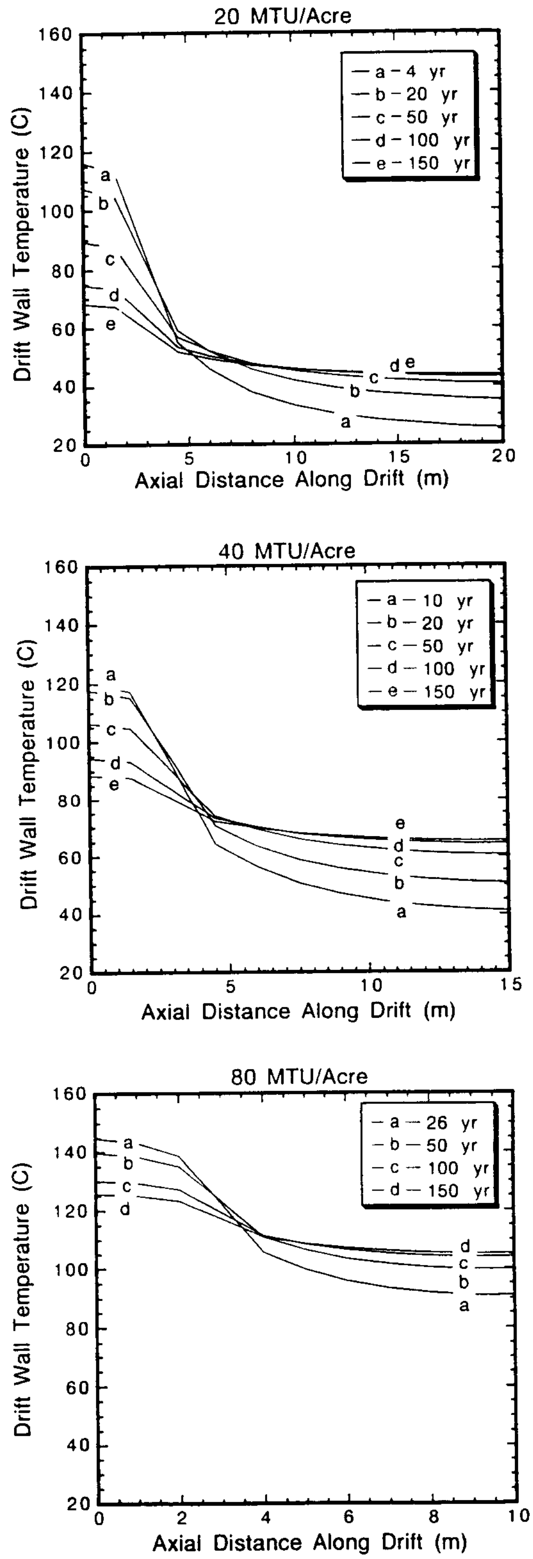

FIGURE 4 AXIAL DRIFT WALL TEMPERATURE FOR 20, 40, AND 80 MTU/ACRE AREAL MASS LOADINGS

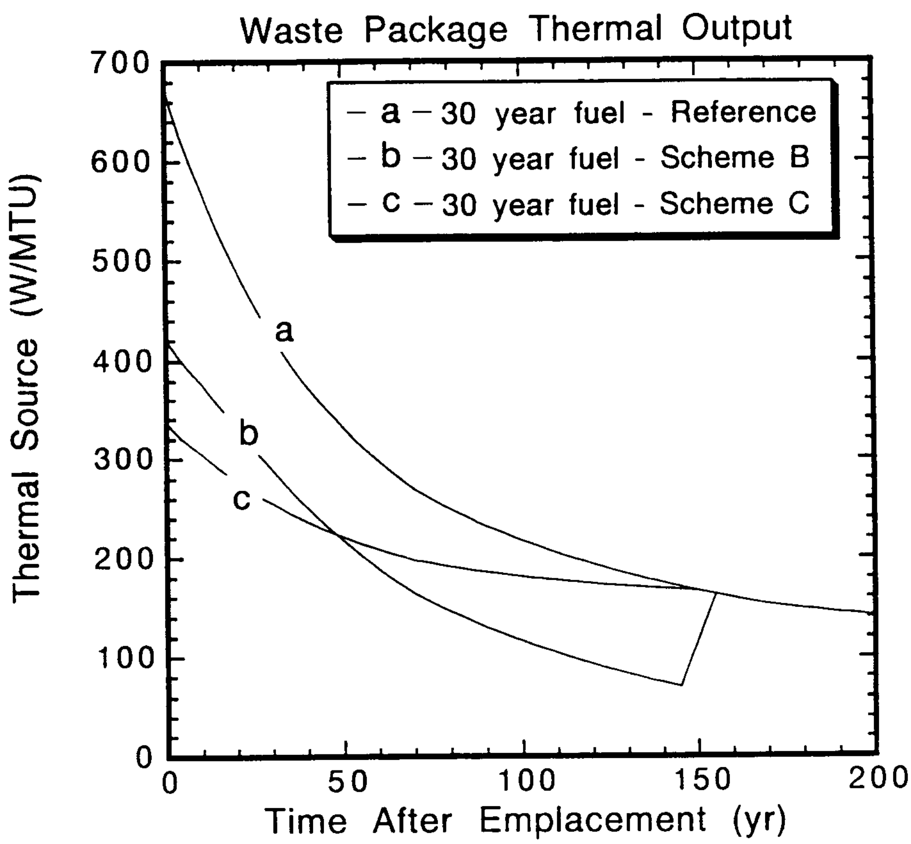

FIGURE 5 THERMAL OUTPUT OF WASTE PACKAGE FOR NO VENTILATION (REFERENCE), AND TWO VENTILATION SCHEMES

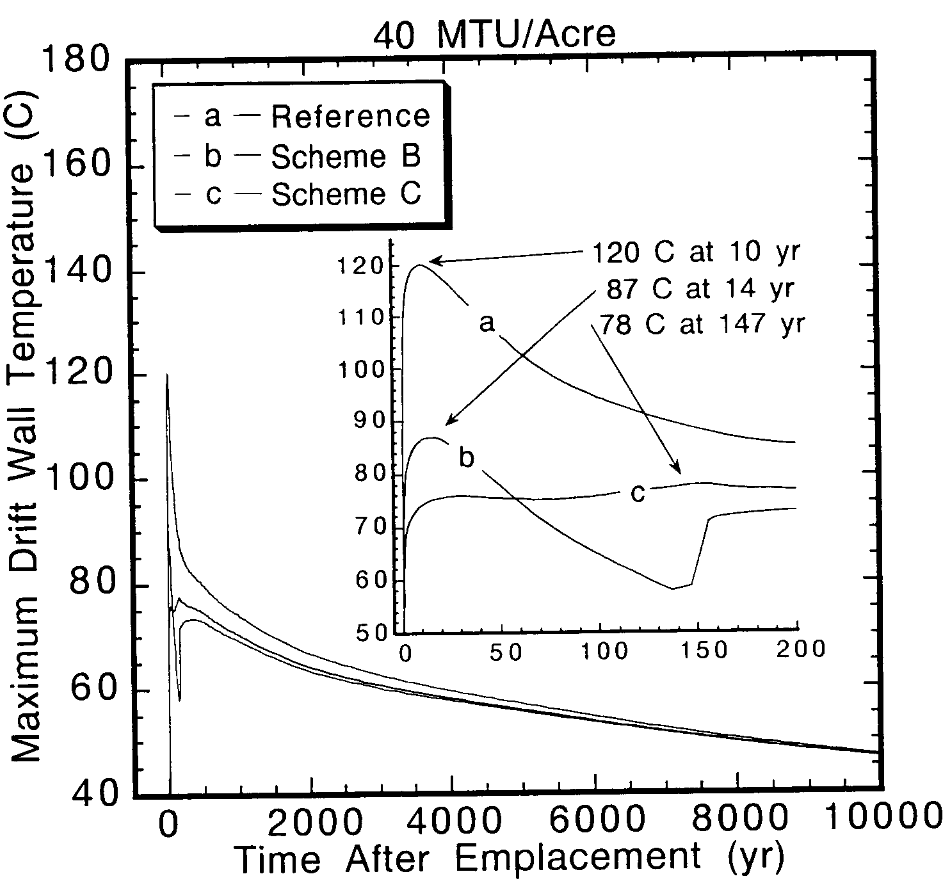

FIGURE 6 MAXIMUM DRIFT WALL TEMPERATURE FOR THREE SCHEMES

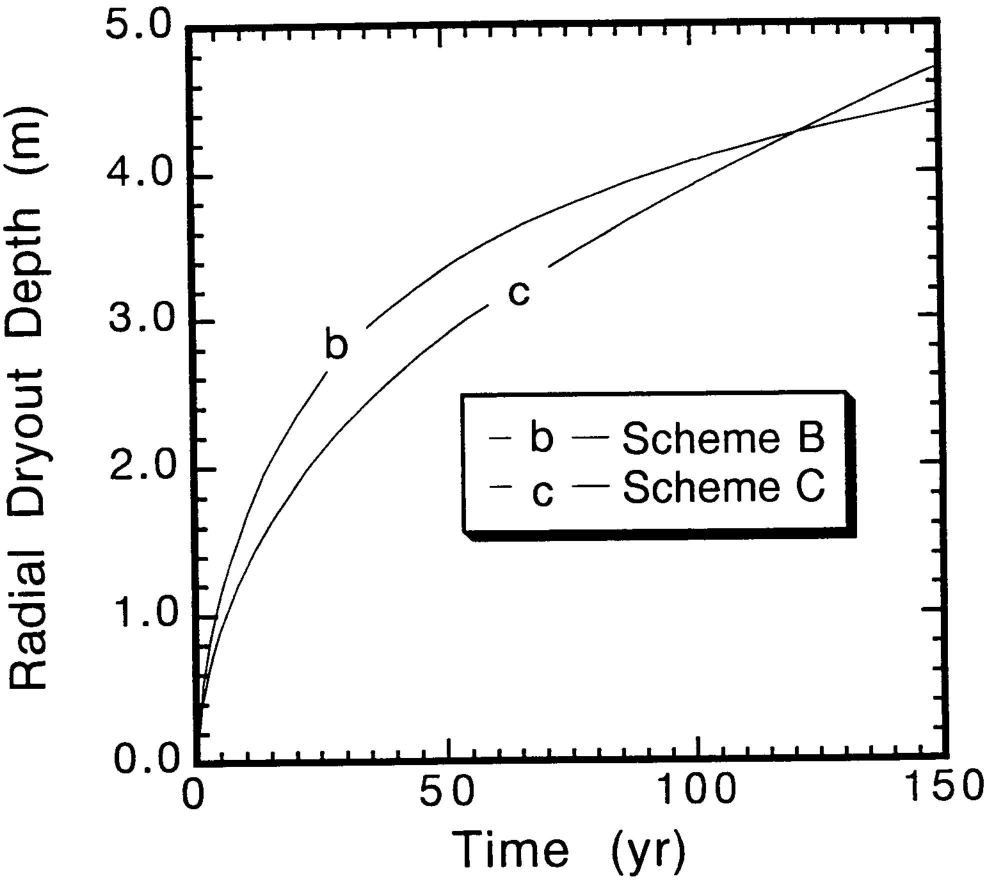

FIGURE 7 RADIAL DRYOUT DEPTH FOR TWO SCHEMES HAVING VENTILATION