MASTER

Heat Transfer Studies in Salt and Granite

R. A. Just

OAK RIDGE NATIONAL LABORATORY

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HEAT TRANSFER STUDIES IN SALT AND GRANITE

R. A. Just

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**OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
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DEPARTMENT OF ENERGY**

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FOREWORD

This report was prepared by the Engineering Division of Union Carbide Corporation, Nuclear Division, in cooperation with the Office of Waste Isolation and is part of the National Waste Terminal Storage Program. The principal objective of this program is to establish facilities in various deep geologic formations at several locations in the United States which will safely dispose of commercial radioactive waste. This report considers the waste to be either unprocessed spent fuel or high-level waste. As part of the Thermal Analysis Studies of the Office of Waste Isolation, this report compares the thermal responses to the burial of spent fuel and high-level waste in hypothetical repositories in salt and granite, using both single- and multi-level burial configurations.

1. SUMMARY

This report presents a scoping study of the feasibility of using a multi-layer terminal repository design in both salt and granite formations to store either high-level waste or spent fuel. Calculations have been made to determine temperature profiles within the repository and to provide an estimate of the thermal uplift that can be expected.

Near-field models developed to compare temperature profiles in the regions close to the waste canisters indicated that maximum thermal gradients and maximum temperature increases could be significantly reduced by changing from a single to a multi-layer repository design. For both high-level waste and for spent fuel, the maximum temperature increase in the multi-level repositories was reduced to approximately 60% of the temperature increase predicted for the single-level repositories at the same areal loading.

After the near-field models had verified that maximum thermal gradients and temperature increases could be reduced by using a multi-level repository design, a series of far-field models was developed. The far-field models used to provide qualitative comparisons of the maximum thermal uplift indicate that the thermal uplift is roughly proportional to the energy supplied to the formation. Changing from a single- to a multi-layer repository but keeping the areal loading constant results in increased thermal uplifts.

2. INTRODUCTION

Granite formations have been proposed as an alternative to salt formations for use as terminal repositories for spent fuel (SF) and high-level waste (HLW). Because excavation costs in hard rock, such as granite, are substantially greater than those in salt, it has been suggested that a multi-level storage concept, in which a number of waste canisters are buried in a single vertical hole, could be used to reduce excavation costs. It may be possible to increase the permissible areal heat loads without adverse effects either on the environment or on containment integrity.

Energy generated by the decay of the radioactive waste is dissipated into the surrounding medium by conduction and is transmitted to the surface of the earth where it is released into the atmosphere. As the energy is released into the geologic formation, temperatures increase within the medium. These increased temperatures cause adverse structural, thermal, and environmental effects, such as decreased thermal conductivity, accelerated creep rate, and increased thermal uplift. The decreased thermal conductivity will cause increased temperatures and thermal gradients, which in turn cause increased thermal stresses. Accelerated creep of the formation leads to accelerated room closure. Thermal uplift, caused by thermal expansion of the rock mass, can have adverse effects on the integrity of the containment and on the environment.

To maintain structural integrity within the repository and to attain an acceptable environment impact, it is necessary to limit the energy release into the formation. Limiting the energy release also

limits the temperature gradients, temperature increases, and thermal uplift within the rock mass, as these effects are approximately proportional to the energy release.

The purpose of this study is to determine the feasibility of a multi-level burial scheme in a granite formation. The multi-level burial scheme used in this study, which assumes three waste canisters located in a single vertical hole with 100 ft of concrete fill between the canisters, is shown in Fig. 1.

The temperature profile and thermal uplift predicted for the single-level repository concept shown in Fig. 2 are compared with the results calculated for the multi-level scheme at the same areal loading, so that the effects of multi-level storage may be estimated. Repositories in salt formations are also analyzed for purposes of comparison with repositories in granite formations.

Vertical dispersion of the heat source, resulting from a multi-level storage concept will yield a lower volumetric heat-generation rate, as a larger volume of waste is assumed to release the same amount of energy. The reduced volumetric heat-generation rate, coupled with an increased heat transfer area, will result in lower maximum temperatures in a multi-level repository.

This scoping study develops repository models for hypothetical salt and granite formations. Although the properties and stratigraphy may be typical of actual sites, the models do not represent any particular site. The hypothetical repositories are assumed to cover a circular area of 2000 acres (5266 ft radius). Mine construction is assumed to be room and pillar, with the room floor at a depth of 2000 ft. Sixty-foot-wide

Fig. 1. Multi-Level Storage Configuration.

pillars separate rooms 25 feet high by 20 feet wide. Waste canisters are buried in vertical holes in the floor so that the highest canister is 8 ft below room floor level. Concrete is used to backfill the hole up to room floor level and to separate the canisters in the multi-level storage concepts.

Two-dimensional, cartesian, near-field thermal models were developed for qualitative comparisons of pillar temperatures and local temperatures in the media surrounding the waste, and far-field models of the entire repository were developed so that comparisons of thermal uplifts for the different burial schemes could be made.

3. SOLUTION TECHNIQUE

A large system of nonlinear partial differential equations must be solved in order to calculate the transient temperature distributions resulting from the placement of a decaying heat source in a medium in which the thermal diffusivity is temperature dependent. HEATING5, a general purpose, finite-difference, heat transfer code,¹ was chosen to perform the thermal calculations.

3.1 Thermal Model

HEATING5 is designed to solve steady-state and transient heat conduction problems with temperature- and spatially-dependent thermal properties as well as time-dependent heat-generation rates. Boundary conditions may be specified as adiabatic, forced convection, natural convection, radiation, isothermal, or as constant heat flux. Various explicit and implicit techniques are available for the solution of transient heat conduction problems.

The flexibility of HEATING5 and the fact that the author has had extensive experience using the code led to the selection of HEATING5 as the means of calculating temperature distributions resulting from the different repository concepts.

HEATING5 is designed to solve a transient problem by numerical schemes which include the Classical Explicit Procedure, Levy's modification to the Classical Explicit Procedure, the Crank-Nicholson technique, and the Classical Implicit Procedure. Because it is stable for a time

step of any size, the Crank-Nicholson technique was selected as the solution technique for the transient analysis.

Heat is generated within the radioactive waste material by radioactive decay. Because radioactive decay for a given waste is a sum of exponentials with respect to time, exponential interpolation of the decay curves was used in an attempt to obtain more accurate results than would be the case for linear interpolation. Linear interpolation would overestimate the energy for a decaying exponential. HEATING5 was modified so that exponential interpolation rather than linear interpolation of the decay curve would be made between the available data points, and a modification was made to allow a thermal uplift calculation to be made internal to the code.

3.2 Thermal Uplift Model

Energy generated by the decaying waste increases the temperature within the repository and results in a volumetric thermal expansion of the material. This thermal expansion causes an uplift of the rock mass in which the waste is buried. The maximum thermal uplift will be at the center of the repository, where the maximum increase in temperature within the strata will occur for the assumed model. Because calculated uplifts for the different repository concepts are intended to be used for qualitative comparisons only, a simplified, conservative, one-dimensional model was formulated to calculate the maximum thermal uplift. The uplift model is based on the assumption that the repository will be constrained within its 5266 ft radial boundary and allowed to move freely in the axial direction. A constant temperature profile across the

repository, equal to the maximum temperature at any given elevation, was assumed to simplify the model. The resulting highly conservative model of the thermal uplift is expressed by

$$U(\theta) = \int_0^L \alpha \Delta T \frac{1 + \mu}{1 - \mu} dz,$$

where

$U(\theta)$ = the vertical displacement at the surface at time θ ,

ΔT = the change in temperature along the axis of the repository,
as a function of depth and time,

α = the linear coefficient of thermal expansion for the rock,
at depth z ,

μ = Poisson's ratio for the rock at depth z ,

L = the depth of the model.²

The actual calculation of the thermal uplift was made by taking the predicted temperature profile and numerically integrating, using trapezoidal integration of the above equation.

4. HEAT SOURCES AND DECAY RATES

The heat sources studied are assumed to be either 10-year-old, PWR high-level waste (HLW) or PWR spent fuel (SF). A spent fuel element containing 0.4614 metric tons of uranium (MTU), is modeled as a homogeneous heat-generating region 16 in. in diameter and 16 ft long. The high-level waste is contained in canisters 16 in. in diameter and 10 ft long with 2.09 MTU per canister with an active length of 8 ft at the bottom of the canister.

The time-dependent heat-generation rates used in this study for high-level waste and spent fuel are those calculated by D. W. Turner,³ through the use of the ORIGEN computer code.⁴ The initial heat-generation rates at burial for the SF and HLW canisters are 0.55 kW and 2.2 kW per canister, respectively.

Normalized heat-generation rates for both SF and HLW were obtained by dividing the time-dependent heat-generation rates by their values at burial. Exponential interpolation between the data points was used to establish the normalized decay (heat-generation rate) curves shown in Fig. 3.

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Fig. 3. Decay Rates of Spent Fuel and High-Level Waste.

5. ENERGY SUPPLIED TO THE FORMATION

Energy released by decay of HLW and SF is first absorbed by the surrounding geologic formation, and then it is conducted to the surface and released to the environment. The total amount of energy released from the waste to the rock mass is obtained by integration of the decay curves with respect to time.

Figure 4 shows a comparison of the thermal energy generated by a high-level waste canister to that generated by a spent-fuel assembly. After approximately 3000 years, the same amount of energy has been generated by either a single canister of high-level waste or an assembly or spent fuel.

The energy releases per acre are compared in Fig. 5 for high-level waste and spent fuel, with areal loadings of 150 kW/acre and 60 kW/acre, respectively. The same amount of energy has been released by each after approximately 600 years.

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TOTAL ENERGY SUPPLIED TO THE ROCK MASS PER CANISTER

Fig. 4. Total Energy Supplied to the Rock Mass Per Canister.

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Fig. 5. Total Energy Supplied to the Rock Mass for High-Level Waste and Spent Fuel at Areal Loadings of 150 kW/acre and 60 kW/acre.

6. STRATIGRAPHY

Hypothetical stratigraphies have been chosen for salt and for granite formations because the stratigraphy of a formation will be site dependent. The salt formation is assumed to have an overburden with a constant thermal conductivity extending from the surface to a depth of 800 ft and a homogeneous body of salt, with temperature-dependent thermal conductivity below 800 ft. The granite formation was assumed to consist of a single homogeneous body of granite, with temperature-dependent thermal conductivity extending downward from ground level.

7. THERMAL-PHYSICAL PROPERTIES

Thermal-physical properties used in this study, as summarized in Table 1, are typical properties of soil, concrete, salt, and granite. Since comparison of salt and granite repositories is part of the scope of this study, it is of interest to compare the properties of salt and granite. The thermal conductivities of salt and granite both decrease with increasing temperature, as shown in Fig. 6. Because the thermal conductivity of salt is approximately twice that of granite and it is easier for energy to diffuse away from the waste in salt than in granite, lower temperatures would be expected in salt. Salt, however, has a coefficient of thermal expansion approximately five times that of granite.

Table 1. Thermo-physical properties

Material	Temperature (°F)	Thermal conductivity (Btu/hr·ft·°F)	Density (lb/ft ³)	Heat capacity (Btu/lb·°F)	Poisson's Ratio ¹	Emissivity ²	Linear coefficient of thermal expansion (ft/ft·°F) ³
Granite ^{4,5}	32	1.61	165	0.2	0.15	0.45	4.5×10^{-6}
	122	1.51					
	212	1.43					
	392	1.33					
Salt ^{6,7}	32	3.53	135	0.2	0.4	0.9	23.5×10^{-6}
	122	2.90					
	212	2.43					
	302	2.08					
	392	1.80					
	482	1.60					
	572	1.44					
	662	1.33					
	752	1.20					
Concrete ⁸		0.5	125	0.21			
Overburden ⁹		1.0	120	0.2	0.2		4×10^{-6}

¹Poisson's ratios for all materials were obtained from S. P. Clark, Jr., *Handbook of Physical Constants*, Geological Society of America, New York, 1966.

²The thermal emissivities of salt and granite are assumed values.

³The coefficients of thermal expansion for salt and granite were obtained from S. P. Clark, Jr., *Handbook of Physical Constants*.

⁴The thermal conductivity of granite was obtained from S. P. Clark, Jr., *Handbook of Physical Constants*.

⁵The density and specific heat of granite were obtained from A. J. Chapman, *Heat Transfer*, Macmillan, New York, 1974.

⁶The thermal conductivity of salt was obtained from F. Birch and H. Clarke, *Am. J. Sci.*, 238: 613-35 (1940).

⁷The density and specific heat of salt were obtained from A. L. Edwards, *A Compilation of Thermal Property Data for Computer Heat-Conduction Calculations*, UCRL-50589, Lawrence Radiation Laboratory, Livermore, Calif. (1969).

⁸Thermal properties of concrete were obtained from A. J. Chapman, *Heat Transfer*.

⁹All properties of the overburden are assumed values.

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Fig. 6. Thermal Conductivities of Salt and Granite.

8. BOUNDARY AND INITIAL CONDITIONS

Boundary conditions specified for both the near- and far-field models used in this study include the ground-level surface temperature and the geothermal heat flux. A radiative boundary condition was also applied across the room in the near-field models.

8.1 Isothermal Boundary Condition

Ground level surface temperatures are subject to both diurnal and seasonal fluctuations. Observations have shown that these fluctuations decrease with depth and that they are negligible at depths below 50 ft.⁵

Thermal transients included in this study span time frames of up to 7500 years. It is clear that time steps significantly greater than one year must be used to obtain solutions that are economically feasible. However, if time steps greater than one year are used, it becomes impossible to model the diurnal and seasonal perturbations in the ground surface temperature. Therefore, it was decided to assume a constant surface temperature of 60°F, which is approximately the mean surface temperature within the continental United States.⁶ This assumption should not seriously limit the usefulness of the results of the study.

8.2 Geothermal Heat Flux

The geothermal heat flux is site dependent. Therefore, the mean geothermal heat flux ($0.0167 \text{ Btu/hr}\cdot\text{ft}^2$) for the continental United States⁶ was used in this analysis and was imposed on the lower (z -direction) boundary of all heat transfer models used in this report.

8.3 Radiation Boundary Condition for the Near-Field Models

A significant amount of heat is transferred by radiation heat transfer among the floor, walls, and ceiling of the room. Because HEATING5 cannot model radiation heat transfer between nonparallel surfaces, the radiation heat transfer from the walls to the floor and ceiling was neglected.

Radiation heat transfer is dependent on the surface conditions and materials of the radiating surfaces as well as on the geometry of the surfaces. The geometrical dependence is expressed in terms of a radiation shape or view factor, and the surface properties are included in the thermal emissivities of the surfaces.

A radiation view factor of 0.35 was calculated for two infinitely long parallel planes, 20 ft wide, which are separated by a distance of 25 ft. Thermal emissivities of 0.9 and 0.45 were assumed for the radiating salt and granite surfaces, respectively.

8.4 Initial Conditions

Initial conditions were established by calculation of the steady-state temperature profile that existed within the formation before excavation had begun. The steady-state profile was established by applying a geothermal heat flux at the base of the model and an isothermal boundary condition at ground level.

9. NEAR-FIELD MODELS

Two-dimensional, x - z , cartesian, near-field thermal models developed for comparison of the different repository concepts are intended to be used for qualitative comparisons of pillar temperatures and local temperatures in the media surrounding the waste. As shown in Figs. 1 and 2, the pitch between adjacent rows of waste canisters is 80 ft. Symmetry of the repository makes possible development of a near-field model spanning only 40 ft. The near-field thermal analysis was limited to a span of 50 years that covers the time in which the mine is excavated, the waste is deposited, and the mine is backfilled.

Implicit to any two-dimensional model is the assumption of uniformity in the third dimension. Therefore, formulation of a two-dimensional cartesian near-field model is equivalent to the assumption that the heat-generating regions representing the waste are infinitely long in the y -direction. In reality, the heat-generation regions in an actual repository are concentrated in waste canisters. The effect of dispersing or spreading out the heat-generating regions is to decrease the volumetric heat-generation rate in the thermal model. Accordingly, the near-field models will underpredict temperatures in the repository in areas close to the waste. A more accurate prediction of the temperature profile would require development of three-dimensional repository models, which is beyond the scope of this study.

Parametric studies utilizing one-dimensional models indicated that extension of the near-field models to a depth of 5000 ft would ensure an isothermal boundary throughout a 50-year transient.

Boundary conditions applied to the near-field models, as described in Sect. 8, include a geothermal heat flux applied at a depth of 5000 ft, an isothermal boundary temperature applied at ground level, and a radiative boundary condition across the room.

Radiation is the predominant mode of heat transfer across the room. Therefore, it was decided to neglect conduction and convective heat transfer so that computer costs could be decreased by simplification of the model.

Near-field models used to analyze the burial of high-level waste and spent fuel in both granite and salt formations are summarized in Table 2.

Table 2. Summary of near-field models

Type of model	Spent fuel			High-level waste		
	60 $\frac{\text{kW}}{\text{acre}}$	90 $\frac{\text{kW}}{\text{acre}}$	180 $\frac{\text{kW}}{\text{acre}}$	150 $\frac{\text{kW}}{\text{acre}}$	180 $\frac{\text{kW}}{\text{acre}}$	210 $\frac{\text{kW}}{\text{acre}}$
Single-level	X	X		X	X	
Multi-level		X	X		X	X

X = modeled for salt and granite formations.

9.1 Burial Models

Single-level burial schemes with a single canister per hole were used to compare the thermal response with that for multi-level burial schemes. Near-field models representing the single-burial level of HLW and SF in granite and salt formations are presented in Figs. 7-10. Except for the regions representing the waste canisters, the HLW and SF models are identical.

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Fig. 7. Near-Field Single-Level Thermal Model for Storage of Spent Fuel in Granite.

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Fig. 8. Near-Field Single-Level Thermal Model for Storage of Spent Fuel in Salt.

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Fig. 9. Near-Field Single-Level Thermal Model for Storage of High-Level Waste in Granite.

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Fig. 10. Near-Field Single-Level Thermal Model for Storage of High-Level Waste in Salt.

Thermal properties of the region representing the waste are assumed to be the same as that of the surrounding geological formation. Multi-level repository models, as shown in Figs. 11-14, consider the burial of three waste canisters in each vertical hole. Concrete is used to cap the holes as well as to separate the waste canisters.

9.2 Near-Field Results

Use of a multi-level burial concept significantly reduces maximum average repository temperature increases for the same areal thermal loading. These maximum temperature increases occur at the canister midplane for the single-level models, and at the midplane of the center canister for the multi-level models. The predicted peak average temperature increases in the rock formation that occur at the outer radius of the waste are summarized in Table 3.

The magnitude and time of a peak temperature increase depend on the geometry of the thermal model, the thermal properties of the medium, and the decay rate of the waste material. The actual time of peak average temperature increase is difficult to determine because of the small slope of the time-temperature curve. Therefore, the predicted time of the peak average temperature increase may be as much as 5 years in error.

The results summarized in Table 3 show that an additional 20 years were required for the SF, single-level burials to reach a maximum average temperature increase, as compared to the HLW, single-level burial scheme. The additional time required for the SF to reach a maximum average temperature increase results from the different decay rates of SF and HLW for the same initial thermal loading.

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Fig. 11. Near-Field Multi-Level Thermal Model for Storage of Spent Fuel in Granite.

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Fig. 12. Near-Field Multi-Level Thermal Model for Storage of Spent Fuel in Salt.

Fig. 13. Near-Field Multi-Level Thermal Model for Storage of High-Level Waste in Granite.

Fig. 14. Near-Field Multi-Level Thermal Model for Storage of High-Level Waste in Salt.

Table 3. Maximum average temperature increases predicted by the near-field models^a

Model	Storage medium			
	Salt dome		Granite formation	
	Temperature increase (°F)	Time ^b (years)	Temperature increase (°F)	Time ^b (years)
Spent fuel				
Single-level				
60 kW/acre	120	45	150	40
90 kW/acre	210	40	230	40
Spent fuel				
Multi-level				
90 kW/acre	130	50	140	50
180 kW/acre	270	50	280	50
High level waste				
Single-level				
150 kW/acre	290	25	360	18
180 kW/acre	360	25	420	18
High level waste				
Multi-level				
180 kW/acre	220	50	240	50
210 kW/acre	270	50	280	50

^aTemperature increase calculated for the outer radius of the waste.

^bA time of 50 years means the average temperatures have not peaked at the end of the 50 year transient.

Peak *average* temperature increases occur later for the multilayer burial models than for the single-level burial models. This additional time lag is proportional to the time required for the thermal wave fronts emanating from the middle and outer canisters to meet.

The multi-level burial models do not attain a maximum *average* temperature increase during the 50-year transient; i.e., the maximum temperature within the formation is still increasing with time. The near-field analyses were terminated at 50 years, and the far-field models described in subsequent sections verify that the time of maximum *average* temperature increase is delayed and that the magnitude of the increase is reduced when a multi-level burial scheme is used.

10. FAR-FIELD MODELS

Two-dimensional, cylindrical, far-field thermal models have been developed for comparison of the single- and multi-level repository concepts. Results of the far-field analyses are used to make *qualitative* comparisons of predicted temperatures and thermal uplifts between the different burial schemes. Because the primary purpose of the far-field analyses in this report is to predict the magnitude of the maximum thermal uplift, the transient calculations were terminated at 2500 years or the time of maximum uplift, whichever is later.

Since the far-field analyses will cover time spans of thousands of years, the time in which the rooms are not backfilled (less than 50 years) is negligible when compared with the time in which they are backfilled. Therefore, the excavated areas in the repository are assumed to be backfilled, with the backfill material having identical properties of the surrounding geologic formation throughout the far-field analysis.

Heat generated by the radioactive decay of the waste was uniformly distributed in 2000-acre circular disks (5266 ft radius) and having properties of the surrounding medium. The waste is conservatively assumed to be loaded simultaneously throughout the repository.

Both the radial and axial boundaries of the models were chosen to extend to 15,000 ft. The 15,000 ft boundaries were chosen so as to ensure isothermal boundaries throughout the transient analysis. Parametric studies utilizing one-dimensional models were used to determine the location of the isothermal boundaries. Boundary conditions applied to

the far-field models, as described in Sect. 8, include a geothermal heat flux applied at a depth of 15,000 ft and an isothermal boundary temperature of 60°F applied at ground level. Far-field models used in this study are summarized in Table 4.

Table 4. Summary of far-field models

Type of model	Spent fuel		High-level waste	
	60 kW/acre	180 kW/acre	150 kW/acre	210 kW/acre
Single-level	X ^a		X	
Multi-level		X		X

^aX = Modeled for salt and granite formations.

10.1 Single-Level Far-Field Models

Far-field models representing the single-level schemes for the burial of HLW and SF in salt and granite formations are presented in Figs. 15-18. The heat-generating region representing the waste is modeled as a single homogeneous disk.

10.2 Multi-Level Far-Field Models

Multi-level models, shown in Figs. 19-22, depict the burial of three waste canisters in each vertical hole. Heat-generating regions representing the waste are modeled as three parallel, homogeneous disks.

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Fig. 15. Far-Field Single-Level Thermal Model for Storage of Spent Fuel in Granite.

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Fig. 16. Far-Field Single-Level Thermal Model for Storage of Spent Fuel in Salt.

ORNL-DWG 78-11006

Fig. 17. Far-Field Single-Level Thermal Model for Storage of High-Level Waste in Granite.

ORNL-DWG 78-11007

Fig. 12. Far-Field Single-Level Thermal Model for Storage of High-Level Waste in Salt.

ORNL-DWG 78-11008

Fig. 19. Far-Field Multi-Level Thermal Model for Storage of Spent Fuel in Granite.

ORNL-DWG 78-11009

Fig. 20. Far-Field Multi-Level Thermal Model for Storage of Spent Fuel in Salt.

ORNL-DWG 78-11010

Fig. 21. Far-Field Multi-Level Thermal Model for Storage of High-Level Waste in Granite.

ORNL-DWG 78-11011

Fig. 22. Far-Field Multi-Level Thermal Model for Storage of High-Level Waste in Salt.

10.3 Comparison of Maximum Average Temperature Increases

The far-field models as well as the near-field models show that utilization of a multi-layer burial scheme will result in a reduced peak *average* temperature increase. Homogenization of the heat-generating regions will result, of course, in lower maximum *average* temperatures that will occur at a later time. These maximum *average* temperatures occur at the center of the repository at the midplane of the heat-generating region (or regions). A summary of maximum *average* temperature increases predicted by the far-field models is presented in Table 5.

Table 5. Maximum *average* temperature increases calculated by the far-field models^a

Model	Storage medium			
	Salt formation		Granite formation	
	Temperature increase (°F)	Time (years)	Temperature increase (°F)	Time (years)
Spent fuel				
60 kW/acre single-level	100	60	130	70
180 kW/acre multi-level	280	125	110	175
High-level waste				
150 kW/acre single-level	230	35	270	35
210 kW/acre multi-level	250	60	270	60

^aThe maximum *average* temperature increases occur along the center-line of the repository at the midplane of the heat-generating region. Because the far-field results underpredict the maximum temperature increases, these results should be used only for *qualitative* comparisons.

10.4 Comparison of Maximum Thermal Uplifts

Thermal uplift in a repository is dependent on the repository material properties, the rate of energy supply to the formation, the total energy supplied to the formation, and the location of the energy source within the repository.

A simplified uplift model, as described in Sect. 3.2, was used to calculate the thermal uplift for each far-field calculation. Predicted uplifts are summarized in Table 6 and presented in graphical form in Figs. 23 and 24.

Table 6. Summary of maximum thermal uplift

Model	Storage medium			
	Salt dome		Granite formation	
	Uplift ^a (ft)	Time ^b (years)	Uplift ^a (ft)	Time ^b (years)
Spent fuel				
60 kW/acre single-level	12	3500	1.2	7000
180 kW/acre multi-level	36	4000	3.9	7500
High-level waste				
150 kW/acre single-level	8	700	0.79	1000
210 kW/acre multi-level	11	800	1.1	1250

^aThe predicted magnitudes of thermal uplift are highly conservative upper limits, and they should be used for *qualitative* comparison only.

^bThe predicted times of peak thermal uplift were taken at the print-out time at which the peak uplift occurred. As a finite number of print-out times were used, the times of peak uplift should be considered as estimates, and they should be used for *qualitative* comparisons only.

Examination of the maximum uplifts tabulated in Table 6 indicates that the thermal uplift is roughly proportional to the energy supplied to the formation. For example, increasing the areal loading from

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Fig. 23. Thermal Uplift in Granite.

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Fig. 24. Thermal Uplift in Salt.

60 kW/acre to 180 kW/acre results in the peak uplift increasing by a factor of 3.3 for the burial of spent fuel in granite and of 3.1 in salt formations.

The uplift curves shown in Figs. 23 and 24 are relatively flat, and the maximum uplift is "maintained" over a span of hundreds of years. For example, for spent fuel loaded in a granite formation at 60 kW/acre, the uplift does not peak until 7000 years. However, the peak uplift is essentially reached after only 3000 years.

The predicted time at which the peak thermal uplift occurs varies from 700 to 7500 years, depending on both the burial configuration and the areal thermal loadings. Other studies have indicated that the time of maximum thermal uplift will occur substantially earlier. For example, high-level waste buried in a salt formation with an areal loading of 150 kW per acre, is predicted by Lincoln, Larson, and Sisson⁷ to reach a peak thermal uplift after only 150 years, unlike the present study, which predicts that it will peak after 700 years. This discrepancy is still unresolved and will be the subject of future investigations.

11. COMPARISON OF THERMAL PROFILES

Temperatures predicted throughout the transient analyses were generated as output from HEATING5 in the form of tabular data, and output from the near-field analysis was converted by a post processor, HEATPLOT,⁸ into contour plots that depict lines of constant temperature increase. Examination of these contour plots yields additional insight into the thermal effects of the different repository concepts.

Representative contour plots of the near-field results at 1, 5, and 50 years after burial of the waste in salt and granite formations are presented in Appendices A and B, respectively.

11.1 Single and Multi-Level Repositories

It is of interest to examine and compare the temperature profiles predicted for the single-level and multi-level repository models in which the repository material, areal loading, and type of waste are identical.

There are two main thermal effects in changing from a single-level to a multi-level repository. First, both thermal gradients and maximum temperature increases are significantly reduced by dispersion of the waste in a multi-layer repository. Therefore, maximum thermal stresses are reduced. The maximum temperature increase in the multi-level repository considered in this study will occur at the midplane of the middle canister of waste. For the assumed decay curves of HLW and SF, the time of maximum temperature increase will occur after the thermal wave fronts emanating from the upper and lower canisters reach the

middle canister. The additional time required for the wave fronts to reach the middle canister is the primary reason that the time of maximum temperature increase occurs later in a multi-level repository than in a single-layer repository.

11.2 Effect of the Repository Material Properties

Comparisons of the results presented in Appendices A and B indicate that changing the repository material (i.e., thermal properties) has an appreciable effect on the results. Salt, which has a higher thermal conductivity than granite, will allow energy generated by the waste to diffuse faster. This increased heat diffusion accounts for lower temperature increases and thermal gradients being predicted for a salt repository. That the thermal expansion coefficient of salt is approximately five times larger than that of granite accounts for the much higher thermal uplift in a salt formation.

12. CONCLUSIONS AND RECOMMENDATIONS

A scoping study has been completed to determine the effects of a multi-level, terminal repository design for the storage of either high-level waste or spent fuel. Near-field calculations have been made in both salt and granite formations to estimate the temperature profile in the region close to the waste. Far-field calculations were also made so that *qualitative* comparisons of peak thermal uplifts could be made, for the same initial areal thermal loading.

Results of this study indicate that changing from a single- to a multi-layer repository design yields decreased thermal gradients and temperature increases. However, the peak thermal uplift is increased by using a multi-layer repository design for the same loading conditions.

There are two primary reasons for the increased thermal uplift in a multi-layer repository. First, the axial dispersion of heat results in a larger amount of material being heated. Because the thermal conductivity of salt and granite decrease with temperature, and because of the existence of a geothermal gradient, the effect of moving the heat generating region downward is to decrease the thermal conductivity of the surrounding medium. This reduced conductivity retards the dispersal of heat, which results in increased maximum temperatures and thermal uplifts.

Changing the repository material (i.e., thermal properties) was found to have an appreciable effect on the results. The higher thermal conductivity of salt, as compared to that of granite, resulted in lower temperature increases and thermal gradients being predicted for a salt repository. The higher thermal expansion coefficient of salt also resulted in a much larger thermal uplift in a salt formation.

The maximum thermal uplift in a repository is dependent on the waste material, areal loading, repository material, and the type of storage configuration used. At constant areal loading, as the number of waste canisters in a vertical hole is increased, two opposing effects occur: the heat generating region is increased in the vertical direction, which tends to increase the maximum thermal uplift; however, the heat source becomes more dispersed (with an increased heat transfer area), which tends to decrease the maximum thermal uplift. Therefore, because of the many interacting factors that influence the maximum thermal uplift in a repository, the uplift results calculated as part of this study should not be extrapolated to other types of multi-level repository concepts.

Increased accuracy can be obtained by using the actual repository stratigraphy of a proposed site to formulate the thermal model. Furthermore, the thermophysical properties of the repository material should be measured and used in the analysis, since they are a key factor in the modeling accuracy.

After the model has been refined to reflect an actual rather than a hypothetical repository, both near- and far-field analyses should be repeated. If a multi-level repository still appears to be a feasible alternative, a detailed three-dimensional near-field model should be developed to estimate the temperature profile better in the region close to the waste canisters. This model should also be formulated so that the effects of air circulation and room cooling are considered.

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Appendix A

THERMAL CONTOUR PLOTS FOR WASTE BURIAL IN SALT

ORNL DWG. 78-13473

Fig. 25. Isothermal Plot at 1 Year for High-Level Waste Buried in Salt at an Areal Loading of 180 kW per Acre Using a Single-Level Burial Configuration.

TIME = 5 YEARS

CONTOUR VALUES (ADEGF)

LEGEND

□	80.0
○	90.0
△	100.0
+	110.0
x	120.0
◇	140.0
▽	160.0
■	180.0
×	200.0
◆	220.0
●	240.0
■	260.0

Fig. 26. Isothermal Plot at 5 Years for High-Level Waste Buried in Salt at an Areal Loading of 180 kW per Acre Using a Single-Level Burial Configuration.

TIME = 50 YEARS

CONTOUR VALUES (ADEGF)

LEGEND

□	240.0
○	250.0
△	260.0
+	270.0
x	280.0
◇	300.0

Fig. 27. Isothermal Plot at 50 Years for High-Level Waste Buried in Salt at an Areal Loading of 180 kW per Acre Using a Single-Level Burial Configuration.

Fig. 28. Isothermal Plot at 1 Year for High-Level Waste Buried in Salt at an Areal Loading of 180 kW per Acre Using a Multi-Level Burial Configuration.

Fig. 29. Isothermal Plot at 5 Years for High-Level Waste Buried in Salt at an Areal Loading of 180 kW per Acre Using a Multi-Level Burial Configuration.

ORNL DWG. 78-13480

TIME- 50 YEARS

CONTOUR VALUES (DEG F)

LEGEND	
●	150.0
×	160.0
■	170.0
□	175.0
○	180.0
△	185.0
+	190.0
×	195.0
○	200.0
△	205.0
+	210.0
×	215.0
○	220.0

Fig. 30. Isothermal Plot at 50 Years for High-Level Waste Buried in Salt at an Areal Loading of 180 kW per Acre Using a Multi-Level Burial Configuration.

Fig. 31. Isothermal Plot at 1 Year for Spent Fuel Buried in Salt at an Areal Loading of 90 kW per Acre Using a Single-Level Burial Configuration.

TIME = 5 YEARS

CONTOUR VALUES (ADEGF)

Fig. 32. Isothermal Plot at 5 Years for Spent Fuel Buried in Salt at an Areal Loading of 90 kW per Acre Using a Single-Level Burial Configuration.

ORNL DWG. 78-13483

TIME = 50 YEARS

CONTOUR VALUES (°DEG F)

LEGEND

o	=	140.0
A	=	150.0
+	=	160.0
x	=	170.0
◇	=	180.0
▽	=	200.0

Fig. 33. Isothermal Plot at 50 Years for Spent Fuel Buried in Salt at an Areal Loading of 90 kW per Acre Using a Single-Level Burial Configuration.

ORNL DWG. 78-13484

TIME = 1 YEAR

CONTOUR VALUES (ADEGF)

LEGEND

□ = 5.0
○ = 10.0
△ = 20.0

Fig. 34. Isothermal Plot at 1 Year for Spent Fuel Buried in Salt at an Areal Loading of 90 kW per Acre Using a Multi-Level Burial Configuration.

ORNL DWG. 78-13485

TIME - 5 YEARS

CONTOUR VALUES (ADEGF)

LEGEND	
○	15.0
△	20.0
+	25.0
x	30.0
◇	35.0
▽	40.0

Fig. 35. Isothermal Plot at 5 Years for Spent Fuel Buried in Salt at an Areal Loading of 90 kW per Acre Using a Multi-Level Burial Configuration.

TIME = 50 YEARS

CONTOUR VALUES (ADEGF)

Fig. 36. Isothermal Plot at 50 Years for Spent Fuel Buried in Salt at an Areal Loading of 90 kW per Acre Using a Multi-Level Burial Configuration.

Appendix B

THERMAL CONTOUR PLOTS FOR BURIAL OF WASTE IN GRANITE

ORNL DWG. 78-13487

TIME - 1 YEAR

CONTOUR VALUES (ADEGF)

LEGEND

□	10.0
○	20.0
△	30.0
+	40.0
x	60.0
◇	80.0
▽	100.0
■	150.0
×	200.0
◆	250.0
●	300.0

Fig. 37. Isothermal Plot at 1 Year for High-Level Waste Buried in Granite at an Areal Loading of 180 kW per Acre Using a Single-Level Burial Configuration.

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Fig. 38. Isothermal Plot at 5 Years for High-Level Waste Buried In Granite at an Areal Loading of 180 kW per Acre Using a Single-Level Burial Configuration.

Fig. 39. Isothermal Plot at 50 Years for High-Level Waste Buried in Granite at an Areal Loading of 180 kW per Acre Using a Single-Level Burial Configuration.

Fig. 40. Isothermal Plot at 1 Year for High-Level Waste Buried in Granite at an Areal Loading of 180 kW per Acre Using a Multi-Level Burial Configuration.

ORNL DWG. 78-13491

TIME- 5 YEARS

CONTOUR VALUES (ADEGF)

LEGEND

○	10.0
△	20.0
+	30.0
x	40.0
◇	60.0
▽	80.0
■	100.0
×	120.0

Fig. 41. Isothermal Plot at 5 Years for High-Level Waste Buried in Granite at an Areal Loading of 180 kW per Acre Using a Multi-Level Burial Configuration.

Fig. 42. Isothermal Plot at 50 Years for High-Level Waste Buried in Granite at an Areal Loading of 180 kW per Acre Using a Multi-Level Burial Configuration.

Fig. 43. Isothermal Plot at 1 Year for Spent Fuel Buried in Granite at an Areal loading of 90 kW per Acre Using a Single-Level Burial Configuration.

Fig. 44. Isothermal Plot at 5 Years for Spent Fuel Buried in Granite at an Areal Loading of 90 kW per Acre Using a Single-Level Burial Configuration.

ORNL DWG. 78-13495

TIME = 50 YEARS

CONTOUR VALUES (ADEGF)

LEGEND

□	150.0
○	160.0
△	170.0
+	180.0
x	190.0
◇	200.0
▽	210.0
■	220.0

Fig. 45. Isothermal Plot at 50 Years for Spent Fuel Buried in Granite at an Areal Loading of 90 kW per Acre Using a Single-Level Burial Configuration.

ORNL DWG. 78-13496

TIME = 1 YEAR

CONTOUR VALUES (ADEGF)

LEGEND

□	2.0
○	6.0
△	10.0
×	15.0
+	20.0
◇	30.0

Fig. 46. Isothermal Plot at 1 Year for Spent Fuel Buried in Granite at an Areal Loading of 90 kW per Acre Using a Multi-Level Burial Configuration.

ORNL DWG. 78-13497

TIME = 5 YEARS

CONTOUR VALUES (ADEGF)

LEGEND

□	10.0
○	14.0
△	18.0
+	20.0
x	25.0
◇	30.0
▽	35.0
■	40.0
✕	45.0
◆	50.0
●	50.0

Fig. 47. Isothermal Plot at 5 Years for Spent Fuel Buried in Granite at an Areal Loading of 90 kW per Acre Using a Multi-Level Burial Configuration.

ORNL DWG. 78-13498

TIME - 50 YEARS

CONTOUR VALUES (ADEGF)

LEGEND	
■	75.0
□	80.0
◻	85.0
○	90.0
△	95.0
+	100.0
x	110.0
◇	115.0
▽	120.0
■	125.0
■	130.0
◆	135.0

Fig. 48. Isothermal Plot at 50 Years for Spent Fuel Buried in Granite at an Areal Loading of 90 kW per Acre Using a Multi-Level Burial Configuration.

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