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HEAT TRANSFER ANALYSES FOR GROUT DISPOSAL OF RADIOACTIVE DOUBLE-SHELL SLURRY AND CUSTOMER WASTES

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PREFACE

Heat Transfer Analyses for Grout Disposal of Radioactive Double-Shell Slurry and Customer Wastes documents a study performed for Rockwell Hanford Operations by the Cement and Concrete Applications Center at Oak Ridge National Laboratory during the fall of 1983. Some of the terminology is no longer valid. The primary purpose of this report is to document the history of the Transportable Grout Facility program at Rockwell Hanford.

HEAT TRANSFER ANALYSES FOR GROUT DISPOSAL OF RADIOACTIVE DOUBLE-SHELL SLURRY AND CUSTOMER WASTES

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ABSTRACT

Transient heat transfer calculations were made using the HEATING6 computer code to predict temperature profiles in solidified low-level radioactive waste disposal scenarios at the Rockwell Hanford site. The calculations provide guidance for the development of safe, environmentally acceptable grout formulas for the Transportable Grout Facility.

1. INTRODUCTION

Grout immobilization is being considered by Rockwell Hanford Operations (Rockwell Hanford) as a permanent disposal method for several radioactive waste streams. These include disposal of customer and double-shell slurry wastes in earthen trenches and in single-shell underground waste storage tanks. Heat transfer studies[1,2,3] have previously been made to determine the maximum heat loading for grout disposal of various wastes under similar conditions, but a sensitivity analysis of temperature profiles to input parameters was needed. This document presents the results of heat transfer calculations for trenches containing grouted customer and double-shell slurry wastes and for in situ disposal of double-shell wastes in single-shell, domed concrete storage tanks. It discusses the conditions that lead to maximum grout temperatures of 250°F during the curing stage and 350°F thereafter and shows the dependence of these temperatures on input parameters such as soil and grout thermal conductivity, grout specific heat, waste loading, and disposal geometries.

2. DESCRIPTION OF MODELS

Transient heat transfer calculations were made using the HEATING6[4] computer code, a multidimensional heat conduction program which solves problems with finite difference schemes. These problems are solved using the Classical Implicit Procedure, a point-successive overrelaxation iterative method.

The detailed geometric models used to represent earthen trenches and single-shell tanks are shown in Figs. 1 and 2, respectively. The trench dimensions are taken from Rockwell Hanford's present reference case,[5] and the million-gallon storage tank[1] is used in this model because it has a lower surface-area-to-volume (S/V) ratio than the other single-shell tanks. This lower S/V ratio should result in higher peak temperatures because the heat flux would be lower than for tanks with higher S/V ratios.

The single-shell tanks are assumed to be filled with four materials. The single-shell tank waste (dry sludge) originally in the tanks will make up the bottom layer. Backfill material will probably be placed above the single-shell waste, and grout containing double-shell slurry waste will be pumped in above it. Any remaining area in the tank will be filled with fresh concrete so that no air space will remain in the tank. Initial computer runs were made using a depth dimension of 23.75 ft of waste-containing grout, 1 ft of backfill (assumed to be soil), and 10 ft of single-shell waste.

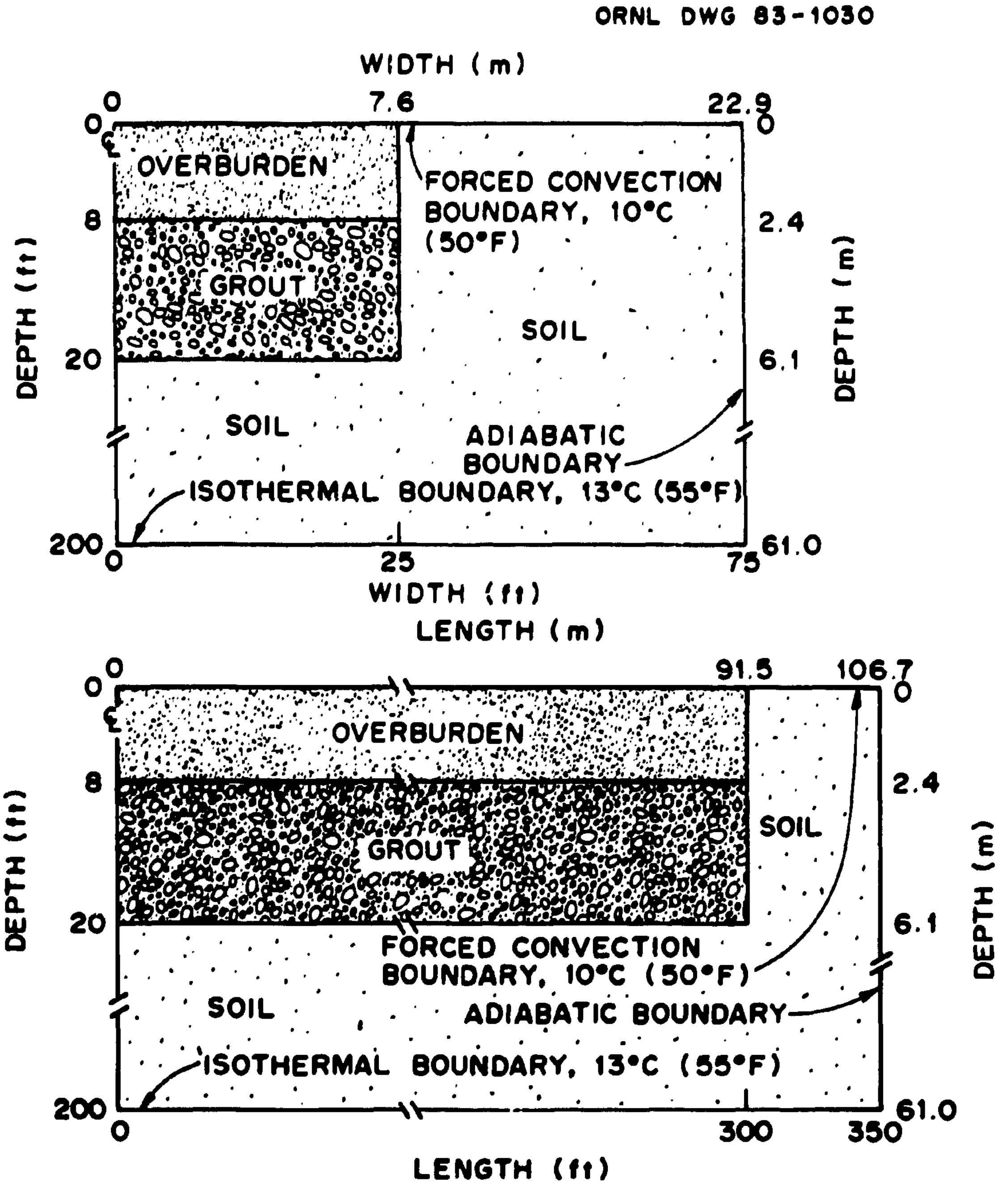

Fig. 1. Earthen trench heat transfer model. The top drawing is an end perspective; the bottom drawing is a side perspective.

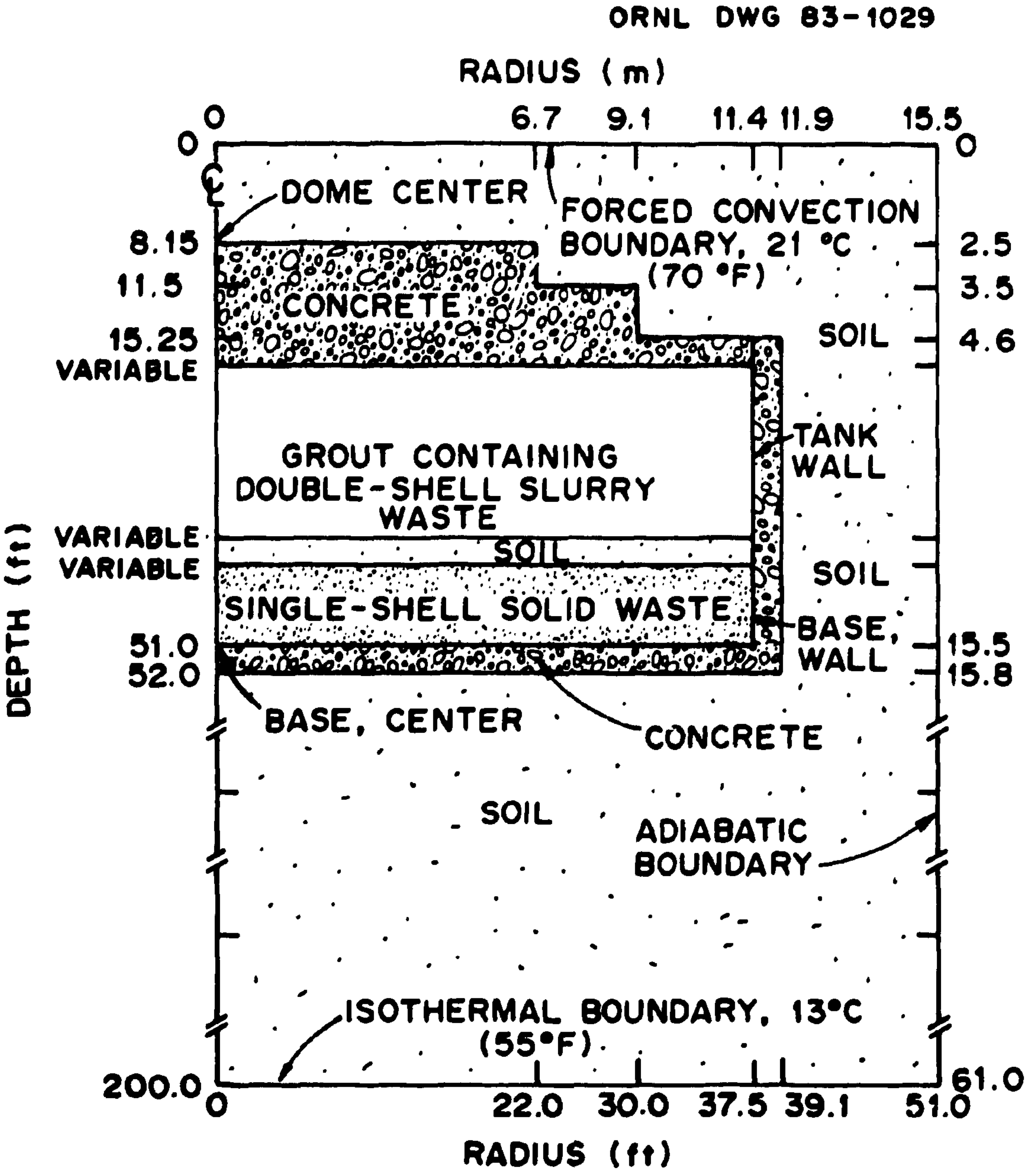

Fig. 2. Million-gallon single-shell tank heat transfer model.

Heat transfer through the wastes, concrete, soil, and overburden is assumed to be by conduction only. Heat is assumed to be transferred to the ambient air by forced convection.

Many of the input parameters for the model are unsubstantiated now or will vary for different wastes and disposal sites. Initial heat transfer calculations were made using the most likely and/or most conservative estimates, and these were used as base cases for analyses. Further calculations proved the dependence of the temperature profiles on these parameters. This section describes the input parameters for these base cases and the assumptions on which they are based.

2.1 ASSUMPTIONS

Several simplifying assumptions were made in order to model the grout-filled trenches and tanks with the HEATING6 computer program. The following assumptions and boundary conditions were used in these analyses:[1,2,3]

1. An adiabatic or insulated boundary was placed at a radial distance of 51 ft from the single-shell tank center. This simulates a tank in the middle of a large array of tanks, all generating the same amount of heat.
2. In most runs, trenches were placed at a 150-ft center-to-center spacing. At this spacing, trenches containing customer and double-shell slurry wastes act as isolated trenches. The adiabatic boundary was then varied to determine the heat effects due to a trench in the middle of an array of trenches, all generating the same amount of heat.

3. The lower boundary conditions were placed at 200 ft below grade level at a constant geothermal temperature of 55°F.
4. The ambient air temperature was 50°F for the trenches[2] and 70°F for the tanks.[3] Calculations made for trenches at 70°F indicated that increased ambient temperatures did not affect the maximum grout temperatures.
5. A forced convective boundary condition was placed on the earth's surface with a forced convection coefficient of 2.0 Btu/(h·ft^2·°F).[1,2,3]
6. The metal liner for the single-shell tank and the hypalon® liner for the trench were ignored.
7. The initial temperature of the soil and tank walls was 55°F. The grout, overburden, and fresh concrete in the single-shell tank was 50°F. The single-shell solids waste temperature was 110°F.[3]
8. The grout and concrete temperatures were limited to 250°F during curing and to 350°F after curing. Experience at Oak Ridge National Laboratory (ORNL) has shown that grout pore water generally boils at ~250°F. Since this water is essential to the cementitious reactions, the grout must be cured at temperatures <250°F. The maximum allowable temperature in single-shell storage tanks as determined by Rockwell Hanford is 350°F.[5] This value was also arbitrarily applied to the grout after the 90-d curing stage.
9. The overburden was assumed to have the same thermal properties as soil in all cases.

10. Axisymmetric flow was assumed for the tanks, and a two-dimensional cylindrical (R, Z coordinates) model was used. Symmetry along the centerline was assumed for the trenches, and a three-dimensional (X, Y, and Z coordinates) model was used.
11. The materials in the tank and trench were assumed to be cylindrical or rectangular slabs of uniform thickness, thermal conductivity, and power density. Actual tanks have layered solids and varying degrees of nonuniformity of thermal properties. The resultant temperatures may be somewhat higher or lower, depending on how the heat-generating material is distributed.
12. In order to simplify modeling, the concrete dome of the tank was assumed to have the same properties as the soil. This will make the dome temperatures increase slightly, resulting in a more conservative model.

2.2 THERMAL PROPERTIES AND HEAT GENERATION RATES

The composition of the customer and double-shell slurry wastes used in the calculations is shown in Tables 1 and 2, respectively.[6,7] Customer waste is diluted, un-neutralized decontamination waste. We assume that neutralization will not appreciably change the volume and that the evaporation process will reduce the waste to half the original volume.[8] The double-shell slurry waste was assumed to be diluted by a factor of 2.5 before processing. The ORNL preliminary reference composition for grouts containing these wastes is shown in Tables 3 and 4.

The thermal properties used for the base cases are given in Table 5. The values for the concrete, soil, and wastes were taken from reference 3,

Table 1. Composition of customer waste

Component	Molarity	Major Radionuclides	Concentration (µCi/L)
Na_2HPO_4	0.20	^{60}Co	330
Na_3PO_4	0.007	^{58}Co	25
NaOH	0.010	^{59}Fe	50
$NaNO_2$	0.011	^{51}Cr	38.5
		^{54}Mn	28.4
		^{103}Ru	5.8
		^{137}Cs	not detectable
		^{239}Pu	1.4

Table 2. Composition of double-shell slurry waste

Component	Molarity	Component	Concentration
$NaAlO_2$	2.8	Total organic carbon	12.0 g/L[a]
NaOH	6.5	^{137}Cs	1.2 Ci/L
$NaNO_3$	5.0	^{90}Sr	5×10^3 μCi/L
$NaNO_2$	4.0	^{239}Pu	~10^4 g/L
Na_2SO_4	0.05	Density	1.8 kg/L
Na_3PO_4	0.10		
Na_2CO_3	0.20		
Na_2CrO_4	0.10		
NaCl	0.20		
NaF	0.05		

[a] 12.0 g/L total organic carbon (TOC) is equivalent to any one of the following: 0.10 m HEDTA, 0.10 m EDTA, 0.1667 m sodium citrate, 0.5 m sodium acetate, or 0.5 m sodium oxalate. It is assumed that 30% of the organic carbon contribution is from HEDTA, 10% from EDTA, 40% from sodium citrate, 10% from sodium acetate, and 10% from sodium oxalate. Following are gram amounts to be dissolved in 1 L to give a TOC concentration of 12.0 g/L:

Component	g/L
HEDTA (N-hydroxethylethylenediaminetriacetic acid, trisodium salt), MW = 344.2	10.33
EDTA (ethylenediaminetetracetic acid, tetrasodium salt dihydrate), MW = 416.2	4.16
sodium citrate ($Na_3C_2H_3O_2$), MW = 294.10	19.61
sodium acetate ($NaC_2H_3O_2$), MW = 82.03	4.10
sodium oxalate ($Na_2C_2O_4$), MW = 134.0	.70

Table 3. Composition of grout[a] containing customer waste

Component	Wt %
Portland cement, type I	16
Kingston, Tenn., fly ash	16
Attapulgite-150 clay	8
Neutralized, concentrated waste[b]	60

[a] Waste loading of 6 lb solids/gal waste with a grout density of 86.6 lb/ft^3.

[b] Waste is reduced to half the original volume by evaporation.

Table 4. Composition of grout[a] containing double-shell slurry waste

Component	Wt %
Portland cement, type I	16.05
Kingston, Tenn., fly ash	16.05
Attapulgite-150 clay	6.39
Indian red pottery clay	3.21
Diluted waste[b]	58.30

[a] Waste loading of 8 lb solids/gal waste with a grout density of 102.5 lb/ft^3.

[b] Waste diluted by a factor of 2.5 to a density of 83.6 lb/ft^3.

Table 5. Thermal properties

Material	Thermal conductivity [Btu/(h·ft·°F)]	Density (lb/ft^3)	Specific heat [Btu/(lb·°F)]
Concrete	0.54	144.0	0.21
Soil	0.25	113.0	0.22
Single-shell tank waste	0.25	65.0	0.30
Double-shell tank waste	0.25	103.0	0.30
Customer waste grout	0.3	86.6	0.43
Double-shell tank grout	0.3	102.5	0.43

and the grout properties are calculated in Appendix A. These values are assumed to be constant with respect to temperature.

Heat is generated by two sources—from radioactive decay of the wastes and from the heat of hydration which occurs as cement cures. Hydration generates heat quickly and then dies out. The heat generated by customer and double-shell slurry wastes is at a much lower level, but it persists much longer.

The heat of hydration[9] for various types of Portland cements is shown in Fig. 3. The temperature at which hydration takes place greatly affects the rate of heat development. Data by Neville[10] suggest that the curve for type I cement in Fig. 3 was obtained at 105°F. Lower temperatures slow the heat generation rate and reduce the peak concrete temperatures produced by the hydrating cement. Equations found to fit the curve for type I cement determined the cumulative heat generated for hydrating cements. Heat generation rates were derived by adding a waste-loading term to account for the percentage of noncementitious materials in the

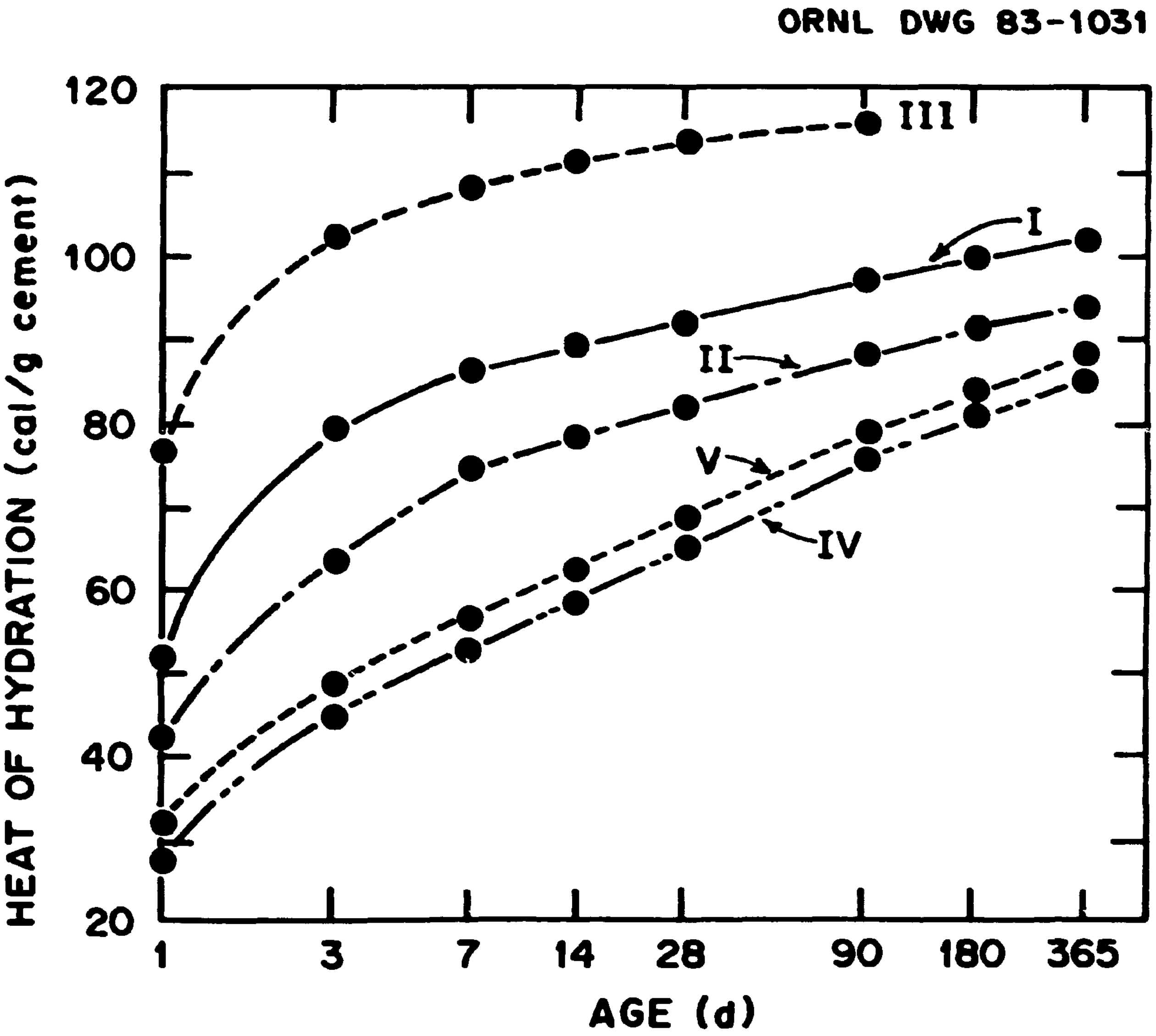

Fig. 3. Heat of hydration for various types of Portland Cement.

grout and differentiating:

$$H_G = 133.8\ (1 - x) \qquad 0 < t \le 24$$

$$H_G = (-3.38 + 0.014t + 6.84 \times 10^4 t^{-2})(1 - x) \qquad 24 < t \le 168$$

$$H_G = \frac{(1 - x)(459 - 47.7 \ln t)e^{\tau}}{t} \qquad 168 < t \le 8760$$

$$H_G = 0 \qquad t > 8760$$

where

$$\tau = 0.1525 \ln t - 7.92 \times 10^{-3} (\ln t)^2, \text{ and}$$

where

H_G = heat generation rate, Btu/(ft^3•h);

t = time, h;

x = weight percent waste.

A maximum value of 54 Btu/(ft^3•h) occurs within 24 h for grouts of the composition shown in Tables 3 and 4.

The heat generation rates due to the decay of radioactive materials in the grouts containing customer waste and double-shell slurry waste were obtained from the radionuclides listed in Tables 1 and 2. ORIGEN2,[11] a computer program designed to calculate the composition and characteristics of nuclear materials for nuclear fuel operations as a function of decay time, was used to calculate the heat generation rates due to decay in the grouts for up to 30 years. The following equations were derived from the results of the ORIGEN2 calculations:

$$H_{CD} = (a - bt + ct^2 - dt^3)\ x$$

where

$a = 1.35 \times 10^{-3}$
$b = 1.97 \times 10^{-8}$
$c = 1.05 \times 10^{-13}$
$d = 1.88 \times 10^{-19}$, and

$$H_{DD} = (0.227x)\, e^{(-2.6411 \times 10^{-6})t} .$$

where

H_{CD} = heat generation rate of customer waste,

H_{DD} = heat generation rate of double-shell slurry waste.

The initial heat loading is 8×10^{-4} Btu/(ft^3·h) for a grout containing 60 wt % customer waste and 0.132 Btu/(ft^3·h) for a grout containing 60 wt % double-shell slurry wastes.

The initial heat loading for single-shell solid waste varies greatly. If the total heat loading (decayed to 1995) for all tanks were evenly distributed among all the 75-ft-diameter tanks and if the average height of the waste were 10 ft, the initial heat generation rate would be 0.297 Btu/(ft^3·h) (ref. 3). Riley[1] reports an initial heat loading of 0.775 Btu/(ft^3·h) for 10 ft of waste in a million-gallon tank. Since Riley's figure represents a more conservative estimate, it was used for the base case; but this parameter was later varied between these two extremes. Since most of the heat is generated by strontium and cesium decay,[3] a half-life of 30 years was assumed. The base case equation for calculating the heat generated by the single-shell sludge is

$$H_{SD} = 0.775 e^{(-2.637 \times 10^{-6})t} .$$

where

H_{SD} = heat generation rate of single-shell slurry waste.

3. RESULTS

Transient heat transfer calculations were made for grout-filled trenches and for in situ disposal in single-shell tanks of grout containing double-shell slurry wastes using the assumptions and conditions described in Sect. 2. The results at these conditions were used as base cases since they are based on the best estimates of unsubstantiated parameters. Calculations were then made to show how sensitive the temperature profiles are to uncertain thermal properties and boundary conditions. Thermal conductivity of the wastes and soil, the adiabatic-boundary radius, boundary temperatures, wastes' specific heat, initial heat-generation rates, waste volumes, and trench dimensions were each varied, one at a time, to determine their individual effects on peak temperatures. In addition, the extreme conditions were combined to determine a worst case scenario for grout-filled trenches. The base case conditions and ranges for each variable are listed in Appendix B.

3.1 TRENCHES

The grout-filled trench was modeled with an initial heat loading that ranged from 8×10^{-4} Btu/(ft^3·h) for customer wastes to 0.132 Btu/(ft^3·h) for double-shell slurry wastes. Figure 4 shows the temperature profiles for the base case and for the extreme worst case, which is described later. The results indicate that the temperature peaks in less than 10 d and that the heat of hydration is the dominant factor at these low-waste heat loadings. The profiles are very similar, with each having a maximum temperature of 110°F under base conditions. This compares well with 108°F

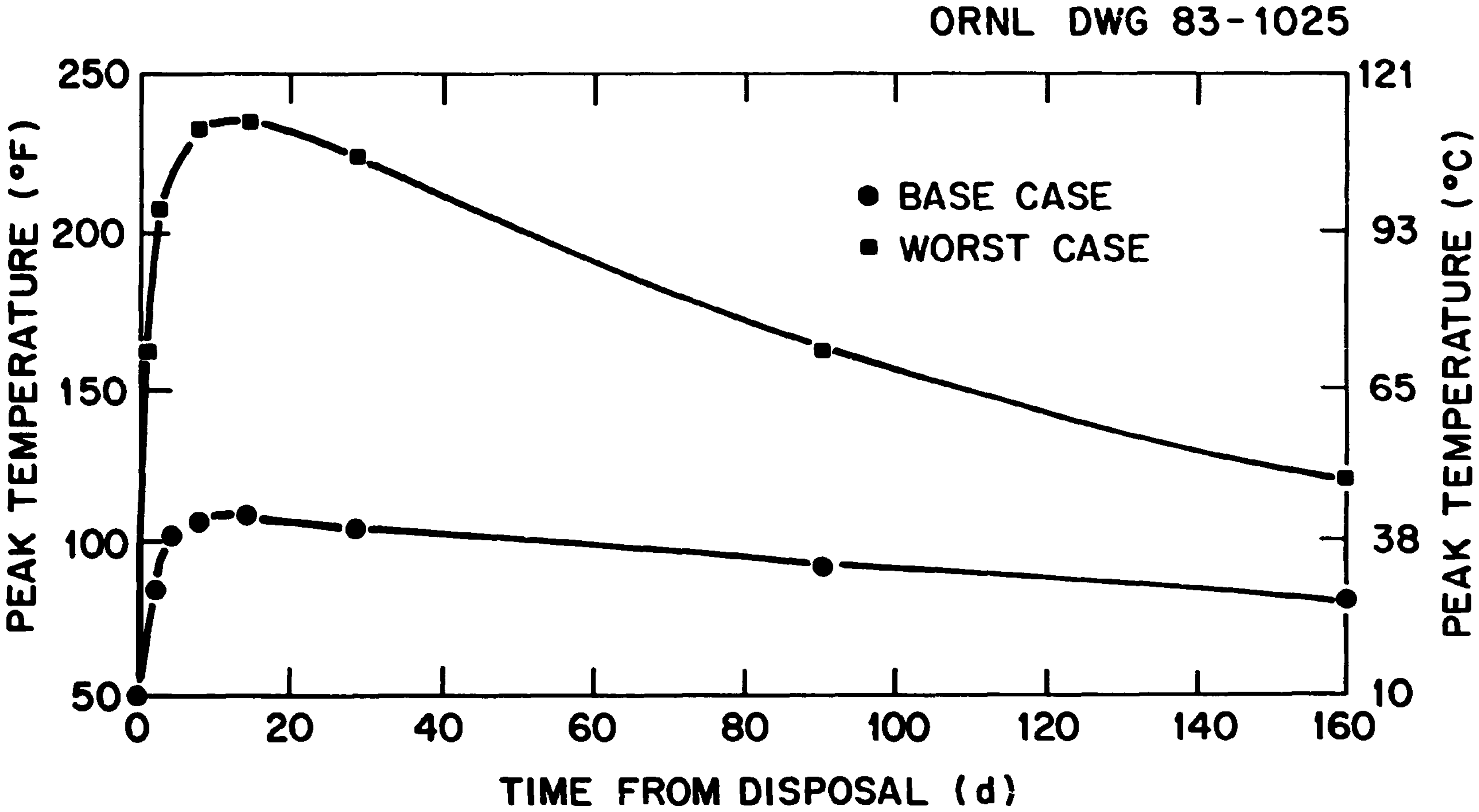

Fig. 4. Temperature profile for trench containing grouted waste.

for double-shell slurry waste calculated by Riley.[2] Even under extreme conditions, the maximum temperature never reaches the 250°F limit for curing grout. The different waste heat loadings have very little effect—after one year the double-shell slurry grout maximum temperature is ~15°F higher than the base case.

Very few input parameters significantly affect the peak temperatures or the time when they occur. In all cases, the peak temperatures were reached within 7—14 d. The effects of the specific heat and thermal conductivity of the grouts on temperature peaks are shown in Figs. 5 and 6. Because the peak temperatures are determined by the heat of hydration when the heat generation due to radioactive decay is low, increasing the waste loading decreases the amount of cement and, therefore, reduces the maximum temperature for these grouts (Fig. 7).

The average thermal conductivity of the Hanford soil in the SX Tank Farm area ranges from 0.1 to 1.11 Btu/(ft•h•°F) and has an average value of 0.25 (ref. 12). Varying the soil thermal conductivity between these extremes does not affect the center line temperature until a half year after disposal, well past the time the temperature peaks. Changing the air temperature from 50 to 70°F also has very little effect.

The base case assumes a 600 × 50 × 12 ft trench with a 150-ft center-to-center spacing (100 ft of soil between trenches) that acts as an isolated trench. Varying the trench dimensions and spacings changes the long-term heat transfer rate (>1 year) but does not significantly affect the peak grout temperature. The length of the trench was varied from 10 to 600 ft, the width from 10 to 100 ft, the height from 12 to 19 ft, and the width of the soil between trenches from 10 to 100 ft.

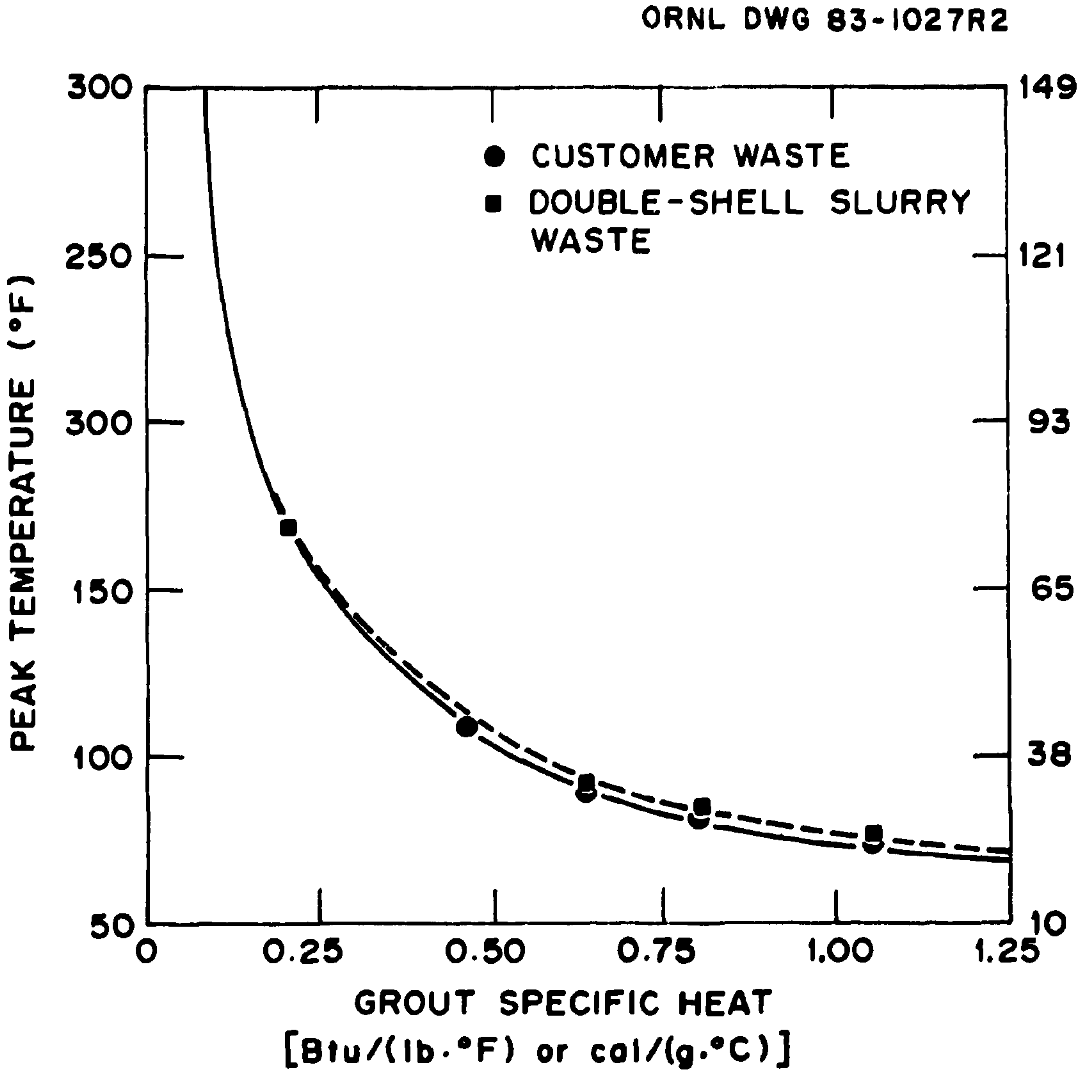

Fig. 5. Sensitivity of trench temperature to variations in heat capacity of the grout.

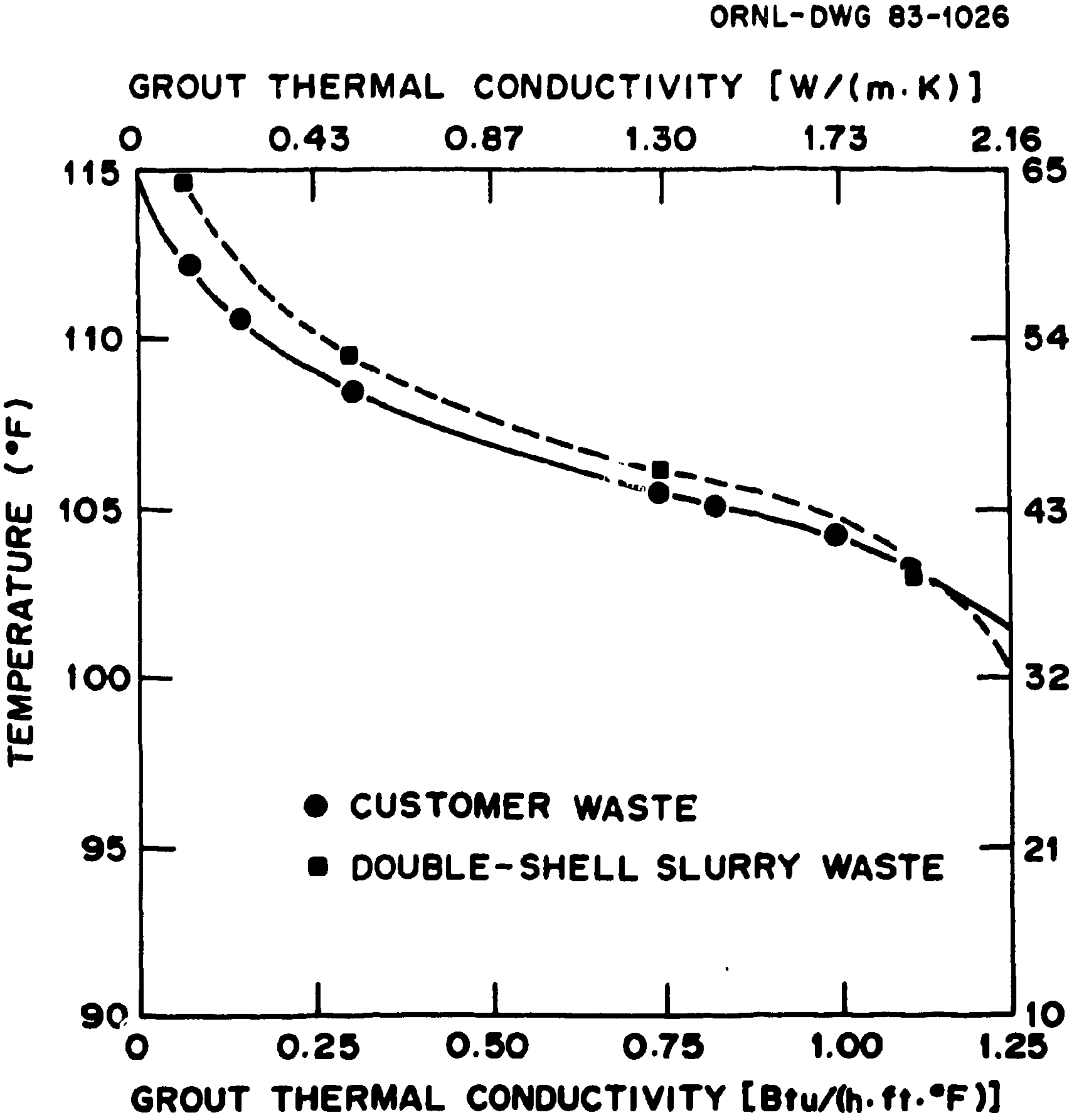

Fig. 6. Sensitivity of trench temperature to variations in thermal conductivity of the grout.

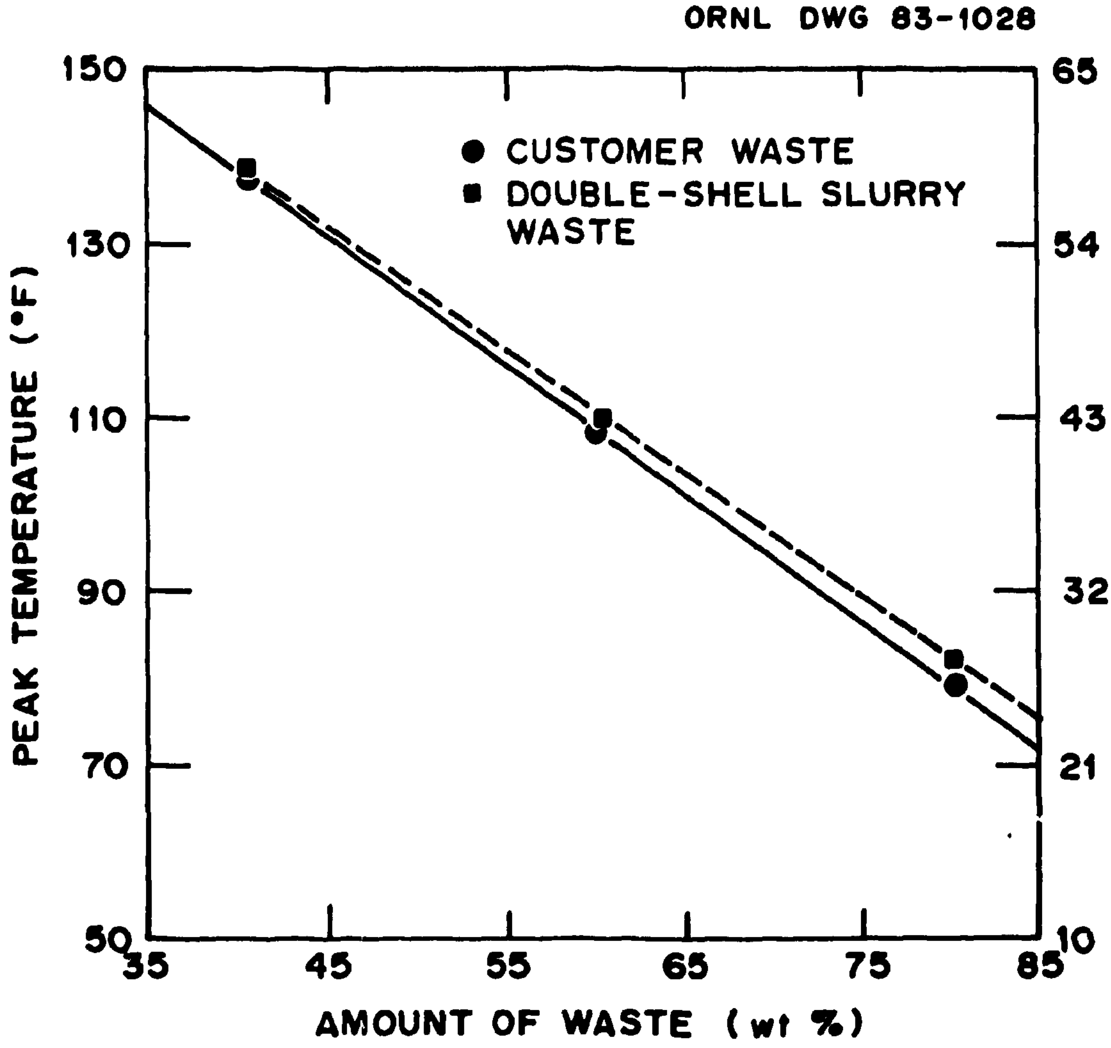

Fig. 7. Sensitivity of trench temperatures to variations in waste loading.

As mentioned previously, the extreme values for each of the parameters that significantly affect the maximum temperature were used to determine a worst case temperature profile. The results of calculations using a 0.15 Btu/(ft·h·°F) grout thermal conductivity, 0.2 Btu/(lb·°F) grout specific heat, and 40 wt % waste loading are shown in Fig. 4.

3.2 SINGLE-SHELL TANKS

The base case for this heat transfer model assumes very conservative conditions. It is based on a high initial heat loading for the single-shell waste [0.775 Btu/(ft^3·h)] with an average of 10 ft of waste in the tanks. The 1 ft of soil between the waste and the grout can be neglected for heat transfer considerations, and the grout is filled to within 1 ft of the top of the cylindrical portion of the tank. Neglecting variations in thermal parameters, this geometric model should give an extreme temperature profile as shown in Fig. 8. The temperatures of interest are the peak single-shell waste temperature at the tank centerline, the peak grout/fresh concrete temperature at the centerline, the peak concrete wall temperature (which occurs at the centerline at the base of the tank), and the concrete dome temperature at the centerline. A 250°F limit is placed on the grout and fresh concrete until the cement cures, and a 350°F limit is placed on all concrete and grout after curing.[1] As Fig. 8 indicates, the grout and concrete do not reach the 250°F range until well after curing is complete, but the grout and the tank walls exceed 350°F after 10 years. The single-shell waste and grout temperatures peak at ~20 years, and the tank wall peaks at ~30 years under these conditions.

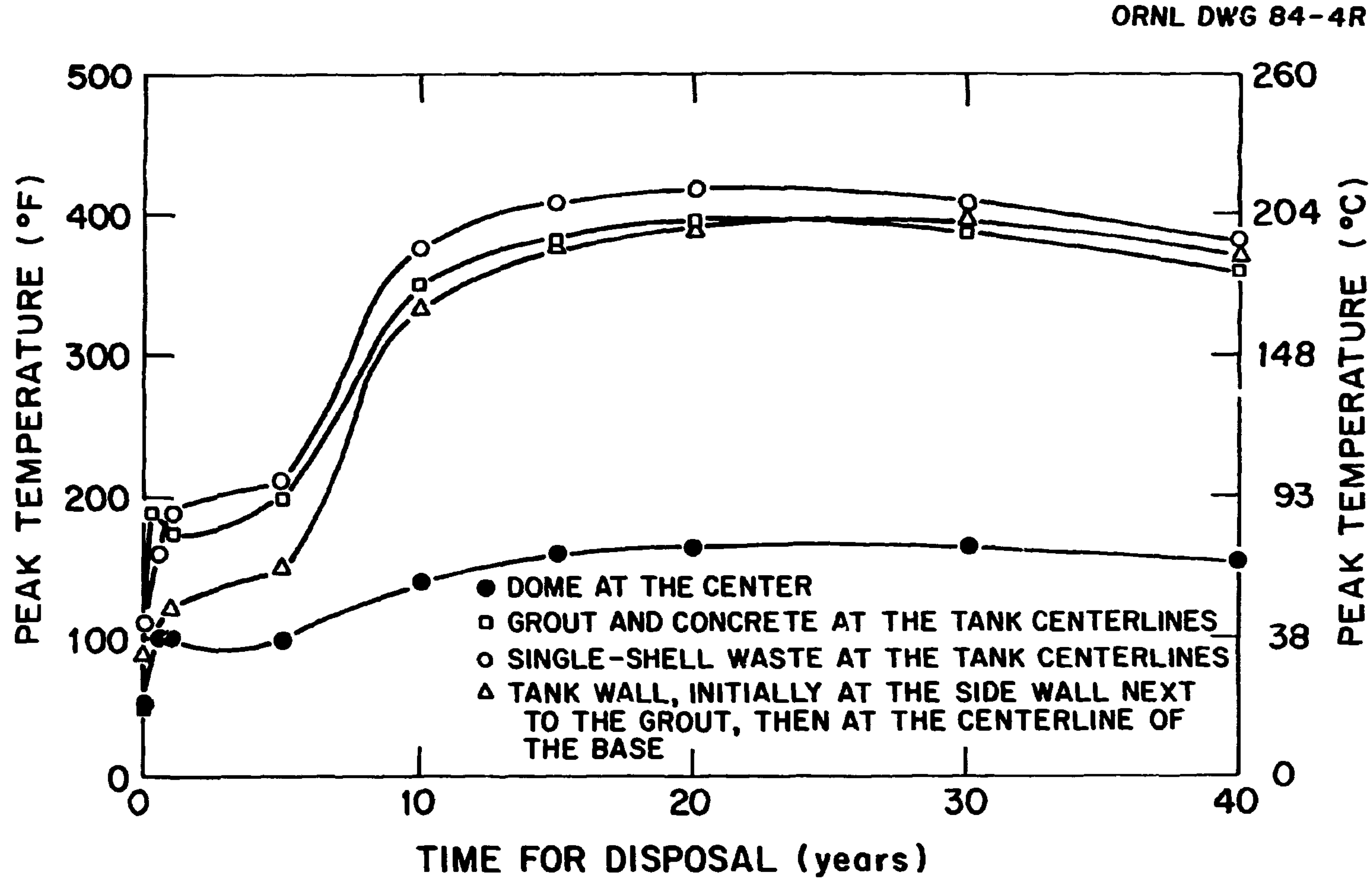

Fig. 8. Temperature profile for single-shell tank containing grouted double-shell slurry waste.

The heat of hydration that causes the initial rise in temperatures in Fig. 8 has much less effect in this model than in the previous one. The height and waste-heat loading of the single-shell waste have the largest effect on the peak temperatures (Fig. 9). When the initial heat loading is reduced to 0.3 Btu/(ft^3•h), the maximum grout and concrete temperatures will never reach the 350°F limit under base conditions.

Assuming the single-shell waste has an initial heat loading of 0.775 Btu/(ft^3•h) and a height of 10 ft, the effect of soil height, soil and waste thermal conductivity, waste specific heat, and adiabatic radius on the temperature profile is shown in Figs. 10—14. In all cases, the temperatures peak after 15—30 years. The peak tank wall temperatures always occur at the centerline at the base of the tank.

Increasing the soil layer between the single-shell waste and the grout can reduce the peak grout and tank wall temperatures to the 350°F limit. The soil thermal conductivity in and surrounding the tanks begins to affect the centerline temperatures after about 5 years and can significantly affect both the peak grout and the peak tank wall temperatures. The thermal conductivity and specific heat of the single-shell waste and grout were varied simultaneously and had much less effect on the peak temperatures. The adiabatic radius between tanks also affects the peak temperatures and could determine whether the concrete and grout reach the 350°F limit for large single-shell waste heat loadings and/or heights.

Varying the waste loading in the grout from 40 to 80 wt % changes the peak grout temperatures ~10 %. Increasing the waste loading initially decreases the peak grout temperature because it lowers the heat of

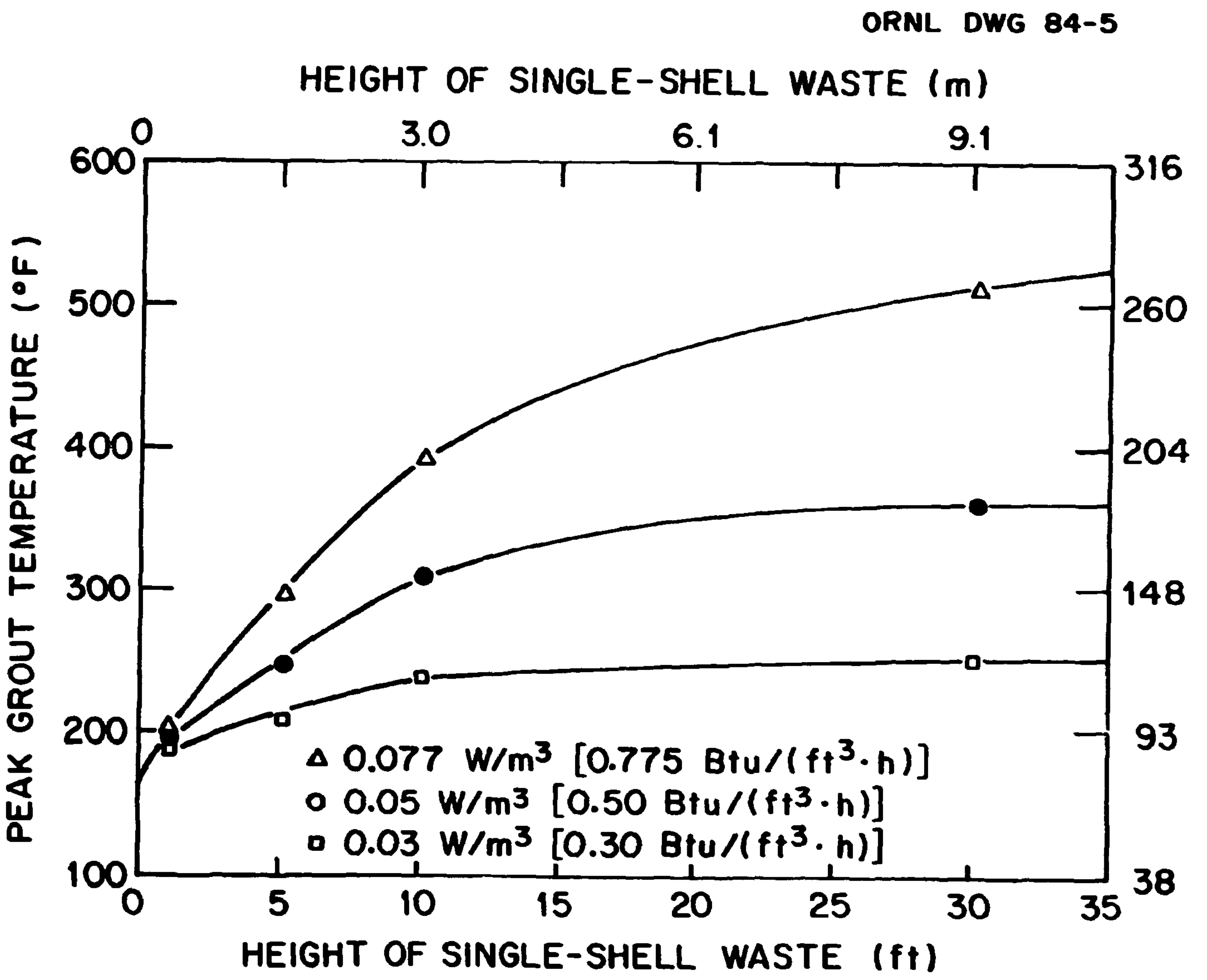

Fig. 9. Sensitivity of single-shell tank temperatures to variations in the height of single-shell waste heat generation.

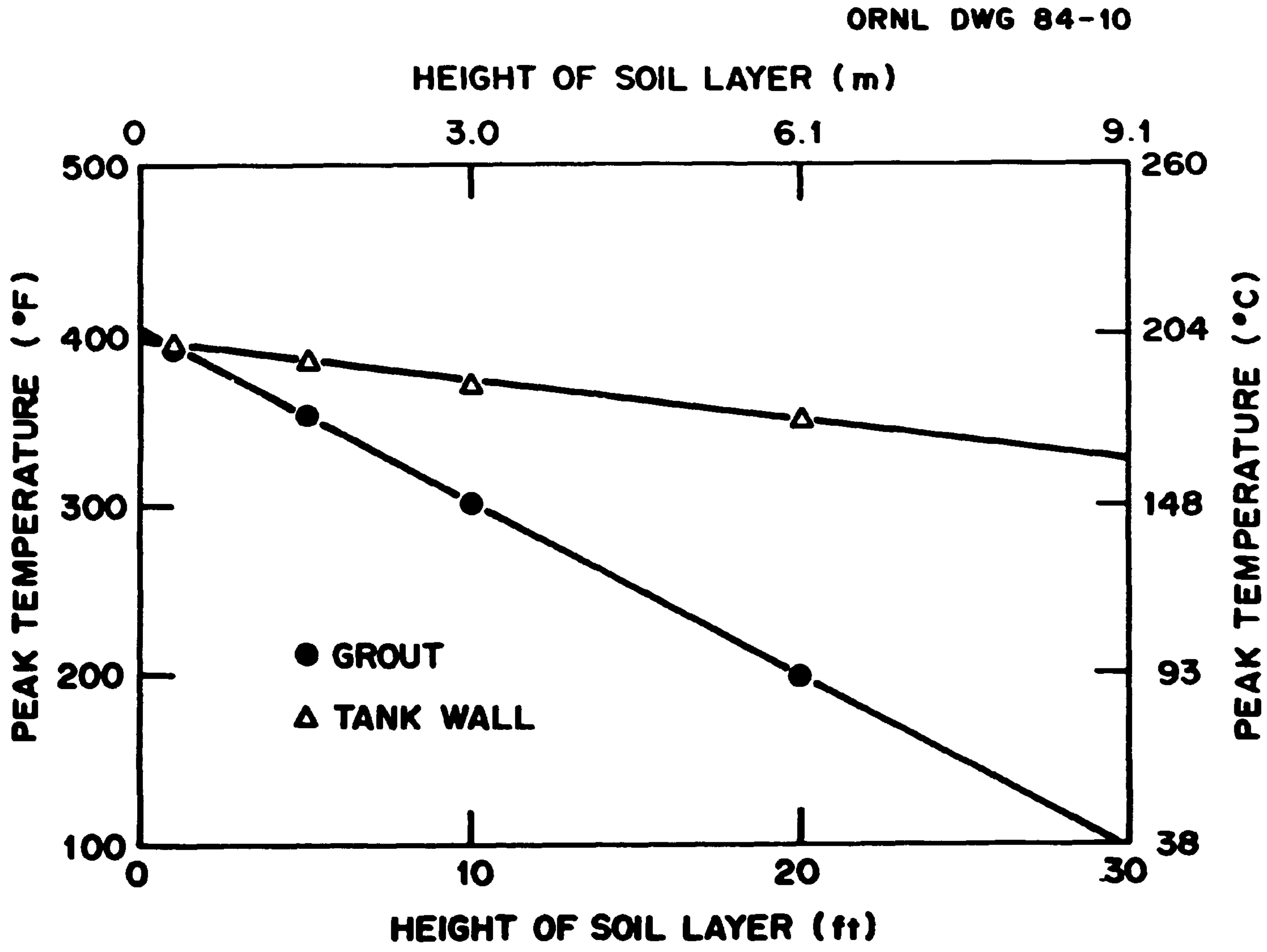

Fig. 10. Sensitivity of single-shell tank temperatures to variations in soil height.

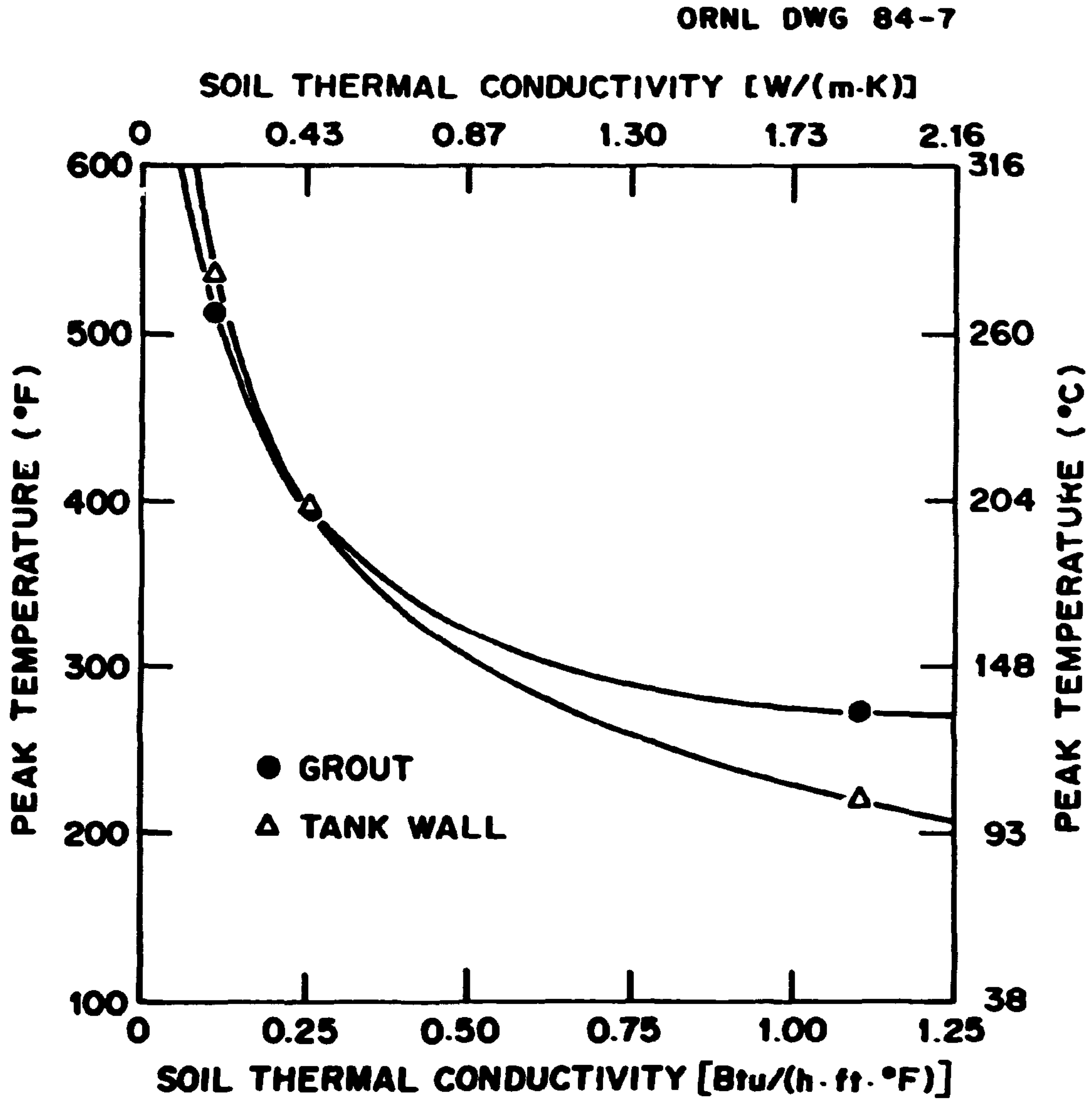

Fig. 11. Sensitivity of single-shell tank temperatures to variations in soil thermal conductivity.

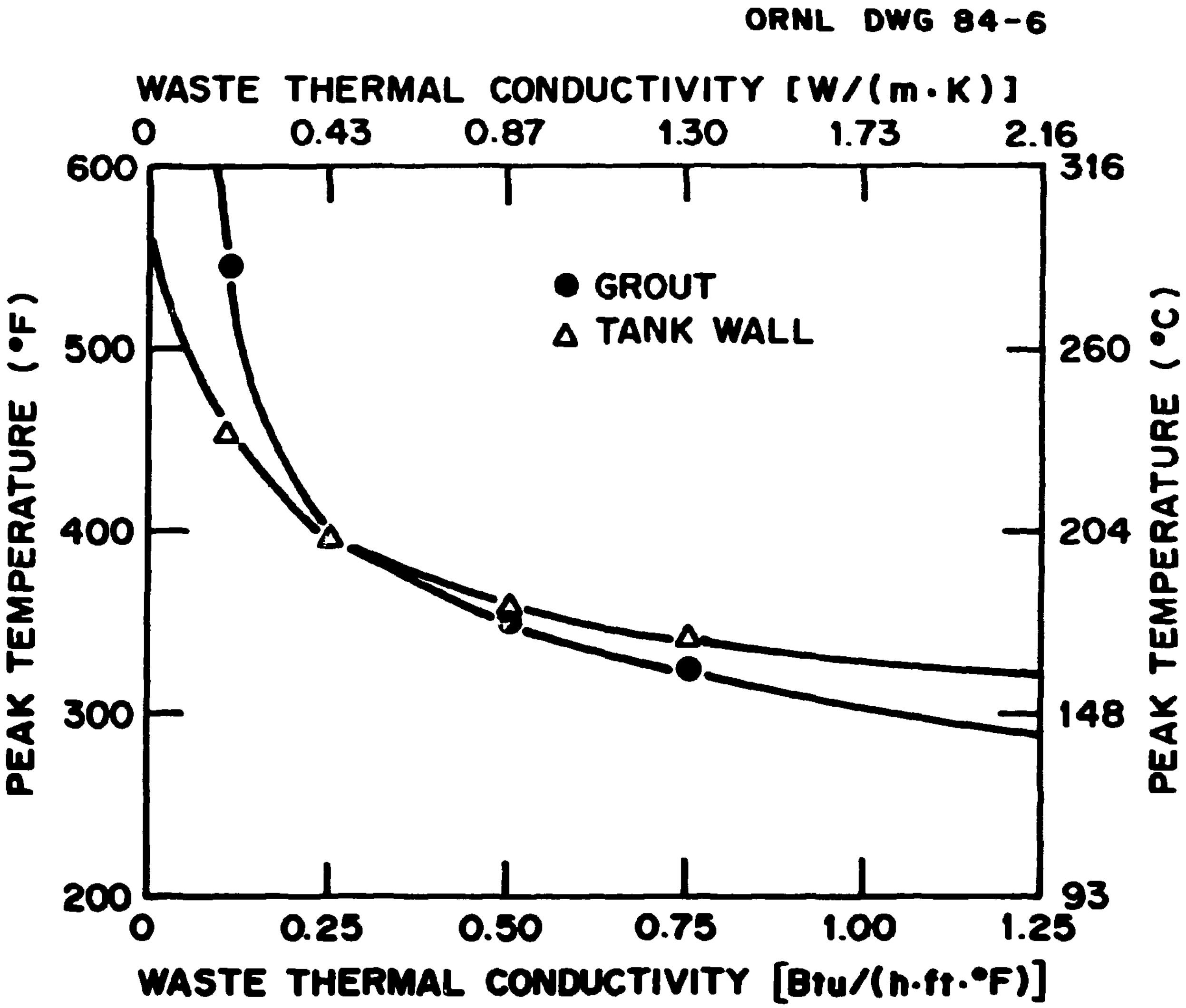

Fig. 12. Sensitivity of single-shell tank temperatures to variations in waste thermal conductivity.

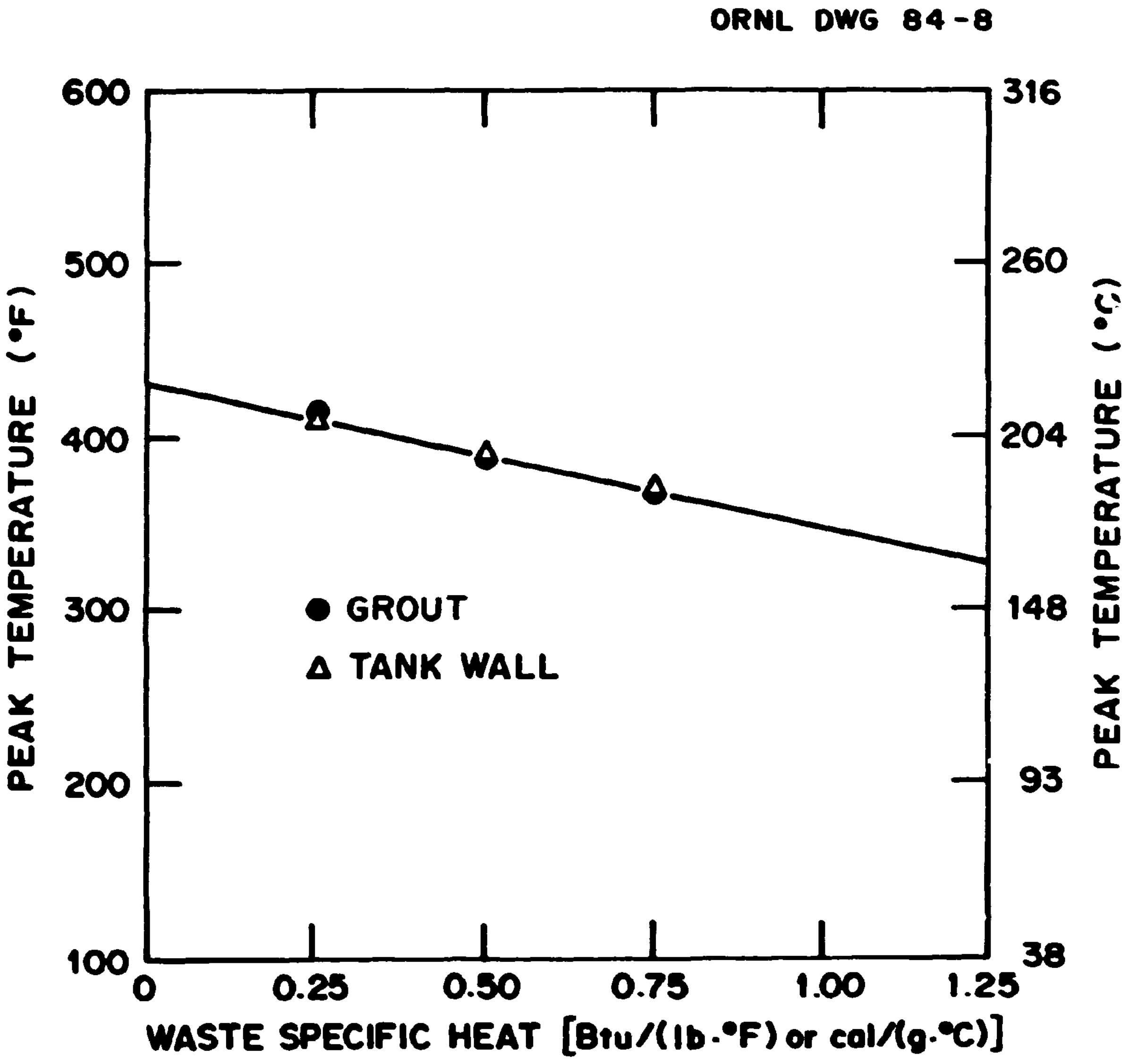

Fig. 13. Sensitivity of single-shell tank temperatures to variation in waste specific heat.

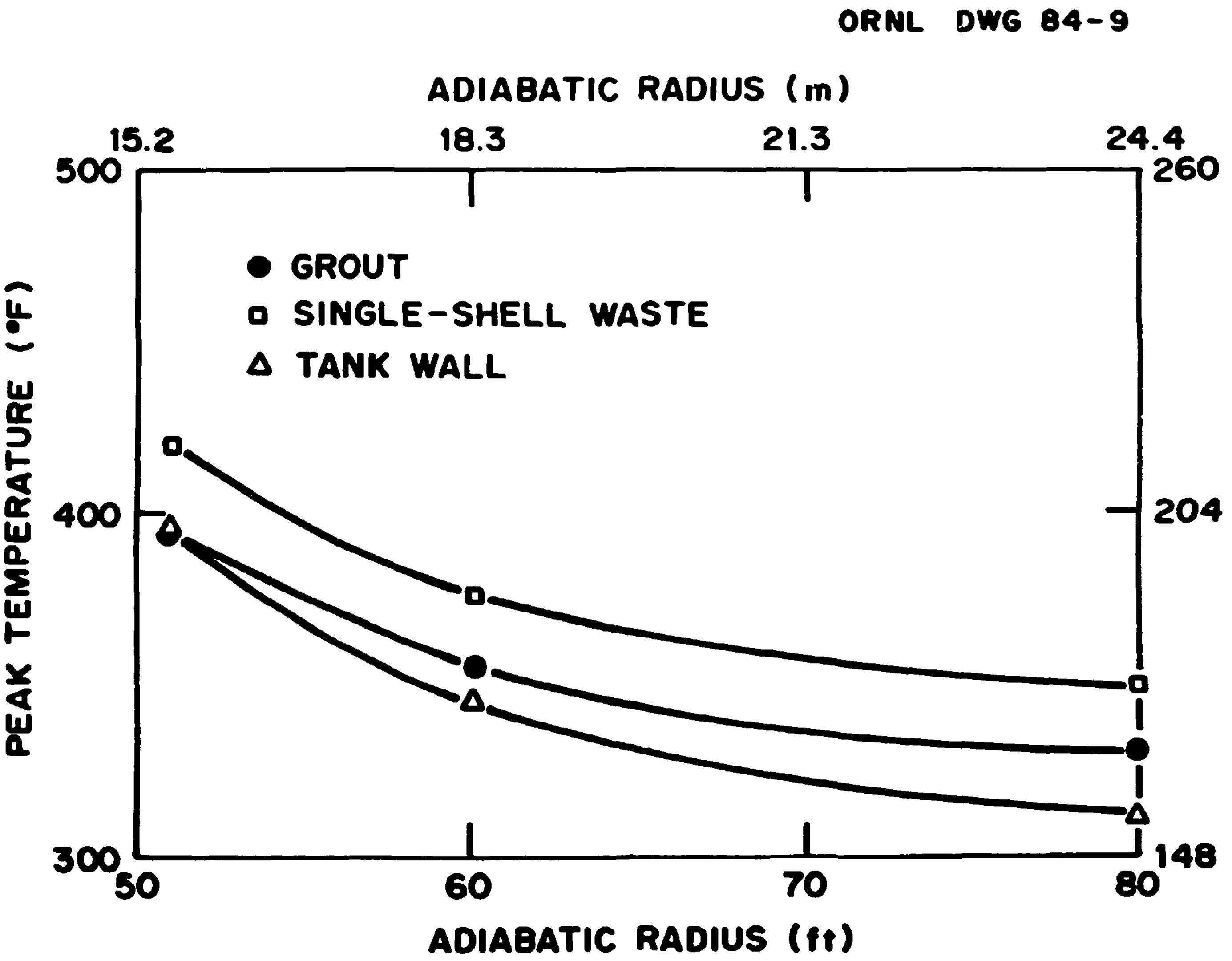

Fig. 14. Sensitivity of single-shell tank temperatures to variations in adiabatic radius.

hydration. Between 5 and 10 years after disposal, the influence of the increased decay heat causes the peak grout temperature to increase.

4. SUMMARY

Parametric heat transfer calculations were made for trenches and single-shell tanks containing grouted customer and double-shell slurry wastes to predict the maximum temperatures possible in the grouts and concrete structures during in situ disposal. Due to the variability and uncertainty of many of the parameters, calculations were made to determine the sensitivity of temperatures to certain thermal properties and boundary conditions. Transient calculations were made until the temperatures at points of interest reached their peak values with respect to time.

Models were made for the disposal of customer waste [initial heat loading of 8×10^{-4} Btu/(ft^3·h)] and double-shell slurry waste [initial heat loading of 0.13 Btu/(ft^3·h)] in earthen trenches. At these low heat loadings, the heat of hydration of the grout [initially 54 Btu/(ft^3·h)] dominates the heat transfer calculations. Using the base conditions, the grout temperature peaks at 110°F in less than 10 d after disposal for both waste types. The grout temperature never reaches the 250°F limit, even under the worst conditions. At these low waste heat loadings, decreasing the waste loadings increases peak temperature, primarily because the increased cement content increases the heat of hydration. The grout thermal conductivity and specific heat have no deleterious effect on peak temperatures until the values become less than those for the surrounding soil. If this unlikely combination occurs, the grout matrix offers the greatest resistance to heat transfer and acts as a self-insulating material.

The peak trench temperature can be controlled to a large degree by minimizing the cement content and maximizing the waste content of the grout. A main objective of the ORNL formulation studies is to optimize waste loadings while minimizing the waste disposal volume increases. An increased waste loading accomplishes all of these, since reducing the cement content significantly reduces increases in volume.

Using base case thermal properties, the trench dimensions and spacing did not significantly affect the peak temperatures, even though the model assumed a single massive grout pour. In all cases the bottom of the trench was at a depth of 20 ft. Increasing the height of waste-containing grout from 12 to 19 ft had no significant effect on peak temperatures. The overburden can be partially replaced by clean grout with no adverse effects on heat transfer. The non-effect of trench dimensions and spacing indicates that the construction and environmental release constraints, rather than thermal effects, should control these parameters for the ORNL preliminary reference grout composition.

A model was also developed for the disposal of grouted double-shell slurry waste in single-shell storage tanks. The system studied was a million-gallon tank that initially contained various amounts of single-shell waste sludge with varying heat loadings. The temperatures were limited to 250°F when the grout was curing and 350°F for concrete and cured grout. The grout does not reach the 250°F limit until well after the curing stage, but the grout and tank walls can exceed the 350°F limit if the tank contains more than 10 ft of single-shell waste that has a heat loading of 0.50 Btu/($ft^3 \cdot h$) or more, assuming the base conditions are correct. Placing soil between the layers of waste and grout can bring the temperatures within the limits. The soil thermal conductivity has a large effect on the heat transfer, while the waste thermal conductivity and specific heat, waste loading, and the adiabatic radius have much less effect.

Thus, the primary variable controlling the peak temperature for this disposal scenario is the heat generated by the single-shell tank waste presently in the tanks. The waste heat generation rate, on a volumetric basis, will determine the height of the waste that will limit the peak temperatures to acceptable levels. If detailed values are not available for the heat generation rates of the single-shell waste, conservative allowable waste heights must be chosen as indicated by Riley.[1] The layer of backfill material placed between the single-shell waste and the grout can act as insulation, shielding the grout from the heat effects of the single-shell waste until the heat generated by the curing grout has dissipated. Therefore, the peak grout temperature can be reduced to acceptable levels. The viability of this approach is beyond the scope of this report and needs to be addressed by Rockwell Hanford. Note that under the given conditions, the single-shell waste temperature will rise when any material is placed above it. The effects of temperature on tank waste is unknown to the authors.

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6. APPENDIXES

APPENDIX A.

PROCEDURES USED TO DETERMINE GROUT THERMAL PROPERTIES

This appendix describes the procedures used to determine grout thermal properties. The grout densities were physically determined at ORNL by the Cement and Concrete Applications Group using simulated wastes. The thermal conductivity and specific heat of the grouts were determined by the summation of the individual components multiplied by the percent composition for each.

The values of physical properties used in these calculations are given in Table A.1.

Table A.1. Physical properties of components used in calculations

Component	Thermal conductivity [Btu/(h·ft·°F)]	Specific heat [Btu/(lb·°F)]
Water (80°F)	0.352	1.0
Cement	0.172	0.186
Concrete	0.196	0.156
Clay	-	0.224
Silica	0.62	0.316
Soil	0.080	-

Source: R. H. Perry and C. H. Chilton, Chemical Engineers' Handbook, 5th ed., McGraw, 1973.

The double-shell slurry waste was diluted with water before processing. This diluted solution contained 52.39 wt % waste and 47.61 wt % water. The diluted waste properties are calculated below:

Thermal conductivity:

$(0.5239)(0.25) + (0.4761)(0.352) = 0.299$ Btu/(h·ft·°F)

Specific heat:

$(0.5239)(0.3) + (0.4761)(1.0) = 0.63$ Btu/(lb·°F)

The grout properties were calculated in the same manner using the composition listed in Table 4; the fly ash is assumed to have the properties of silica. A summary of the data is given in Table A.2.

Table A.2. Calculated properties of grouts containing double-shell slurry

Component	Wt fraction (%)	Thermal conductivity [Btu/(h•ft•°F)]	Specific heat [Btu/(lb•°F)]
Cement	16.05	0.172	0.186
Fly ash	16.05	0.62	0.316
Clay	9.60	0.080	0.224
Diluted waste	58.30	0.299	0.63
Grout	100.00	0.31	0.47

The properties of customer waste were calculated assuming that the waste contains 92 wt % water and 8 wt % solids that have the properties of soil. These properties are listed in Table A.3.

Table A.3. Calculated properties of grout containing customer waste

Component	Wt fraction (%)	Thermal conductivity [Btu/(h•ft•°F)]	Specific heat [Btu/(lb•°F)]
Cement	16.0	0.172	0.186
Fly ash	16.0	0.62	0.316
Clay	8.0	0.080	0.224
Waste solids	4.8	0.080	0.224
Water	55.2	0.352	1.0
Grout	100.0	0.33	0.66

Since the values for the double-shell slurry waste are based on better known data and are more conservative, the double-shell slurry thermal properties were also used for the base calculation for customer waste.

APPENDIX B

BASE CASE CONDITIONS AND RANGE OF VARIABLES

This appendix presents the assumed conditions for the base case. It also lists the ranges of variables addressed in this report.

Table B.1. Base case conditions and ranges of variables for earthen trenches

Parameter	Base value	Range
Trench width	50 ft	10–100 ft[a]
Trench length	600 ft	10–600 ft[a]
Trench spacing, edge to edge	100 ft	10–100 ft[a]
Height of overburden	8 ft	1–8 ft[a]
Height of grout	12 ft	12–19 ft[a]
Soil thermal conductivity	0.25 Btu/(h•ft•°F)	0.1–1.11 Btu/(h•ft•°F)(ref. 12)
Air temperature	50°F	50–70°F (ref. 1,2,3)
Grout thermal conductivity	0.3 Btu/(h•ft•°F)	0.0075–1.1 Btu/(h•ft•°F)[a]
Grout specific heat	0.43 Btu/(lb•°F)	0.0075–1.1 Btu/(lb•°F)[a]
Waste loading	60 wt %	40–80 wt % (ORNL extreme values)

[a] Estimated extremes

Table B.2. Base case conditions and ranges of variables for single-shell tanks

Parameter	Base Value	Range
Tank radius inside	37.5 ft	-
Tank height	43.85 ft	-
Single-shell waste depth	10 ft	1–30 ft
Backfill depth	1 ft	1–20 ft
Waste-grout depth	23.75 ft	3.75–23.75 ft
Clean grout depth to dome	1 ft	-
Soil thermal conductivity	0.25 Btu/(h•ft•°F)	0.11–1.11 Btu/(h•ft•°F)
Air temperature	70°F	-
Grout thermal conductivity	0.3 Btu/(h•ft•°F)	0.1–0.75 Btu/(h•ft•°F)
Grout specific heat	0.43 Btu/(lb•°F)	0.25–0.75 Btu/(lb•°F)
Waste loading	58 wt %	40–80 wt %
Adiabatic radius	51 ft	51–80 ft

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