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**HEAT TRANSFER FROM SOLIDIFIED WASTES
IN UNDERGROUND STORAGE TANKS**

W. E. WILLINGHAM and G. JANSEN, JR.

OCTOBER, 1966

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HEAT TRANSFER FROM SOLIDIFIED WASTES
IN UNDERGROUND STORAGE TANKS

By

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ABSTRACT

Steady state temperature distributions in and around buried radioactive waste storage tanks have been calculated for solidified cakes containing heat-generating fission products. The most important factors influencing the maximum cake and wall temperatures were the quantity of heat generated, the soil thermal conductivity, and the soil cover depth with the heat transfer conditions inside the tank of secondary importance.

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NOMENCLATURE

h_1	= convection heat transfer coefficient, top of cake-to-vapor, $1.5 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})$
h_2	= convection heat transfer coefficient, top of vapor space-to-soil, $1.5 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})$
h_{Q1}	= convection heat transfer coefficient, side of vapor space-to-soil, $1.5 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})$
h_A	= convection heat transfer coefficient, soil-to-air, $0.555 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F})$
k_c	= thermal conductivity of the cake, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
k_d	= thermal conductivity of the nonheat-generating layer of the cake below the heat-generating layer, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
k_g	= thermal conductivity of the heat-generating layer of the cake, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
k_m	= thermal conductivity of the concrete tank liner, $0.5 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
k_s	= thermal conductivity of the soil, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
k_t	= thermal conductivity of the nonheat-generating layer of the cake above the heat-generating layer, $\text{Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
k_v	= thermal conductivity of vapor, $200 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
ℓ_1	= soil cover depth, ft
ℓ_2	= height of tank vapor space, ft
$\ell_2 + \ell_c$	= tank height, ft
ℓ_3	= distance from bottom of tank to water table, ft
ℓ_c	= cake thickness, ft
ℓ_d	= thickness of the nonheat-generating layer of the cake below the heat-generating layer, ft
ℓ_g	= thickness of the heat-generating layer of the cake, ft

- Q = total heat generated in the cake, Btu/(hr), subscripts refer to parts of this flux
- r = tank radius, ft
- R = half the center-to-center tank spacing, ft
- S = volumetric heat generation rate, Btu/(hr)(ft³)
- T_A = atmospheric temperature, 70 °F
- T_{MAX} = maximum temperature in the cake, °F
- T_V = average temperature of the vapor space, °F
- T_W = water table temperature, 70 °F
- T_1 = maximum temperature at the top of the heat-generating layer of the cake, °F
- T_2 = maximum temperature at the bottom of the heat-generating layer of the cake, °F

All overall heat transfer coefficients are based on the tank horizontal cross-sectional area.

- U_D = overall heat transfer coefficient, bottom of heat-generating layer of the cake-to-the water table, Btu/(hr)(ft²)(°F)
- U_U = overall heat transfer coefficient, top of heat-generating layer of the cake to the atmosphere
- U_{Q1} = heat transfer coefficient, side of cake-to-atmosphere
- U_{Q2} = heat transfer coefficient, side of vapor space-to-atmosphere
- U_{Q3} = heat transfer coefficient, side of cake-to-water table
- U_{QU} = heat transfer coefficient, for linear flow from the top of the cake to the atmosphere
- U_{QD} = heat transfer coefficient, for linear flow from the bottom of the cake to the water table
- X_N = position of the null plane and maximum cake temperature, measured from the bottom of the heat-generating layer of the cake, ft

HEAT TRANSFER FROM SOLIDIFIED WASTES IN UNDERGROUND STORAGE TANKS

INTRODUCTION

One of the most important problems that arise in the underground storage of waste material containing radioactive fission products is the high temperature produced by poor heat dissipation through the surrounding soil. A thermal analysis of underground tank systems has been undertaken by Battelle-Northwest in support of in-tank waste solidification studies⁽¹⁾ conducted by Isochem Inc., as part of the Isochem Waste Management Program.

Solidification is proposed for bismuth phosphate wastes, coating wastes, and aged Redox and Purex wastes, which are presently stored in the underground tanks and which contain alkaline solutions with high concentrations of sodium salts. New wastes, after removal of most of the long lived, heat generating fission products Cs^{137} and Sr^{90} , would be stored for an interim period until the short lived fission products decay sufficiently to permit solidification.⁽²⁾

Previous studies have been concerned with the transient thermal histories involved in startup of tanks containing boiling solutions⁽³⁾ and evaluation of the combined thermal stresses and load stresses, which determine the amount of solution that can safely be held by a tank.⁽⁴⁾ A heat transfer analogue consisting of electrically conductive paper has been developed,⁽⁵⁾ and its application to steady state temperatures in boiling tanks has been discussed.⁽⁶⁾ Temperatures in tanks which have lost their liquid cover have been calculated, and heat transfer in leaks from buried tanks has been analyzed.⁽⁷⁾

Primarily, this work provides methods for predicting the temperature distributions to be expected in an underground tank system. This analysis deals only with steady state conditions and with idealized materials having thermal properties independent of

position and temperature. Because of this the results must be regarded only as a reference system with which to compare analyses of real cases and not as a definitive description of the true thermal characteristics of operational waste tank farms.

Parts of this work have been previously reported in quarterly reports^(8,9,10) and at the Richland waste symposium in February 1966.⁽¹¹⁾

SUMMARY

Steady state temperature distributions in and around buried waste storage tanks containing solidified cakes have been related to fission product heat generation rates for use in the Isochem In-Tank Waste Solidification Program. The maximum cake and concrete wall temperatures were calculated as a function of soil and cake thermal conductivities, cake thickness, heat generation rate, and soil cover depth by an iterative computer program. Steady state temperature gradients across the concrete tank wall were estimated for a typical system.

The calculations were made for a 75 ft diam tank in a tank farm with 120 ft center-to-center spacing and with heat losses by convection to the atmosphere and to a water table at a depth of 202 ft. For this system, about 85% of the generated heat flows to the atmosphere and the remainder to the water table. About 53% of the heat flowing to the atmosphere passes through the soil layer directly above the tank. If the total heat generation rate from fission products is assumed constant, variations in the cake thickness have only a small effect on the temperatures in the system. Because most of the resistance to heat flow is in the soil, the thermal conductivity and the depth of the soil above the tank strongly affect the maximum temperatures. The cake thermal conductivity is of secondary importance, and the convective heat transfer coefficients and the tank height have almost no effect on the temperatures. In one example, increasing the tank spacing

from 120 to 600 ft lowers the maximum cake temperature only slightly, from 408 to 332 °F. Stratification of the heat-generating fission products has little effect on the maximum cake temperature. The calculated temperature gradients in the concrete wall for a maximum cake temperature of 350 °F are less than 10 °F per foot of wall thickness.

An approximate model which subdivides the heat flow into five distinct paths was developed. It calculates only the temperatures along the tank axis in contrast to the iterative program, which calculates complete temperature maps throughout the system. The model includes all the independent variables used in the more complex iterative computer program, and the calculated maximum temperatures agree within 5% for the range of investigation. The model can be used to vary many parameters rapidly and to extrapolate from experimental data to other conditions inside the tank.

Generalized correlations for the effect of tank size, height and spacing, soil cover depth, water table depth, and thermal properties of the system are presented. Six example problems are given to aid in calculating maximum temperatures from given information.

HANFORD WASTE STORAGE TANKS

The quantity of heat-generating fission products that can be stored in an underground tank is limited by the temperatures achieved in the system. The temperature of the solidified waste should remain below its melting point to prevent volatilization of fission products. To maintain structural integrity, the temperature of the tank wall should not exceed the operating limits of the concrete shell. The thermal gradients in the tank wall should not be so high that thermal stresses cause concrete failure.

At the present time the melting point of the actual solid waste is not known. Although it is dependent upon the composition within a particular tank, it is not expected to exceed 400 °F. The spalling temperature of the concrete was assumed to be 320 °F, the temperature at which it begins to lose its water of hydration.⁽¹²⁾

Several difficulties arise in attempting to describe heat transfer in an underground tank system containing solidified wastes. Inside the tank the heat-generating fission products are not homogeneously distributed, the thermal properties of the solid are not uniform or known accurately, and the heat generation rate varies with time as the fission products decay. Outside the tank, the soil properties are not uniform because of loose backfill near and above the tank, unpredictable variations in moisture content, and an effective soil thermal conductivity which is a strong function of temperature due to heat transfer by moisture recycle. Since the soil is a good insulator, long periods of time are required to establish thermal equilibrium within the soil.

With the above points in mind, we shall limit the discussion to an idealized treatment of the type of waste storage tank that exists at Hanford. The maximum steady-state temperatures to be expected within the system will be calculated for various conditions.

The system considered is

- A steel tank with a concrete shell
 - 75 ft diam
 - 36 ft high
 - Ellipsoidal roof
 - 11 ft nominal soil cover above the tank closure
 - 120 ft center-to-center spacing.

The factors considered are

- Thermal conductivity of the soil
- Thermal conductivity of the solid waste
- Heat generation rate
- Film coefficients between the cake and vapor, vapor and tank, and the ground surface and the air
- Thickness of soil cover above the tank
- Thickness of the solidified cake
- Sink temperatures (air and water table)
- Heat transfer only by convection and conduction.

COMPUTER PROGRAM FOR ITERATIVE CALCULATIONS

To study successfully all the factors involved, it was necessary to make use of the IBM-7090 and Univac 1107 digital computers available at Hanford.

The program used is a modified version of Program 001 "Equilibrium Temperatures in a Generalized Heat Transfer System" which is listed in the FORTRAN Library.⁽¹³⁾

The system to be studied is divided into a maximum of 600 sections, or nodes, not necessarily uniform in size; and these may be numbered either horizontally or vertically. The area, volume, and location of the centroid of each node is required for the calculation. After assuming an initial temperature distribution throughout the system, the program starts at the lowest number node and proceeds through an iterative type calculation for the total number of nodes specified. The iterative calculation is based on the Gauss-Seidel method and is a step-by-step process. No discussion of the method will be given as it is readily available in various texts.^(14,15,16)

The program considers the heat generation in a finite cylinder with fixed boundaries and a fixed heat generation rate; the buildup to or decay from this value is not considered.

After all new temperatures are calculated, a heat balance is made to compare the heat leaving the system with the heat being generated. If this balance does not check within preset limits, the calculation is repeated until either the time limit on the program is exceeded or the heat balance is acceptable.

When the calculation is complete, the results are printed as shown for a typical case in Appendix A, in which is also shown a brief flow diagram of the computer program, and a list of the input data.

The following parameters were used in the calculations:

Cake thickness, ft	4 to 24
Soil thickness, ft	7, 11
Heat generation rate,	
Btu/hr	10,000 to 50,000
Btu/(hr)(ft ³)	0.071 to 2.83
Thermal conductivity of the soil,	
Btu/(hr)(ft ²)(°F/ft)	0.15 to 0.65
Effective thermal conductivity of the vapor,	
Btu/(hr)(ft ²)(°F/ft)	200
Film coefficients,	
Btu/(hr)(ft ²)(°F)	0.001 to 6.0

After several trial cases were processed on the computer, it was found that the film coefficients had very little effect upon the temperature unless they were very small; these were held constant at reasonable values throughout the calculations.

Boundary conditions assumed for the system are (1) no radial heat flow beyond a 60 ft radius, which approximates the existence of an infinite array of identical tanks in a tank farm with 120 ft center-to-center spacing; (2) a water table at 202 ft depth which serves as an infinite heat sink at 70 °F; and (3) convection to

the air at ground level (11 feet above the top of the tank). A schematic diagram of a tank is shown in Figure 1. The concrete shell is assumed to have the same thermal properties as the soil for the iterative calculations.

FIGURE 1. Schematic Diagram of an Underground Waste Storage Tank.

TEMPERATURE DISTRIBUTION IN THE SYSTEM

The temperature fields for normal soil [$k = 0.33 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$] and for dry soil [$k = 0.15 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$] are shown in Figures 2 and 3. The maximum temperature in the tank wall, occurring at the center of the bottom of the tank, is 339°F and 559°F for normal soil and dry soil, respectively. The maximum cake temperature occurs near the bottom of the cake and is 352°F and 562°F , only slightly higher than the wall temperature. Overall energy balances

show that 84.2% and 85.4% of the heat flows through the soil to the atmosphere for Figures 2 and 3, respectively. Of the heat going to the atmosphere 52.0% and 52.9% passes through the soil directly above the tank.

In Figure 4 the temperature profile is presented for a horizontal plane passing through a 16 ft cake at the point of maximum temperature. The cake is generating a total of 35,300 Btu/hr and reaches a maximum of ~ 560 °F at the centerline. At the tank wall (37.5 ft away from the centerline), the temperature is still 500 °F and is 410 °F at the 60 ft insulated radius. Figure 5 shows a vertical temperature profile through the same cake as shown in Figure 4, along the centerline of the tank.

EFFECT OF CAKE THICKNESS

In Figure 6 the maximum cake temperature is shown as a function of the volumetric heat generation rate with cake thickness as a parameter. The temperature increases linearly with volumetric heat generation rate and increases with cake thickness because the total heat generation rate rises. Using 320 °F at the tank surface as a limit, the quantity of heat-generating material that can be stored drops very rapidly as the cake thickness increases.

Figure 7 contains the same information as in Figure 6 but total heat generation is used as the parameter. The effect of cake thickness on maximum temperature is shown to be small when the total heat generation rate (i.e., the quantity of fission products in the tank) is held constant.

EFFECT OF SOIL DEPTH

The effect of soil cover depth is shown in Figure 8. The temperature is decreased only 14.9% by removing 4 ft of the 11 ft dry soil cover, when $k_s = 0.15$ Btu/(hr)(ft²)(°F/ft), $k_c = 0.33$ Btu/(hr)(ft²)(°F/ft) and $S = 0.4$ Btu/(hr)(ft³).

FIGURE 2. Temperatures Around an Underground Waste Storage Tank Containing a Solid Cake. Soil Thermal Conductivity = $0.33 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$.

FIGURE 3. Temperatures Around an Underground Waste Storage Tank Containing a Solid Cake. Soil Thermal Conductivity = $0.15 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$.

FIGURE 4. *Temperature Profile in the Horizontal Plane of Maximum Temperature*

FIGURE 5. *Temperature Profile in the Vertical Plane Along the Axis of the Tank*

FIGURE 6. Maximum Temperature in Buried Storage Tanks, Effect of Volumetric Heat Generation Rate

FIGURE 7. Heat Dissipation from Buried Radioactive Waste Storage Tanks (Effect of Cake Thickness)

However, this might be enough to allow the tank to remain in service without exceeding the limits. One factor which must be taken into consideration before removing the soil is the loss of radiation protection. It may be necessary to leave the soil in place in order to have sufficient protection.

FIGURE 8. Maximum Temperature in Buried Waste Storage Tanks (Effect of Soil Cover Depth)

EFFECT OF THERMAL CONDUCTIVITY

An overall picture of the effect of thermal conductivity and total heat generation rate is shown in Figure 9. Although this is an unusual way of plotting the data, a great deal of information is presented in the figure.

FIGURE 9. Maximum Temperature in Buried Waste Storage Tanks
(Effect of Thermal Conductivity and Heat Generation)

Planes of constant soil and cake thermal conductivity along with curved surfaces of constant total heat generation are plotted against maximum cake temperature. Using $k_c = 0.33$ Btu/(hr)(ft²)(°F/ft) as an example and a heat generation rate of 60,000 Btu/hr, one may obtain the change in maximum temperature over the range of k_s values from 0.15 Btu/(hr)(ft²)(°F/ft) [dry soil] to 0.65 Btu/(hr)(ft²)(°F/ft) [wet soil]. The temperature is 905 °F for $k_s = 0.15$ then drops to 550 °F for $k_s = 0.33$ and finally to 380 °F for $k_s = 0.65$. This shows the very important effect of soil thermal conductivity on the system.

When the cake thermal conductivity, k_c , is varied from 0.33 to 0.65 to 1.20 Btu/(hr)(ft²)(°F/ft) and k_s is held constant at 0.15 Btu/(hr)(ft²)(°F/ft), a change in temperature

from 905 to 780 to 750 °F is obtained. This change is appreciably smaller than that brought about by a variation in soil thermal conductivity.

The presented data is only for the case of a 16 ft cake with an 11 ft soil cover. Data for other geometries could be presented in the same manner.

Another way of correlating the temperatures is shown in Figure 10. Although too many variables are involved to make useful dimensionless correlations including all parameters, a limited dimensional correlation of the form

$$\frac{k_s}{S}(T_{MAX} - T_A) = \phi\left(\frac{k_c}{k_s}, l_c\right) \quad (1)$$

FIGURE 10. Correlation of Maximum Temperature with Thermal Conductivity

is successful in presenting the effects of cake and soil thermal conductivities, cake thickness, and heat generation rate. As in Figure 9, the maximum temperature is strongly dependent on the soil thermal conductivity because the soil is a good insulator and is only a weak function of the cake thermal conductivity.

APPROXIMATE MODEL

DEVELOPMENT OF THE MODEL

Since the iterative technique proved to be difficult to adjust for changes in system geometry and consumed large amounts of computer time because of its complexity, an approximate model was developed to permit easier interpolation and variation of less important parameters. A sketch of the model is shown in Figure 11. The model is intended to calculate temperatures only along the axis of the tank and not a temperature distribution throughout the system as the iterative approach does.

A horizontal plane of maximum temperature across which no heat flows can be drawn through the heat-generating cake. All the heat is assumed to flow vertically through the cake so that a parabolic vertical temperature profile is present within the cake. Effective heat transfer coefficients for heat flow from the cake to the water table and to the atmosphere, are defined as follows:

U_U = the overall heat transfer coefficient for heat transfer from the top of the cake to the air, based on the cross sectional area of the cylindrical tank, $\text{Btu}/(\text{hr})(^\circ\text{F})(\text{ft}^2)$.

U_D = the overall heat transfer coefficient for heat transfer from the bottom of the cake to the water table, based on the cross sectional area of the cylindrical tank, $\text{Btu}/(\text{hr})(^\circ\text{F})(\text{ft}^2)$.

FIGURE 11. *Approximate Model for Heat Flow in a Waste Tank Containing Solidified Wastes*

The heat transfer coefficients are functions of the following variables:

$$U_U = U_{Q_1} + U_{Q_2} + U_{Q_U}$$

$$= \phi(k_c, k_s, k_v, h_1, h_2, h_A, h_{Q_1}, l_1, l_2, l_c, R, r) \quad (1)$$

$$U_D = U_{Q_3} + U_{Q_D} = \phi(k_s, R, r, l_3) \quad (2)$$

Derivations of the exact form of Equations (1) and (2) are given in Appendix B. A computer program for rapid calculation of the maximum temperatures is given in Appendix C. With the assumption that the water table temperature is equal to that of the air, the maximum temperature at the bottom of the cake is given by:

$$T_2 - T_A = \frac{S \ell_c (1 + \frac{U_U \ell_c}{2k_c})}{U_U + U_D (1 + \frac{\ell_c U_U}{k_c})} \quad (3)$$

COMPARISON OF THE MODEL WITH ITERATIVE RESULTS

The correlation of maximum cake temperature with thermal conductivity was shown in Figure 10. The maximum temperature at the bottom of the tank next to the cake, which is slightly lower than the maximum cake temperature, may also be correlated in the same way. A comparison of the prediction of the approximate model with the results of the iterative calculation is made for the maximum tank bottom temperature in Figure 12. The greatest deviation is in the region of low cake thermal conductivity, which indicates that the model is not as good at predicting heat flow through the cake as it is for the soil. The high temperature prediction indicates that the assumed resistance to flow through the cake is too high. This seems to be consistent since the assumption of no heat losses out the side of the cake used in establishing the vertical temperature gradient through the cake would result in too high a resistance to flow in the cake. A statistical analysis of the difference between the results of the approximate model and the iterative calculations is given in Table I.

STRATIFICATION OF HEAT-GENERATING FISSION PRODUCTS

The effect of stratification of the heat-generating fission products can be predicted by the approximate model, as shown in the derivation in Appendix B. In Figure 13, for a 16 ft cake, the maximum temperature at the bottom of the heat-generating layer is shown as a function of the fraction of the total cake occupied by the heat-generating layer with the total heat generation rate held constant at 70,700 Btu/hr. Stratification might be present if the tank is filled intermittently with different age solutions or if precipitation of fission products occurred only during one stage of the solidification process. Localization to the top of the cake

FIGURE 12. Comparison of Approximate Model with Iterative Calculations

TABLE I. Temperature at the Bottom of a Waste Storage Tank
Summary of Comparison: Approximate Equation versus Iterative Method

The Iterative Method is Assumed Correct in these Comparisons, and the Errors are Calculated for the Temperature Rise Above Ambient.

Cake Thickness, ft	Number of Cases Iterative Method(a)	Number of Cases Approximate Equation	Bias of The Mean %	Max. Bias %	Standard Dev. from Iterative Case %
4	9	5	-3.1	-7.4	4.95
8	14	10	-1.4	-4.3	2.33
16	14	11	-0.9	+7.7	3.59
24	12	9	+4.6	+12.8	7.39
Total	49	35	+0.6	-7.4 < x < 12.8	4.8

(a) Includes Duplicates with Differing Heat Generation Rates which were Averaged After Converting to the form $(T_2 - T_W)/S$.

FIGURE 13. *Effect of Stratification of Fission Products on the Maximum Cake Temperature*

actually lowers the temperature, while stratification to the bottom of the cake produces a small temperature increase. The principal reason for the temperature change when heat sources are concentrated into layers is the difference in path length through the cake from the heat generation zone to the atmosphere. This is in contrast to localization of fission products toward a small spherical volume, for which the temperature becomes very high because the area for heat flow from the sphere is also reduced as the volume is decreased.

TEMPERATURE GRADIENTS IN THE CONCRETE LINER

The steady-state temperature gradients across the concrete liner for various surfaces of the tank can be estimated from the heat fluxes across the surfaces. Comparison of the approximate calculations with the results of the iterative technique shows that the best estimate of the gradient through the liner at the bottom of the tank is made by assuming that all the heat which reaches the water table flows directly through the bottom of the tank. A comparison of the temperature gradients from the approximate equation and from the iterative method is given in Table II. The approximate gradients are in good agreement with the iterative method only for the concrete at the bottom and top of the tank. Much larger temperature gradients would be expected to occur during the transient heating period before steady-state is reached.

USE OF THE APPROXIMATE MODEL

For a particular tank configuration, the conditions inside the tank have little effect on the overall external heat transfer coefficients, because the major resistance to heat flow is in the soil. The overall heat transfer coefficients U_U and U_D may be estimated in any one of three ways: (1) measurement of the top and bottom cake temperatures and the heat generation rate in an existing system, (2) calculation of the top and bottom cake temperatures by the iterative technique, or (3) direct estimation of the heat transfer coefficients by calculating the heat transfer coefficients U_{Q_1} , U_{Q_2} , U_{Q_3} , U_{Q_U} , and U_{Q_D} for each flow path from the thermal properties of the system. Methods (1) and (2) involve the use of Equation (3) and the relationship between the top and bottom temperatures given in Equation (5) of Appendix B.

TABLE II. *Temperature Gradients in Concrete Liner*

	Approximate Formula	Gradient, °F/ft of Concrete Thickness	
		Approximate	Iterative Method
1. Through the bottom of the tank	$\frac{SX_N}{k_m}$	2.75	2.86
2. Through the side of the tank below the null plane	$\frac{Sr}{2k_m} \cdot \frac{U_{Q_3}}{U_D}$	1.06	3.5
3. Through the side of the tank next to the cake above the null plane	$\frac{Sr}{2k_m} \cdot \frac{U_{Q_2}}{U_U}$	0.25	0.73 to 3.93
4. Through the side of the tank next to the vapor space	$\frac{Sr}{2k_m} \cdot \frac{l_2}{l_c - X_N} \cdot \frac{U_{Q_1}}{U_U}$	0.66	0.18 to 3.2
5. Through the top of the tank	$\frac{S(l_c - X_N)}{k_m} \cdot \frac{U_{Q_U}}{U_U}$	8.4	6.3

Comments

Soil thermal conductivity, $k_s = 0.33 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
 Cake Thermal conductivity, $k_c = 0.33 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
 Volumetric heat generation rate, $S = 0.5 \text{ Btu}/(\text{hr})(\text{ft}^3)$
 Concrete thermal conductivity, $k_m = 0.5 \text{ Btu}/(\text{hr})(\text{ft}^2)(^\circ\text{F}/\text{ft})$
 Cake thickness, $l_c = 16 \text{ ft}$
 Soil cover depth, $l_1 = 11 \text{ ft}$
 Tank diameter, $2r = 75 \text{ ft}$
 . Position of Maximum temperature, $X_N = 2.75 \text{ ft}$ above the tank bottom

The heat transfer coefficients U_U and U_D calculated by method (3) are correlated in Figure 14 as a function of soil thermal conductivity for several cake thicknesses and soil cover depths. Since they refer to conditions outside the cake, they are not a function of the cake thermal conductivity. The values of U_U calculated by method (2) are also shown in Figure 14 for comparison.

Several example problems are given in Appendix D to show how to calculate U_U and U_D and how to use them to vary conditions in the cake.

Direct use of the approximate model equations for ratios of (tank spacing / tank diameter) greater than 1.6 are not recommended because the proper heat flow paths and areas for flow are no longer the simple arithmetic averages used in the approximate model. Since it is difficult to determine the proper areas, a technique which estimates the heat flux escaping across the radius $R = 1.6r$ (60 ft radius for a 37.5 ft radius tank) is used. The results of this technique are explained in the discussion of Figure 16 (p. 29) and in Appendix B.

GENERALIZED CORRELATIONS

DIMENSIONAL ANALYSIS

The temperature at any given point in the system is a function of the following variables:

$$T = \phi(h_1, h_2, h_A, h_{Q_1}, k_c, k_s, k_v, l_1, l_2 + l_c, l_3, l_c, r, R, S, T_A, T_W) \quad (4)$$

In dimensionless form, this might be represented as follows; if r , the tank radius, is taken as the reference dimension, T_A the atmospheric temperature is the reference temperature and k_s is the reference thermal property.

FIGURE 14. Overall Heat Transfer Coefficients

$$\frac{k_s(T - T_A)}{Sr^2} = \phi \left[\frac{h_1 r}{k_s}, \frac{h_2 r}{k_s}, \frac{h_A r}{k_s}, \frac{h_{Q1} r}{k_s}, \frac{k_c}{k_s}, \frac{k_v}{k_s}, \frac{\ell_1}{r}, \frac{\ell_2 + \ell_c}{r}, \frac{\ell_3}{r}, \frac{\ell_c}{r}, \frac{R}{r}, \frac{k_s(T_A - T_W)}{Sr^2} \right]. \quad (5)$$

Using twelve independent dimensionless groups in Equation (5) is little better than having the sixteen independent variables listed in Equation (4). The next step of simplification involves neglecting changes in variables which have little effect on the temperature. Thus, one may hold the heat transfer coefficients h_1 , h_2 , h_A , h_{Q1} and the vapor thermal conductivity k_v constant and set $T_W = T_A$ to obtain Equation (6).

$$\frac{k_s(T - T_A)}{Sr^2} = \phi \left[\frac{k_c}{k_s}, \frac{\ell_1}{r}, \frac{\ell_2 + \ell_c}{r}, \frac{\ell_3}{r}, \frac{\ell_c}{r}, \frac{R}{r} \right] \quad (6)$$

The next degree of simplification involves fixing the tank radius r at 37.5 ft and correlating maximum temperature with the major variables as shown in Equation (7).

$$\frac{k_s(T - T_A)}{S} = \phi \left[\frac{k_c}{k_s}, \ell_1, \ell_1 + \ell_c, \ell_3, \ell_c, R \right]. \quad (7)$$

In the tank farms operated by Isochem at Hanford, the tank height ($\ell_2 + \ell_c$), the tank spacing ($2R$), and the distance from the tank bottom to the water table (ℓ_3) are usually fixed so that the correlation reduces to Equation (8),

$$\frac{k_s(T - T_A)}{S} = \phi \left[\frac{k_c}{k_s}, \ell_1, \ell_c \right]. \quad (8)$$

Varying degrees of complexity are involved in the correlations presented here. All the variables present in Equation (4) are included in the approximate model, Equation (7) includes

the major variables generally present in tank farm systems, but Equation (8) includes only the variables involved in practical analyses of the existing Hanford tank farms. The major independent variables at Hanford are soil cover depth, cake thickness, soil thermal conductivity, cake thermal conductivity, and heat generation rate. Since the tank radius r is fixed, a new reference dimension may be used to reduce the number of groups in Equation 8. Taking the cake thickness ℓ_c as the new reference dimension,

$$\frac{k_s (T - T_A)}{S \ell_c^2} = \phi \left[\frac{k_c}{k_s}, \frac{\ell_1}{\ell_c} \right]. \quad (9)$$

This correlation has been made with results of the iterative technique for an assumed form of the function ϕ to give

$$\frac{k_s (T_{\text{Max}} - T_A)}{S \ell_c^2} = 1.04 \left(\frac{k_c}{k_s} \right)^{-0.22} \left(\frac{\ell_1}{\ell_c} \right)^{-0.88} \quad (10)$$

The standard deviation for a least squares fit of all the results of the iterative calculations over the region of application $7 \leq \ell_1 \leq 11$, $0 \leq \ell_c \leq 24$, $0.33 < k_c < 1.20$, $0.15 \leq k_s \leq 0.65$ is + 8.6% to -7.9% from the values calculated by Equation (10). The approximate effect of each independent variable on the maximum temperature is found by rearranging Equation (10).

$$T_{\text{MAX}} - T_A = 1.04 S k_s^{-0.78} k_c^{-0.22} \ell_c^{1.22} \ell_1^{0.88} \quad (11)$$

CORRELATION OF MAJOR VARIABLES

If the tank diameter is fixed at 75 ft, Equation (7) applies:

$$\frac{k_s (T - T_A)}{S} = \phi \left[\frac{k_c}{k_s}, \ell_1, \ell_2 + \ell_c, \ell_3, \ell_c, R \right] \quad (7)$$

To illustrate the effect of each variable, plots of $k_s(T - T_A)/S$ versus ℓ_1 , $\ell_2 + \ell_c$, ℓ_3 , ℓ_c , or R individually can then be made with k_c/k_s as a parameter and the remaining variables held constant at fixed values. Such effects, given in Figures 15, 16, 19 (p. 34) and 20 (p. 35) were calculated by the approximate model. The influence of cake thickness, ℓ_c , has previously been illustrated in Figures 10 and 12.

The dimensional plots may be converted to other tank radii by using the fact that the ratio of each dimension factor in Equation (6) to the reference dimension, r , must be kept constant. Thus, if the tank radius, r , is changed to r' , the new variables and fixed parameters in Equation (7) and Figures 10, 12, 15, 16, 19, and 20 are given by:

$$\begin{aligned}\ell_1' &= \ell_1 r'/r; \ell_2' + \ell_c' = (\ell_2 + \ell_c) r'/r; \\ \ell_3' &= \ell_3 r'/r; \ell_c' = \ell_c r'/r; \text{ and } R' = R r'/r.\end{aligned}\tag{12}$$

Example 6 of Appendix D illustrates this procedure.

EFFECT OF SOIL COVER DEPTH

The effect of soil cover depth on the maximum temperature at the bottom of a 16 ft cake as calculated by the approximate model is shown in Figure 15. It is seen that the removal of soil cover can lower the maximum temperatures appreciably. However, the increased gamma radiation through the layers of soil may dictate that a relatively thick layer be maintained, as was mentioned in the discussion of Figure 8.

EFFECT OF TANK SPACING

The effect of tank spacing on the maximum tank bottom temperature for a 16 ft cake is shown in Figure 16. All

FIGURE 15. Maximum Temperature at the Bottom of a Storage Tank, Effect of Soil Cover Depth

FIGURE 16. Maximum Temperature at the Bottom of a Waste Storage Tank (Effect of Tank Spacing)

calculations were made using an insulated radius, R , around the tank to simulate a tank farm. This is not strictly correct because rectangular tank spacing would result in an insulated rectangular shell in an infinite size tank farm and equilateral triangular spacing would result in an insulated hexagonal shell in an infinite size tank farm of identical tanks. Three points corresponding to insulated radii of 37.5, 60, and 300 ft are available from the iterative calculations. The approximate model is used to calculate the temperature for less than 120 ft center-to-center spacing. For larger radii, it is necessary to use the point source correction to the approximate model discussed in Appendix B to estimate the heat flux across the 60 ft radius. The effect of tank spacing is small with spacings larger than 250 ft.

A comparison of the vertical and horizontal temperature profiles in a single tank and one in a matrix, or tank farm, is made in Figures 17 and 18 for a 2 ft cake generating 32,800 Btu/hr. A temperature of 408 °F is reached in the cake for the tank within a tank farm as specified, while the cake in the solitary tank reaches only 332 °F. The close approach to ambient temperature of 70 °F at radii greater than 200 ft shows that the assumed boundary condition of no radial heat flow across a 300 ft radius gives a good approximation to a single tank in an infinite radius medium.

Comparison of the vertical temperature profiles along the axes of tanks in the two systems shows that the temperature gradients toward the soil surface and the water table are quite similar, although much more heat flows radially in the larger system. For the 60 ft insulated radius, 85.6% of the heat generated goes to the atmosphere and the remainder to the water table. For the solitary tank, 68.5% of the heat is distributed

FIGURE 17. Vertical Temperature Profile at the Axis of a Waste Tank

FIGURE 18. *Temperature Profile in the Plane of Maximum Temperature (Comparison of a Solitary Tank with One in a Tank Farm)*

to the atmosphere and the water table within the 60 ft radius and the remainder outside this radius. The split between the atmosphere and the water table is the same as for the tank with 60 ft insulated radius.

EFFECT OF WATER TABLE DEPTH

In Figure 19, the water table depth is shown to have a small effect in arid surroundings because very little heat is conducted to it. However, when the water table approaches the tank bottom, appreciable heat flows to it and the assumption that the water table is a sink with no thermal resistance is probably unjustified.

EFFECT OF TANK HEIGHT

Within limits, the height-to-diameter ratio of the tank has no effect on the maximum temperature as is shown in Figure 20. The higher the tank the more heat is lost out the sides through the vapor space, but this is compensated by longer flux paths to the surface. Since the cake thickness is held constant at 16 ft in Figure 20, a 16 ft deep tank has no vapor space and a 36 ft deep tank has a 20 ft vapor space. Since the soil cover depth remains constant for the correlation, increasing the tank height means lowering the tank bottom.

FIGURE 19. Maximum Temperature at the Bottom of a Storage Tank Containing Solidified Wastes, Effect of Water Table Depth

FIGURE 20. Maximum Temperature at the Bottom of a Waste Storage Tank (Effect of Tank Height)

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APPENDIX A

RESULTS OF ITERATIVE CALCULATIONS

APPENDIX A

RESULTS OF ITERATIVE CALCULATIONS

For proper use of Program 001 the following input information is required:

- Area, volume, centroid location of each node
- Material type of each node
- Thermal conductivity of each material type
- Heat generation rate
- Sink temperatures and locations
- Film coefficients and locations
- Acceptable error limits
- Running time for each case

A simplified flow diagram and typical computer print-out along with the computer results are shown in Figure A-1 and Tables A-1, A-2, A-3.

FIGURE A-1. Block Diagram of Heat Transfer Program 001

TABLE A-1. Summary of Results of the Iterative Calculations (Heat Generation Throughout the Cake)

Run No.	k_s	k_c	S	ℓ_c	ℓ_1	T_{MAX}	$T_{WALL}(a)$	T_2	$\frac{k_s(T_{MAX}-T_A)}{S}$ ft ²	U_U/k_s ft ⁻¹
105	0.15	0.33	2.00	4.0	11.0	482.4	456.9	480.8	30.9	0.1243
110	0.15	0.33	2.83	4.0	11.0	651.6	615.2	649.2	30.8	0.1254
111	0.15	0.80	2.83	4.0	11.0	618.2	603.1	617.4	29.0	0.1295
103	0.15	0.80	2.00	4.0	11.0	457.0	446.4	456.4	29.0	0.1296
104	0.15	1.20	2.83	4.0	11.0	610.8	600.3	610.3	28.7	0.1295
109	0.15	1.20	2.00	4.0	11.0	452.8	445.3	452.4	28.7	0.1293
1000	0.33	0.33	2.00	4.0	11.0	288.4	258.1	286.0	36.0	0.1185
102	0.33	0.33	1.00	4.0	11.0	179.0	163.9	177.8	36.0	0.1188
100	0.33	0.80	2.83	4.0	11.0	347.7	329.2	346.6	32.4	0.1198
101	0.33	1.20	2.00	4.0	11.0	261.4	254.6	260.9	31.6	0.1197
107	0.65	0.33	2.83	4.0	11.0	262.3	216.1	257.3	44.2	0.1066
108	0.65	0.80	2.83	4.0	11.0	234.6	212.7	233.1	37.8	0.1067
106	0.65	1.20	2.00	4.0	11.0	182.2	170.9	181.6	36.5	0.1060
2000	0.15	0.33	1.00	8.0	11.0	505.6	468.2	503.6	65.3	0.1334
203	0.15	0.33	1.42	8.0	11.0	688.0	635.0	685.2	65.3	0.1323
200	0.15	0.80	1.42	8.0	11.0	625.9	606.4	625.0	58.7	0.1336
204	0.15	0.80	1.00	8.0	11.0	463.3	449.5	462.7	59.0	0.1328
201	0.15	1.20	1.42	8.0	11.0	611.4	598.8	610.9	57.2	0.1338
202	0.33	0.33	1.00	8.0	11.0	309.8	267.8	306.8	79.1	0.1264
205	0.33	0.33	1.42	8.0	11.0	409.8	350.6	405.6	78.9	0.1269
207	0.33	1.20	1.42	8.0	11.0	339.7	325.0	339.0	62.6	0.1284
211	0.65	0.33	1.00	8.0	11.0	221.6	179.5	217.1	98.5	0.1258
210	0.65	0.80	1.42	8.0	11.0	241.0	215.4	239.4	78.2	0.1185
208	0.65	1.20	1.42	8.0	11.0	228.5	211.6	227.6	72.5	0.1185
209	0.65	1.20	0.283	8.0	11.0	101.9	98.48	101.7	73.3	0.1169
213 ^(b)	0.15	0.80	1.42	8.0	7.0	521.4	503.1	520.7	47.7	0.1724
214 ^(b)	0.15	1.20	1.00	8.0	7.0	376.7	368.4	376.4	46.0	0.1729
302	0.15	0.33	0.498	16.0	11.0	561.6	501.8	558.9	147.5	0.1354
303	0.15	0.33	0.142	16.0	11.0	210.7	193.7	209.9	148.6	0.1338
309	0.15	0.80	0.707	16.0	11.0	663.1	631.8	662.1	125.9	0.1336
308	0.15	1.20	0.707	16.0	11.0	636.8	617.0	636.2	120.3	0.1378
3000	0.33	0.33	0.498	16.0	11.0	351.6	287.3	338.8	185.6	0.1530
300	0.33	0.33	0.142	16.0	11.0	150.1	132.2	148.0	186.1	0.2537
301	0.33	0.33	0.707	16.0	11.0	468.5	378.8	458.1	186.0	0.2537
304	0.33	0.33	0.071	16.0	11.0	110.4	101.4	109.3	188.6	0.1405
307	0.33	0.33	1.00	16.0	11.0	632.6	506.0	617.9	185.6	0.1456
305	0.33	0.80	0.498	16.0	11.0	293.8	268.6	292.7	147.7	0.1298
310	0.33	0.80	0.142	16.0	11.0	133.7	126.6	133.4	148.0	0.1294
306	0.33	1.20	0.707	16.0	11.0	363.5	340.9	362.7	137.0	0.1287

TABLE A-1. (Contd)

Run No.	k_s	k_c	S	z_c	z_1	T_{MAX}	$T_{WALL}(a)$	T_2	$\frac{k_s(T_{MAX}-T_A)}{S}$ ft ²	U_U/k_s ft ⁻¹
313	0.65	0.33	0.707	16.0	11.0	329.2	240.0	309.3	238.3	0.2008
314	0.65	0.80	0.498	16.0	11.0	208.9	182.2	206.4	180.6	0.1289
311	0.65	1.20	0.142	16.0	11.0	102.5	97.67	102.2	148.8	0.1459
312	0.65	1.20	0.707	16.0	11.0	247.2	222.3	245.7	162.9	0.1234
315 ^(b)	0.15	0.33	0.707	16.0	7.0	664.0	582.1	660.4	126.0	0.1791
316 ^(b)	0.15	0.80	0.498	16.0	7.0	416.0	394.9	415.3	104.2	0.1737
317 ^(b)	0.15	1.20	0.142	16.0	7.0	163.1	159.4	163.0	98.4	0.0711
503	0.15	0.33	0.472	24.0	11.0	801.1	701.3	792.1	232.2	0.1565
506	0.15	0.80	0.472	24.0	11.0	681.9	645.7	680.2	194.5	0.1403
505	0.15	1.20	0.472	24.0	11.0	649.0	637.6	648.2	184.0	0.1382
5000	0.33	0.33	0.472	24.0	11.0	493.4	387.0	471.2	295.3	0.2357
507	0.33	0.33	1.00	24.0	11.0	966.1	740.8	921.3	295.7	0.2342
500	0.33	0.80	0.472	24.0	11.0	400.8	359.4	397.3	231.3	0.1476
501	0.33	1.20	0.472	24.0	11.0	373.6	347.4	371.9	212.3	0.1395
502	0.33	1.20	0.094	24.0	11.0	131.2	126.0	130.9	214.9	0.1366
508	0.65	0.33	0.472	24.0	11.0	351.7	243.4	313.3	387.9	-
509	0.65	0.80	0.472	24.0	11.0	276.6	232.2	269.1	284.5	0.1774
511	0.65	0.80	0.330	24.0	11.0	214.9	183.8	209.5	285.3	0.1763
510	0.65	1.20	0.472	24.0	11.0	254.8	225.8	251.5	254.5	0.1481

(a) T_{WALL} is the tank wall temperature in the same horizontal plane as the maximum cake temperature.

(b) 7 ft soil cover

TABLE A-2. *Summary of Results of the Iterative Calculations (Heat Generation in Horizontal Layers)*

	<u>Run No.</u>	<u>k_s</u>	<u>k_c</u>	<u>k_g</u>	<u>S</u>	<u>ℓ_c</u>	<u>ℓ_g</u>	<u>ℓ₁</u>	<u>T_{MAX}</u>	<u>T_{WALL}</u>	<u>T₂</u>
Concentrated Heat Source Centerline 1 ft Above Bottom of Tank	321	0.15	0.33	0.33	5.67	16.0	2.0	11.0	953.7	814.6	947.8
	322	0.15	0.33	0.80	3.96	16.0	2.0	11.0	673.3	603.0	671.7
	323	0.15	0.33	1.20	1.13	16.0	2.0	11.0	242.0	224.8	241.7
	318	0.33	0.33	0.33	5.67	16.0	2.0	11.0	623.1	467.4	612.9
	319	0.33	0.33	0.80	1.13	16.0	2.0	11.0	170.2	147.1	169.4
	320	0.33	0.33	1.20	3.96	16.0	2.0	11.0	438.7	367.5	436.9
Concentrated Heat Source Centerline 7 ft Above Tank Bottom	330	0.15	0.33	0.33	5.67	16.0	2.0	11.0	820.3	723.7	787.7
	331	0.15	0.33	0.80	3.96	16.0	2.0	11.0	582.3	534.3	562.6
	332	0.15	0.33	1.20	1.13	16.0	2.0	11.0	216.7	204.9	211.3

APPENDIX B

DERIVATION OF EQUATIONS
FOR THE APPROXIMATE MODEL

APPENDIX B DERIVATION OF EQUATIONS FOR THE APPROXIMATE MODEL

Since the iterative technique has proved to be difficult to adjust for changes in soil geometry and has consumed large amounts of computer time because of its complexity, an approximate model has been developed to permit easier interpolation and variation of less important parameters. A sketch of the model is shown in Figure 11. A horizontal plane of maximum temperature across which no heat flows can be drawn through the heat-generating cake. All the heat is assumed to flow vertically through the cake so that a parabolic vertical temperature profile is present. This is a good assumption only near the axis of the tank because radial heat losses will reduce the temperature near the walls.

The total heat generated in the cake is conducted to the water table and the atmosphere with effective overall heat transfer coefficients as is shown in Equations (B-1) and (B-2).

$$S \pi r^2 \ell_c = \pi r^2 U_D (T_2 - T_W) + \pi r^2 U_U (T_1 - T_A) \quad (B-1)$$

$$S \pi r^2 X_N = \pi r^2 U_D (T_2 - T_W) \quad (B-2)$$

The relationship between the temperature T_1 at the top of the cake and T_2 at the bottom of the cake is found by equating the null plane temperatures calculated from both sides;

$$T_{MAX} = T_2 + \frac{S X_N^2}{2 k_c} = T_1 + \frac{S (\ell_c - X_N)^2}{2 k_c} \quad (B-3)$$

Solving Equations (B-1), (B-2), and (B-3) simultaneously for X_N , T_1 and T_2 gives

$$X_N = \frac{U_D}{S} (T_2 - T_W), \quad (B-4)$$

$$T_1 = T_2 \left(1 + \frac{U_D \ell_c}{k_c} \right) - \frac{S \ell_c^2}{2k_c} - \frac{\ell_c U_D T_W}{k_c} \quad (B-5)$$

and

$$T_2 = \frac{S \ell_c \left(1 + U_U \ell_c / 2k_c \right) + U_U T_A + U_D T_W \left(1 + U_U \ell_c / k_c \right)}{U_U + U_D \left(1 + \ell_c U_U / k_c \right)} \quad (B-6)$$

When the sink temperatures are equal $T_A = T_W$,

$$\checkmark T_2 - T_A = \frac{S \ell_c \left(1 + U_U \ell_c / 2k_c \right)}{U_U + U_D \left(1 + \ell_c U_U / k_c \right)} \quad (B-7)$$

The evaluation of U_U and U_D is based upon the heat flow paths shown in Figure 11. The average areas for flow and the driving forces are given in Table B-1. The flux to the water table may be split up into two parallel flows so that

$$U_D = U_{Q_3} + U_{Q_D} \quad (B-8)$$

The heat transfer coefficient for flow out the bottom of the cake is then

$$U_{Q_D} = \frac{k_s}{\ell_3} \quad (B-9)$$

and out the side of the cake is

$$U_{Q_3} = \frac{k_s \left(\frac{R^2}{r^2} - 1 \right)}{\ell_3 + R/2} \quad (B-10)$$

The flux to the atmosphere may be split up into three paths so that

$$U_U = U_{Q_U} + U_{Q_1} + U_{Q_2} \quad (B-11)$$

TABLE B-1. Heat Flow Assumptions in Approximate Model

	Flux	Path Length	Average Area for Flow	Driving Force
From Top of Tank to Air	Q_U	ℓ_1	πr^2	$T_1 - T_A$
From Side of Vapor Space to Air	Q_1	$\ell_1 + \frac{\ell_2}{2} + \frac{R - r}{2}$	$\left(\frac{1}{2}\right) [\pi (R^2 - r^2) + 2 \pi r \ell_2]$	$T_V - T_A$
From Side of Cake to Air	Q_2	$\ell_1 + \ell_2 + \frac{\ell_c}{2} + \frac{R}{2}$	$\left(\frac{1}{2}\right) [\pi (R^2 - r^2) + 2 \pi r \ell_c]$	$T_1 - T_A$
From Bottom of Tank to Water Table	Q_D	ℓ_3	πr^2	$T_2 - T_W$
From Side of Cake to Water Table	Q_3	$\ell_3 + \frac{R}{2}$	$\pi (R^2 - r^2)$	$T_2 - T_W$

The heat that flows out the side of the cake is assumed to leave the cake at temperature T_1 so that

$$U_{Q_2} = \frac{\frac{1}{2} k_s \left(\frac{R^2}{r^2} - 1 + \frac{2 \ell_c}{r} \right)}{\ell_1 + \ell_2 + \frac{\ell_c}{2} + \frac{R}{2}} \quad (B-12)$$

The heat transfer coefficient for flow vertically through the vapor space and the soil cover above the tank is found by adding the series resistances to flow.

$$U_{Q_U} = \frac{1}{\frac{1}{h_1} + \frac{\ell_2}{k_v} + \frac{1}{h_2} + \frac{\ell_1}{k_s} + \frac{1}{h_A}} \quad (B-13)$$

The effect of the heat that flows out the side of the vapor space on the vertical temperature gradient is neglected in the calculation of U_{Q_U} . The effects of the vertical heat flow and the cake to vapor heat transfer coefficient are neglected in the calculation of the heat transfer coefficient for flow from the side of the vapor space to the atmosphere.

$$U_{Q_1} = \frac{1}{\frac{2\ell_2}{h_{Q_1}r} + \frac{\ell_1 + \ell_2 + \frac{R-r}{2}}{\frac{1}{2}k_s \left(\frac{R^2}{r^2} - 1 + \frac{2\ell_2}{r} \right)} + \frac{1}{h_A \left(\frac{R^2}{r^2} - 1 \right)}} \quad (B-14)$$

The side of vapor space-to-soil, conduction through soil, and soil-to-air heat transfer coefficients are treated as series resistances to flow.

The temperature of the vapor space can be estimated from

$$T_V = T_1 - \frac{S(\ell_c - x_N)}{h_1} \left(1 - \frac{U_{Q_2}}{U_U} \right) \quad (B-15)$$

When the heat-generating fission products are concentrated in a layer within the cake, the internal structure of the cake must be taken into account. If ℓ_g is the heat-generating layer thickness with thermal conductivity k_g , ℓ_d is the thickness of the nongenerating layer of the cake below the heat generators with thermal conductivity k_d , and $\ell_c - \ell_g - \ell_d$ is the thickness of the nongenerating layer above the heat generators with thermal conductivity k_t , the overall heat transfer coefficients U_U and U_D and T_2 and T_1 may be redefined to refer to the heat-generating layer. The temperature at the bottom of the heat-generating layer is then

$$T_2 = \frac{S\ell_g \left(1 + U_U\ell_g/2k_g \right) + U_U T_A + U_D T_W \left(1 + U_U\ell_g/k_g \right)}{U_U + U_D \left(1 + \ell_g U_U/k_g \right)} \quad (B-16)$$

The expressions for U_U and U_D are then

$$U_U = \frac{1}{\frac{\ell_c - \ell_g - \ell_d}{k_t} + \frac{1}{U_{Q_U} + U_{Q_1} + U_{Q_2}}} \quad (B-17)$$

and

$$U_D = \frac{1}{\frac{l_d}{k_d} + \frac{1}{U_{Q_D} + U_{Q_3}}} \quad (B-18)$$

POINT SOURCE APPROXIMATION

The equation for the temperature field around a continuous point source in an infinite medium of soil is

$$T = \frac{Q}{4 \pi k_s y} \quad (B-19)$$

where Q is the total heat generated in Btu/hr and y is the distance from the source to the point of temperature measurement. If a plane surface at atmospheric temperature T_A is introduced at distance D from the source and the point in question is distance x from the plane and distance r from the normal to the plane through the source, the temperature field found by using a negative reflection of the source across the plane is:⁽¹⁷⁾

$$T(r, x) - T_A = \frac{Q}{4 \pi k_s} \left\{ [r^2 + (D - x)^2]^{-1/2} - [r^2 + (D + x)^2]^{-1/2} \right\} \quad (B-20)$$

The introduction of a plane surface water table with temperature T_A at depth w in the soil may be accommodated by multiple reflections of the source about the planes to give

$$\begin{aligned} \frac{4 \pi k_s [T(r, x) - T_A]}{Q} = & [r^2 + (D - x)^2]^{-1/2} - [r^2 + (D + x)^2]^{-1/2} \\ & + \sum_{n=2}^{\infty} \left\{ [r^2 + (nw - D - x)^2]^{-1/2} \right. \\ & + [r^2 + (nw - D + x)^2]^{-1/2} \\ & + [r^2 + (nw - D - x)^2]^{-1/2} \\ & \left. + [r^2 + (nw + D + x)^2]^{-1/2} \right\} \end{aligned}$$

The heat flow across a given radius R is found by differentiating Equation (B-21) to give

$$Q_R = -k_s (2 \pi R) \int_0^w \left[\frac{dT(r,x)}{dr} \right]_{r=R} dx \quad . \quad (B-22)$$

For a first approximation it may be assumed that the fraction, f , of heat going to the atmosphere is independent of the outer radius of the system as was shown in the analysis of Figure 18. Then

$$Q_R = \frac{-k_s (2 \pi R)}{f} \int_0^D \left[\frac{dT(r,x)}{dr} \right]_{r=R} dx \quad . \quad (B-23)$$

Since the region of the integration is far removed from the water table, Equation (B-20) is sufficient to express the temperature and substitution into Equation (B-23) gives

$$\left. \frac{dT}{dx} \right|_{r=R} = \frac{-Q_R}{4 \pi k_s} \left\{ [R^2 + (D - x)^2]^{-3/2} - [R^2 + (D + x)^2]^{-3/2} \right\} \quad . \quad (B-24)$$

$$\frac{fQ_R}{Q} = [1 + (R/D)^2]^{-1/2} - [4 + (R/D)^2]^{-1/2} \quad . \quad (B-25)$$

Using $R = 60$ ft and $D = 47$ ft gives a value of fQ_R/Q , the fraction of heat going to the atmosphere outside the 60 ft radius for a solitary tank, which is 27.0%, somewhat lower than the value of 31% given in the analysis of Figure 19. Reducing D to 35 ft to allow for the high thermal conductivity of the vapor space matches the iterative results at large distances from the tank.

In another application of the point source approximation, all the space between the bottom of the tank and the atmosphere was shrunk by 35/47 and the first set ($n = 2$) of terms of the summation in Equation (B-21) was used throughout the region

outside the 60 ft radius between the water table and the atmosphere to obtain an initial guess for the iterative technique. This appears to work well in decreasing the time to convergence of the iterative technique.

For tank spacings greater than 120 ft, an insulated radius R_1 of half the tank spacing can be assumed for the calculation of the heat transferred across $R = 60$ ft

$$Q_R = \frac{1}{F} \left\{ \left[1 + (R/D)^2 \right]^{-1/2} - \left[4 + (R/D)^2 \right]^{-1/2} - \left[1 + (R_1/D)^2 \right]^{-1/2} + \left[4 + (R_1/D)^2 \right]^{-1/2} \right\} \quad (B-26)$$

and the heat generated within the cake can be reduced to $Q - Q_R$ for calculation within the 60 ft radius. This will give a cake temperature which is somewhat too low because the influence of the radial heat flow upon temperature gradients within the 60 ft system is not considered. Such a correction is made in the point source correction to the approximate model in Figure 16.

APPENDIX C

UTTA
COMPUTER PROGRAM FOR CALCULATIONS
USING THE APPROXIMATE MODEL

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- ELT UTTA/MOD3S,1,660404, 59685
- EOF -
C      1107 PROGRAM UTTA
C AN UNDERGROUND TANK TEMPERATURE APPROXIMATION ROUTINE  FORTRAN IV
C FOR ESTIMATING TEMPERATURES IN BURIED TANKS OF RADIOACTIVE WASTE
C HEAT GENERATION MAY BE UNIFORM THROUGHOUT CAKE OR MAY BE CONFINED TO
C SOME FRACTION OF THE CAKE
C
C      NOMENCLATURE
C      ALL THERMAL CONDUCTIVITY UNITS ARE BTU/(HR SQFT DEGF/FT)
C      S(I) VOLUMETRIC HEAT GENERATION RATE IN THE HEAT GENERATING
C      PORTION OF THE CAKE. BTU/(HR CU FT)
C      GR(I) RATIO OF HEIGHT OF GENERATING CAKE TO HEIGHT OF ENTIRE CAKE.
C      L1(I) THICKNESS OF SOIL COVER OVER TANK (FT).
C      KC(I) THERMAL CONDUCTIVITY OF CAKE.
C      KS(I) THERMAL CONDUCTIVITY OF SOIL.
C      X(1) RADIUS OF INSULATED SURFACE,BIGR (FT).
C      X(2) AIR TEMPERATURE,TA (DEG F).
C      X(3) WATER TABLE TEMPERATURE,TW (DEG F).
C      X(4) HEAT TRFR COEFF. SOIL TO AIR, HA (BTU/(HR SQFT DEG F)).
C      X(5) HEAT TRFR COEFF. CAKE TO VAPOR SPACE,H1.
C      X(6) HEAT TRFR COEFF. TOP OF VAPOR SPACE TO SOIL,H2
C      X(7) HEAT TRFR COEFF. SIDE OF VAPOR SPACE TO SOIL,HQ1.
C      X(8) THERMAL CONDUCTIVITY OF VAPOR, KV.
C      X(9) DISTANCE FROM BOTTOM OF TANK TO WATER TABLE,L3 (FT).
C      X(10) RADIUS OF TANK, L1R (FT).
C      X(11) HEIGHT OF TANK, L1P2 (FT).
C      X(12) TOTAL CAKE HEIGHT (GENERATING + NON-GENERATING),, LC (FT).
C      X(13) DIST FROM TK BOTTOM TO BOTTOM OF HEAT GEN LAYER, LD (FT).
C      X(14) PROGRAM CONTROL VARIABLE, PCV, ON TYPE B CARD
C      --IF PCV IS BLANK OR ZERO PROGRAM EXPECTS TO READ A NEW SET
C      OF TYPE C,D,E,F,G CARDS IMMEDIATELY AFTER THE B-CARD.
C      --IF PCV IS 1.0,PROGRAM RETAINS VALUES FROM PREVIOUSLY READ
C      C,D,E,F,G CARDS AND EXPECTS NEXT CARD SET TO BE ONLY TWO
C      CARDS, AN A CARD AND A B CARD
C      NGR  NUMBER OF GR VALUES ON C-CARD      8 MAXIMUM
C      NKS  NUMBER OF KS VALUES ON D-CARD      8 MAXIMUM
C      NL1  NUMBER OF L1 VALUES ON E-CARD      8 MAXIMUM
C      NKC  NUMBER OF KC VALUES ON F-CARD      8 MAXIMUM
C      NS   NUMBER OF S  VALUES ON G-CARD      8 MAXIMUM
C
C*** *** ** FORMATS FOR INPUT *** **
C A-CARD FIRST DATA CARD OF EACH SET CONTAINS 72 COLUMNS OF ALPHAMERIC
C INFORMATION
C (12A6)
C
C B-CARD      X(I),I=1,14
C (14F5.0)
C
C C-CARD      NGR,(GR(I),I=1,NGR)
C (12,8F7.3)
C
C D-CARD      NKS,(KS(I),I=1,NKS)
C (12,8F7.3)
C
C E-CARD      NL1,(L1(I),I=1,NL1)

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C (I2,8F7.3)
C
C F-CARD      NKC,(KC(I),I=1,NKC)
C (I2,8F7.3)
C
C G-CARD      NS, (S(I),I=1,NS)
C (I2,8F7.3)
C
C -ONLY NEW (CHANGED) VALUES NEED BE PUNCHED ON B-CARDS AFTER THE FIRST
C B-CARD
C -IF FIELD 14 ON A B-CARD IS BLANK OR ZERO THE B-CARD MUST BE FOLLOWED
C BY A COMPLETELY PUNCHED SET OF C,D,E,F,G CARDS.
C -IF FIELD 14 IS NOT BLANK OR NOT ZERO THE C,D,E,F,G CARDS MUST BE
C OMITTED, AND PREVIOUS VALUES WILL BE RETAINED FOR GR,KS,L1,KC,AND S.
C -ON CHANGE CASES, TO CHANGE ANY VARIABLE TO ZERO WHEN IT HAS HAD A
C VALUE NON-ZERO IN PRECEDING CASE, ENTER -1. IN PROPER FIELD.
C *****EXPLANATION OF OUTPUT HEADINGS *****
C XN= POSITION OF THE NULL PLANE AND MAX CAKE TEMP, MEASURED FROM THE
C BOTTOM OF THE HEAT GENERATING LAYER OF THE CAKE,DEG F.
C TV1= AVERAGE TEMPERATURE OF THE VAPOR SPACE, DEG F.
C T1=MAXIMUM TEMPERATURE AT THE TOP OF HEAT GEN LAYER OF CAKE,DEG F.
C TN= MAXIMUM TEMPERATURE IN THE CAKE, DEGF
C K*DELT/Q=KS*(T2-TW)/S
      CALL SETIO (2,1)
      CALL SETIO (3,2)
      REAL LCI,S(8),L1(8),KC(8),KS(8),L2,X(14),Y(14),UUOKS(8,8,8),
2      KCOKS(8,8,8),T2MTW(8,8,8),T2(8,8,8),XN(8,8,8),TN(8,8,8),T1(8,8
3      3,8),TV1(8,8,8),KSJ,L1K,KCL,GR(8),LG(8),LGN,TG(8,8,8),TOSL(8,8,8),T
4      EXT(12),LD
      INTEGER PAGE
1      FORMAT (14F5.3)
2      FORMAT (12A6)
3      FORMAT (1H1,12A6,38X,4HPAGE,I4//5H BIGR,F8.3,3H FT,15X,2HHA,F8.3,
212H BTU/HR SQFT,7X,2HTA,F7.2,6H DEG F/5H LILR,F8.3,18X,2HH1,F8.3,
319X,2HTW,F7.2/5H L1+2,F8.3,18X,2HH2,F8.3,19X,2HLD,F7.2/
45H L3,F8.3,17X,3HHQ1,
5F8.3,19X,2HKV,F8.3,25H (BTU FT)/(HR SQFT DEG F)//4H LC,4X,2HKS,
64X,2HL1,4X,2HKC,6X,1HS,7X,2HGR,3X,2HLG,5X,2HT2,5X,2HXN,4X,2HTN,
75X,2HT1,5X,3HTV1,4X,5HUU/KS,6X,5HKC/KS,4X,5HT2-TW,3X,9HK*DELT/Q //
8)
4      FORMAT(1H ,0PF5.2,F6.3,F6.1,F6.3,1PE11.4,0PF5.2,F6.2,F7.1,F6.2,
2F7.1,F7.1,F7.1,1PE11.4,0PF9.3,F9.2,1PE11.4)
5      FORMAT(I2,8F7.3)
6      FORMAT(1H0)
7      FORMAT(1H1)
C
C CLEAR ARRAYS
      DO 50 I=1,8
      GR(I)=1.E-15
      L1(I)=1.E-15
      KC(I)=1.E-15
      KS(I)=1.E-15
      S (I)=1.E-15
50 CONTINUE
      DO 55 I=1,14
55 X (I)=1.E-15

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2222 CONTINUE
      PAGE=1
      LINE=45
      READ(2,2) TEXT
      READ(2,1) (Y(I),I=1,14)
      DO 60 I=1,14
      IF(Y(I)) 56,60,58
56    X(I)=1.E-15
      GO TO 60
58    X(I)=Y(I)
60    CONTINUE
      LOOP = 1
      RIN=X(1)
      ADJR=1.6*X(10)
      IF(RIN-ADJR) 613,613,615
613  ASSIGN 8000 TO JOG
      GO TO 616
615  ASSIGN 7000 TO JOG
      X(1)=ADJR
616  CONTINUE
      LCI=X(12)
      LD=X(13)
62  IF(Y(14)-1.E-10) 63,63,70
63  CONTINUE
      READ (2,5) NGR,(GR(I),I=1,NGR)
      READ (2,5) NKS,(KS(I),I=1,NKS)
      READ (2,5) NL1,(L1(I),I=1,NL1)
      READ (2,5) NKC,(KC(I),I=1,NKC)
      READ (2,5) NS,(S(I),I=1,NS)
70  CONTINUE
      RH1=1./X(5)
      RH2=1./X(6)
      RHA=1./X(4)
      SM=S(M)
      RQM1=X(1)**2/X(10)**2-1.
      RO2=X(1)/2.
      DO 80 I=1,NGR
      LG(I)=(LCI-LD)*GR(I)
80  CONTINUE
      L2=X(11) - LCI
      PD5=RH1+RHA+L2/X(8) +RH2
6000 DO 6999 J=1,NKS
      KSJ=KS(J)
      UQ3=KSJ*RQM1/(X(9)+RO2)
      UD1D=KSJ/X(9)
5000 DO 5999 K=1,NL1
      L1K = L1(K)
      DEE= (X(11)+L1K)* 0.74468085
      FEE = (ADJR/DEE)**2
      FOO = (RIN/DEE)**2
4555 DO 5555 L=1,NKC
      KCL=KC(L)
      UD=1./(LD/KCL+1./(UD1D+UQ3))
      KCOKS(J,K,L)=KCL/KSJ
4000 DO 4999 I=1,NGR

```

```

LGN=LG(I)
UU1D=1./ (PD5+L1K/KSJ)
UQ1=1./ ((2.*L2/(X(7)*X(10)))+(L1K+L2+(X(1)-X(10))/2.)/( .5*KSJ*(RQM
21+2.*L2/X(10)))+RHA/RQM1)
TOP=.5*KSJ*(RQM1+2.*LCI/X(10))
BOT=L1K+L2+LCI/2.+X(1)/2.
UQ2=TOP/BOT
UU=UQ2+1./ ((LCI-LD-LGN)/KCL + 1./ (UU1D+UQ1))
UUOKS(K,L,I) = UU/KSJ
3000 DO 3999 M=1,NS
SM=S(M)
3010 TNUM=SM*LGN*(1.+(UU*LGN/2./KCL))+UU*X(2)+UD*X(3)*(1.+LGN*UU/KCL)
TDEN=UU+UD*(1.+LGN*UU/KCL)
T2(L,I,M)=TNUM/TDEN
TT2=T2(L,I,M)
T2MTW (L,I,M)= TT2-X(3)
TOSL(L,I,M) = KSJ*T2MTW(L,I,M)/SM
XN(L,I,M) = UD * T2MTW(L,I,M)/SM
TXN=XN(L,I,M)
GO TO JOG,(7000,8000)
7000 GO TO (7200,7600),LOOP
7200 SM = SM * (1.-(LG/(LG-TXN)))*((1.+FEE)**(-.5)-(4.+FEE)**(-.5)-(1.+
2FOO)**(-.5)+(4.+FOO)**(-.5)))
LOOP=2
UUOKS(K,L,I)=UUOKS(K,L,I) * S(M)/SM
GO TO 3010
7600 CONTINUE
8000 TN(L,I,M) = TT2 + SM * TXN**2/2./KCL
TOSL(L,I,M) = KSJ * T2MTW(L,I,M)/S(M)
TG(L,I,M)=TT2-SM*LGN*(LGN/2.-TXN)/KCL
TTG=TG(L,I,M)
T1(L,I,M)=TTG-SM*(LGN-TXN)*(LCI-LGN-LD)*(1.-UQ2/UU)/KCL
TV1(L,I,M)=T8(L,I,M)-SM*(LGN-TXN)*(1.-UQ2/UU)/X(5)
LOOP = 1
3999 CONTINUE
4999 CONTINUE
5555 CONTINUE
DO 599 LL=1,NKC
DO 499 II=1,NGR
DO 399 MM=1,NS
IF (LINE-44) 6100,6030,6030
6030 CONTINUE
C START NEW PAGE AND WRITE HEADINGS
LINE= 10
WRITE(3,3)TEXT,PAGE,RIN,X(4),X(2),X(10),X(5),X(3),X(11),X(6),
2X(13),X(9),X(7),X(8)
PAGE=PAGE+1
6100 CONTINUE
C WRITE ANSWERS
WRITE(3,4)LCI,KS(J),L1(K),KC(LL),S(MM),GR(II),LG(II),T2(LL,II,MM),
2XN(LL,II,MM),TN(LL,II,MM),T1(LL,II,MM),TV1(LL,II,MM),UUOKS( K,LL,
3II),KCOKS(J,K,LL),T2MTW(LL,II,MM),TOSL(LL,II,MM)
LINE=LINE+1
399 CONTINUE
499 CONTINUE
599 CONTINUE
WRITE(3,6)
LINE=LINE + 1
5999 CONTINUE
6999 CONTINUE
GO TO 2222
END

```


EXAMPLE CASE FOR PROGRAM UT TA

BIGR 60.000 FT		HA		.555 BTU/HR SQFT		TA 70.00 DEG F											
L1LK	37.500	H1	1.500	L2	1.500	TW	70.00										
L1+2	36.000	H2	1.500	L3	1.500	LD	.00										
L3	155.000	HQ1	1.500	KV	200.000	(BTU FT)/(HR SQFT DEG F)											
LC	KS	L1	KC	S	GR	LG	T2	X/N	TN	T1	TV1	UU/KS	KC/KS	T2-TW	K*DELTA/Q		
16.00	.330	11.0	.330	1.0000+00	.05	.80	103.2	.16	103.3	82.0	81.7	5.9118-02	1.000	33.22	1.0962+01		
16.00	.330	11.0	.330	1.0000+00	.10	1.60	136.1	.32	136.3	94.2	93.6	6.0553-02	1.000	66.12	2.1820+01		
16.00	.330	11.0	.330	1.0000+00	.13	2.08	155.7	.42	156.0	101.7	100.9	6.1462-02	1.000	85.70	2.8281+01		
16.00	.330	11.0	.330	1.0000+00	.20	3.20	200.9	.64	201.5	119.6	118.4	6.3740-02	1.000	130.86	4.3184+01		
16.00	.330	11.0	.330	1.0000+00	.25	4.00	232.6	.80	233.6	132.7	131.2	6.5516-02	1.000	162.63	5.3666+01		
16.00	.330	11.0	.330	1.0000+00	.50	8.00	383.9	1.54	387.5	203.4	200.1	7.6938-02	1.000	313.94	1.0360+02		
16.00	.330	11.0	.330	1.0000+00	.75	12.00	516.9	2.20	526.2	283.9	278.5	9.5486-02	1.000	448.87	1.4813+02		
16.00	.330	11.0	.330	1.0000+00	1.00	16.00	631.0	2.76	642.5	376.7	369.1	1.3086-01	1.000	560.99	1.8513+02		
16.00	.150	11.0	.330	1.0000+00	.05	.80	125.4	.12	125.4	100.1	99.8	8.2457-02	2.200	55.36	8.3037+00		
16.00	.150	11.0	.330	1.0000+00	.10	1.60	180.1	.25	180.2	130.6	129.9	8.4029-02	2.200	110.12	1.6518+01		
16.00	.150	11.0	.330	1.0000+00	.13	2.08	212.7	.32	212.8	149.1	148.2	8.5009-02	2.200	142.68	2.1403+01		
16.00	.150	11.0	.330	1.0000+00	.20	3.20	287.8	.49	288.1	192.8	191.3	8.7413-02	2.200	217.77	3.2666+01		
16.00	.150	11.0	.330	1.0000+00	.25	4.00	340.6	.60	341.2	224.4	222.6	8.9237-02	2.200	270.61	4.0592+01		
16.00	.150	11.0	.330	1.0000+00	.50	8.00	594.0	1.17	596.0	388.7	385.0	1.0000-01	2.200	523.95	7.8593+01		
16.00	.150	11.0	.330	1.0000+00	.75	12.00	826.7	1.69	831.1	564.1	558.3	1.1457-01	2.200	756.73	1.1351+02		
16.00	.150	11.0	.330	1.0000+00	1.00	16.00	1035.2	2.15	1042.3	751.8	743.8	1.3537-01	2.200	965.22	1.4478+02		

APPENDIX D
EXAMPLE PROBLEMS

APPENDIX D
EXAMPLE PROBLEMS

EXAMPLE 1. CALCULATION OF THE MAXIMUM TEMPERATURE
FOR A TYPICAL HANFORD TANK

- Data: $k_c = 0.33$, $k_s = 0.15$, $\ell_1 = 11$ ft, $\ell_2 + \ell_c = 36$ ft,
 $\ell_c = 16$ ft, $k_m = 0.5$, $\ell_3 = 155$ ft, $R = 60$ ft,
 $r = 37.5$ ft, $T_A = T_W = 70$ °F

Total heat generation rate Q is 40,000 Btu/hr.

- What are the maximum temperatures at the bottom of the tank and in the cake?

Ratio of thermal conductivities: $k_c/k_s = 0.33/0.15 = 2.2$.
From Figure 12, $k_s (T_2 - T_A)/S = 150 \text{ ft}^2$.

$$\left. \begin{array}{l} \text{Volumetric heat} \\ \text{generation rate} \end{array} \right\} = \frac{Q}{\pi r^2 \ell_c} = \frac{40,000}{(\pi)(37.5)^2(16)} = 0.564 \text{ Btu/(hr)(ft}^3\text{)}.$$

Maximum temperature at the bottom of the cake:

$$T_2 = 70 + \frac{(150)(0.564)}{0.15} = 636 \text{ °F}.$$

Overall cake-to-water table heat transfer coefficient from Equation (B-8):

$$U_D = \frac{k_s}{\ell_3} + \frac{k_s \left(\frac{R^2}{r^2} - 1 \right)}{\ell_3 + R/2} = \frac{0.15}{155} + \frac{(0.15) \left(\frac{60^2}{37.5^2} - 1 \right)}{155 + 60/2}$$

$$= 0.002233 \text{ Btu/(hr)(ft}^2\text{)(°F)}.$$

Position of maximum cake temperature, Equation (B-4):

$$X_N = \frac{U_D}{S} (T_2 - T_W) = \frac{(0.002233)(636 - 70)}{0.564} = 2.23 \text{ ft}.$$

Maximum temperature in the cake, Equation (B-3):

$$T_{MAX} = T_2 + \frac{SX_N^2}{2k_c} = 636 + \frac{(0.564)(2.23)^2}{(2)(0.33)} = 640 \text{ } ^\circ\text{F} \quad .$$

This maximum temperature could have been gotten directly from Figure 9, or from the maximum cake temperature group given in Figure 10.

Maximum steady-state temperature gradient across the concrete (below the cake) from Table II:

$$\frac{dT}{dX} = \frac{SX_N}{k_m} = \frac{(0.564)(2.23)}{0.5} = 2.5 \text{ } ^\circ\text{F/ft} \quad .$$

Maximum temperature at the top of the cake, Equation (B-3):

$$\begin{aligned} T_1 &= T_{MAX} - \frac{S(\ell_c - X_N)^2}{2k_c} \\ &= 640 - \frac{(0.564)(16 - 2.23)^2}{2(0.33)} = 477 \text{ } ^\circ\text{F} \quad . \end{aligned}$$

Temperature of the vapor space, Equation (B-15):

$$T_V \approx T_1 - \frac{S(\ell_c - X_N)}{h_1} = 477 - \frac{(0.564)(13.77)}{1.5} = 472 \text{ } ^\circ\text{F} \quad .$$

EXAMPLE 2. REMOVAL OF SOIL COVER

- Data: Same as Example 1, except the soil cover depth ℓ_1 is 7 ft instead of 11 ft.
- What is the maximum temperature at the bottom of the cake?

From Figure 15,

$$\frac{k_s(T_2 - T_A)}{S} = 125 \text{ ft}^2$$

$$T_2 = 70 + \frac{(125)(0.564)}{0.15} = 542 \text{ } ^\circ\text{F} \quad .$$

EXAMPLE 3. ESTIMATION OF MAXIMUM TEMPERATURES
FROM SYSTEM PROPERTIES

- Data: $k_c = 1.0$, $k_s = 0.25$, $\ell_1 = 5$ ft, $\ell_2 + \ell_c = 30$ ft,
 $\ell_c = 10$ ft, $k_v = 100$, $\ell_3 = 120$ ft, $R = 55$ ft,
 $r = 30$ ft, $T_A = 35$ °F, $T_W = 100$ °F, $h_{Q1} = 1$, $h_A = 1$,
 $h_1 = 1$ $h_2 = 1$, $S = 2$ Btu/(hr)(ft³)
- What is the maximum temperature at the bottom of the tank?

Since the values of the parameters in this problem are different from those presented in the graphical correlations, the heat transfer coefficients must be calculated by the equations in Appendix B.

Cake-to-water table heat transfer coefficient, Equation (B-8):

$$U_D = \frac{k_s}{\ell_3} + \frac{k_s \left(\frac{R^2}{r^2} - 1 \right)}{\ell_3 + R/2} = \frac{0.25}{120} + \frac{0.25 \left[\left(\frac{55}{30} \right)^2 - 1 \right]}{120 + 55/2}$$

$$= 0.00608 \text{ Btu/(hr)(ft}^2\text{)(°F)} .$$

Cake-to-atmosphere heat transfer coefficient, Equation (B-11):

$$U_U = \frac{\frac{1}{2} k_s \left(\frac{R^2}{r^2} - 1 + \frac{2\ell_c}{r} \right)}{\ell_1 + \ell_2 + \frac{\ell_c}{2} + \frac{R}{2}} + \frac{1}{\frac{1}{h_1} + \frac{\ell_2}{k_v} + \frac{1}{h_2} + \frac{\ell_1}{k_s} + \frac{1}{h_A}}$$

$$+ \frac{1}{\frac{2\ell_2}{h_{Q1} r} + \frac{\ell_1 + \ell_2 + \frac{R-r}{2}}{\frac{1}{2} k_s \left(\frac{R^2}{r^2} - 1 + \frac{2\ell_2}{r} \right)} + \frac{1}{h_A \left(\frac{R^2}{r^2} - 1 \right)}}$$

$$\begin{aligned}
 U_U = & \frac{(0.5)(0.25)\left(\frac{55^2}{30^2} - 1 + \frac{(2)(10)}{30}\right)}{5 + 20 + (10/2) + 55/2} + \frac{1}{\frac{1}{1} + \frac{20}{100} + \frac{1}{1} + \frac{5}{0.25} + \frac{1}{1}} \\
 & + \frac{1}{\frac{(2)(20)}{(1)(30)} + \frac{5 + 20 + (55 - 30)/2}{(0.5)(0.25)[(55/30)^2 - 1 + 2(20)/(30)]} + \frac{1}{1[(55^2/30^2) - 1]}} \\
 = & 0.0066 + 0.0431 + 0.0121 = 0.0618 \text{ Btu/(hr)(ft}^2\text{)(}^\circ\text{F)}.
 \end{aligned}$$

The maximum temperature at the bottom of the tank, Equation (B-6):

$$\begin{aligned}
 T_2 = & \frac{S\ell_c \left(1 + U_U\ell_c/2k_c\right) + U_U T_A + U_D T_W \left(1 + U_U\ell_c/k_c\right)}{U_U + U_D \left(1 + \ell_c U_U/k_c\right)} \\
 = & \{ (2)(10)[(1 + (0.0618)(10)/(2)(1)) + (0.0618)(30) \\
 & + (0.00608)(100)(1 + 0.0618)(35)/(1)] \\
 & \div [(0.0618) + 0.00608 [1 + 10(0.0618)/1]] \} \\
 = & 409^\circ\text{F}
 \end{aligned}$$

EXAMPLE 4. EXTRAPOLATION OF EXPERIMENTAL DATA
FROM ONE TANK TO ANOTHER

- Data: $\ell_c = 12 \text{ ft}$, $k_c = 0.6$, $Q = 40,000 \text{ Btu/hr}$,
 $T_A = T_W = 70^\circ\text{F}$ $r = 37.5 \text{ ft}$
- The measured temperature T_2 at the bottom of the cake is 500°F and it is estimated that 5000 Btu/hr goes to the water table. Suppose a solidification in a similar tank is planned, which will contain heat generators emitting $20,000 \text{ Btu/hr}$ to be concentrated to an 8 ft cake, with a cake thermal conductivity of 0.3 .
- What is the maximum temperature in the cake?

Position of maximum cake temperature:

$$X_N = 12 \text{ ft} \times \frac{5,000}{40,000} = 1.5 \text{ ft} .$$

The volumetric heat generation rate:

$$S = \frac{Q}{\pi r^2 \ell_c} = \frac{40,000}{(\pi)(37.5)^2(12)} = 0.755 \text{ Btu/(hr)(ft}^3) .$$

The cake-to-water table heat transfer coefficient Equation (B-4):

$$U_D = \frac{SX_N}{T_2 - T_W} = \frac{(0.755)(1.5)}{500 - 70} = 0.00263 \text{ Btu/(hr)(ft}^2)(^\circ\text{F)} .$$

The cake-to-atmosphere heat transfer coefficient Equation (B-7):

$$\begin{aligned} U_U &= \frac{S\ell_c - U_D(T_2 - T_W)}{(T_2 - T_W) \left[1 + (U_D\ell_c/k_c) \right] - (S\ell_c^2/2k_c)} \\ &= \{[(0.755)(12) - (0.00263)(500 - 70)] \\ &\quad \div [(500 - 70)[1 + (0.00263)(12)/(0.6)] \\ &\quad - (0.755)(12)^2/(2)(0.6)]\} \\ &= 0.0219 \text{ Btu/(hr)(ft}^2)(^\circ\text{F)} . \end{aligned}$$

It is a good approximation to assume that U_U and U_D do not change as the cake thickness is changed.

For the new tank

$$S = \frac{Q}{\pi r^2 \ell_c} = \frac{20,000}{(\pi)(37.5)^2(8)} = 0.566 \text{ Btu/(hr)(ft}^3) .$$

The maximum temperature at the bottom of the cake, Equation (B-7):

$$\begin{aligned}
 T_2 &= T_W + \frac{S \ell_c \left(1 + U_U \ell_c / 2k_c\right)}{U_U + U_D \left(1 + \ell_c U_U / k_c\right)} \\
 &= 70 + \frac{(0.566)(8) [1 + (0.0219)(8)/(2)(0.3)]}{(0.0219) + (0.00263) [1 + (0.0219)(8)/0.3]} \\
 &= 294 \text{ } ^\circ\text{F}.
 \end{aligned}$$

The position of the maximum cake temperature:

$$X_N = (1.5) \left(\frac{8}{12}\right) = 1.0 \text{ ft}.$$

The maximum cake temperature, Equation (B-3):

$$\begin{aligned}
 T_{\text{MAX}} &= T_2 + \frac{S X_N^2}{2k_c} \\
 &= 294 + \frac{(0.566)(1)^2}{(2)(0.3)} = 295 \text{ } ^\circ\text{F}.
 \end{aligned}$$

EXAMPLE 5. EFFECT OF STRATIFICATION

- In the case of Example 4, a core drill sample of the 8 ft cake shows that all the heat-generating fission products are concentrated in a layer located between 3 and 3.5 ft above the bottom of the cake.
- What is the maximum temperature in the cake?

U_U redefined as the heat transfer coefficient from the top of the heat-generating layer, Equation (B-17):

$$U_U = \frac{1}{\frac{8 - 3.5}{0.3} + \frac{1}{0.0219}} = 0.0165 \text{ Btu/(hr)(ft}^2\text{)(}^\circ\text{F)}.$$

U_D redefined as the heat transfer coefficient from the top of the heat-generating layer, Equation (B-18):

$$U_D = \frac{1}{\frac{3.0}{0.3} + \frac{1}{0.00263}} = 0.00257 \text{ Btu/(hr)(ft}^2\text{)(}^\circ\text{F)}.$$

The volumetric heat-generation rate, S:

$$S = \frac{Q}{\pi r^2 \ell_g} = \frac{20,000}{(\pi)(37.5)^2(0.5)} = 9.06 \text{ Btu/(hr)(ft}^3\text{)} .$$

The maximum temperature at the bottom of the heat generating layer Equation (B-16), assuming $T_A = T_W$:

$$\begin{aligned} T_2 &= T_A + \frac{S \ell_g \left(1 + \frac{U_{U \ell_g}}{U_D} \right)}{U_U + U_D \left(1 + \frac{U_{U \ell_g}}{U_{U \ell_g/k}} \right)} \\ &= 70 + \frac{(9.06)(0.5) \left[1 + \frac{(0.0165)(0.5)}{(0.0165)} \right]}{0.0165 + 0.00257 \left[1 + \frac{(0.0165)(0.5)}{(0.0165)} \right]} \\ &= 310 \text{ }^\circ\text{F} . \end{aligned}$$

The position of the maximum temperature:

$$X_N = 1.0 \times \frac{0.5}{8} = 0.0625 \text{ ft above the bottom of the heat generating layer.}$$

The maximum temperature is

$$\begin{aligned} T_{\text{MAX}} &= T_2 + \frac{S X_N^2}{2k_g} \\ &= 310 + \frac{(9.06)(0.0625)^2}{(2)(0.3)} = 310.06 \text{ }^\circ\text{F} . \end{aligned}$$

In this example, concentrating the heat generators slightly raises the maximum temperature because the heat flow path of most of the heat, through the top of the cake is lengthened by only 9 in.

EXAMPLE 6. USE OF THE GENERALIZED CORRELATIONS

- Suppose a buried tank had half the diameter of the one in Example 1.
- What would have to be the other properties of the system in order to use the information given in Figures 10, 12, 15, 16, 19, and 20?

Using Equation (12), page 27, the answers are:

$$x'_1 = 5.5 \text{ ft}, x'_2 + x'_c = 18 \text{ ft}, x'_c = 8 \text{ ft}, x'_3 = 78.5 \text{ ft},$$

$$R' = 30 \text{ ft}, r' = 18.75 \text{ ft}, T_A = T_W.$$

- If the total heat generation rate were 3000 Btu/hr and the thermal conductivities were $k_c = 1.20$, $k_s = 0.15$, $T_A = 70^\circ\text{F}$, what would the maximum temperature be at the bottom of the tank?

$$k_c/k_s = 1.20/0.15 = 8.$$

$$S = \frac{3000}{(\pi)(18.75)^2(8)} = 0.340 \text{ Btu/(hr)(ft}^3\text{)}.$$

From Figure 12 ($x_c = 16 \text{ ft}$, $k_c/k_s = 8$)

$$\frac{k_s(T_2 - T_A)}{S} = 120 \text{ ft}^2.$$

The maximum temperature

$$T_2 = 70 + \frac{(120)(0.340)}{0.15} = 342^\circ\text{F}.$$

With the tank diameter fixed only one other dimension at a time can be different from the basic case. For example, suppose R' were changed to 40 ft (80 ft center-to-center tank spacing). Then $R = 80 \text{ ft}$ and from Figure 16

$$\frac{k_s(T_2 - T_A)}{S} = 173 \text{ ft}^2 \text{ for } 2R = 160 \text{ ft}.$$

Thus $T_2 = 462^\circ\text{F}$ for this case.

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	J. M. Atwood	R. W. Nelson
	R. E. Burns	D. W. Pearce
	C. R. Cooley	A. M. Platt
	W. V. DeMier	W. H. Swift
	A. G. Gibbs	E. E. Voiland
	W. A. Haney	M. T. Walling
	E. R. Irish	W. E. Willingham (10)
	G. Jansen (10)	Technical Information (5)
	B. M. Johnson	Technical Publications (2)