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TECHNIQUES FOR CALCULATING TANK TEMPERATURES AND SOIL TEMPERATURES NEAR LEAKS - APPLICATION TO PUREX WASTE TANK 105A

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TECHNIQUES FOR CALCULATING TANK TEMPERATURES AND SOIL TEMPERATURES NEAR LEAKS - APPLICATION TO PUREX WASTE TANK 105A

INTRODUCTION

Large quantities of radioactive waste solutions and sludges are now being stored at United States Atomic Energy Commission production sites and may be stored near commercial fuel processing plants in the future. Storage systems for these wastes are designed to assure means of radiolytic heat dissipation under all normal operating conditions. If leakage of heat generating wastes from a storage tank occurs, the designed means of heat dissipation are compromised, and the thermal conditions that may occur outside the basic tank structure must be considered.

Although the methods of analysis developed in this report are of general applicability, this study is specifically directed at the Hanford Purex Plant alkaline waste storage Tank TK-105A, the integrity of which is in question as a result of known deformation of its steel liner and the presence of significant levels of fission products in the soil immediately under the tank.

An obvious action to be taken after a detected tank failure is to remove the waste from the suspect tank. However, for alkaline wastes a major fraction of the heat generating fission products resides in a precipitated sludge that is dependent upon vaporization of liquid for heat dissipation. Arbitrary removal of the liquid cover to eliminate the source of leakage may result in greater problems than those associated with the initial leakage. The problem is further complicated by the ability of the soil surrounding the tank to sorb fission products and to filter out the dispersed fission product-bearing solids.

Earlier work has been directed toward estimating the transient temperature gradients in the concrete tank wall during normal operations,[1] and waste storage tank systems have been successfully simulated by analogs composed of electrically conductive paper.[2] The methods used in this report for steady-state thermal analysis of waste storage tanks containing solid cakes and boiling solutions are presented elsewhere.[3] The techniques

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for estimating soil temperatures in and around leaks containing heat generating radioactivity are described in HW-80848.[4]

This report presents an analysis of the temperatures that might be attained as a result of removal of supernatant liquid from Tank 105A and the temperatures that would occur in the soil because of a leak. The theoretical internal tank temperatures calculated here are conservatively high because of the assumption of thermal equilibrium, which in some cases may require months to approach and which is always perturbed by radioactive decay of the heat-generating source. Heat transfer by vaporization of water in the soil is not included in this analysis.

SUMMARY AND CONCLUSIONS

The temperatures around waste tanks containing boiling solutions and heat generating sludge layers are compared for dry (low thermal conductivity) and wet (high thermal conductivity) soils. In all cases most of the conducted heat flows from the top of the tank, through the soil layer above the tank, and to the atmosphere. With the tank temperature held constant by boiling supernate that is refluxed by a condenser, more heat is dissipated into the surrounding soil when it is wet than when it is dry. The temperature distribution throughout the soil-tank system is nearly independent of the moisture content or thermal conductivity of the soil if all the soil in the system has the same thermal conductivity; however, if a localized wet region appears only adjacent to the tank wall, higher temperatures will be found in this region of the soil than in nearby dry areas.

Removal of all liquid from waste tanks without removing the sludge will result in extremely high temperatures. If the supernate had been removed from Tank 105A on May 1, 1965, and the only means of heat removal from the radioactive sludge were conduction through the surrounding dry soil, equilibrium tank temperatures as high as 20,000 °F can be calculated. Of course, the tank would have collapsed long before thermal equilibrium was reached, radically altering the heat transfer conditions. The adiabatic temperature rise is estimated at 17 °F per hr so that a long time would be

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needed to approach this temperature. Even after a 10 yr period of radioactive decay, the temperature can be as high as 2000 °F. Passing cooling air through the tank offers little relief from this condition. At a flow rate of 100 ft^3/min, exit air and equilibrium tank temperatures in excess of 10,000 °F are still calculated. Spraying the dry sludge with water to keep its surface at the boiling point of water could keep the bottom of the tank below 500 °F, provided the cake were sufficiently thin and the sludge thermal conductivity were high.

Temperature rise maps are provided for hemispherical leaks varying from 100 to 100,000 gal, for wet and dry soil and for various types of fission products. These maps may prove useful in analyzing temperature records to determine the size and location of a leak. Accurate records are essential for such analyses, since the temperature rises are superimposed on a previously existing temperature gradient around intact tanks. A computer program has been devised for calculating temperature rise maps around hemispherical leaks and hemispheroidal leaks of varying shapes. Higher temperatures are reached in prolate hemispheroidal leaks than in hemispherical leaks of equal volume.

Leaks of alkaline supernate containing only cesium cannot cause dangerously high soil temperatures. In a 50,000 gal leak from Tank 105A the maximum rise in concrete-soil interface temperature is only 35 °F, with a maximum soil temperature rise of 524 °F at a distance of 8 ft from the tank wall. From the measured temperature rises in the laterals below the tank, the present leak from Tank 105 A is estimated to be 5,000 to 15,000 gal. Even the flashing off of the water in the supernate at the leak point would not cause high temperatures because the large quantities of inert salts dilute the fission products. The leakage of even small volumes (less than 1000 gal) of alkaline sludge that might be slurried in the supernate or of acid solutions containing highly adsorbent zirconium and cerium can cause high temperatures at the concrete-soil interface because of the localized high concentrations of fission products at the leak point.

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DISCUSSION

Temperatures Around Intact Tanks

Heat Generation Rates

Purex waste tanks may contain up to one million gallons of alkaline wastes. The high salt content and alkalinity result in a sludge layer on the bottom of the tank which contains most of the heat generating fission products. Cesium remains in the supernate. The composition of the fission products and the heat generated in Purex Waste Tank 105A are listed in Table I. The

TABLE I. COMPOSITION OF THE SLUDGE AND SUPERNATE IN PUREX WASTE TANK 105A

	Sludge		Supernate	
	Ci/ℓ	Btu/(hr)(ft^3)	Ci/ℓ	Btu(hr)(ft^3)
Sr-90	33	21	0.009	0.1
Cs-137	6.5	3	8.1	2.5
Ce-144	216	168	<0.005	<0.007
Ru-106	68	64	<0.02	<0.4
Zr-Nb-95	220	104	<0.005	<0.04
Total		361		2.6

bulk of the heat is generated in the sludge and is removed by boiling of the liquid with reflux condensation in an external cooling system. The estimated volumetric heat generation rate in the sludge is presented in Figure 1 as a function of aging of the waste. If the tank were left undisturbed, the heat generation rate would have decreased from 361 Btu/(hr)(ft^3) on May 1, 1965 to 90 Btu/(hr)(ft^3) in 1 yr and to ~~20~~ 19 Btu/(hr)(ft^3) in 10 yr.

The above values are based on analyses supplied by S. J. Beard.[5]

The heat generated in Tank 105A is divided as follows: 3,200,000 Btu/hr in the settled sludge, 5,500,000 Btu/hr in the solids slurried in the supernate, and 200,000 Btu/hr in solution in the supernate. The settled sludge is about 2 ft thick and the supernate volume including the settled sludge is about 870,000 gal.

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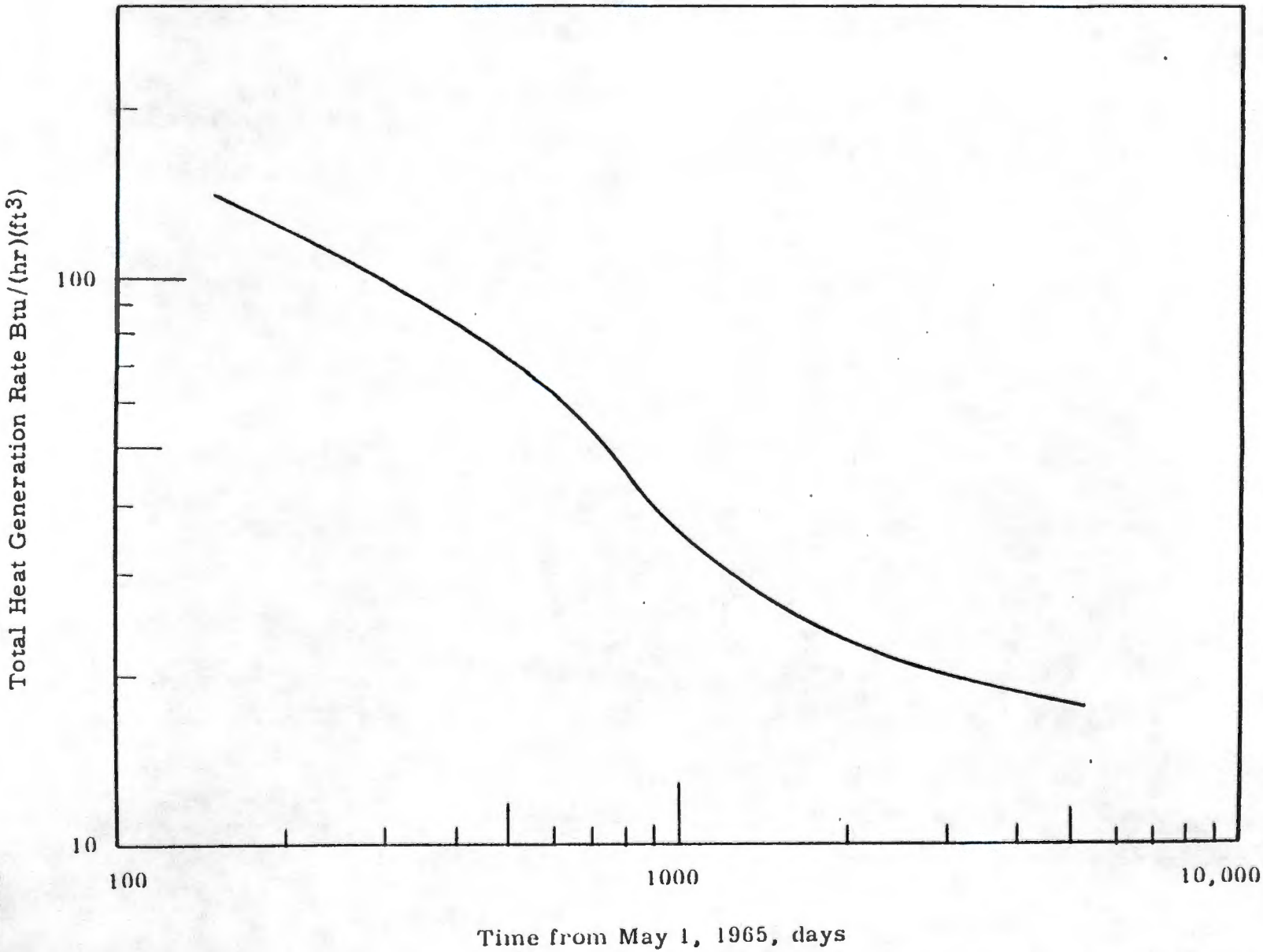

FIGURE 1. VOLUMETRIC SLUDGE HEAT GENERATION RATE AS A FUNCTION OF AGING TIME

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Tanks Containing Boiling Solutions

For tanks containing boiling solutions only a small fraction of the heat generated is conducted away from the tank through the soil; therefore, the temperature of the boiling supernate is known more accurately than the heat conducted through the soil. Calculations were made using the methods given in Reference (3) to match the surrounding temperatures in the boiling supernate temperature. The system properties used in the calculations are given in Table II. The temperature field for dry soil (k = 0.15 Btu/(hr)(ft^2)(°F/ft) is shown in Figure 2. The system was assumed to be insulated at a 60 ft radius, which approximately simulates an infinite array of identical tanks in a tank farm with 120 ft center-to-center spacing. Since heat flow is greatest where isotherms are close together, Figure 2 shows that most of the conducted heat flows through the soil above the tank.

TABLE II. SYSTEM PROPERTIES FOR CALCULATION OF TEMPERATURES WITH BOILING SOLUTIONS

Tank diameter	75 ft
Center-to-center tank spacing	120 ft
Soil overburden depth	7 ft
Tank height to top of dome	46 ft
Depth of water table	202 ft
Sludge thickness	2 ft
Liquid depth including sludge thickness	26 ft
Air-to-soil heat transfer coefficient	0.55 Btu/(hr)(ft^2)(°F)
Vapor space-to-soil heat transfer coefficient	1.5 Btu/(hr)(ft^2)(°F)
Sludge-to-liquid contact coefficient (Figure 2 only)	1.5 Btu/(hr)(ft^2)(°F)
Sludge thermal conductivity	999 Btu/(hr)(ft^2)(°F/ft)
Vapor thermal conductivity	200 Btu/(hr)(ft^2)(°F/ft)
Liquid thermal conductivity	999 Btu/(hr)(ft^2)(°F/ft)

Soil temperatures and heat transferred through the soil are given in Table III for several conditions. For dry soil (k = 0.15) only about 19,000 Btu/hr is transferred through the soil to the surroundings at equilibrium.

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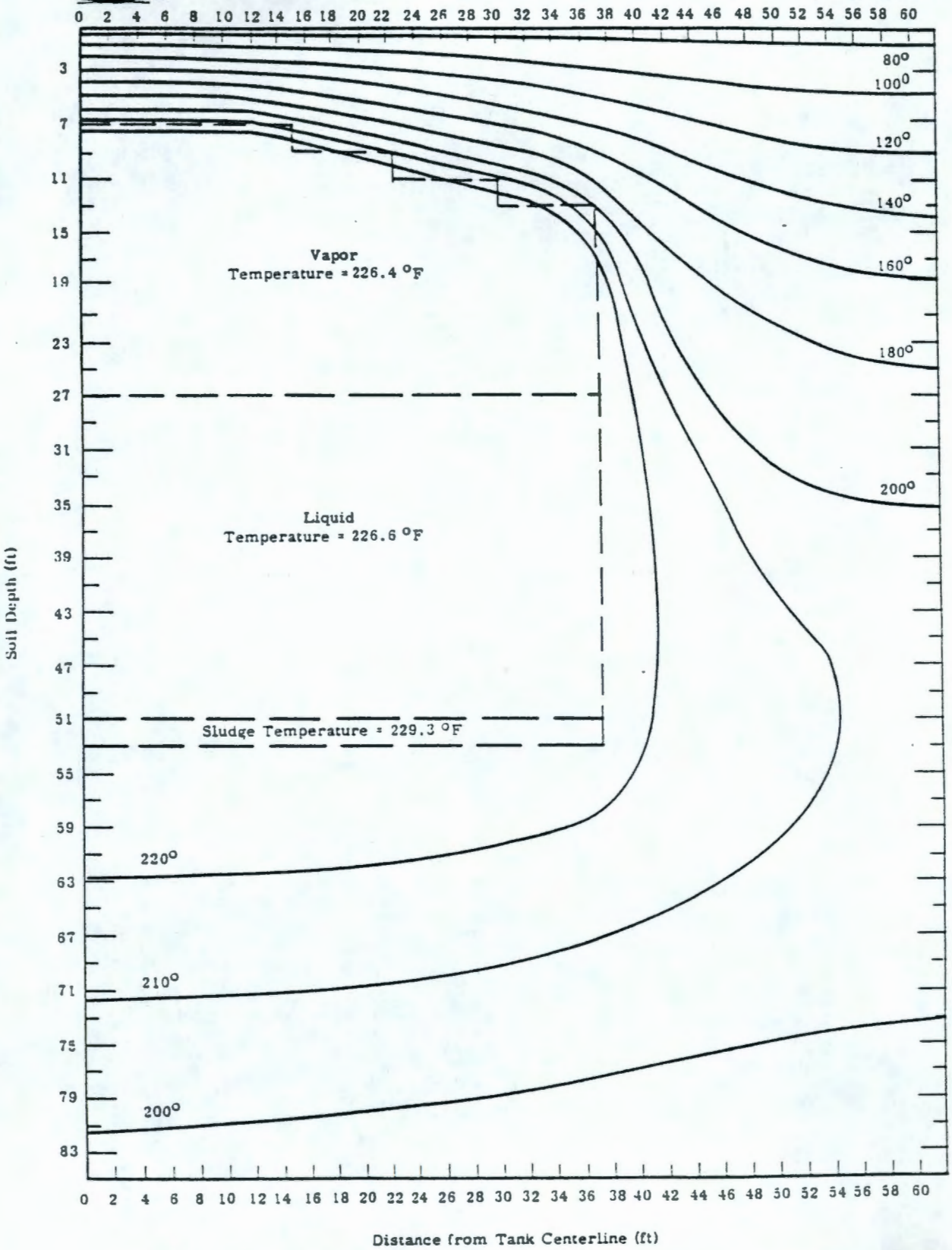

FIGURE 2. TEMPERATURES AROUND PUREX TANK, 105A, CONTAINING A BOILING SOLUTION
(Dry Soil: k = 0.15 Btu/(hr)(ft^2)(°F/ft)

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TABLE III. THERMAL EFFECTS FOR DIFFERENT SOIL CONDITIONS

Input Data	Dry Soil	Wet Soil	Local Wet Region
Soil thermal conductivity, Btu/(hr)(ft^2)(°F/ft)	0.15	0.65	0.15*
Temperature of sludge, °F	230	230	230
Temperature of liquid, °F	230	230	230
Calculated Results			
Centerline temperature, °F - 3 ft above the tank	162.1	163.6	162.2
11.25 ft below the tank	217.8	217.8	223.5
Heat conducted to ground surface, Btu/hr	16,700	66,100	16,700
Heat conducted to water table, Btu/hr	2,140	9,300	2,180
Total heat removed from tank through the soil, Btu/hr	18,840	75,400	18,880

* A 7.5 ft thick by 75 ft diam slab of soil immediately below the tank has a thermal conductivity of 0.65 Btu/(hr)(ft^2)(°F/ft).

If all the soil is wet (k = 0.65), nearly 75,000 Btu/hr are transferred through the soil, but all of the temperatures in the system remain the same as for dry soil. If only a local region near the tank is wetted, the temperatures in and near the region rise because of the better heat transfer from the tank to the region.

Temperature measurements[5] in the laterals located 10 ft below Tank 105A give an average temperature of 193 °F, which is significantly lower than the calculated value of 218 °F for uniform conductivity soil. If all the temperature gradients around the tank were this much greater, the heat flux by conduction through the soil would be about three times higher than the calculated values. The explanation for the difference in temperature is not apparent.

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Measurements[5] made in Purex waste tanks indicate that the heat loss from boiling tanks may be as high as 500,000 Btu/hr. Such high heat losses cannot be accounted for by steady state conduction through the soil surrounding the tank. At least three explanations are possible. The passage of gases through the vapor space by natural or forced convection could remove appreciable heat. Air flowing at 100 ft^3/min could remove 23,000 Btu/hr. Penetrations through the soil cover above the tank could remove additional heat, but calculations show that this effect is negligible. The transient thermal gradients just after a cold tank is filled are much larger than the steady state values and they are dissipated slowly, so that higher heat losses may occur for some time after startup.

The assumed effective thermal conductivities for the vapor, liquid, and sludge are so high that the tank is essentially an isothermal region for the results in Figure 2 and Table III. For a real case, the sludge temperature will be somewhat higher than the liquid temperature because much of the heat generated originates in the sludge and its transfer from the sludge to the liquid was not included in these calculations. If the sludge thermal conductivity were near 1.0 (a reasonable value for a solid) the high real heat generation rate would raise the sludge temperature to a value many times higher than is actually observed. The true effective thermal conductivity of the sludge must be very high due to boiling in the sludge; otherwise much higher temperatures would be observed.

Factors which might strongly influence the temperatures comparison are nonuniform distribution of the heat generating sludge layer, wide variation in soil properties with position and the errors introduced by inserting highly conductive measuring devices into the soil which is a good thermal insulator. Experiments with simulated waste tanks have shown that gas lift circulators tend to deplete the sludge layer just below the circulator but leave it relatively uniform throughout the rest of the tank.

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Tanks Containing Sludge Only

After the supernate has been removed from a tank by leakage or by deliberate pumping of the supernate, the only method remaining for heat removal from the tank is by conduction through the soil. If 2 ft of sludge with the composition given in Table I were left in Tank 105A, the heat generation rate would be 3,200,000 Btu/hr. The resulting equilibrium temperatures could be extremely high if no change in tank geometry or mode of heat removal intervened. With the assumption that the tank is alone, rather than in an infinite array of tanks containing similar contents, and with the same dry soil properties as for boiling tanks, the maximum calculated temperature is 21,300 °F, far above the boiling point of all the materials involved.

In Table IV, taken from Reference (8), is shown the temperature field in a 750,000 gal tank, typical of those in the 241 BY tank farm. Although the assumed heat generation rate is still 3,200,000 Btu/hr, the soil cover is 11 ft instead of 7 ft and the tank height is 36 ft instead of 46 ft resulting in the higher maximum temperature of 24,000 °F. The primary resistance to heat flow is in the soil so that the contents of the tank are at a relatively uniform temperature.

If Tank 105A were placed in an infinite tank farm array of similar tanks with 120 ft center-to-center distances, the maximum calculated temperature would be 30,400 °F, about 43% higher than for a solitary tank. All further discussions will be based on an infinite array of identical tanks, since the methods of calculation used here and described in Reference (3) are most easily applied to tank farm systems.

With a heat generation rate of 361 Btu/(hr)(ft^3), the adiabatic rate of temperature rise is about 17 °F/hr. With this information and an estimate of the overall heat transfer coefficient for heat removal from the tank of 0.02 Btu/(hr)(ft^2)(°F), the temperature rise of the dry cake as a function of time can be estimated. The results shown in Table V are only a rough estimate, since radioactive decay of the heat generators and the heat capacity of the concrete and the soil were not considered, but they do show that heating up of the tank is a slow process and that it would take about a year to approach the equilibrium temperatures given in Table IV. After only a week, however, temperatures above 2000 °F could be reached in the sludge and in the vapor space of the tank. This would probably cause the tank to collapse. A more exact analysis of the transient temperatures in the tank is needed to estimate the time of irreversible damage accurately.

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TABLE IV. TEMPERATURES AROUND A SOLITARY UNDERGROUND WASTE STORAGE TANK CONTAINING DRY SLUDGE [Soil Thermal Conductivity = 0.15 Btu/(hr)(ft^2)(°F/ft); Cake Thermal Conductivity = 0.3 Btu/(hr)(ft^2)(°F/ft)]

Soil Depth, ft	Radius, ft: 0.5	5.75	18.75	33.75	41.25	48.75	63.75	82.50	137.50	245
0	70	70	70	70	70	70	70	70	70	70
1	3,054	3,029	2,569	1,809	1,347	961	513	277	109	74
3	7,271	7,215	6,099	4,270	3,144	2,211	1,135	569	164	81
5	11,520	11,450	9,651	6,760	3,449	2,425	1,750	858	220	87
7	15,810	15,740	13,240	9,301	6,736	4,667	2,352	1,144	275	94
9	20,150	20,110	16,860	11,920	8,526	5,856	2,939	1,424	329	101
11	22,540	22,540	20,520	14,650	10,300	7,005	3,506	1,697	383	107
13	22,550	22,550	22,550	17,540	12,050	8,100	4,048	1,962	436	114
15	22,550	22,550	22,550	20,660	13,750	9,123	4,564	2,218	488	120
17	22,550	22,550	22,550	22,550	15,370	10,060	5,048	2,463	539	125
19	22,560	22,560	22,560	22,550	16,480	10,870	5,499	2,697	589	133
21	22,560	22,560	22,560	22,550	17,270	11,570	5,914	2,920	638	139
23	22,570	22,570	22,570	22,560	17,830	12,160	6,292	3,129	686	145
25	22,570	22,570	22,570	22,560	18,230	12,640	6,632	3,325	732	151
27	22,580	22,580	22,570	22,570	18,530	13,040	6,935	3,507	777	157
29	22,580	22,580	22,580	22,570	18,730	13,350	7,199	3,675	821	163
31	22,590	22,590	22,580	22,570	18,870	13,590	7,426	3,828	862	168
33	22,590	22,590	22,590	22,580	18,960	13,750	7,616	3,967	902	174
35	22,600	22,600	22,590	22,580	18,980	13,860	7,771	4,092	941	180
37	22,600	22,600	22,600	22,590	18,960	13,900	7,892	4,202	977	185
39	22,610	22,610	22,600	22,590	18,860	13,880	7,980	4,298	1,013	190
41	22,620	22,610	22,610	22,600	18,690	13,790	8,036	4,380	1,046	195
43	22,620	22,620	22,620	22,610	18,400	13,640	8,063	4,449	1,077	200
45	23,920	23,910 *	23,890	23,660	17,940	13,420	8,063	4,505	1,106	205
49.75	22,140	22,120	21,830	20,010	16,220	12,760	8,002	4,609	1,170	215
57.25	18,930	18,890	18,340	16,140	13,810	11,420	7,636	4,618	1,245	230
71	13,730	13,680	13,100	11,460	10,280	9,023	6,684	4,419	1,352	252
91	9,300	9,266	8,889	7,932	7,301	6,618	5,246	3,739	1,285	263
151	2,284	2,280	2,228	2,097	2,009	1,910	1,693	1,412	7,487	238
201	70**	70	70	70	70	70	70	70	70	70

VAPOR SPACE

* Solid Sludge
** Water table

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TABLE V. TEMPERATURE RISE IN CAKE (DRY)

Time from Present*, hr	Temperature, °F
0	100
10	260
24 (1 day)	480
100	1,700
168 (1 week)	2,650
720 (1 mo)	9,900
1000	10,700
5000	28,200
∞	30,400

* Present is May 1, 1965

The assumption that equilibrium has been reached at each cooling time allows the maximum temperatures to be calculated as a function of cake thickness and time. These temperatures are shown in Figure 3 for dry soil. The calculated temperatures at short cooling periods are much too high because the time to heat up to equilibrium is quite long, and the calculated temperatures at long cooling times are slightly low because the time for the tank to cool down is of the same order of magnitude as the half-lives of the heat generating fission products. An exact analysis of transient conditions in waste tanks would be too complex to be justified for the present case where it is clear that the temperatures are unreasonably high.

Methods for Maintaining Low Tank Temperatures

Several steps have been suggested for lowering high temperatures in the tanks. These include:

- Wetting the soil above and beside the tank
- Passing cooling air through the vapor space
- Removing soil from above the tank
- Spraying the dry sludge with water.

Wetting the soil above the tank would reduce the temperature as long as the water remained in the soil. The thermal conductivity of wet soil is about 4 or 5 times that of dry soil and the sludge temperature is

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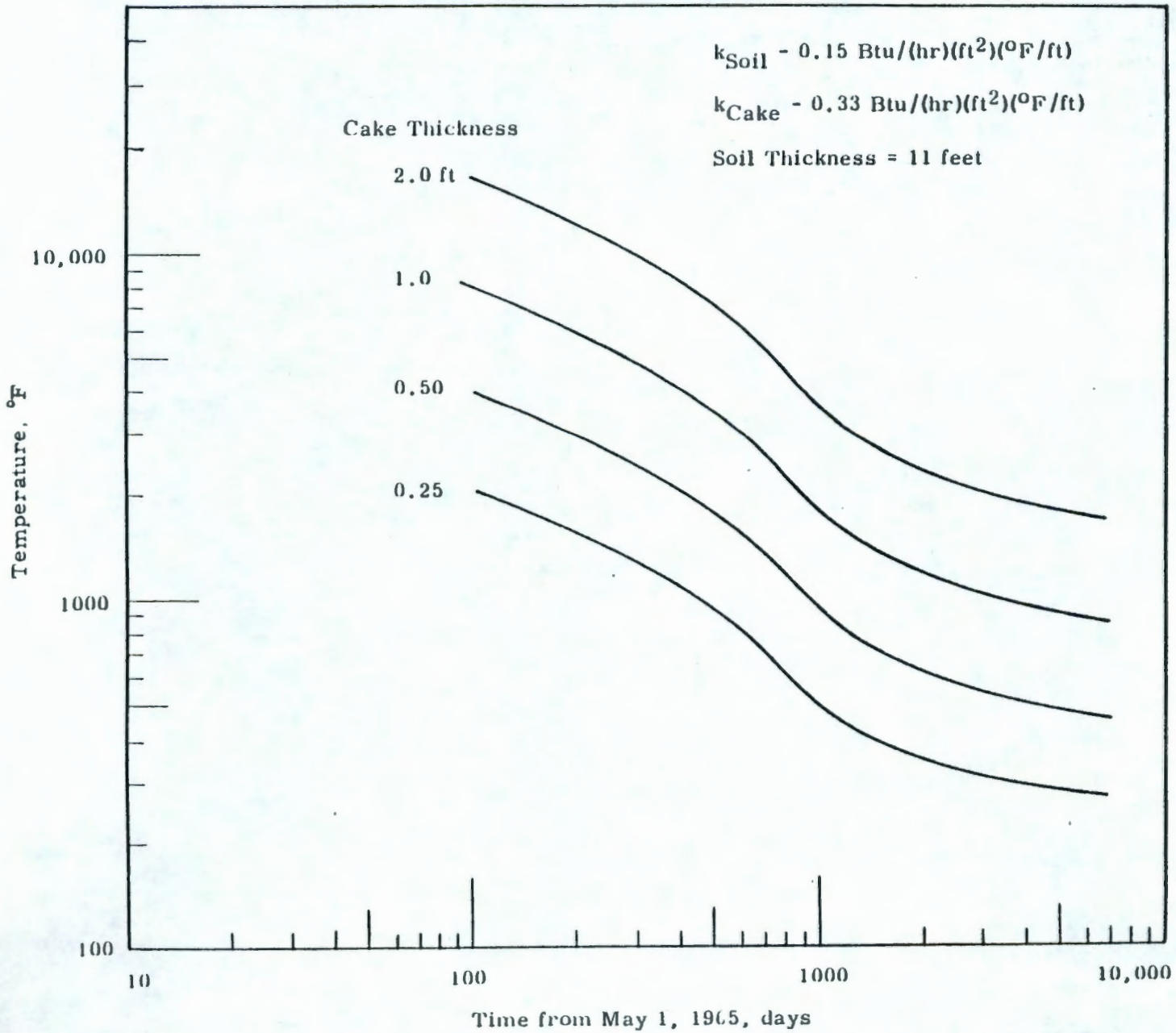

FIGURE 3. TEMPERATURE AT THE BOTTOM OF THE CAKE AS A FUNCTION OF CAKE THICKNESS AND COOLING TIME

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inversely proportional to the soil thermal conductivity. Vaporization of the water in the soil would also remove heat.

Passing cooling air through the vapor space at the rates contemplated would not be effective. A temperature of 30,000 °F for a 2 ft cake is reduced to 13,000 °F by passing 100 ft^3/min air through the vapor space. The exit air would be quite hot, near 12,000 °F.

Removing soil from above the tank would reduce the temperature, since it is roughly proportional to the overlying soil thickness. The amount of soil which could be removed would probably be limited by radioactive shielding considerations.

Spraying the dry sludge with water, and maintaining a liquid layer, would bring the surface of the cake to the boiling point of water. If the water did not penetrate the cake the temperature of the bottom of the cake would be a function of the cake thermal conductivity and the cake thickness as shown in Table VI. Temperatures high enough to damage the tank liner could still be achieved in some cases, and if the water spray were turned off temperature elevation would begin.

None of the above remedies appears to be an adequate substitute for the presence of a boiling solution percolating through the sludge. It is suggested that when the supernate is removed from a tank, as much sludge as possible should be removed with it.

Soil Temperatures Around Leaks

Since the Purex waste tanks are surrounded by dense concrete, a leak appears to start from a hole in the concrete as shown in Figure 4.

The total volume of the leak is not usually equal to the volume of solution that leaked from the tank because the solution occupies only the void space in the soil, and the fission products generating heat may concentrate by sorption on the soil or precipitation. The soil may be only partially saturated with liquid because of capillary forces in the soil. The methods of deriving the equations are given in a previous reports,[4]

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TABLE VI. TEMPERATURE AT THE BOTTOM OF THE TANK WHEN USING A WATER SPRAY ON CAKE SURFACE (Soil Thermal Conductivity = 0.15 Btu/(hr)(ft^2)(°F/ft))

Cake Thickness, ft	Cake Thermal Conductivity, Btu/(hr)(ft^2)(°F/ft)	Time from May 1, 1965, days	Volumetric Heat Generation Rate, Btu/(hr)(ft^3)	Temperature, °F
2.0	0.33	180	129.6	1782
		1000	36.0	648
		3600	18.8	440
	0.80	180	129.6	860
		1000	36.0	392
		3600	18.8	306
	1.20	180	129.6	642
		1000	36.0	332
		3600	18.8	275
1.0	0.33	180	129.6	605
		1000	36.0	321
		3600	18.8	269
	0.80	180	129.6	374
		1000	36.0	257
		3600	18.8	236
	1.20	180	129.6	320
		1000	36.0	242
		3600	18.8	228

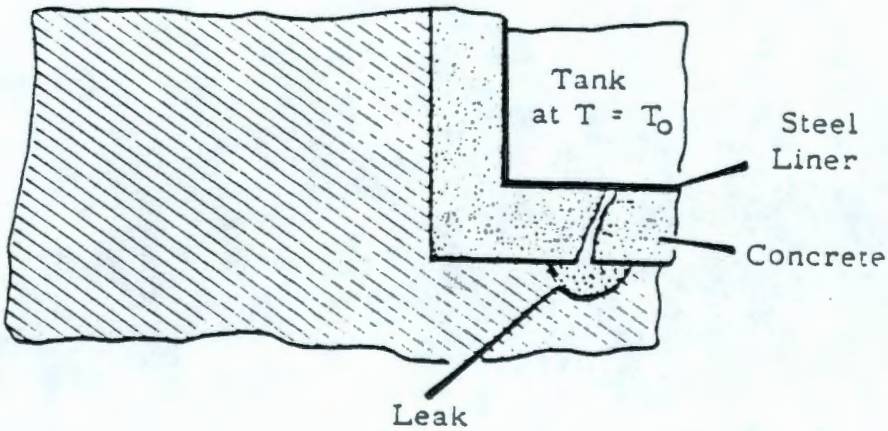

FIGURE 4. SCHEMATIC DIAGRAM OF A LEAK IN A PUREX WASTE TANK

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and will not be discussed here. The basic assumptions, which are vital to an understanding of the results, are listed below:

1. The leak is hemispheroidal.
2. The heat generating material is uniformly distributed throughout the leak volume, which is completely saturated with liquid.
3. The leak is small enough so that the tank wall may be represented as an infinite plane surface.
4. The size of the leak stabilizes long enough for steady state temperatures to be reached.
5. The thermal properties of the soil are uniform.
6. All the leak water has evaporated so that the thermal properties of the soil are the same inside the leak volume as in the external soil.
7. The soil temperature at infinite distance from the tank is the same as the tank temperature.

Assumption No. 6 may be the most unrealistic one for evaluating the true temperatures in a leak; the presence of water may increase the thermal conductivity of the soil by a factor of 4 or 5, reducing the temperature within the leak volume appreciably. On the other hand a leak will eventually dry up and highest soil temperatures will be reached without water in the system. For a detailed analysis of the effect of soil characteristics and moisture content upon soil thermal properties the reader is referred to a recent review by the American Institute of Electrical Engineers.[6]

Assumption No. 7 may be removed by superimposing the calculated temperature rises caused by the leak upon the temperature field around an intact tank as is shown in Figures 10 and 11, on pp. 29 and 30.

Three chemical types of fission products were considered in this analysis:

- Cs^{137} and Sr^{90}, which sorb on the soil with a volumetric distribution coefficient K_D of 0.6 (Ci/ft^3 of soil)/(Ci/ft^3 of solution), just enough to make the final volume of the leak equal to the initial volume of solution which leaked from the tank, if the soil void fraction is 0.35.
- Ruthenium, which does not sorb on the soil.
- $Zr\text{-}Nb^{95}$ and Ce^{144} which are present only in the sludge in alkaline tanks or in solution in acid tanks and which precipitate or adsorb in the soil to give effective distribution coefficients greater than 500.[7] The question of whether these fission products precipitate due to high pH or sorb is an interesting one, since if they precipitate they might eventually redissolve in an acid leak or be dispersed throughout a greater volume of soil, thus reducing the thermal hazard. Present data indicates that the cerium precipitates and the zirconium adsorbs.

In Figure 5 are shown the temperature isotherms around a 5000 gal hemispherical leak of alkaline supernate of the composition given in Table I for Tank 105A. The void fraction in the soil is assumed to be 0.35. After the water has evaporated the leak stabilizes to a radius of 6.95 ft. The background temperature is assumed to be zero everywhere. The two temperatures of greatest interest, the concrete-soil interface temperature and the maximum soil temperature, are 11.8 °F and 49.7 °F for this case.

The temperature variations are shown as a function of leak volume in Figure 6. It is clear that the concrete-soil interface temperature increase stays below 50 °F for all conditions and that even a 50,000 gal leak has a maximum soil temperature rise of only 550 °F at 10 ft from the tank wall.

Leaks of small quantities of sludge into the soil can cause high temperatures at the soil-concrete interface because the specific heat generation rate of the sludge is over 100 times greater than that of the supernate. It is unlikely that solid sludge would leak out of the tank, but if sludge suspended in the supernate leaked into the soil and concentrated in the soil near the leak

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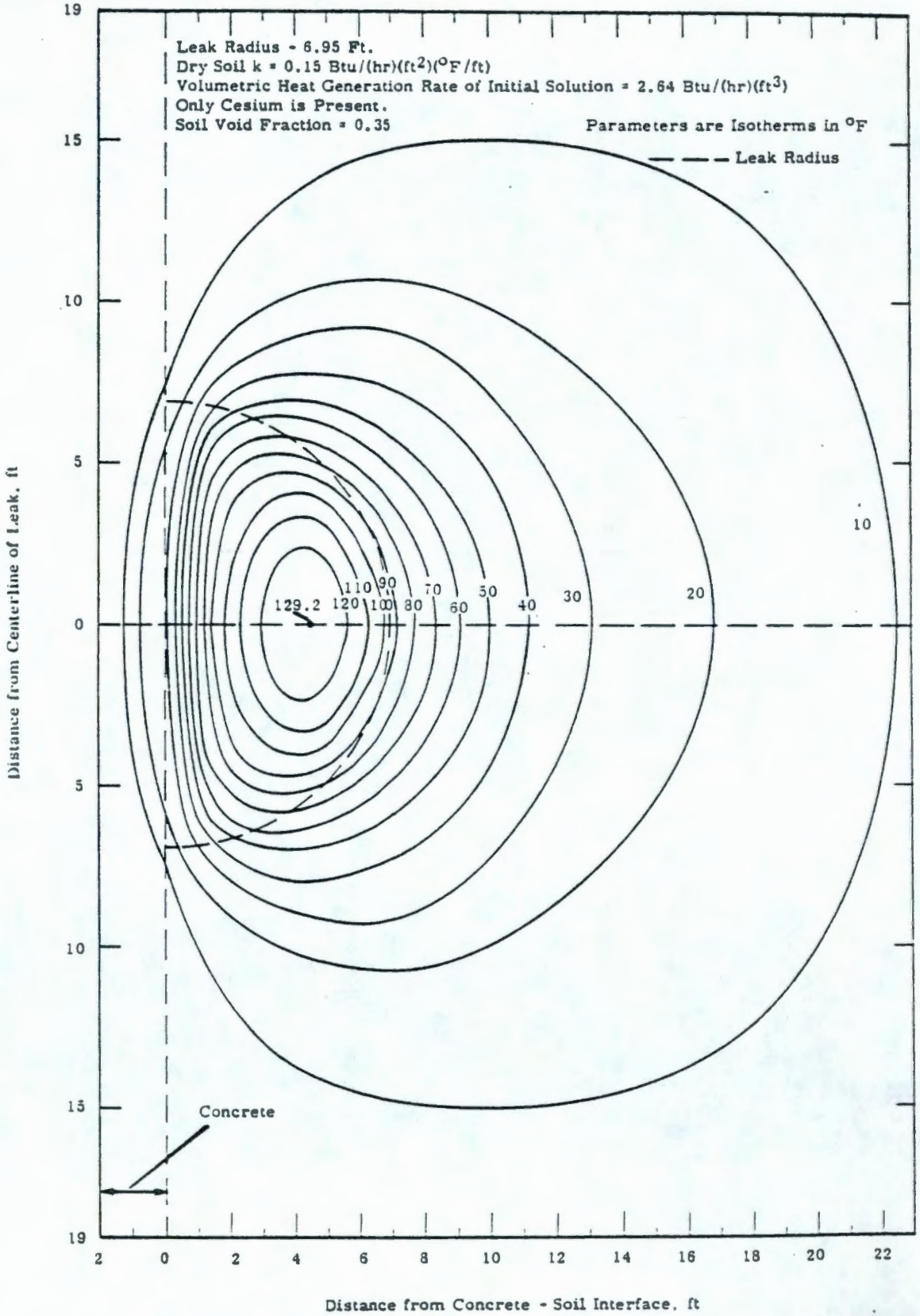

FIGURE 5. TEMPERATURE RISES NEAR A 5000 gal LEAK OF ALKALINE SUPERNATE

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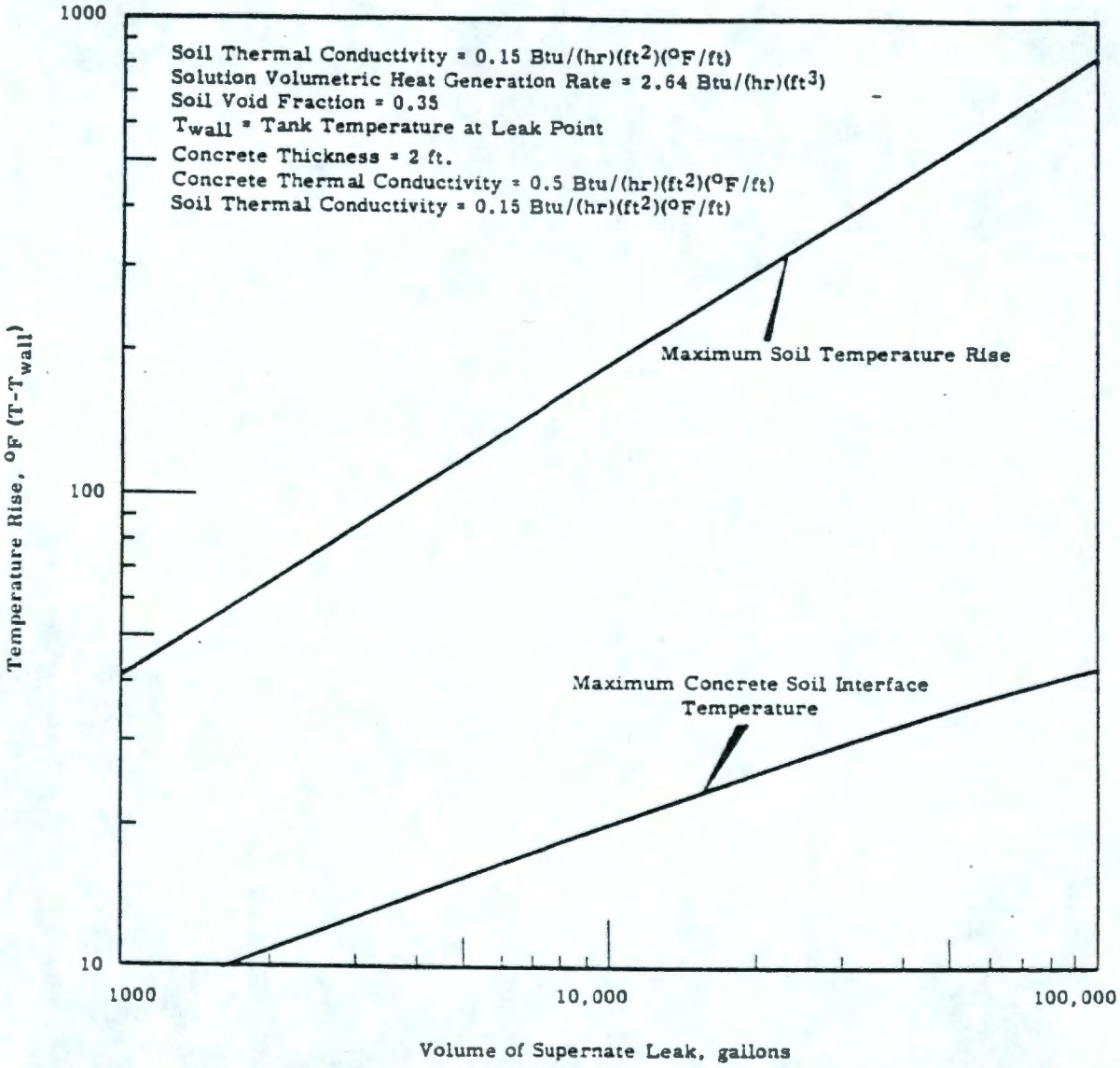

FIGURE 6. SOIL TEMPERATURES IN SUPERNATE LEAKS AS A FUNCTION OF LEAK VOLUME

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point an equivalent result would be obtained. According to Table VII a sludge leak of 175 gal could raise the soil temperature to 1500 °F above the tank temperature. Experiments[7] have shown that solids suspended in the supernate tend to collect in the soil at the point of leakage and block off the further penetration of solids into the soil.

In Figure 7 the effect of variation in shape of the leak upon the maximum temperature is shown. The 5000 gal leak is allowed to elongate into a prolate hemispheroid and to spread along the tank wall to form an oblate hemispheroid without changing total volume. The leak dimensions are given in Figure 8 as a function of leak shape. Figure 7 shows that as the eccentricity, or ratio of the leak radius at the tank wall to the maximum penetration depth into the soil, is varied the maximum soil temperature passes through a maximum at an eccentricity of 0.25, which is an elongated or prolate leak. The concrete-soil interface temperature is nearly independent of leak shape, which indicates the hemisphere results are applicable to other shape leaks; however, the eccentricity at which the maximum soil temperature occurs changes with leak volume.

If the water in the supernate had flashed off to steam as it left the tank, leaving behind salts to fill the pores of the soil, and then more liquid percolated through the dried salts, the cesium and strontium could be distributed throughout the soil without adsorbing. Since the sodium concentration in solidified Purex alkaline supernate is about 22M, the initial concentration in the supernate is about 7M, and the void fraction in the soil is only 0.35, no great concentration of fission products is effected, and the temperature distribution is coincidentally the same as for a regular supernate leak.

The temperature rises for a variety of cases are compared in Table VII for an initial solution heat generation rate of 1.0 Btu/(hr)(ft^3). Temperatures for other heat generation rates may be found by simple ratio. The importance of soil thermal conductivity and fission product distribution coefficients are quite evident. Leaks from acid tanks could result in much higher temperatures than supernate leaks from alkaline tanks because the cerium and zirconium may concentrate at the point of the leak and produce high specific heat generation rates.

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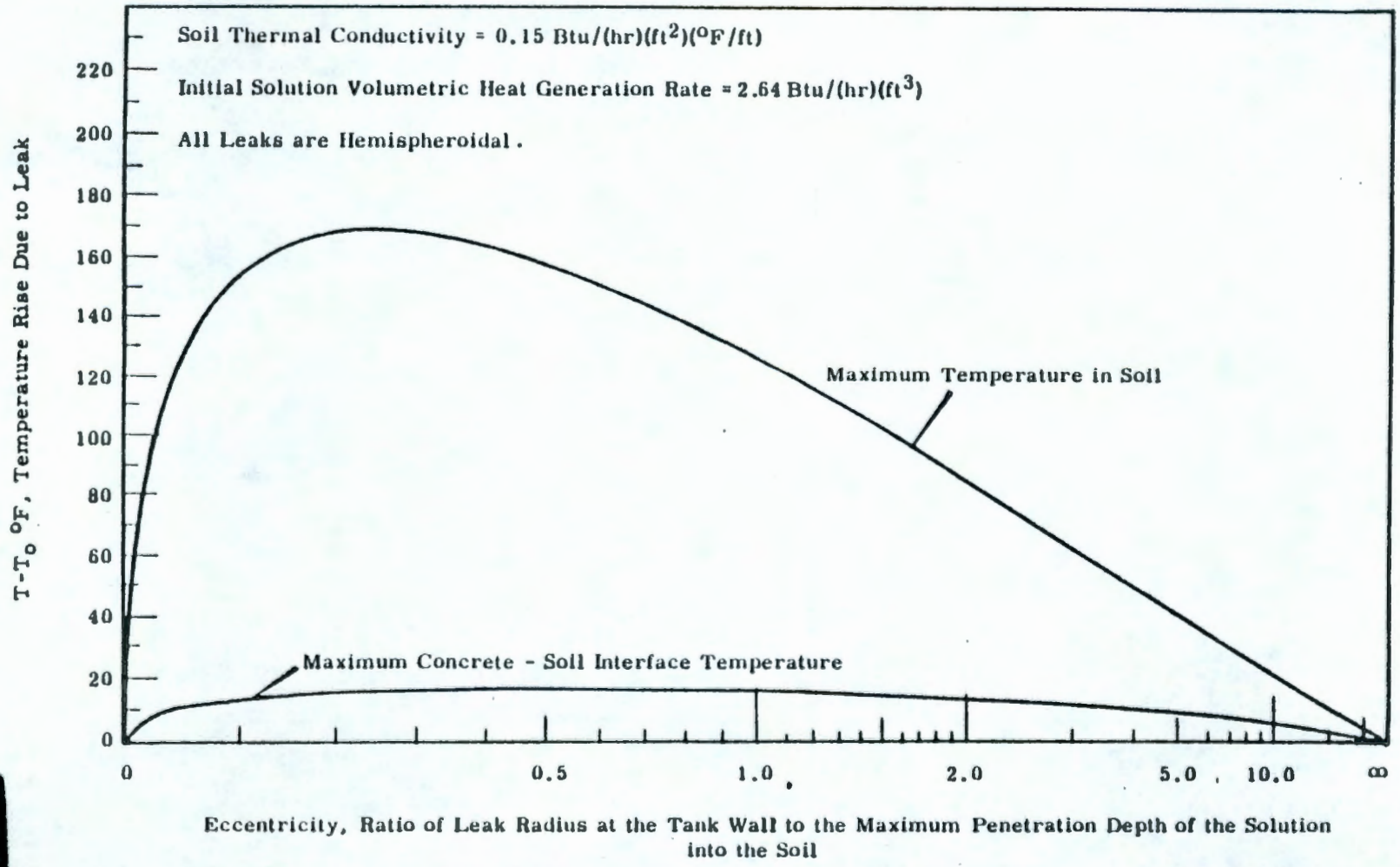

FIGURE 7. EFFECT OF LEAK SHAPE ON MAXIMUM SOIL TEMPERATURE, 5000 gal LEAK OF ALKALINE SUPERNATE

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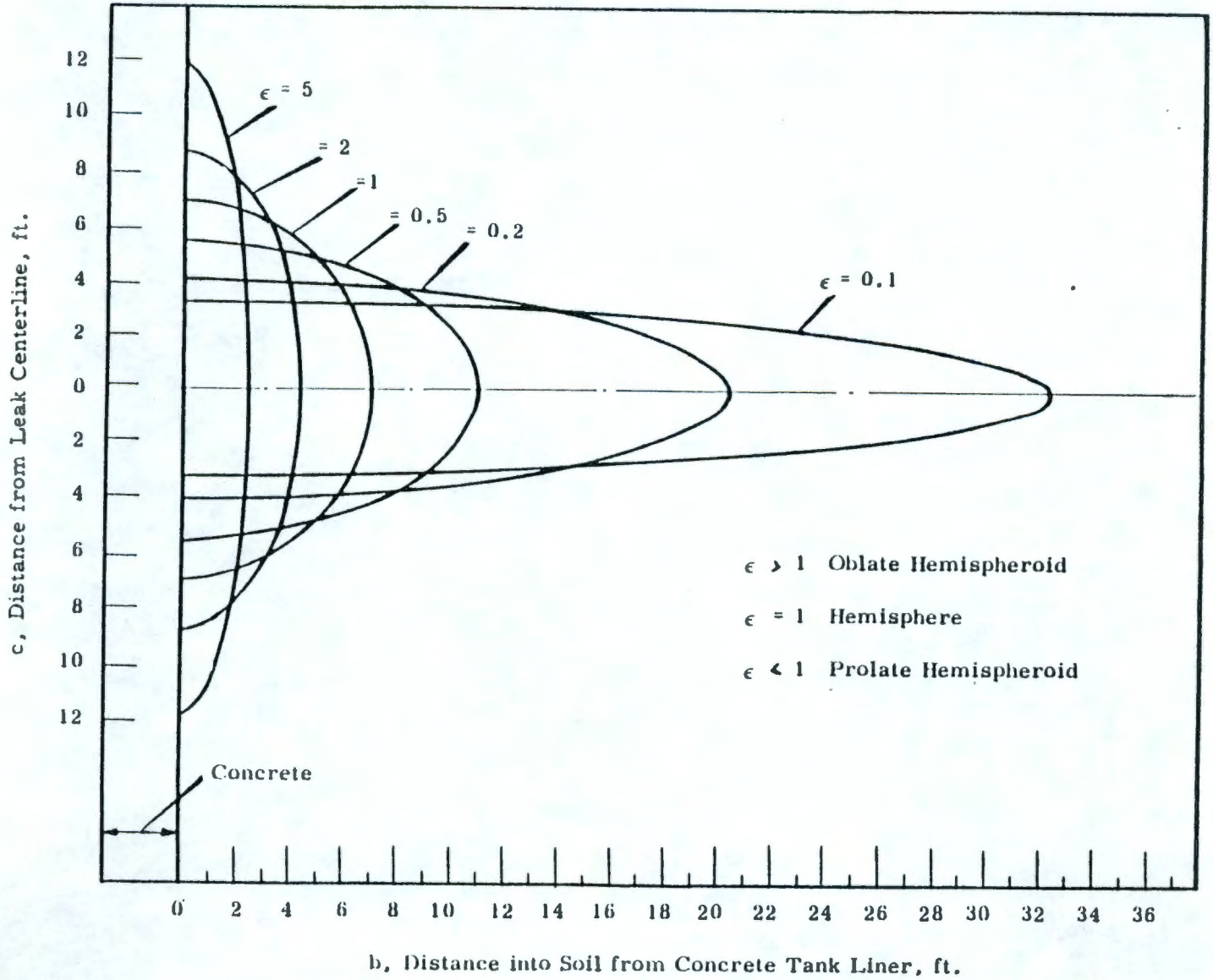

FIGURE 8. LEAK DIMENSIONS AS A FUNCTION OF LEAK SHAPE - 5000 gal LEAK

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TABLE VII. TEMPERATURE RISES IN UNDERGROUND TANK LEAKS
(Heat Generation Rate of Solution in Tank = 1.0 Btu/(hr)(ft3))

Case	Leak Volume, gal	Fission Product Distr. Coeff.	Soil Thermal Cond.	Leak Radius	Maximum Wall Temperature, °F	Maximum Soil Temperature, °F
	V	K_D	k	a, ft	$T_W - T_O$	$T_{max} - T_O$
1	1,000	0*	0.15	5.67	1.9	11.2
2	1,000	0	0.6	5.67	1.5	3.2
3	1,000	0.6**	0.15	4.07	3.5	16.4
4	1,000	0.6	0.6	4.07	2.7	5.0
5	5,000	0	0.15	9.70	3.3	32.6
6	5,000	0	0.6	9.70	2.9	9.2
7	5,000	0.6	0.15	6.95	6.2	47.4
8	5,000	0.6	0.6	6.95	5.3	13.5
9	10,000	0	0.15	12.22	4.1	52.6
10	10,000	0	0.6	12.22	3.8	14.3
11	10,000	0.6	0.15	8.76	8.0	74.0
12	10,000	0.6	0.6	8.76	7.0	20.8
13	25,000	0	0.15	16.58	5.7	96.0
14	25,000	0	0.6	16.58	5.3	25.7
15	25,000	0.6	0.15	11.89	10.9	134.9
16	25,000	0.6	0.6	11.89	9.9	37.0
17	50,000	0	0.15	20.89	7.2	149.6
18	50,000	0	0.6	20.89	6.8	39.3
19	50,000	0.6	0.15	14.98	13.9	209.4
20	50,000	0.6	0.6	14.98	12.8	57.1
21	100,000	0	0.15	26.32	9.1	237.9
22	100,000	0	0.6	26.32	8.7	62.5
23	100,000	0.6	0.15	18.87	17.5	329.6
24	100,000	0.6	0.6	18.87	16.5	88.4
25	100	500†	0.15	0.23	35.4	- -
26	100	500	0.6	0.23	10.7	- -
27	500	500	0.15	0.40	87.8	- -
28	500	500	0.6	0.40	29.8	- -
29	1,000	500	0.15	0.50	126.8	- -
30	1,000	500	0.6	0.50	46.0	- -
31	5,000	500	0.15	0.86	279.3	- -
32	5,000	500	0.6	0.86	122.4	- -
37	10,000	500	0.15	1.08	382.1	606.5
38	10,000	500	0.6	1.08	183.5	190.1
33	25,000	500	0.15	1.47	566.1	1237.0
34	25,000	500	0.6	1.47	307.1	403.8
35	50,000	500	0.15	1.85	751.6	2003.4
36	50,000	500	0.6	1.85	445.9	642.7

* Ruthenium
** Cesium and strontium
† Zirconium-niobium and cerium

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Soil Temperatures Due to Leak in Tank 105A

Temperature measurements[5] in the laterals located 10 ft below tank 105A give an average temperature of 193 °F. In lateral No. 3 there is a hot spot which reaches 260 °F, about 67 °F above the average temperature. The hot spot could possibly be due to:

- a pile of heat generating sludge above the hot spot
- moisture between the bottom of the tank and the lateral which locally raise the thermal conductivity of the soil
- a dried leak which would heat the soil locally.

Only the last cause seems likely since the pile of sludge would transmit most of its heat to the solution within the tank and moisture which was initially present should evaporate at the measured temperatures.

If the measured hot spot were directly below the leak and the soil thermal conductivity were 0.15, a reasonable value for dry soil, the hot spot could be caused by a 6000 gal hemispherical leak of supernate. The radius of the leak would be about 7.5 ft and the hottest spot would be about 340 °F at 4 ft below the tank bottom.

If the soil thermal conductivity were 0.6, a reasonable value for wet soil, the minimum hemispherical leak volume would be 18,000 gal.

The hot spot in the lateral does not necessarily occur directly below the leak; i.e., the lateral could be a few feet from the verical axis of the leak. If the hot spot in the lateral was 10 ft from the leak axis in dry soil, the leak volume could be 14,000 gal.

Calculated Temperatures Around Leaks

No analytical solutions have been found for the general case of temperatures around even a hemispherical leak. A summary of the general solutions is given in Reference 8. Consequently, a computer program called GULP (Generalized Underground Leak Program) for determining temperatures around hemispherical and hemispheroidal leaks was devised.[8] Temperature rise maps computed by GULP are presented in the Appendix for the 38 cases listed in Table VII. Some accuracy was sacrificed to obtain the wide range of

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variation desired. The poorest accuracy was obtained on the centerline of the leak at the concrete near the leak point, where estimated temperature rises may be a factor of two high. At the point of maximum temperature the values are within 5 percent of the correct ones. After the Appendix was compiled, the computer program was modified to calculate the temperatures along the leak center line by the analytical solutions discussed below.

Analytical solutions, available only for temperatures along the centerlines of leaks, are presented in Reference 8 for hemispherical and hemisphe-leaks. For a hemispherical leak the temperature rise in degrees Fahrenheit at the leak point is particularly simple:

$$T - T_0 = \frac{Sa^2}{k}\left(\frac{1}{6}\left(\frac{mk}{ak_m}\right)^2 + \frac{1 - [1 + (mk/ak_m)^2]^{3/2}}{6\, mk/ak_m}\right) \qquad (1)$$

where S is the volumetric heat generation rate of fission products per unit volume of soil within the leak, Btu/(hr)(ft^3), m is the concrete thickness, ft, k is the thermal conductivity of the concrete, and a is the radius of the hemispherical leak, ft. Care should be taken to include the dilution of the liquid by the soil and the sorption of fission product on the soil in the calculation of S and a from initial solution volumes.

Temperature maps calculated by GULP for examples of the three classes of hemispheroidal leaks are given in Table VIII. The distance away from the concrete is given by B in feet, and the distance from the axis of leak is given by C in feet. The temperatures on the axis (C = 0) were calculated by an exact equation, and the temperatures not on the centerline were calculated by finite difference techniques.

Because of the nature of the heat sources involved it is possible to superimpose the results of several calculations. Thus the temperature around a 5000 gal acid leak of solution which initially contained heat generation of 1 Btu/(hr)(ft^3) each by cesium-strontium, zirconium-cerium, and ruthenium can be built up by superimposing Cases 5, 7 and 31 of the Appendix as is shown in Figure 9.

TABLE VIII. TEMPERATURE RISE MAPS FOR HEMISPHEROIDAL LEAKS

m = Concrete thickness, ft = 2.0
E = Void fraction in soil = .350
D = Distribution coefficient = .600
K Soil, Btu/(hr sq ft °F/ft) = .150
K Concrete, Btu/(hr sq ft °F/ft) = .500
Temperature rises are in °F

V = Leak volume = 5000 gal
S′ = Heat generation rate of initial solution, 1.0 Btu/(hr)(ft^3)
R = Concentration factor = 1.053

Prolate Hemispheroidal Leak, ε = 0.5 Leak length, a = 11.03 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	8.0	6.0	4.0	2.0	.0
.00	.1	.2	.5	1.4	2.5	5.1	9.5	11.6	6.5
1.00	.2	.6	1.3	3.8	6.5	12.8	23.2	28.5	25.5
2.00	.3	.9	2.1	5.9	10.0	18.8	32.9	40.6	39.4
4.40	.6	1.7	3.7	9.7	15.4	26.2	44.0	55.5	57.0
5.00	.6	1.9	4.0	10.3	16.1	26.7	44.6	56.7	58.6
6.95	.8	2.4	4.8	11.3	16.9	26.0	41.7	55.1	58.1
8.00	.9	2.6	5.1	11.4	16.5	24.5	37.4	51.2	54.6
10.00	1.1	2.9	5.4	11.0	15.0	20.6	28.4	38.7	42.6
15.00	1.3	3.1	5.1	8.4	10.1	12.1	14.0	15.4	15.5
20.00	1.4	2.9	4.2	5.9	6.7	7.4	8.0	8.4	8.2
30.00	1.3	2.1	2.6	3.1	3.3	3.5	3.6	3.7	3.5

Hemispherical leak, ε = 1.0 Leak length a = 6.95 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	8.0	6.0	4.0	2.0	.0
.00	.0	.1	.4	1.4	3.1	7.3	10.0	11.3	6.2
1.00	.1	.4	1.1	3.8	7.7	17.4	24.1	27.5	24.1
2.00	.2	.7	1.7	5.8	11.1	23.4	33.3	38.5	36.5
4.40	.4	1.3	2.9	8.5	14.2	24.6	38.6	47.0	47.4
5.00	.4	1.4	3.2	8.8	14.1	23.4	36.8	45.7	46.3
6.95	.6	1.8	3.7	8.9	13.0	19.0	26.5	33.7	35.3
8.00	.6	1.9	3.8	8.6	12.1	16.7	22.1	26.9	27.5
10.00	.7	2.1	3.9	7.8	10.2	13.1	16.1	18.4	18.3
15.00	.9	2.2	3.5	5.5	6.5	7.5	8.3	8.9	8.6
20.00	1.0	2.0	2.8	3.9	4.3	4.7	5.0	5.2	4.9
30.00	.9	1.4	1.7	2.1	2.2	2.3	2.3	2.4	2.2

Oblate hemispheroidal leak, ε = 2.0 Leak length, a = 4.38 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	8.0	6.0	4.0	2.0	.0
.00	.0	.1	.3	1.7	5.0	7.6	9.0	9.7	5.3
1.00	.1	.3	.9	4.3	11.3	17.6	21.2	23.2	19.9
2.00	.1	.5	1.4	5.9	13.0	22.2	27.9	31.0	28.6
4.40	.3	1.0	2.3	7.2	11.7	17.9	24.1	28.7	28.1
5.00	.3	1.1	2.5	7.2	11.2	16.4	21.6	25.4	24.7
6.95	.4	1.3	2.8	6.7	9.3	12.4	15.5	17.6	16.9
8.00	.5	1.4	2.9	6.3	8.4	10.8	13.1	14.7	14.0
10.00	.5	1.5	2.9	5.5	6.9	8.4	9.8	10.8	10.1
15.00	.6	1.5	2.5	3.8	4.3	4.9	5.4	5.7	5.2
20.00	.7	1.4	1.9	2.6	2.9	3.1	3.3	3.4	3.1
30.00	.6	1.0	1.2	1.4	1.5	1.5	1.6	1.6	1.4

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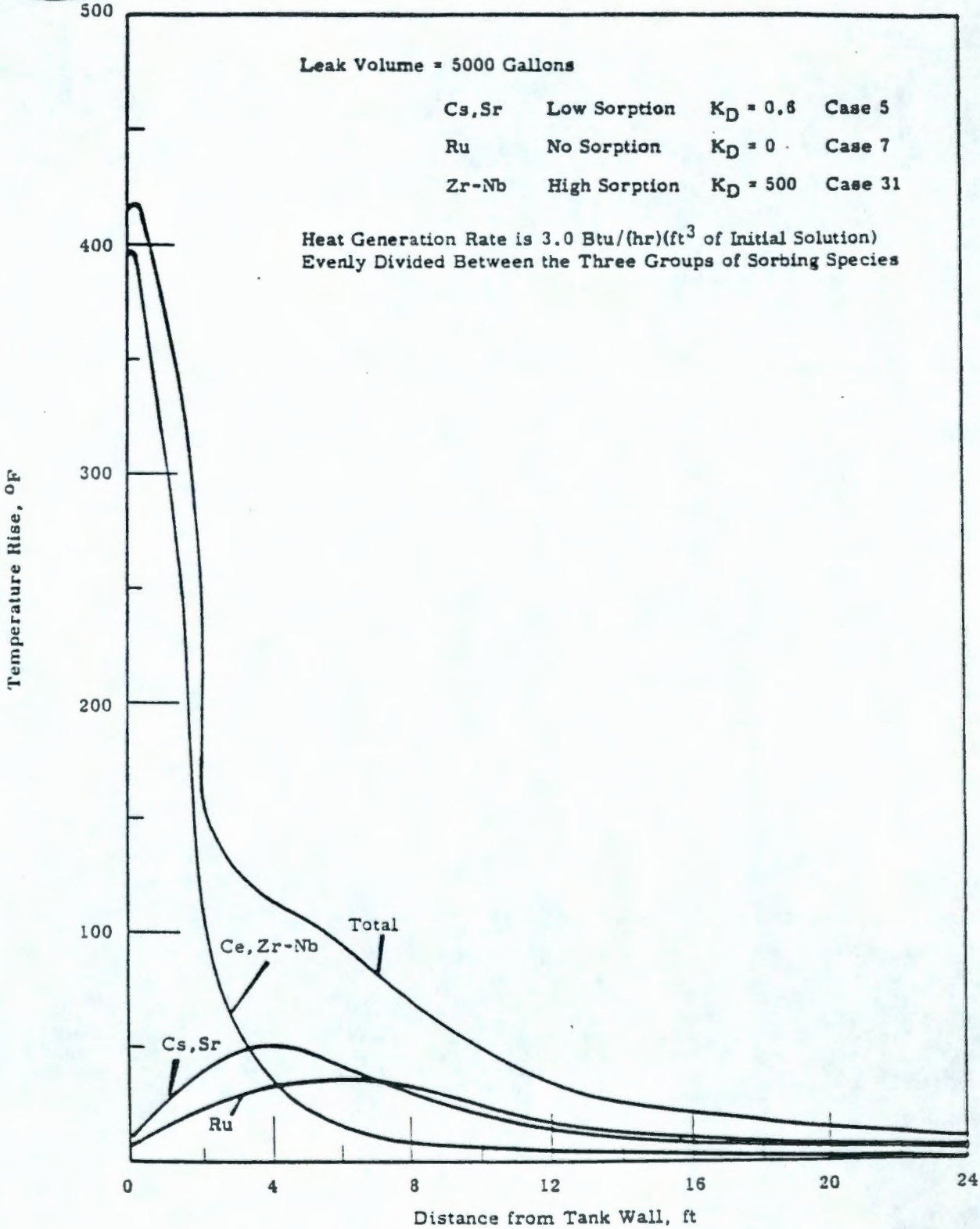

FIGURE 9. LEAK CENTERLINE TEMPERATURES IN AN ACID LEAK

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The most useful aspect of superimposition of leak temperature involves adding the temperature rise in the leak to the undisturbed temperature around the tank to obtain the total temperature in the leak. Thus any one of the 38 cases in the Appendix could be added to the temperatures given in Figure 2 for intact tanks. Such additions are shown in Figure 10 for a 5000 gal leak of alkaline supernate into dry soil and in Figure 11 for a 50,000 gal leak.

The possibility exists for monitoring soil temperatures over extended periods of time to determine background temperatures, and then interpreting sudden temperature rises as being leaks. With the information in the Appendix it may be possible to estimate the approximate size and location of a leak from 3 noncolinear measuring points. One complicating factor may be the introduction of moisture into the soil by the leak. This would tend to raise the background temperature field but would reduce the field due to the heat generators in the leak itself.

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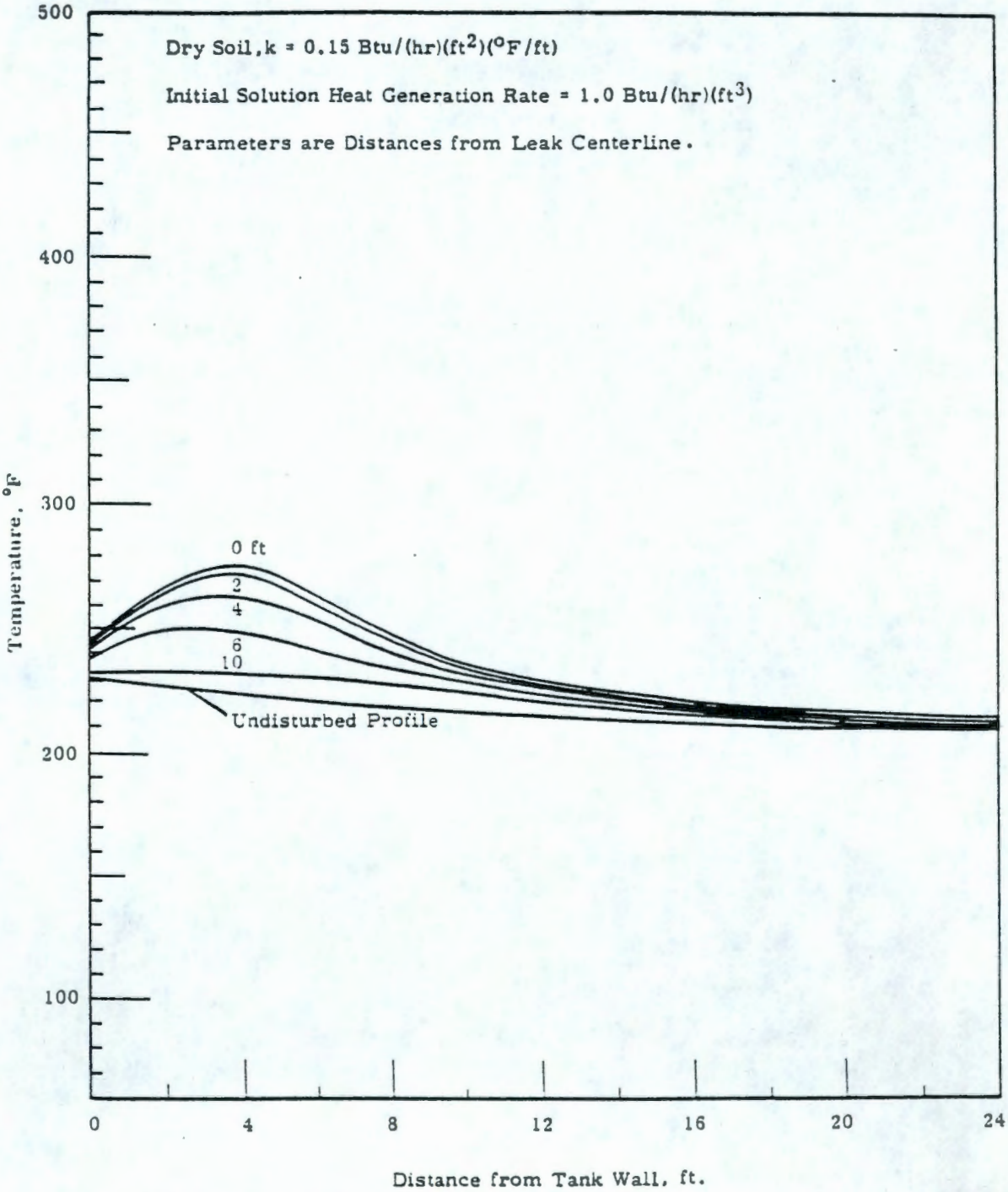

FIGURE 10. TEMPERATURES IN A 5000 gal LEAK OF ALKALINE SUPERNATE

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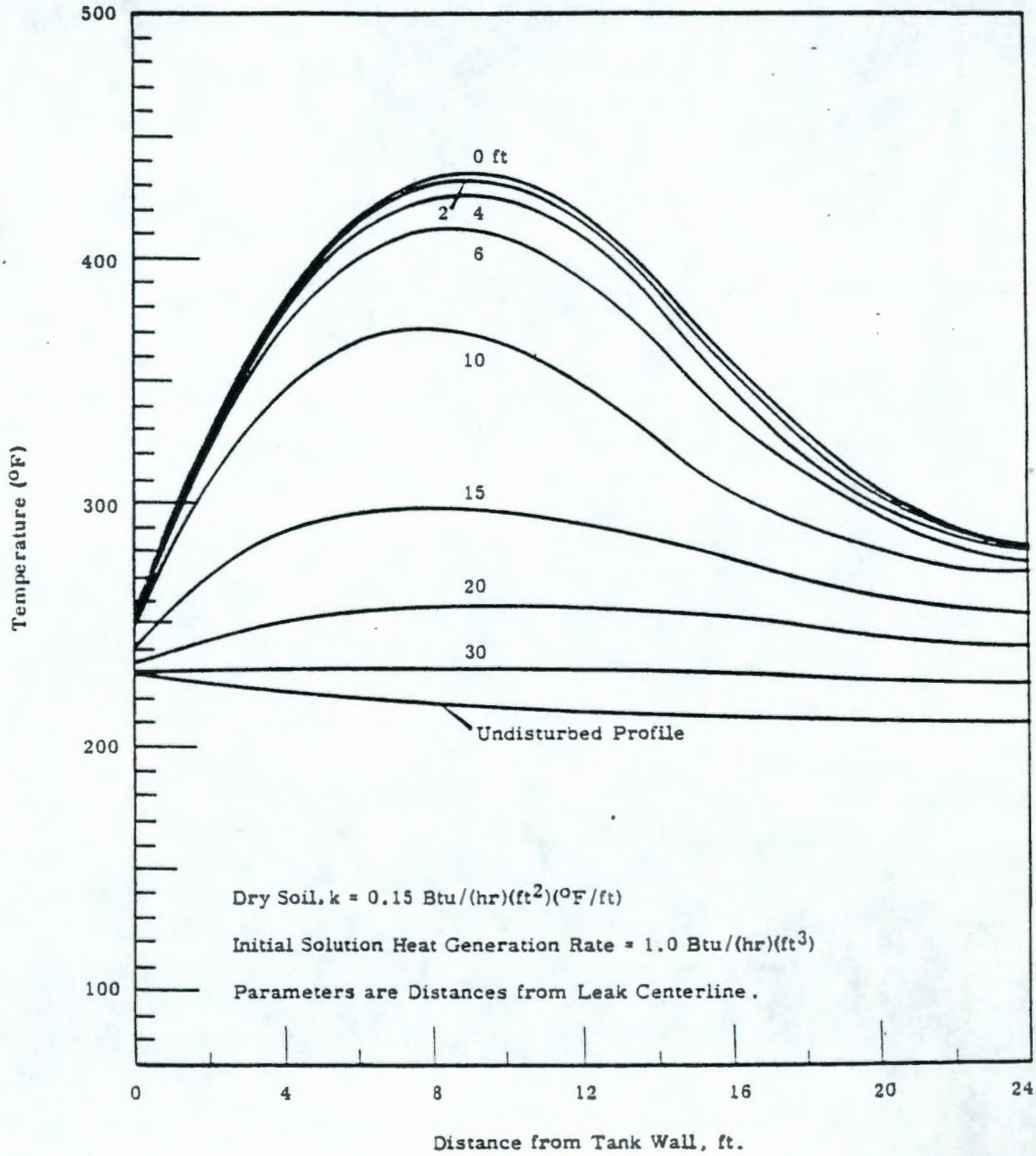

FIGURE 11. TEMPERATURES IN A 50,000 gal LEAK OF ALKALINE SUPERNATE

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ACKNOWLEDGMENTS

This work was performed under the guidance of W. H. Swift, Manager, Engineering Development Unit, Chemical Development, Battelle-Northwest.

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The encouragement and cooperation of S. J. Beard and J. J. Shefcik of the Chemical Processing Department, Hanford Atomic Products Operation, General Electric Company, were decisive in the completion of the work.

We would also like to acknowledge the assistance of G. E. Lysher of Chemical Development, Battelle-Northwest, in producing the original graphs and tables used in this report.

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APPENDIX

Temperature maps for the cases listed in Table A-1 are given in the Appendix.

The nomenclature on the tables is as follows:

V = Volume of initial solution leaked, gal

K = Soil thermal conductivity, Btu/(hr)(ft^2)(°F/ft)

D = Distribution coefficient of fission products, ft^3 of soil/ft^3 of solution

R = Ratio of final volume of leak to initial volume of solution leaked

A = Leak radius, ft

C = Distance from centerline of leak, ft

B = Distance from tank wall, ft

E = Void fraction in soil, taken as 0.35

The temperature rises in the leaks may be adjusted for initial solution heat generation rates different from unity by a simple ratio.

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TABLE A-1. TEMPERATURE RISES IN HEMISPHERICAL UNDERGROUND TANK LEAKS CALCULATED BY GULP [Heat Generation Rate of Solution in Tank = 1.0 Btu/(hr)(ft^3)]

Case	Leak Volume, gal	Fission Product Distr. Coeff.	Soil Thermal Cond.	Leak Radius	Maximum Wall Temperature, °F	Maximum Soil Temperature, °F
	V	D	K	A, ft	T_W-T_O*	T_{max}-T_O*
1	1,000	0	0.15	5.67	3.5(1.9)	11.8(11.2)
2	1,000	0	0.6	5.67	2.4(1.5)	3.7(3.2)
3	1,000	0.6	0.15	4.07	6.4(3.5)	17.9(16.4)
4	1,000	0.6	0.6	4.07	3.9(2.7)	5.8(5.0)
5	5,000	0	0.15	9.70	6.2(3.3)	34.1(32.6)
6	5,000	0	0.6	9.70	4.9(2.9)	10.3(9.2)
7	5,000	0.6	0.15	6.95	11.8(6.2)	49.7(47.4)
8	5,000	0.6	0.6	6.95	8.6(5.3)	15.0(13.5)
9	10,000	0	0.15	12.22	8.0(4.1)	54.1(52.6)
10	10,000	0	0.6	12.22	6.6(3.8)	15.7(14.3)
11	10,000	0.6	0.15	8.76	15.2(8.0)	77.3(74.0)
12	10,000	0.6	0.6	8.76	11.7(7.0)	23.2(20.8)
13	25,000	0	0.15	16.58	11.0(5.7)	98.3(96.0)
14	25,000	0	0.6	16.58	9.6(5.3)	27.7(25.7)
15	25,000	0.6	0.15	11.89	21.1(10.9)	139.4(134.9)
16	25,000	0.6	0.6	11.89	17.4(9.9)	40.5(37.0)
17	50,000	0	0.15	20.89	14.0(7.2)	152.1(149.6)
18	50,000	0	0.6	20.89	12.6(6.8)	41.7(39.3)
19	50,000	0.6	0.15	14.98	26.9(13.9)	218.0(209.4)
20	50,000	0.6	0.6	14.98	23.1(12.8)	62.0(57.1)
21	100,000	0	0.15	26.32	17.7(9.1)	241.8(237.9)
22	100,000	0	0.6	26.32	16.3(8.7)	66.0(62.5)
23	100,000	0.6	0.15	18.87	34.1(17.5)	325.0(329.6)
24	100,000	0.6	0.6	18.87	30.3(16.5)	95.2(88.4)
25	100	500	0.15	0.23	40.0(35.4)	- -
26	100	500	0.6	0.23	11.0(10.7)	- -
27	500	500	0.15	0.40	107.1(87.8)	- -
28	500	500	0.6	0.40	31.5(29.8)	- -
29	1,000	500	0.15	0.50	161.2(126.8)	- -
30	1,000	500	0.6	0.50	49.3(46.0)	- -
31	5,000	500	0.15	0.86	395.9(279.3)	- -
32	5,000	500	0.6	0.86	137.2(122.4)	- -
37	10,000	500	0.15	1.08	568.5(382.1)	679.1(606.5)
38	10,000	500	0.6	1.08	211.3(183.5)	- - (190.1)
33	25,000	500	0.15	1.47	894.3(566.1)	1437.1(1287.0)
34	25,000	500	0.6	1.47	369.6(307.1)	444.3(403.8)
35	50,000	500	0.15	1.85	1236.3(751.6)	2258.1(2008.4)
36	50,000	500	0.6	1.85	558.2(445.9)	717.4(642.7)

* Temperatures calculated by the analytical expression now included in GULP, which give exact answers, are given in parentheses.

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TEMPERATURE MAPS AROUND HEMISPHERICAL LEAKS

Numbers in Table are $T-T_0$, °F

Case 1 V = 1000 gal. K = 0.1, D = 0, R = 2.857, A = 5.67 ft.

C ACROSS	0.	2.0	4.0	6.0	6.9	10.0	15.0	20.0	30.0
B DOWN									
0.	3.5	3.3	2.6	1.3	0.8	0.2	0.1	0.0	0.0
1.00	8.2	7.7	6.2	3.0	1.9	0.6	0.2	0.1	0.0
2.00	11.1	10.4	8.0	3.9	2.7	0.9	0.3	0.1	0.0
4.40	11.8	10.7	7.3	4.1	3.2	1.4	0.5	0.2	0.1
5.00	10.8	9.6	6.5	4.0	3.1	1.5	0.5	0.2	0.1
6.95	6.4	5.9	4.6	3.2	2.7	1.5	0.6	0.3	0.1
8.00	5.0	4.7	3.8	2.9	2.4	1.5	0.6	0.3	0.1
10.00	3.3	3.2	2.8	2.2	2.0	1.3	0.7	0.4	0.1
15.00	1.6	1.5	1.4	1.3	1.2	0.9	0.6	0.4	0.2
20.00	0.9	0.9	0.9	0.8	0.8	0.7	0.5	0.3	0.2
30.00	0.4	0.4	0.4	0.4	0.4	0.4	0.3	0.2	0.1

Case 2 V = 1000 gal, K = 0.6, D = 0, R = 2.857, A = 5.67 ft.

C ACROSS	0.	2.0	4.0	6.0	6.9	10.0	15.0	20.0	30.0
B DOWN									
0.	2.4	2.2	1.8	1.1	0.8	0.3	0.1	0.0	0.0
1.00	3.3	3.1	2.5	1.4	1.0	0.4	0.1	0.1	0.0
2.00	3.7	3.5	2.8	1.6	1.1	0.5	0.2	0.1	0.0
4.40	3.6	3.2	2.3	1.4	1.2	0.6	0.2	0.1	0.0
5.00	3.2	2.9	2.1	1.4	1.1	0.6	0.2	0.1	0.0
6.95	2.0	1.9	1.5	1.1	1.0	0.6	0.3	0.1	0.0
8.00	1.6	1.5	1.3	1.0	0.9	0.5	0.3	0.1	0.1
10.00	1.1	1.1	0.9	0.8	0.7	0.5	0.3	0.1	0.1
15.00	0.5	0.5	0.5	0.5	0.4	0.3	0.2	0.1	0.1
20.00	0.3	0.3	0.3	0.3	0.3	0.2	0.2	0.1	0.1
30.00	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Case 3 V = 1000 gal, K = 0.6, D = 0.6, R = 1.053, A = 4.07 ft

C ACROSS	0.	2.0	4.0	6.0	6.9	10.0	15.0	20.0	30.0
B DOWN									
0.	6.4	5.7	3.0	0.9	0.5	0.2	0.1	0.0	0.0
1.00	14.5	12.7	6.5	2.1	1.4	0.5	0.1	0.1	0.0
2.00	17.9	15.3	7.5	2.9	2.0	0.7	0.2	0.1	0.0
4.40	11.6	9.4	5.7	3.2	2.4	1.1	0.4	0.2	0.1
5.00	9.3	7.8	5.1	3.1	2.4	1.1	0.4	0.2	0.1
6.95	5.2	4.7	3.6	2.5	2.1	1.2	0.5	0.2	0.1
8.00	4.0	3.7	3.0	2.2	1.9	1.1	0.5	0.2	0.1
10.00	2.6	2.5	2.2	1.8	1.6	1.0	0.5	0.3	0.1
15.00	1.2	1.2	1.1	1.0	0.9	0.7	0.5	0.3	0.1
20.00	0.7	0.7	0.7	0.6	0.6	0.5	0.4	0.3	0.1
30.00									

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Case 4 V = 1,000 gal, K = 0.6, D = 0.6, R = 1.053, A = 4.07 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.0	0.0	0.1	0.3	0.7	0.9	2.1	3.5	3.9
1.00	0.0	0.1	0.1	0.4	0.9	1.2	2.7	4.7	5.3
2.00	0.0	0.1	0.2	0.4	1.0	1.3	2.8	5.0	5.8
4.40	0.0	0.1	0.2	0.5	1.0	1.2	2.0	3.1	3.7
5.00	0.0	0.1	0.2	0.5	1.0	1.2	1.8	2.6	3.0
6.95	0.0	0.1	0.2	0.5	0.8	1.0	1.3	1.6	1.8
8.00	0.0	0.1	0.2	0.5	0.7	0.9	1.1	1.3	1.4
10.00	0.0	0.1	0.2	0.4	0.6	0.7	0.8	0.9	1.0
15.00	0.1	0.1	0.2	0.3	0.4	0.4	0.4	0.5	0.5
20.00	0.1	0.1	0.2	0.2	0.2	0.3	0.3	0.3	0.3
30.00	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Case 5 V = 5,000 gal, K = 0.15, D = 0, R = 2.857, A = 9.70 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.1	0.2	0.6	2.4	4.8	5.2	5.8	6.1	6.2
1.00	0.2	0.6	1.5	6.0	11.8	12.8	14.4	15.3	15.6
2.00	0.3	1.0	2.4	8.7	16.9	18.6	21.1	22.5	22.9
4.40	0.5	1.8	4.1	11.9	22.9	25.6	29.8	32.2	33.0
5.00	0.6	1.9	4.3	12.1	23.1	26.0	30.6	33.2	34.1
6.95	0.8	2.4	5.0	12.0	20.9	24.3	29.8	33.0	34.0
8.00	0.8	2.6	5.2	11.5	18.8	21.7	27.4	30.8	31.9
10.00	1.0	2.8	5.2	10.3	15.2	17.0	20.6	23.3	24.4
15.00	1.2	2.9	4.6	7.3	9.2	9.7	10.8	11.5	11.8
20.00	1.3	2.6	3.7	5.1	5.9	6.1	6.5	6.8	6.9
30.00	1.2	1.9	2.3	2.7	2.9	3.0	3.1	3.1	3.2

Case 6 V = 5,000 gal, K = 0.6, D = 0, R = 2.857, A = 9.70 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.1	0.3	0.7	2.2	3.7	4.0	4.6	4.8	4.9
1.00	0.1	0.4	1.0	2.9	5.1	5.6	6.3	6.7	6.8
2.00	0.2	0.5	1.2	3.5	6.1	6.7	7.6	8.1	8.3
4.40	0.2	0.8	1.6	4.1	7.2	7.9	9.2	9.9	10.1
5.00	0.3	0.8	1.7	4.1	7.1	8.0	9.3	10.0	10.3
6.95	0.3	0.9	1.8	3.9	6.3	7.3	8.7	9.6	9.9
8.00	0.3	1.0	1.8	3.7	5.7	6.5	8.0	8.9	9.2
10.00	0.4	1.0	1.8	3.3	4.6	5.1	6.1	6.8	7.1
15.00	0.4	1.0	1.5	2.3	2.8	3.0	3.3	3.5	3.6
20.00	0.5	0.9	1.2	1.6	1.9	1.9	2.0	2.1	2.1
30.00	0.4	0.6	0.8	0.9	1.0	1.0	1.0	1.0	1.0

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Case 7 V = 5,000 gal, K = 0.15, D = 0.6, R = 1.053, A = 6.95 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.0	0.2	0.4	1.5	5.2	7.4	10.0	11.4	11.8
1.00	0.1	0.5	1.1	3.8	12.4	17.4	24.2	27.6	28.6
2.00	0.2	0.7	1.7	5.8	16.7	23.4	33.3	38.5	40.2
4.40	0.4	1.3	2.9	8.5	18.9	24.6	38.6	47.0	49.7
5.00	0.4	1.4	3.2	8.8	18.4	23.4	36.8	45.7	48.6
6.95	0.6	1.8	3.7	8.9	15.9	19.0	26.5	33.7	36.8
8.00	0.6	1.9	3.8	8.6	14.4	16.7	22.1	26.9	28.8
10.00	0.7	2.1	3.9	7.8	11.7	13.1	16.1	18.4	19.3
15.00	0.9	2.2	3.5	5.5	7.0	7.5	8.3	8.9	9.1
20.00	1.0	2.0	2.8	3.9	4.5	4.7	5.0	5.2	5.3
30.00	0.9	1.4	1.7	2.1	2.2	2.3	2.3	2.4	2.4

Case 8 V = 5,000 gal, K = 0.6, D = 0.6, R = 1.053, A = 6.95 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.1	0.3	0.6	1.7	4.2	5.4	7.5	8.3	8.6
1.00	0.1	0.3	0.8	2.3	5.7	7.4	9.9	11.4	11.8
2.00	0.1	0.4	1.0	2.8	6.4	8.5	11.6	13.4	13.9
4.40	0.2	0.6	1.3	3.3	6.4	8.0	11.9	14.3	15.0
5.00	0.2	0.7	1.4	3.3	6.2	7.6	11.3	13.7	14.5
6.95	0.3	0.8	1.5	3.2	5.3	6.2	8.2	10.2	11.0
8.00	0.3	0.8	1.5	3.0	4.8	5.4	6.9	8.2	8.7
10.00	0.3	0.8	1.5	2.7	3.9	4.3	5.1	5.8	6.0
15.00	0.4	0.8	1.3	1.9	2.4	2.5	2.8	2.9	3.0
20.00	0.4	0.7	1.0	1.4	1.6	1.6	1.7	1.8	1.8
30.00	0.3	0.5	0.6	0.7	0.8	0.8	0.8	0.8	0.8

Case 9 V = 10,000 gal, K = 0.15, D = 0, R = 2.857, A = 12.22 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.2	0.6	1.5	5.4	6.9	7.2	7.7	7.9	8.0
1.00	0.4	1.6	4.1	13.5	17.3	18.1	19.3	20.0	20.3
2.00	0.7	2.5	6.4	19.8	25.8	27.0	29.0	30.1	30.4
4.40	1.3	4.5	10.5	28.7	38.7	40.9	44.3	46.3	47.0
5.00	1.5	4.9	11.1	29.6	40.4	42.9	46.6	48.8	49.6
6.95	1.9	6.0	12.6	29.8	42.7	45.7	50.4	53.1	54.0
8.00	2.1	6.4	12.9	28.4	41.9	45.1	50.2	53.2	54.1
10.00	2.5	6.9	13.0	25.2	36.6	40.1	45.8	49.2	50.3
15.00	3.0	7.1	11.3	17.6	22.0	23.4	25.8	27.4	28.0
20.00	3.1	6.4	9.1	12.3	14.2	14.8	15.7	16.3	16.5
30.00	2.8	4.6	5.6	6.6	7.1	7.3	7.5	7.6	7.7

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Case 10 V = 10,000 gal, K = 0.6, D = 0, R = 2.857, A = 12.22 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.2	0.7	1.7	4.4	5.6	5.9	6.3	6.6	6.6
1.00	0.3	1.0	2.3	6.1	7.8	8.2	8.8	9.1	9.2
2.00	0.4	1.3	2.9	7.4	9.5	10.0	10.7	11.2	11.3
4.40	0.6	1.8	3.8	9.1	12.1	12.7	13.8	14.4	14.6
5.00	0.6	1.9	3.9	9.3	12.4	13.1	14.2	14.9	15.1
6.95	0.7	2.2	4.2	9.0	12.6	13.4	14.7	15.5	15.7
8.00	0.8	2.3	4.2	8.6	12.2	13.1	14.4	15.3	15.5
10.00	0.9	2.4	4.2	7.6	10.6	11.5	13.0	13.9	14.2
15.00	1.0	2.3	3.5	5.3	6.5	6.9	7.5	7.9	8.1
20.00	1.1	2.0	2.8	3.7	4.3	4.4	4.7	4.8	4.9
30.00	0.9	1.4	1.8	2.0	2.2	2.2	2.3	2.3	2.3

Case 11 V = 10,000 gal, K = 0.15, D = 0.6, R = 1.053, A = 8.76 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.1	0.4	1.0	4.0	10.6	11.9	13.8	14.9	15.2
1.00	0.3	1.1	2.7	10.2	25.8	29.2	34.1	36.8	37.7
2.00	0.5	1.8	4.3	15.1	36.3	41.5	49.1	53.2	54.6
4.40	1.0	3.2	7.3	21.3	45.7	53.8	66.3	73.5	75.8
5.00	1.1	3.5	7.8	21.8	45.0	53.6	67.1	74.8	77.3
6.95	1.4	4.3	9.0	21.8	38.5	45.5	60.7	69.9	72.9
8.00	1.5	4.7	9.4	21.0	34.7	40.1	52.3	61.9	65.1
10.00	1.8	5.1	9.6	18.9	28.1	31.4	38.2	43.5	45.5
15.00	2.2	5.3	8.5	13.4	16.9	17.9	19.9	21.3	21.8
20.00	2.3	4.8	6.8	9.3	10.8	11.3	12.0	12.5	12.7
30.00	2.1	3.4	4.2	5.0	5.4	5.5	5.7	5.8	5.8

Case 12 V = 10,000 gal, K = 0.6, D = 0.6, R = 1.053, A = 8.76 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.2	0.6	1.3	4.0	8.1	9.1	10.6	11.5	11.7
1.00	0.2	0.8	1.8	5.4	11.1	12.5	14.6	15.8	16.2
2.00	0.3	1.0	2.2	6.4	13.2	14.9	17.5	19.0	19.5
4.40	0.5	1.4	3.0	7.6	14.5	16.8	20.4	22.4	23.1
5.00	0.5	1.5	3.1	7.6	14.1	16.5	20.3	22.5	23.2
6.95	0.6	1.7	3.4	7.3	12.0	13.9	17.9	20.4	21.2
8.00	0.6	1.8	3.4	6.9	10.8	12.3	15.5	18.1	18.9
10.00	0.7	1.9	3.4	6.2	8.8	9.7	11.5	13.0	13.5
15.00	0.8	1.9	2.9	4.3	5.4	5.7	6.2	6.5	6.8
20.00	0.9	1.7	2.3	3.1	3.5	3.6	3.9	4.0	4.0
30.00	0.8	1.2	1.4	1.7	1.8	1.8	1.9	1.9	1.9

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Case 13 V = 25,000 gal, K = 0.15, D = 0, R = 2.857, A = 16.58 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.6	2.2	6.4	9.3	10.2	10.5	10.8	11.0	11.0
1.00	1.5	5.8	16.3	23.8	26.3	26.8	27.7	28.2	28.4
2.00	2.5	9.3	24.5	36.2	40.2	41.0	42.4	43.3	43.5
4.40	4.6	16.1	38.1	58.3	65.4	67.1	69.6	71.1	71.6
5.00	5.0	17.4	40.2	62.1	70.1	71.9	74.7	76.4	77.0
6.95	6.5	20.9	44.2	71.1	81.1	83.4	87.1	89.3	90.0
8.00	7.2	22.2	44.7	73.6	84.6	87.2	91.3	93.7	94.5
10.00	8.3	23.7	44.0	74.3	86.9	89.8	94.6	97.4	98.3
15.00	10.0	23.7	37.4	56.8	69.9	73.6	79.4	82.9	84.1
20.00	10.5	21.1	29.7	39.7	45.6	47.2	50.0	51.8	52.4
30.00	9.4	15.0	18.3	21.5	23.1	23.5	24.2	24.6	24.7

Case 14 V = 25,000 gal, K = 0.6, D = 0, R = 2.857, A = 16.58 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.7	2.4	5.5	8.0	8.8	9.0	9.4	9.5	9.6
1.00	1.0	3.4	7.7	11.1	12.3	12.6	13.1	13.3	13.4
2.00	1.2	4.2	9.5	13.8	15.3	15.7	16.3	16.6	16.7
4.40	1.8	5.8	12.4	18.5	20.7	21.2	22.0	22.5	22.7
5.00	2.0	6.1	12.8	19.3	21.7	22.2	23.1	23.6	23.8
6.95	2.3	6.9	13.5	21.0	23.9	24.5	25.6	26.2	26.4
8.00	2.5	7.2	13.5	21.4	24.5	25.2	26.3	27.0	27.2
10.00	2.8	7.4	13.1	21.2	24.6	25.4	26.7	27.4	27.7
15.00	3.2	7.2	10.9	16.1	19.5	20.5	22.0	22.9	23.2
20.00	3.3	6.3	8.7	11.4	12.9	13.3	14.1	14.6	14.7
30.00	2.9	4.5	5.4	6.3	6.7	6.8	7.0	7.1	7.1

Case 15 V = 25,000 gal, K = 0.15, D = 0.6, R = 1.053, A = 11.89 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.4	1.4	3.7	13.8	18.0	18.8	20.1	20.9	21.1
1.00	1.1	3.8	9.8	34.4	45.1	47.4	50.8	52.7	53.4
2.00	1.7	6.1	15.4	50.1	66.9	70.4	75.8	78.9	79.9
4.40	3.3	10.9	25.3	71.5	99.4	105.5	115.1	120.7	122.5
5.00	3.6	11.9	26.9	73.5	103.6	110.3	120.9	127.0	129.0
6.95	4.6	14.5	30.6	72.5	108.2	116.4	129.3	136.9	139.4
8.00	5.1	15.6	31.5	69.2	105.1	113.9	127.9	136.2	138.9
10.00	6.0	16.9	31.7	61.6	89.5	99.0	114.7	123.9	127.0
15.00	7.3	17.3	27.7	43.1	53.9	57.1	63.1	67.2	68.6
20.00	7.7	15.6	22.1	30.1	34.8	36.1	38.4	39.9	40.4
30.00	6.9	11.1	13.7	16.2	17.4	17.7	18.3	18.6	18.7

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Case 16 V = 25,000 gal, K = 0.6, D = 0.6, R = 1.053, A = 11.89 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.5	1.8	4.2	11.2	14.6	15.3	16.5	17.2	17.4
1.00	0.7	2.5	5.7	15.5	20.2	21.3	22.9	23.8	24.1
2.00	0.9	3.1	7.0	18.8	24.7	26.0	28.0	29.2	29.6
4.40	1.4	4.4	9.3	22.9	31.0	32.9	35.8	37.5	38.1
5.00	1.5	4.6	9.7	23.1	31.7	33.7	36.8	38.6	39.2
6.95	1.8	5.3	10.3	22.2	31.9	34.1	37.7	39.8	40.5
8.00	2.0	5.5	10.4	21.0	30.7	33.0	36.9	39.1	39.8
10.00	2.2	5.8	10.2	18.6	26.1	28.6	32.7	35.2	36.0
15.00	2.5	5.7	8.7	13.0	16.0	16.9	18.5	19.6	19.9
20.00	2.6	5.0	6.9	9.2	10.5	10.9	11.5	11.9	12.0
30.00	2.3	3.6	4.3	5.0	5.4	5.5	5.6	5.7	5.8

Case 17 V = 50,000 gal, K = 0.15, D = 0, R = 2.857, A = 20.89 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	1.5	7.1	10.8	12.7	13.4	13.6	13.8	14.0	14.0
1.00	4.0	18.3	27.8	32.9	34.7	35.2	35.8	36.3	36.4
2.00	6.5	27.9	42.8	50.9	53.9	54.6	55.7	56.3	56.5
4.40	12.0	45.4	70.9	85.8	91.4	92.7	94.7	96.0	96.4
5.00	13.2	48.6	76.3	92.8	99.0	100.4	102.8	104.1	104.6
6.95	16.9	56.2	90.2	111.2	119.2	121.1	124.1	125.9	126.5
8.00	18.6	58.7	95.1	118.4	127.4	129.5	132.9	134.9	135.5
10.00	21.3	61.4	100.6	127.6	138.2	140.7	144.6	147.0	147.8
15.00	25.4	59.6	92.2	126.1	139.6	142.8	148.0	151.1	152.1
20.00	26.3	52.4	72.6	95.9	109.2	112.8	118.7	122.3	123.5
30.00	23.3	36.8	44.8	52.3	56.0	57.0	58.6	59.5	59.9

Case 18 V = 50,000 gal, K = 0.6, D = 0, R = 2.857, A = 20.89 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	1.7	6.4	9.5	11.3	12.0	12.1	12.4	12.5	12.6
1.00	2.4	8.9	13.3	15.8	16.7	17.0	17.3	17.5	17.6
2.00	3.1	11.7	16.6	19.8	21.0	21.3	21.7	22.0	22.1
4.40	4.5	15.0	22.7	27.5	29.2	29.7	30.3	30.7	30.9
5.00	4.8	15.7	23.9	29.0	30.9	31.4	32.1	32.5	32.7
6.95	5.8	17.3	26.8	32.9	35.3	35.8	36.7	37.2	37.4
8.00	6.2	17.8	27.8	34.4	37.0	37.6	38.5	39.1	39.3
10.00	6.9	18.9	28.8	36.2	39.1	39.7	40.9	41.5	41.7
15.00	7.8	17.5	25.9	34.7	38.3	39.1	40.5	41.3	41.6
20.00	7.8	15.0	20.4	26.5	29.9	30.8	32.4	33.3	33.6
30.00	6.8	10.5	12.7	14.7	15.6	15.9	16.3	16.6	16.7

Case 19 V = 50,000 gal, K = 0.15, D = 0.6, R = 1.053, A = 14.98 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	1.0	3.8	11.4	21.6	24.5	25.2	26.2	26.7	26.9
1.00	2.7	10.1	29.2	54.9	62.5	64.2	66.9	68.4	68.9
2.00	4.4	16.1	44.0	82.7	94.9	97.5	101.8	104.3	105.1
4.40	8.2	28.4	67.8	129.4	151.2	156.1	163.7	168.2	169.7
5.00	9.0	30.7	71.4	136.9	160.8	166.2	174.7	179.8	181.4
6.95	11.6	37.9	78.7	152.0	181.8	188.6	199.5	205.9	208.0
8.00	12.9	39.6	80.1	154.3	186.8	194.3	206.2	213.3	215.6
10.00	15.0	42.6	79.5	148.2	185.0	193.5	207.2	215.3	218.0
15.00	18.2	43.1	68.2	104.5	129.4	136.7	150.1	159.2	162.4
20.00	19.0	38.5	54.2	73.0	84.0	87.1	92.4	95.8	97.0
30.00	17.1	27.3	33.5	39.4	42.3	43.1	44.4	45.2	45.4

Case 20 V = 50,000 gal, K = 0.6, D = 0.6, R = 1.053, A = 14.98 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	1.3	4.4	10.5	18.2	20.8	21.4	22.4	22.9	23.1
1.00	1.8	6.1	14.5	25.3	29.0	29.8	31.1	31.9	32.2
2.00	2.3	7.6	17.8	31.2	35.9	36.9	38.6	39.5	39.9
4.40	3.3	10.6	22.8	40.9	47.6	49.1	51.5	53.0	53.4
5.00	3.6	11.2	23.6	42.4	49.5	51.1	53.8	55.3	55.8
6.95	4.3	12.7	24.8	45.0	53.4	55.3	58.4	60.2	60.8
8.00	4.7	13.2	24.8	45.0	54.0	56.1	59.4	61.3	62.0
10.00	5.2	13.7	24.2	42.7	52.5	54.8	58.5	60.7	61.4
15.00	5.9	13.3	20.4	30.2	36.7	38.7	42.2	44.5	45.4
20.00	6.1	11.7	16.1	21.3	24.2	25.0	26.5	27.4	27.7
30.00	5.3	8.3	10.0	11.7	12.5	12.7	13.1	13.3	13.4

Case 21 V = 100,000 gal, K = 0.15, D = 0, R = 2.857, A = 26.32 ft

C ACROSS	0.	2.0	4.0	6.0	6.9	10.0	15.0	20.0	30.0
B DOWN									
30.00	143.9	143.1	140.9	137.3	135.1	126.6	109.2	90.5	58.1
20.00	235.4	234.4	231.2	225.9	222.6	208.8	174.8	129.9	66.6
15.00	(241.8)	240.9	238.3	233.9	231.1	219.5	190.6	148.1	65.4
10.00	211.7	211.1	209.1	205.8	203.8	195.1	173.3	140.2	56.4
8.00	188.2	187.7	186.0	183.3	181.6	174.3	155.9	127.8	49.8
6.95	173.0	172.5	171.1	168.6	167.1	160.7	144.2	118.9	45.5
5.00	139.3	139.0	137.9	136.0	134.9	130.0	117.4	97.8	36.0
4.40	127.5	127.2	126.2	124.5	123.5	119.1	107.8	90.1	32.7
2.00	72.7	72.6	72.0	71.2	70.6	68.3	62.3	52.7	17.7
1.00	46.3	46.2	45.9	45.3	45.0	43.6	39.8	33.8	10.8
0. ft	17.7	17.6	17.5	17.2	17.1	16.6	15.1	12.9	3.7

Case 22 V = 100,000 gal, K = 0.6, D = 0, R = 2.857, A = 26.32 ft.

C ACROSS	0.	2.0	4.0	6.0	6.9	10.0	15.0	20.0	30.0
B DOWN									
30.00	38.9	38.7	38.1	37.2	36.6	34.4	29.9	25.0	16.4
20.00	63.3	63.0	62.2	60.8	59.9	56.3	47.5	35.9	19.1
15.00	66.0	65.8	65.1	63.9	63.2	60.1	52.4	41.1	19.1
10.00	60.0	59.8	59.3	58.4	57.8	55.4	49.3	40.2	17.2
8.00	54.9	54.8	54.3	53.5	53.0	50.9	45.6	37.5	15.7
6.95	51.5	51.4	51.0	50.2	49.8	47.9	43.0	35.6	14.7
5.00	44.0	43.9	43.5	42.9	42.6	41.0	37.0	30.9	12.5
4.40	41.3	41.2	40.9	40.3	40.0	38.6	34.9	29.2	11.7
2.00	28.9	28.8	28.6	28.2	28.0	27.1	24.6	20.8	8.0
1.00	22.8	22.8	22.6	22.3	22.2	21.4	19.5	16.5	6.3
0.	16.3	16.2	16.1	15.9	15.8	15.3	13.9	11.8	4.4

Case 23 V = 100,000 gal, K = 0.15, D = 0.6, R = 1.053, A = 18.87 ft

C ACROSS	0.	2.0	4.0	6.0	6.9	10.0	15.0	20.0	30.0
B DOWN									
30.00	110.3	109.7	107.9	104.9	103.1	96.1	82.1	67.4	42.5
20.00	231.1	228.4	220.7	208.8	201.9	176.7	132.9	95.3	47.6
15.00	325.0	322.1	313.2	298.3	289.1	250.0	168.3	107.8	45.7
10.00	337.6	335.3	328.4	316.7	309.5	278.3	198.4	109.4	38.1
8.00	315.3	313.3	307.4	297.5	291.3	264.5	194.6	103.5	33.0
6.95	296.7	294.9	289.6	280.7	275.1	250.9	187.1	98.1	29.9
5.00	248.5	247.1	243.0	236.1	231.8	213.0	162.3	83.2	23.2
4.40	229.9	228.7	225.0	218.8	214.9	197.9	151.7	77.1	20.9
2.00	136.6	136.0	134.0	130.7	128.6	119.4	93.7	45.5	11.1
1.00	88.3	87.9	86.7	84.6	83.3	77.6	61.4	28.8	6.7
0.	34.1	33.9	33.4	32.6	32.1	29.9	23.7	10.4	2.3

Case 24 V = 100,000 gal, K = 0.6, D = 0.6, R = 1.053, A = 18.87 ft

C ACROSS	0.	2.0	4.0	6.0	6.9	10.0	15.0	20.0	30.0
B DOWN									
30.00	31.2	31.0	30.5	29.7	29.2	27.4	23.6	19.6	12.7
20.00	63.7	63.0	61.0	57.9	56.1	49.5	37.9	27.8	14.5
15.00	89.1	88.3	86.0	82.1	79.7	69.4	48.0	31.8	14.3
10.00	95.2	94.5	92.6	89.4	87.4	78.9	57.3	33.3	12.5
8.00	91.2	90.6	88.9	86.1	84.3	76.8	57.3	32.3	11.3
6.95	87.4	86.9	85.4	82.7	81.1	74.1	56.0	31.2	10.5
5.00	77.3	76.9	75.6	73.5	72.1	66.3	51.0	28.0	8.8
4.40	73.3	72.9	71.7	69.7	68.5	63.1	48.7	26.7	8.2
2.00	53.0	52.7	51.9	50.6	49.7	46.1	36.2	19.4	5.5
1.00	42.3	42.1	41.5	40.4	39.8	36.9	29.1	15.5	4.3
0.	30.3	30.1	29.7	28.9	28.4	26.4	20.8	11.1	3.0

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Case 25 V = 100 gal, K = 0.15, D = 500, R = 0.002, A = 0.23 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.6	40.0
1.00	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.9	4.6
2.00	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.7	1.5
4.40	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.4
5.00	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.3	0.3
6.95	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2
8.00	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
10.00	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Case 26 V = 100 gal, K = 0.6, D = 500, R = 0.002, A = 0.23 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.0	0.0	0.0	0.0	0.0	0.1	0.2	0.6	11.0
1.00	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.5	1.6
2.00	0.0	0.0	0.0	0.0	0.1	0.1	0.2	0.4	0.7
4.40	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2
5.00	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.2	0.2
6.95	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1
8.00	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1
10.00	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
15.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Case 27 V = 500 gal, K = 0.15, D = 500, R = 0.002, A = 0.40 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.0	0.0	0.0	0.0	0.1	0.1	0.5	1.0	107.1
1.00	0.0	0.0	0.0	0.1	0.2	0.3	1.0	4.8	25.6
2.00	0.0	0.0	0.0	0.1	0.3	0.5	1.2	3.9	8.5
4.40	0.0	0.0	0.1	0.2	0.4	0.5	1.0	1.7	2.2
5.00	0.0	0.0	0.1	0.2	0.4	0.5	0.9	1.4	1.7
6.95	0.0	0.0	0.1	0.2	0.4	0.4	0.6	0.8	0.9
8.00	0.0	0.0	0.1	0.2	0.3	0.4	0.5	0.7	0.7
10.00	0.0	0.0	0.1	0.2	0.3	0.3	0.4	0.4	0.5
15.00	0.0	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2
20.00	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
30.00	0.0	0.0	0.0	0.0	0.1	0.1	0.1	0.1	0.1

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Case 28 V = 500 gal, K = 0.6, D = 500, R = 0.002, A = 0.40 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.0	0.0	0.0	0.1	0.2	0.3	0.8	2.8	31.5
1.00	0.0	0.0	0.0	0.1	0.3	0.4	0.9	2.7	8.7
2.00	0.0	0.0	0.0	0.1	0.3	0.4	0.9	2.0	3.5
4.40	0.0	0.0	0.1	0.2	0.3	0.4	0.6	1.0	1.1
5.00	0.0	0.0	0.1	0.2	0.3	0.4	0.6	0.8	0.9
6.95	0.0	0.0	0.1	0.2	0.3	0.3	0.4	0.5	0.6
8.00	0.0	0.0	0.1	0.2	0.2	0.3	0.4	0.4	0.4
10.00	0.0	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.3
15.00	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.2
20.00	0.0	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1
30.00	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Case 29 V = 1,000 gal, K = 0.15, D = 500, R = 0.002, A = 0.50 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.0	0.0	0.0	0.1	0.2	0.3	1.0	6.3	161.2
1.00	0.0	0.0	0.0	0.2	0.5	0.7	2.1	10.2	54.2
2.00	0.0	0.0	0.1	0.3	0.7	1.0	2.6	8.2	17.9
4.40	0.0	0.1	0.1	0.4	0.9	1.2	2.1	3.6	4.5
5.00	0.0	0.1	0.1	0.4	0.9	1.1	1.9	3.0	3.6
6.95	0.0	0.1	0.2	0.4	0.8	0.9	1.3	1.8	2.0
8.00	0.0	0.1	0.2	0.4	0.7	0.8	1.1	1.4	1.5
10.00	0.0	0.1	0.2	0.4	0.6	0.6	0.8	0.9	1.0
15.00	0.0	0.1	0.2	0.3	0.3	0.4	0.4	0.4	0.5
20.00	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.3	0.3
30.00	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

Case 30 V = 1,000 gal, K = 0.6, D = 500, R = 0.002, A = 0.50 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.0	0.0	0.1	0.2	0.5	0.7	1.7	5.6	49.3
1.00	0.0	0.0	0.1	0.2	0.6	0.8	1.9	5.4	18.0
2.00	0.0	0.0	0.1	0.3	0.7	0.9	1.8	4.1	7.2
4.40	0.0	0.1	0.1	0.3	0.7	0.8	1.3	1.9	2.3
5.00	0.0	0.1	0.1	0.3	0.6	0.8	1.2	1.7	1.9
6.95	0.0	0.1	0.2	0.3	0.5	0.6	0.8	1.0	1.1
8.00	0.0	0.1	0.2	0.3	0.5	0.6	0.7	0.8	0.9
10.00	0.0	0.1	0.2	0.3	0.4	0.4	0.5	0.6	0.6
15.00	0.0	0.1	0.1	0.2	0.2	0.3	0.3	0.3	0.3
20.00	0.0	0.1	0.1	0.1	0.2	0.2	0.2	0.2	0.2
30.00	0.0	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1

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Case 31 V = 5,000 gal, K = 0.15, D = 500, R = 0.002, A = 0.86 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.0	0.0	0.1	0.4	1.1	1.7	5.6	36.2	395.9
1.00	0.0	0.1	0.3	0.9	2.8	4.2	12.5	59.2	319.5
2.00	0.0	0.2	0.4	1.5	4.0	5.9	15.3	48.2	105.2
4.40	0.1	0.3	0.8	2.3	5.1	6.8	12.4	21.1	26.7
5.00	0.1	0.4	0.9	2.4	5.1	6.5	11.2	17.5	21.2
6.95	0.1	0.5	1.0	2.5	4.5	5.5	7.9	10.4	11.5
8.00	0.2	0.5	1.1	2.4	4.1	4.8	6.6	8.2	8.9
10.00	0.2	0.6	1.1	2.2	3.4	3.8	4.7	5.5	5.8
15.00	0.2	0.6	1.0	1.6	2.0	2.2	2.4	2.6	2.7
20.00	0.3	0.6	0.8	1.1	1.3	1.3	1.4	1.5	1.5
30.00	0.2	0.4	0.5	0.6	0.6	0.6	0.7	0.7	0.7

Case 32 V = 5,000 gal, K = 0.6, D = 500, R = 0.002, A = 0.86 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.0	0.1	0.3	1.0	2.5	3.5	8.5	28.2	137.2
1.00	0.1	0.2	0.4	1.3	3.1	4.3	9.8	28.5	180.0
2.00	0.1	0.2	0.5	1.5	3.5	4.7	9.6	21.9	38.8
4.40	0.1	0.3	0.7	1.8	3.5	4.3	6.9	10.3	12.3
5.00	0.1	0.4	0.7	1.8	3.4	4.1	6.2	8.8	10.1
6.95	0.1	0.4	0.8	1.7	2.9	3.3	4.5	5.5	6.0
8.00	0.2	0.4	0.8	1.7	2.6	2.9	3.8	4.5	4.8
10.00	0.2	0.4	0.8	1.5	2.1	2.3	2.8	3.1	3.3
15.00	0.2	0.4	0.7	1.0	1.3	1.4	1.5	1.6	1.6
20.00	0.2	0.4	0.5	0.7	0.8	0.9	0.9	1.0	1.0
30.00	0.2	0.3	0.3	0.4	0.4	0.4	0.4	0.5	0.5

Case 37 V = 10,000 gal, K = 0.15, D = 500, R = 0.002, A = 1.08 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.0	0.1	0.2	0.8	2.4	3.8	12.2	78.5	568.5
1.00	0.0	0.2	0.6	2.1	6.1	9.2	27.3	129.3	679.1
2.00	0.1	0.4	1.0	3.2	8.8	12.9	33.3	105.3	229.2
4.40	0.2	0.8	1.7	5.0	11.2	14.8	27.1	46.1	58.2
5.00	0.2	0.8	1.9	5.2	11.1	14.3	24.4	38.3	46.2
6.95	0.3	1.1	2.2	5.4	9.9	11.9	17.2	22.7	25.2
8.00	0.4	1.1	2.3	5.3	9.0	10.6	14.3	17.8	19.3
10.00	0.4	1.3	2.4	4.8	7.4	8.3	10.4	12.0	12.7
15.00	0.5	1.3	2.1	3.4	4.4	4.7	5.3	5.7	5.8
20.00	0.6	1.2	1.7	2.4	2.8	2.9	3.1	3.3	3.3
30.00	0.5	0.9	1.1	1.3	1.4	1.4	1.5	1.5	1.5

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Case 38 V = 10,000 gal, K = 0.6, D = 500, R = 0.002, A = 1.08 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.1	0.3	0.6	2.0	5.1	7.2	17.4	57.0	211.3
1.00	0.1	0.4	0.9	2.6	6.4	8.9	20.0	58.8	207.6
2.00	0.1	0.5	1.1	3.1	7.2	9.7	19.8	45.4	81.3
4.40	0.2	0.7	1.5	3.7	7.2	8.9	14.3	21.4	25.5
5.00	0.2	0.7	1.5	3.7	6.9	8.5	12.9	18.2	20.9
6.95	0.3	0.8	1.6	3.6	5.9	6.9	9.2	11.4	12.4
8.00	0.3	0.9	1.7	3.4	5.3	6.1	7.8	9.2	9.8
10.00	0.3	0.9	1.6	3.0	4.3	4.8	5.7	6.5	6.8
15.00	0.4	0.9	1.4	2.1	2.7	2.8	3.1	3.3	3.4
20.00	0.4	0.8	1.1	1.5	1.7	1.8	1.9	2.0	2.0
30.00	0.4	0.6	0.7	0.8	0.9	0.9	0.9	0.9	0.9

Case 33 V = 25,000 gal, K = 0.15, D = 500, R = 0.002, A = 1.47 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.1	0.3	0.7	2.4	7.0	10.8	35.1	223.7	894.3
1.00	0.2	0.7	1.7	6.0	17.4	26.4	78.4	372.1	1437.1
2.00	0.3	1.2	2.8	9.3	25.3	37.1	95.6	301.4	650.3
4.40	0.6	2.2	5.0	14.3	32.1	42.4	77.5	131.9	166.4
5.00	0.7	2.4	5.4	14.9	31.8	41.0	70.0	109.6	132.1
6.95	1.0	3.0	6.3	15.4	28.3	34.1	49.3	64.9	72.0
8.00	1.1	3.3	6.6	15.1	25.8	30.3	41.1	51.1	55.4
10.00	1.3	3.6	6.8	13.8	21.1	23.8	29.6	34.4	36.3
15.00	1.6	3.8	6.2	9.9	12.7	13.5	15.1	16.3	16.7
20.00	1.7	3.5	5.0	6.9	8.1	8.4	9.0	9.4	9.5
30.00	1.5	2.5	3.1	3.7	4.0	4.0	4.2	4.3	4.3

Case 34 V = 25,000 gal, K = 0.6, D = 500, R = 0.002, A = 1.47 ft

C ACROSS / B DOWN	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
0.	0.2	0.7	1.7	5.2	13.2	18.8	44.7	144.6	369.6
1.00	0.3	1.0	2.3	6.9	16.7	23.2	52.1	155.5	444.3
2.00	0.4	1.3	2.8	8.2	18.7	25.3	51.8	120.5	218.1
4.40	0.6	1.8	3.8	9.6	18.8	23.5	37.6	56.7	67.8
5.00	0.6	1.9	4.0	9.7	18.2	22.3	33.9	48.1	55.5
6.95	0.8	2.2	4.3	9.3	15.5	18.1	24.3	30.2	32.8
8.00	0.8	2.3	4.4	8.9	14.0	16.0	20.5	24.4	26.0
10.00	0.9	2.4	4.3	8.0	11.4	12.6	15.2	17.1	17.9
15.00	1.1	2.4	3.7	5.6	7.0	7.4	8.1	8.7	8.8
20.00	1.1	2.1	3.0	4.0	4.6	4.7	5.0	5.2	5.3
30.00	1.0	1.5	1.9	2.2	2.3	2.4	2.4	2.5	2.5

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Case 35 V = 50,000 gal, K = 0.15, D = 500, R = 0.002, A = 1.85 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.2	0.6	1.5	5.3	15.8	24.5	79.5	504.9	1236.3
1.00	0.4	1.6	3.9	13.5	39.3	59.6	177.5	846.2	2258.1
2.00	0.7	2.6	6.4	21.0	57.2	83.7	215.8	678.2	1440.8
4.40	1.5	5.0	11.3	32.3	72.3	95.5	174.3	296.2	373.0
5.00	1.6	5.5	12.2	33.6	71.6	92.3	157.4	246.1	296.2
6.95	2.2	6.8	14.3	34.8	63.7	76.9	111.0	145.9	161.8
8.00	2.4	7.4	15.0	34.0	58.0	68.1	92.4	114.8	124.4
10.00	2.9	8.2	15.4	31.1	47.5	53.6	66.7	77.4	81.6
15.00	3.6	8.6	13.9	22.3	28.5	30.4	34.1	36.6	37.5
20.00	3.8	7.8	11.2	15.5	18.2	18.9	20.3	21.1	21.4
30.00	3.5	5.6	7.0	8.3	8.9	9.1	9.4	9.6	9.6

Case 36 V = 50,000 gal, K = 0.6, D = 500, R = 0.002, A = 1.85 ft

C ACROSS	30.0	20.0	15.0	10.0	6.9	6.0	4.0	2.0	0.
B DOWN									
0.	0.5	1.5	3.6	10.9	27.5	38.9	91.8	293.3	558.2
1.00	0.6	2.1	4.8	14.3	34.8	48.3	108.4	328.8	717.4
2.00	0.8	2.7	6.0	17.1	39.1	52.8	108.3	254.9	462.9
4.40	1.2	3.8	8.0	20.2	39.4	49.2	79.1	119.5	143.1
5.00	1.3	4.0	8.3	20.3	38.0	46.7	71.4	101.3	117.2
6.95	1.6	4.6	9.0	19.6	32.5	37.9	51.1	63.6	69.0
8.00	1.7	4.8	9.2	18.8	29.4	33.6	43.0	51.3	54.7
10.00	1.9	5.1	9.1	16.8	24.0	26.5	31.8	36.0	37.6
15.00	2.2	5.1	7.8	11.8	14.7	15.5	17.1	18.2	18.6
20.00	2.3	4.5	6.2	8.3	9.6	9.9	10.5	10.9	11.1
30.00	2.0	3.2	3.9	4.5	4.9	5.0	5.1	5.2	5.2

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NOMENCLATURE

a, A	Depth of penetration of leak into soil or leak length, ft. It is the radius of a hemispherical leak or the penetration along the axis of symmetry of a hemispheroidal leak. $a = (3VR/2\pi\varepsilon^2)^{1/3}$
b, B	Distance from outside of concrete tank wall, ft
c, C	Distance from axis of symmetry of leak measured parallel to the tank wall, ft
E	Void fraction in the soil, 0.35
k, K	Thermal conductivity of the soil, Btu/(hr)(ft^2)(°F/ft)
k_m	Thermal conductivity of the concrete tank wall, 0.5 Btu/(hr)(ft^2)(°F/ft)
K_D, D	Volumetric fission product distribution coefficient on the soil, (Ci/ft^3 of soil)/(Ci/ft^3 of solution)
m	Thickness of the concrete tank liner, 2 ft
$R = \frac{1}{E + K_D}$	Concentration factor, ratio of final volume of the leak to initial volume of leaking solution
S	Volumetric heat generation rate, Btu/(hr)(ft^3 of final volume of soil occupied by the leak)
S′	Volumetric heat generation rate, Btu/(hr)(ft^3 of solution before leakage)
$T - T_o$	Temperature rise caused by the leak, °F above the undisturbed temperature profile around the tank
V	Volume of the initial solution leaked, gal

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