Estimation of Heat Load in Waste Tanks Using Average Vapor Space Temperatures

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☒	☐	☐	Problem completely defined.
☒	☐	☐	Necessary assumptions explicitly stated and supported.
☐	☐	☒	Computer codes and data files documented.
☒	☐	☐	Data used in calculations explicitly stated in document.
☒	☐	☐	Data checked for consistency with original source information as applicable.
☒	☐	☐	Mathematical derivations checked including dimensional consistency of results.
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☒	☐	☐	Hand calculations checked for errors.
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☐	☐	☒	Code output consistent with input and with results reported in analysis documentation.
☒	☐	☐	Acceptability limits on analytical results applicable and supported. Limits checked against sources.
☐	☐	☒	Safety margins consistent with good engineering practices.
☒	☐	☐	Conclusions consistent with analytical results and applicable limits.
☒	☐	☐	Results and conclusions address all points required in the problem statement.

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**FERROCYANIDE SAFETY PROGRAM: ESTIMATION OF HEAT LOAD IN
WASTE TANKS USING AVERAGE VAPOR SPACE TEMPERATURES**

1.0 INTRODUCTION

This report describes a method for estimating the total heat load in a high-level waste tank with passive ventilation. This method relates the total heat load in the tank to the vapor space temperature and the depth of waste in the tank.

$$Q_{total} = C_f (T_{vapor\ space} - T_{air}) \quad (1)$$

where:

$$C_f = \text{Conversion factor} = \frac{R_0 k_{soil} \cdot \text{area}}{(z_{tank} - z_{surface})}$$

R_0 = Ratio of total heat load to heat out the top
of the tank (function of waste height)

Area = cross sectional area of the tank

k_{soil} = thermal conductivity of soil

$(z_{tank} - z_{surface})$ = effective depth of soil covering the top of tank

$(T_{vapor\ space} - T_{air})$ = mean temperature difference between
vapor space and the ambient air at the surface.

Three terms--depth, area and ratio--can be developed from geometrical considerations. The temperature difference is measured for each individual tank. The remaining term, the thermal conductivity, is estimated from the time-dependent component of the temperature signals coming from the periodic oscillations in the vapor space temperatures.

Finally, using this equation, the total heat load for each of the ferrocyanide Watch List tanks is estimated. This provides a consistent way to rank ferrocyanide tanks according to heat load.

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2.0 DESCRIPTION OF PROBLEM

The waste tanks contain significant amounts of radioactive nuclides that decay and create the heat load in the tanks. For passively vented tanks, this heat is removed primarily by conduction, either out the top, the side or the bottom of the tank. The heat transferred out the top of the tank can be estimated from the vapor space temperature because the ratio of heat lost out the top of the tank to the total heat load, R_0 , is weakly dependent on the total heat load in the tank and depends mainly on the depth and composition of the waste in the tank.

In a one-dimensional model, a waste tank can be represented as a series of slab regions (i.e., soil above tank, vapor space, saltcake, sludge, soil below tank) (see Figure 2-1). Identifying the thermal properties (thermal conductivity, density, heat capacity and heat generation rate) and height of each slab along with the two external boundary conditions at the soil surface provides a complete definition of the problem.

In order to develop a theoretical basis for investigating the problem, a mathematical description is developed in one dimension from the governing differential equation:

$$\rho_i c_i \frac{\partial T(z,t)}{\partial t} = k_i \frac{\partial^2 T(z,t)}{\partial z^2} + a_i \quad (2)$$

where:

$T(z,t)$ = temperature

ρ_i = density in region i

c_i = heat capacity in region i

k_i = thermal conductivity in region i

a_i = heat generation in region i .

A general solution can be written in the following form;

$$T_i(t,z) = U_i(z) + V_i(t,z) \quad (3)$$

where:

$U_i(z)$ = time-independent solution

$V_i(t,z)$ = time-dependent solution.

Figure 2-1. One-Dimensional Model of a Waste Tank.

Substitution of this solution into Equation 2 divides the problem into two parts; a time-independent differential equation that includes the non-homogenous term and a homogeneous time-dependent partial differential equation.

$$k_i \frac{d^2 U(z)}{dz^2} = a_i \quad (4)$$

$$\rho_i c_i \frac{\partial V_i(z,t)}{\partial t} = k_i \frac{\partial^2 V_i(z,t)}{\partial z^2} \quad (5)$$

2.1 TIME-INDEPENDENT SOLUTION

With the appropriate boundary conditions specified, Equation 4 can be easily integrated to give a solution for any region i . When the solution is expressed in the form shown in Equation 6 with the temperature and heat flux known at a boundary, the temperature and flux at the next boundary can be calculated.

$$U(z) = U_{z_i} + \frac{F_{z_i} (z-z_i)}{k_i} - \frac{a_i (z-z_i)^2}{2*k_i} \quad (6)$$

where:

U_{z_i} = temperature at boundary z_i

F_{z_i} = heat flux at boundary z_i .

The complete solution can be obtained by starting at a surface with the heat flux and surface temperature specified and calculating the temperature and flux at the next boundary. The process is repeated for the next slab region and continues until all the interface temperatures and fluxes are found. The temperatures within any of the regions can then be found from Equation 6.

2.2 TIME-DEPENDENT SOLUTION FOR PERIODIC BOUNDARY CONDITIONS

The solution to Equation 5 is a little more complicated for the general case. However, by waiting a long time for the initial thermal transients to decay away (e.g. 3 to 5 years for waste tanks), the solution for a periodic boundary condition has only a periodic time dependence (Carslaw and Jeager 1959).

$$V_i(t,z) = v_i(z) e^{-j(\omega t - \epsilon)} \quad (7)$$

where:

$v_i(z)$ = amplitude at depth z in region i

ω = frequency of periodic oscillation in radians/sec

ϵ = phase shift in radians

$j = \sqrt{-1}$.

Combining Equations 5 and 7 gives the following differential equation:

$$\frac{d^2 v_i(z)}{dz^2} = \frac{j\omega}{\alpha_i} v_i(z) \quad (8)$$

where:

$\alpha_i = \frac{k_i}{\rho_i c_i}$ = thermal diffusivity.

The solution to Equation 8 which remains finite as z goes to infinity looks like:

$$\begin{aligned} v_i(z) &= A_i e^{-z \sqrt{\frac{\omega}{2\alpha_i}}} \\ &= A_i e^{-z(1+j) \sqrt{\frac{\omega}{2\alpha_i}}} \end{aligned} \quad (9)$$

For the boundary condition where the temperature equals $A_0 \cos(\omega t - \epsilon_0)$ at $z = 0$, the solution becomes:

$$v_i(z) = A_0 e^{-\beta_i z} \cos(\omega t - \beta_i z - \epsilon_0) \quad (10)$$

where:

$$\beta = \sqrt{\frac{\omega}{2\alpha_i}}$$

Two interesting properties of the solution for a steady periodic temperature are worth noting:

- The amplitude of the temperature oscillation diminishes exponentially with depth.

$$e^{-\beta_i z} = e^{-z \sqrt{\frac{\omega}{2\alpha_i}}} = e^{-2\pi \frac{z}{\lambda_i}} \quad (11)$$

where:

$$\lambda_i = \text{wavelength} = 2\pi \sqrt{\frac{2\alpha_i}{\omega}}$$

When the surface temperature fluctuations are described in a Fourier series, the higher harmonics disappear more rapidly as one moves down into the soil. At a distance of one wave length λ , the amplitude is attenuated by a factor of more than 500. For example, for soil with a thermal diffusivity of 0.02 ft²/h, the wave length for a frequency of 1 cycle/year is about 50 ft. The relationship between the amplitude and wavelength is expressed in Equation 11.

- There is a phase lag in the temperature oscillation that increases with depth and with frequency:

$$\beta z = z \sqrt{\frac{\omega}{2\alpha_i}} = \frac{2\pi z}{\lambda} \quad (12)$$

It follows from the last two equations that a measurement of the amplitude or phase of either the temperature fluctuations at the surface and at a depth z is sufficient to determine the diffusivity α .

$$\begin{aligned} v(z_1) &= A_0 e^{-\beta z_1}, \quad v(z_2) = A_0 e^{-\beta z_2} \\ \epsilon(z_1) &= \beta z_1 + \epsilon_0, \quad \epsilon(z_2) = \beta z_2 + \epsilon_0 \\ \beta &= \frac{\ln v(z_2) - \ln v(z_1)}{z_2 - z_1} = \frac{\epsilon(z_2) - \epsilon(z_1)}{z_2 - z_1} = \sqrt{\frac{\omega}{2\alpha}} \\ \alpha &= \frac{\omega}{2\beta^2} = \frac{\omega}{2} \left[\frac{(z_2 - z_1)}{\ln v(z_1) - \ln v(z_2)} \right]^2 = \frac{\omega}{2} \left[\frac{(z_2 - z_1)}{\epsilon(z_2) - \epsilon(z_1)} \right]^2 \end{aligned} \quad (13)$$

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3.0 ACTUAL TEMPERATURE MEASUREMENTS

Problems of heat conduction in solids with periodic surface temperature variations arise from the study of fluctuations in temperature of the earth's crust due to periodic heating by the sun. The periodic oscillations in the atmospheric temperature have been used for determining the thermal conductivity of rocks. Observations of the temperature at points near the surface of the earth have established that the variations of surface temperatures from the "heat by day" to the "cool by night" do not affect points at a depth of more than 3 to 4 ft, while the yearly changes from "cold of winter" to the "heat of summer" may be observed up to a depth of 60 to 70 ft (Carslaw and Jeager 1959).

The temperature from the surface of the soil downwards (increasing z), can be approximated in the form of a general Fourier Series. The expansion shown in Equation 14 contains an additional linear term, D , that would not be found in a classic Fourier Series expansion, but is included in this analysis to compensate for the radioactive decay of the tank heat load.

$$\begin{aligned} T(z,t) &= A_0(z) + D(z) t + \sum_{n=1}^{\infty} e^{-k_n z} [A_n(z) \cos(n\omega_0 t) + B_n(z) \sin(n\omega_0 t)] \\ &= A_0(z) + D(z) t + \sum_{n=1}^{\infty} e^{-k_n z} C_n(z) \cos(n\omega_0 t + \epsilon_n(z)) \end{aligned} \quad (14)$$

where:

$$C_n(z) = \sqrt{A_n^2(z) + B_n^2(z)}$$

$$\epsilon_n(z) = \tan^{-1}(B_n(z)/A_n(z))$$

$$D(z) = \text{linear decay term (degrees/time)}.$$

By harmonically analyzing the temperatures T_1 and T_2 , measured at depths z_1 and z_2 , the relationships shown in Equation 13 can be evaluated from the constants in Equation 14. It should be recognized that either the amplitude or the phase of any harmonic may then be used to estimate the thermal diffusivity α .

3.1 ATMOSPHERIC TEMPERATURE FLUCTUATIONS

Figure 3-1 is a plot of the atmospheric temperature recorded for most of three years (January 1990 to November 1992) from the Hanford Meteorological Station, located just east of the 200 West Area. Hourly temperatures were averaged to give a single daily temperature.

Figure 3-1. Seasonal Temperature Fluctuations.

A modified Fourier Series expansion was calculated for the temperature data shown in Figure 3-1 that includes a constant term, a linear term and the first and second harmonic. The calculations were done using the regression capability of the computer spreadsheet program Excel (Microsoft 1990). The error estimates of the coefficients are calculated as a part of the spreadsheet regression analysis (see Appendix B). Calculated values for each of the expansion coefficients are given in Table 3-1.

Any date can be chosen as a reference point for the phase calculation. The fifteenth of July in 1991 was selected and is the zero point on the x-axis of Figure 3-1. This date was chosen so that the yearly cycle has a near zero phase shift because the maximum of the annual temperature fluctuation occurs in July with the minimum in January. When the temperature phase shift in the vapor space of a tank is calculated using this same reference date, the phase shift between the two temperature signals depends only on the vapor space temperature phase shift since the yearly phase shift is essentially zero.

3.2 WASTE TANK VAPOR SPACE TEMPERATURES

The measured temperatures in the vapor space from a number of waste tanks were also analyzed in the same way as the atmospheric temperature. Measured temperature from the uppermost thermocouple were analyzed for six tanks from six different farms, 214-A-101,

241-BY-104, 241-C-103, 241-S-102, 241-T-101 and 241-U-105. The results of the analysis are shown in Table 3-1. Appendix B contains a description of the temperature histories used in the analyses.

Several features of the temperature histories shown in the appendixes are of interest. The yearly cycles are apparent, but the amplitude of these cycles have been significantly attenuated compared to the magnitude of the atmospheric temperature cycles. A phase shift in the location of the minimum and maximum can also be seen. All the tanks, with the exception of 241-A-101, exhibit a decreasing average vapor space temperature. It will be shown later that the temperature history from tank 241-A-101 has other anomalous features.

Table 3-1. Fourier Series Expansion Coefficients For Temperature Data.

Location	A_0 average temperature (°F)	A_d linear trend (°F/yr)	A_1 cosine coefficient (°F)	B_1 sine coefficient (°F)	C_1 magnitude (°F)	ϵ_1 phase shift (days)	Number of data points used and regression coefficient, R^2	
Atmosphere	56.3 ± 0.3	0.5 ± 0.4	21.9 ± 0.5	0.1 ± 0.5	21.9	0.3	517	0.81
Tanks								
241-A-101	96.1 ± 0.2	0.9 ± 0.1	2.8 ± 0.3	4.4 ± 0.3	5.3	58.4	51	0.89
241-BY-104*	79.5 ± 0.1	-0.2 ± 0.1	-0.7 ± 0.2	4.0 ± 0.2	4.0	100.9	166	0.73
241-C-103	105.3 ± 0.1	-1.0 ± 0.1	-0.4 ± 0.2	4.3 ± 0.2	4.3	97.3	108	0.89
241-S-102	80.7 ± 0.1	-1.4 ± 0.1	0.2 ± 0.2	4.5 ± 0.2	4.5	88.4	144	0.85
241-T-101	67.2 ± 0.2	-0.2 ± 0.2	0.5 ± 0.2	5.3 ± 0.2	5.3	86.1	119	0.81
241-U-105	76.3 ± 0.2	-1.5 ± 0.2	1.2 ± 0.2	6.5 ± 0.2	6.6	80.7	106	0.89

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4.0 HEAT LOAD ESTIMATION

For the first layer representing the soil above the tank, there is no heat generation and the complete solution can be written in the following form.

$$T_1(z,t) = T_0 + \frac{F_0 (z_1 - z_0)}{k_1} + A_0 \exp^{-\beta_1 z} \cos(\omega t - \beta_1 z - \epsilon_0) \quad (15)$$

where:

T_0 = average temperature at z_0

F_0 = average flux at z_0

$A_0 \cos(\omega t - \epsilon_0)$ = time dependent component at z_0 .

Since average total heat leaving through the top of the tank is the product of the heat flux times the surface area, the non-periodic portion of this equation can be rearranged to give the total heat rate from the top of the tank.

$$Q_{top} = \frac{k_1 (T_1 - T_0)}{(z_1 - z_0)} \text{ Area} \quad (16)$$

where:

Area = cross sectional area of the tank

k_i = thermal conductivity of soil

$(z_1 - z_0)$ = effective depth of soil covering the top of tank

$(T_1 - T_0)$ = mean temperature difference between
vapor space and soil surface.

This equation includes the following parameters:

Area--The cross sectional area of the tank can be found by using the inner diameter of the tank and ignoring the wall thickness. For a tank with a radius of 37.5 ft, the cross-sectional area of the tank is 4,418 ft². Uncertainty in the area arises only from the definition of what is considered the top of the tank. For a given radius, the area can be calculated precisely.

Soil Thermal Conductivity--A thermal conductivity of 0.6 BTU/h/ft/°F was chosen for the soil above the tank based on a review of thermal modeling being done for the waste tanks. The suitability and uncertainty associated with using this value will be discussed in a later section.

Effective Depth of Soil--The effective depth of soil covering the tanks has to be an approximation to account for the curvature of the dome at the top of the tank. The soil region above the dome can be divided into a series of concentric rings, each covered by a different depth of soil. Each ring provides a parallel path for heat conduction. The total heat conducted out the top of the tank is the sum of all the heat conducted through all the individual paths.

$$Q = \sum_j \frac{\pi(r_j^2 - r_{j-1}^2) \Delta T k_i}{\frac{(z_j + z_{j-1})}{2}} \quad (17)$$

$$= \Delta T k_i \sum \frac{2\pi(r_j^2 - r_{j-1}^2)}{(z_j + z_{j-1})}$$

where:

$j = 1 \dots \text{number of rings.}$

From this equation, it can be seen that the effective height is given by the following expression (see Figure 4-1).

$$z_{eff} = \frac{\text{Area}}{\sum \frac{2\pi(r_j^2 - r_{j-1}^2)}{(z_j + z_{j-1})}} \quad (18)$$

Figure 4-2 shows z_{eff} as a function of the depth of soil covering the tank and includes the additional 15 in. of concrete that makes up the tank dome. For 8 ft of soil covering at the center of the tank, the effective height is about 13.2 ft.

Uncertainty in the effective height is derived mainly from the uncertainty in the depth of soil above the tanks. Nominally, the tanks are covered by 8 ft of soil with the surface graded to compensate for the elevation variation between cascaded tanks. With adjacent cascaded tanks potentially 1 ft different in elevation, the effective depth could range ± 1 ft.

Measured Temperature Differences--The remaining expression in Equation 16 is the measured temperature difference between the atmospheric temperature and the vapor space temperature. The temperature difference can be obtained from a regression fit of the measured temperature data from the vapor space thermocouple as described earlier and demonstrated in Table 3-1. Because the temperature model being presented is based on conduction alone, the atmospheric temperature could be corrected for convective heat transfer at the soil and vapor space boundaries. For

example, a tank with a heat load of 5,000 BTU/h over a surface area of 4,418 ft², using a heat transfer coefficient of 2 BTU/ft²/h/°F would give a temperature drop of less than one °F at the soil surface interface. The temperature drop in the vapor space of the tank is expected to be even less due to the dominating effect of radiative heat transfer as described in Appendix A. Since the magnitude of the heat transfer temperature drop is proportional to the heat flux, neglecting this temperature drop will over-estimate the calculated heat load by the same proportion for all heat loads.

Figure 4-1. Waste Tank Geometry.

Figure 4-2. Effective Depth Versus Soil Cover.

5.0 ESTIMATION OF THE THERMAL CONDUCTIVITY OF THE SOIL

By rearranging Equation 13, the product of β and z_{eff} (hereafter called μ) can be estimated directly from either the amplitude or phase shift from two measured temperature signals. In Table 5-1, this product is estimated using the data from Table 3-1 for the six tanks. Except for the one tank, 241-A-101, there is very good agreement in the value of μ for each tank calculated by using either the amplitude attenuation and phase shift phase estimates.

Figure 5-1 displays a plot of the log of the measured amplitude attenuation versus the phase shift. Most of the measured data points fall, as expected, along a straight line on the semi-log plot. However, for some unexplained reason, tank 241-A-101 deviates significantly from this line. The phase shift of the vapor space temperature for this tank is much smaller than would be expected for the amplitude attenuation. This suggests, perhaps, the possibility of significant direct convective heat transfer between the vapor space and the atmosphere in addition to the heat conduction.

Next, using a best estimate of parameters on the right side of the following rearranged version of Equation 16, the quotient k_i/z_{eff} and the soil thermal conductivity can be estimated. An estimation of the k_i/z_{eff} ratio is of interest because it appears in Equation 16 in the calculation of the heat out the top of the tank.

$$\frac{k_i}{z_{eff}} = \frac{\omega \rho_i c_i z_{eff}}{2 \mu^2} \quad (19)$$

where:

$$\mu = \beta_i z_{eff}$$

= calculated from measured temperature phase and/or amplitude.

A major problem in previous thermal analysis calculations has been the need to select a value for k_{soil} , the soil thermal conductivity. The choice of k_{soil} directly affects the magnitude of the heat load estimates. The primary difficulty arises because values for possible thermal conductivities have a significant range. The thermal conductivity of sand, for example, varies by at least a factor of two for a 10% change in the moisture content of the sand. The estimate of the heat load would necessarily vary by this same factor. Equation 19 uses physical parameters with a smaller range of possible values that are more easily defined, i.e., heat capacity and density, and actual temperature measurements to obtain an estimate of the k_{soil} .

In Table 5-1, the thermal conductivity is evaluated using best estimate values of heat capacity, density, z_{eff} and the measured values of μ . Even when the tank 241-A-101 result is excluded, there is still a considerable variation in the estimated thermal conductivities.

However, this is expected because estimated values in Table 5-1 are a measure of the thermal conductivity for the conditions in the actual soil above each particular tank. This is a distinct improvement in the selection of a representative value for k .

Table 5-1. Waste Tank Results.

		A-101	BY-104	C-103	S-102	T-101	U-105
$\mu = \beta_{soil} z_{eff}$ (From Equation 13 and Table 1)	Amplitude	1.43	1.69	1.62	1.57	1.41	1.20
	Phase	1.00	1.73	1.67	1.52	1.48	1.38
	% Diff.	34.9%	-2.4%	-3.0%	3.2%	-4.8%	-14.0%
$\frac{k_{soil}}{z_{eff}}$ (From Equation 19) $\frac{BTU}{ft^2 \cdot hr \cdot F}$	Amplitude	0.058	0.041	0.045	0.048	0.059	0.082
	Phase	0.118	0.039	0.042	0.051	0.054	0.062
k_{soil} $\frac{BTU}{ft \cdot hr \cdot F}$	Amplitude	0.77	0.54	0.60	0.63	0.78	1.08
	Phase	1.56	0.52	0.55	0.67	0.71	0.82

Frequency ($2\pi/\omega$) = 0.000717 hr⁻¹

z_{eff} = 13.2 ft

Heat capacity (c_p) = 0.22 BTU/lb/°F

Density (ρ) = 113 lb/ft³

Figure 5-1. Attenuation Versus Phase Shift for Six Waste Tanks.

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6.0 ESTIMATION OF TOTAL HEAT FROM TANK

Values for each of the parameters in Equation 16 are needed to estimate the heat being conducted out of the top of the tank. To find the total heat being generated in the tank, the ratio, R_0 , of heat out the top to total heat load has to be estimated. The total heat load is removed from the tank through three paths; out the top of the tank, through the sides and out the bottom of the tank.

The ratio, R_0 , is more a function of the height of the waste being stored in the tank and not dependent on the total heat load. The heat conducted out the side of the tank is a function of the temperature in the vapor space and waste, the effective length of the conduction path from the side to the surface and the conductivity of the soil. The heat out the bottom of the tank depends on the temperature of the waste at the bottom of the tank, the length of the conduction path from the bottom of the tank to the surface and the conductivity of the soil. Because the bottom of the tank is over 150 ft above the anticipated water table, the heat transferred to this sink is neglected. These quantities can be expressed as ratios as seen in the following equations (assuming that the k_{soil} are the same on all three sides of the tank).

$$\begin{aligned}
 Q_{total} &= \frac{k_{soil} \Delta T_{top} area_{top}}{z_{top}} + \frac{k_{soil} \Delta T_{side} area_{side}}{z_{side}} + \frac{k_{soil} \Delta T_{waste} area_{waste}}{z_{waste}} + \frac{k_{soil} \Delta T_{bottom} area_{bottom}}{z_{bottom}} \\
 &= \frac{k_{soil} \Delta T_{top} area_{top}}{z_{top}} [1 + \Gamma_{side} + \Gamma_{bottom}]
 \end{aligned} \tag{20}$$

$$\Gamma_{side} = \frac{\Delta T_{side}}{\Delta T_{top}} \frac{area_{side}}{area_{top}} \frac{z_{top}}{z_{side}} + \frac{\Delta T_{waste}}{\Delta T_{side}} \frac{area_{waste}}{area_{top}} \frac{z_{top}}{z_{waste}}$$

$$\Gamma_{bottom} = \frac{\Delta T_{bottom}}{\Delta T_{top}} \frac{area_{bottom}}{area_{top}} \frac{z_{top}}{z_{bottom}}$$

where:

$$\Delta T_{top} = \delta T, \quad \Delta T_{side} = \delta T, \quad \Delta T_{waste} = \delta T, \quad \Delta T_{bottom} = \delta T \left[1 + \frac{z_{waste}}{z_{top}} \frac{k_{soil}}{k_{waste}} \right]$$

$$area_{top} = \pi r^2, \quad area_{side} = 2\pi r h_{vapor}, \quad area_{waste} = 2\pi r h_{waste}, \quad area_{bottom} = \pi r^2$$

$$z_{top} = z_r, \quad z_{side} = \frac{z_{vapor}}{\ln \left[\frac{z_{wall} + z_{vapor}}{z_{wall}} \right]},$$

$$z_{waste} = \frac{z_{waste}}{\ln \left[\frac{z_{waste} + z_{bottom}}{z_{waste}} \right]}, \quad z_{bottom} = z_{bottom}.$$

Figure 6-1 shows an example of the ratios described in Equation 20. These ratios are combined with Equation 16 to develop a conversion factor for estimating the tank heat load based on the waste volume and vapor space temperature (see Figure 6-2). The product of the conversion factor and the mean temperature difference between atmosphere and the vapor space gives the tank heat load as shown in Table 6-1.

Figure 6-1. Heat Load Fractions.

Figure 6-2. Heat Load Conversion Factor.

Table 6-1. Waste Tank Heat Load Estimation.

	A-101	BY-104	C-103	S-102	T-101	U-105
ΔT (°F)	39.8	23.2	49.0	24.4	10.9	20.0
k (Table 2) (BTU/ft/h/°F)	*	0.53	0.60	0.57	0.65	0.95
Q_{top} (Eq. 16) (BTU/h)		4,100	9,800	4,700	2,400	6,400
Waste volume (kgal)		406	248	549	108	418
Q_{top}/Q_{total} (Eq. 20)		0.509	0.535	0.497	0.536	0.517
Q_{total} (BTU/h)		8,100	18,400	9,400	4,400	12,300

*Lack of agreement between amplitude and phase estimates of the thermal conductivity for this tank suggests a transient temperature situation where this model is not appropriate.

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7.0 FERROCYANIDE WATCH LIST TANKS HEAT LOADS

The mean temperature difference between the vapor space of a tank and the atmosphere has been obtained by fitting a Fourier series expansion to both the tank and atmospheric data. This temperature difference could also be approximated by taking an average vapor space temperature for the month of January or July and subtracting 56.3 °F, the average temperature of the atmosphere. For these two months, the temperature fluctuation in the vapor space passes through the average value, midway between the maximum and minimum.

This logic has been applied to the original ferrocyanide Watch List tanks with the results shown in Table 7-1. The tank capacity (Column 2) and amount of waste (Column 3) were identified for each tank (Column 1). Using the waste volume and Figure 6-2, the conversion factor (Column 4), (C_f from Equation 1), was established for each tank.

Column 5 is a representative vapor space temperature based on the average of four temperature measurements in the month of July of 1992 from the uppermost thermocouple (i.e., lowest temperature) for a single tree in each tank. In some cases, four July temperatures were not available and the existing temperatures were supplemented with appropriate June and January temperatures. It is important to recognize again that during the month of January and July, the component of the sinusoidal seasonal swing in vapor space temperatures is near zero and allows the steady temperature to be estimated.

The temperature difference between the vapor space and the outside is obtained by subtracting 56.3 °F from Column 5. Since the convective heat transfer temperature drop at the two surfaces is ignored, the temperature difference calculated this way is intentionally overestimated. Finally, Column 7 lists the estimated heat load for each of the tanks, calculated as the product of conversion factor (Column 4) and temperature difference (Column 6).

Table 7-1. Ferrocyanide Tank Total Heat Load.

Tank	Size of tank (kgal)	Volume of waste (kgal)	Conversion factor (BTU/h/°F)	Temperature (°F)		Heat load (BTU/h)	
				Vapor space	Delta	Calculated	Current estimate*
BX-102	500	96	364	64.0	7.7	2,800	< 10,000
BX-106	500	31	359	63.3	7.0	2,500	< 10,000
BX-110	500	198	372	62.5	6.2	2,300	< 10,000
BX-111	500	211	373	64.8	8.5	3,200	< 10,000
BY-101	750	387	393	65.8	9.5	3,700	8,200
BY-103	750	400	394	70.3	14.0	5,500	8,600
BY-104	750	406	394	78.5	22.2	8,700	5,500
BY-105	750	503	401	78.0	21.7	8,700	3,400
BY-106	750	642	410	81.0	24.7	10,100	3,300
BY-107	750	266	385	79.3	23.0	8,900	14,500
BY-108	750	228	383	80.3	24.0	9,200	23,000
BY-110	750	398	394	73.8	17.5	6,900	25,200
BY-111***	750	459	398	70.0	31.2	5,500	34,200
BY-112***	750	291	387	72.0	27.2	6,100	< 10,000
C-108**	500	66	361	72.8	16.5	6,000	10,000
C-109	500	62	361	75.8	19.5	7,000	3,800
C-111	500	57	361	74.0	17.7	6,400	< 10,000
C-112	500	104	364	77.0	20.7	7,500	< 10,000
T-101**	500	103	364	67.8	11.5	4,200	< 10,000
T-107**	500	171	370	64.3	8.0	3,000	< 10,000
TX-118	750	347	390	68.0	11.7	4,600	4,900
TY-101**	750	118	375	64.5	8.2	3,100	< 10,000
TY-103**	750	162	378	66.8	10.5	4,000	< 10,000
TY-104	750	43	370	64.3	8.0	3,000	< 10,000
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)

*Estimated heat load for ferrocyanide tanks from Hanlon, 1993.

**Four temperature measurements were not available for July, 1992. Temperature measurements from June and January were used to augment the existing July temperatures.

***Temperatures come from new thermocouple trees from July 1993.

8.0 CONCLUSIONS

A simple method has been presented to estimate the heat load in a high-level waste tank without active ventilation. The method is conservative in that it overestimates the heat load for the following reasons:

- The temperature difference is not adjusted for the small temperature drop between the vapor space and tank wall or soil and air and is therefore overestimated.
- The heat conduction lengths used to estimate the heat being conducted through the bottom and sides of the tank were chosen as the shortest distance to the surface. The heat out the top of the tank would produce a temperature gradient such that the actual path lengths would be longer. This overestimates the heat out the bottom and sides of the tank.

The conversion factor (Figure 6-2) is a measure of sensitivity of the vapor space temperature to the heat load in the tank. For example, a conversion factor of 400 BTU/h/°F means 400 BTU/h (or 120 watts) for each °F change in the vapor space temperature.

The heat loads calculated for tanks 241-BY-104 and 241-T-101 in Table 6-1 are slightly different from the heat loads shown in Table 7-1. The heat loads in Table 6-1 were calculated using the best estimates of thermal conductivities and temperature difference. The heat loads in Table 7-1 are based on a single thermal conductivity from all tank farms and four pieces of temperature data from the month of July. The temperature differences derived from a regression calculation typically used over 100 temperature measurements over a three-year period. Based on the regression analysis results in Appendix B, the uncertainty in the average vapor space temperature at the 95% confidence level is less than ± 1 °F. It is felt that the differences in estimated heat loads for the two tanks should be representative of the kind of repeatability that can be expected from the simplified approach.

Since the vapor space temperatures in only six tanks were analyzed, there remains additional work that could be done to more fully understand and characterize the thermal behavior of the remaining waste tanks.

- With a mathematical description of the yearly temperature fluctuations in the vapor space of a tank, some of the variation in the temperature measurements can be removed. This could provide improved temperature monitoring with quicker detection of an abnormal situation.
- All single-shell tanks with passive ventilation should be investigated to identify any other anomalous behavior as seen in tank 241-A-101.

- This technique could be extended to the thermocouples in the waste. Some of the upper thermocouples in the waste exhibit yearly fluctuations, though not as pronounced as in the vapor space. These temperature histories could be analyzed for amplitude attenuation and phase shift to investigate the thermal properties of the upper regions of the waste.
- The high-heat tanks are on active ventilation and therefore the heat load cannot be estimated from the vapor space temperatures. But heat load estimates might be possible using the adjacent thermocouples located in the upper regions of the waste. In addition, there exists transient data for high-heat tank 241-C-106 taken before, during and after the ventilation system was inoperative. This type of data could easily be modeled, using some of the methods described in this report, to estimate some of the waste thermal properties along with the tank heat load.

9.0 REFERENCES

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10.0 ACKNOWLEDGEMENT

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APPENDIX A
TEMPERATURE PROFILE IN VAPOR SPACE

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APPENDIX A**TEMPERATURE PROFILE IN VAPOR SPACE**

The transfer of decay heat energy upward from the waste surface, through vapor space air to the top of the tank, imposes a temperature difference across the vapor space. The magnitude of the temperature gradient is important in understanding the factors that determine the average vapor space temperature. Also, it is important to recognize the passive heat dissipation capabilities within the tank under dry conditions; i.e., where evaporation and condensation would not play a significant role. For these reasons the magnitude of the temperature drop across the vapor space is discussed in this appendix.

Three distinct heat transport mechanisms for transferring decay heat from the upper surface of the waste to the inner surface of the concrete dome can be identified:

- Evaporation/condensation
- Natural convection
- Radiation.

The first of these, evaporation/condensation, could be important for tanks in which an aqueous supernatant liquid covers the waste. However, for waste with a relatively dry upper surface exposed to the vapor space air, the evaporation/condensation mechanism would be relatively unimportant and can be neglected as a relevant heat transport mechanism.

Natural Convection

Natural convection can be quantified on the basis of heat transfer correlations (McAdams 1954) that relate the Nusselt number to the product Grashov and Prandtl numbers:

$$Nu = a [Gr * Pr]^n \quad (A-1)$$

where:

$$Nu = \text{Nusselt number} = \frac{hL}{k}$$

h = heat transfer coefficient

L = characteristic length

k = thermal conductivity of fluid

$$Gr = \text{Grashov number} = \frac{L^3 \rho^2 \beta \Delta T}{\mu^2}$$

ρ = fluid density

β = fluid thermal expansion coefficient

ΔT = temperature difference in fluid

μ = dynamic viscosity of fluid

$$Nu = \text{Prandtl number} = \frac{C_p \mu}{k}$$

c_p = heat capacity of fluid

a = empirical function of Gr and Pr

n = another empirical function of Gr and Pr .

Values for the constants a and n depend on the computed value of $Gr*Pr$ and the physical configuration of the system being described. For example, the value of $Gr*Pr$ computed for tank C-103 is 7×10^{12} , when L equals 75 ft (the tank diameter), ΔT equals 1°F, and the fluid properties for air are evaluated at 105 °F.

This value of $Gr \cdot Pr$ is in the turbulent range ($> 10^9$), giving n in Equation A-1 a value of $1/3$ (McAdams 1954). For horizontal enclosed spaces heated from below, a simplified form of Equation A-1 is derivable from the work of McAdams (McAdams 1954) to be:

$$h_c = 0.1 \Delta T^{1/3} \quad (A-2)$$

where:

$$h_c = \text{heat transfer coefficient} \left[\frac{BTU}{hr \text{ } ^\circ F \text{ } ft^2} \right]$$

ΔT = temperature difference across boundary layer [$^\circ F$].

The constant, 0.1, in Equation A-2 is valid for air at 1 atmosphere pressure and ordinary temperatures.

Radiation Heat Transfer

Radiation of heat from the waste surface to the tank dome can be quantified on the basis of the following simplifying assumptions and numerical estimates.

- The tank geometry can be represented by two discs (75 ft diameter) separated by a non-absorbing medium, connected with cylindrical walls that are non-conducting but reradiating.
- The distance between discs is 18.5 ft, the estimated distance between the current waste surface in C-103 and the top of the cylindrical wall of the tank.
- A view factor, $\bar{F}$, of 0.77, taken from Figure 4.11 of McAdams (McAdams 1954) for a diameter/spacing ratio of 75/18.5 for the tank.
- Absorption of radiation by water vapor in vapor space air (estimated emissivity $\cong 0.25$) and radiation from air to the dome were judged to be relatively unimportant and are neglected.
- Emissivities of organic liquid which covers the waste surface, and concrete which makes up the dome, were assigned values of 0.82 and 0.91 respectively on the basis of data presented by McAdams (1954).

Based on these assumptions, the radiation flux may be calculated from the following equation:

$$q_1 \leftarrow q_2 = A_1 \mathcal{F}_{12} \sigma (T_1^4 - T_2^4) \quad (\text{A-3})$$

where:

$q_1 \leftarrow q_2$ = radiation heat transport surface 1 to surface 2

A_1 = area of surface 1

$\mathcal{F}_{12}$ = radiation factor

σ = Stefan-Boltzman constant

T_1, T_2 = absolute temperatures of surfaces 1 and 2.

To consider the effect of absorption and reflection on the heat exchange between the surfaces, radiation between non-black bodies is considered. The product $A_1 \mathcal{F}_{12}$ for the case of two source-sink zones (A_1 and A_2) with relatively high emissivities is related to the controlling parameters by the following equation (McAdams 1954):

$$\frac{1}{A_1 \mathcal{F}_{12}} = \frac{1}{A_1} \left(\frac{1}{\epsilon_1} - 1 \right) + \frac{1}{A_2} \left(\frac{1}{\epsilon_2} - 1 \right) + \frac{1}{A_1 \bar{F}_{12}} \quad (\text{A-4})$$

where:

ϵ_1, ϵ_2 = emissivities of surfaces 1 and 2

$\bar{F}_{12}$ = view factor.

Substituting identified values of ϵ_1 , ϵ_2 , and $\bar{F}$ into Equation A-4 results in a predicted $\mathcal{F}_{12}$ value of 0.62.

Sum of Radiation and Convection

Overall heat transfer rate resulting from radiation and convection can be computed by combining Equations A-3 and A-2. For tank 241-C-103, the surface area of the exposed waste is 4418 ft² and the waste surface temperature is 106 °F. Results are summarized in Table A-1 and shown graphically in Figure A-1.

As indicated by the data of Table A-1, radiation is the dominant heat transport mechanism. The other key feature of the results shown in Table A-1 is that the temperature difference across the vapor space air volume is quite small: a few degrees F.

Table A-1. Convection and Radiation Heat Transfer in Tank 241-C-103.

ΔT^* °F	Heat transport rate (BTU/h)		
	Convection	Radiation	Total
1	400	3,800	4,200
2	1,100	7,600	8,700
3	1,900	11,400	13,300
4	2,800	15,200	18,000
5	3,800	19,100	22,900
6	4,800	22,900	27,700

*Temperature of waste surface minus dome surface temperature.

Figure A-1. Heat Transfer Mechanisms.

APPENDIX B
SELECTED WASTE TANK TEMPERATURE DATA

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APPENDIX B**SELECTED WASTE TANK TEMPERATURE DATA**

The figures and tables in this appendix provide a description of the actual thermocouple data used in the regression analysis to calculate the temperature statistics for the selected tanks.

The figures display the actual temperature data points from the thermocouple measurements. The data points shown as white boxes were included in the regression analysis. The data points shown as solid black boxes were excluded because they deviate by more than 4 degrees the predicted value.

Microsoft Excel directly generates the output given in the tables, including an ANOVA table, standard error of y estimates, coefficients, standard error of coefficients, r^2 values, and the number of observations.

A number of interesting features (accented by the circles) can be seen in individual temperature histories shown in the figures.

Figure B-2 Tank 241-A-101--This is the only tank where the mean temperature is increasing with time. It is also the only tank where the phase and amplitude of the annual fluctuation are not consistent. This tank demonstrates a situation where the thermal model developed in the paper does not give satisfactory results. Other thermocouples in the upper region of this tank also show an increasing average temperature. The exhaustor on 241-A-104/105/106 has been out of service since October 1, 1991. It was briefly restarted on August 20, 1992 but remains down with problems (Hanlon 1993). 241-A-101 may still be connected to 241-A-105 through 6-in. ventilation lines. It may be that the loss of the exhaustor on 241-A-105 has reduced the convective heat removal from 241-A-101 and has led to the increasing temperatures in this tank.

Figure B-3 Tank 241-BY-104--There is a distinct change in the magnitude and variation of the temperature measurements for this tank starting around January of 1993. This may correspond to when the thermocouples were connected to the Tank Monitoring and Control System (TMACS) and automatic temperature readings were taken continuously. A significant reduction in the variance of the temperature measurements is noticeable.

Figure B-4 Tank 241-C-103--This tank was on active ventilation during the last two months of 1989. The effect of this can be seen in the figure as the temperature returns to a periodic fluctuation following the removal of the active ventilation.

Figure B-6 Tank 241-T-101--During March of 1993, a total of 25,300 gal of liquid was pumped from this tank. The pumping was completed on April 6, 1993 and the tank was declared to be interim stabilized. This activity appears to have produced a decrease in the vapor space temperature and a departure from the annual temperature cycle.

Figure B-1. Atmospheric Temperature Fluctuations.

Multiple R 0.9013
 R Square 0.8123
 Adjusted R Square 0.8104
 Standard Error 7.5346
 Observations 517

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	5	125521.62	25104.32	442.21	0.00
Residual	511	29009.47	56.77		
Total	516	154531.08			

Regression	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	56.32	0.34	166.95	0.00	55.66	56.98
time	0.50	0.42	1.18	0.24	-0.33	1.32
sin(wt)	0.09	0.48	0.19	0.85	-0.85	1.03
cos(wt)	21.91	0.48	45.73	0.00	20.97	22.85
sin(2wt)	4.00	0.48	8.36	0.00	3.06	4.94
cos(2wt)	0.52	0.46	1.11	0.27	-0.40	1.43
phase reference date					7/15/91	

Figure B-2. Tank 241-A-101.

Multiple R 0.9353
 R Square 0.8747
 Adjusted R Square 0.8671
 Standard Error 1.6271
 Observations 53

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	3	905.97	301.99	114.07	0.00
Residual	49	129.73	2.65		
Total	52	1035.70			

	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	96.19	0.24	408.43	0.00	95.72	96.67
t	0.79	0.10	8.24	0.00	0.60	0.98
cos(wt)	2.82	0.38	7.39	0.00	2.05	3.58
sin(wt)	4.65	0.30	15.74	0.00	4.05	5.24
magnitude	5.43					
phase	59.64					

phase reference date 7/15/91

Figure B-3. Tank 241-BY-104.

Multiple R 0.8569
 R Square 0.7343
 Adjusted R Square 0.7294
 Standard Error 1.7940
 Observations 166

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	3	1440.93	480.31	149.24	0.00
Residual	162	521.39	3.22		
Total	165	1962.33			

	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	79.52	0.14	552.23	0.00	79.23	79.80
linear	-0.17	0.13	-1.27	0.20	-0.42	0.09
cos(wt)	-0.66	0.21	-3.21	0.00	-1.06	-0.25
sin(wt)	3.98	0.19	20.47	0.00	3.60	4.37
magnitude	5.63					
phase(days)	101					
				phase reference date	7/15/91	

Figure B-4. Tank 241-C-103.

Multiple R 0.9441
 R Square 0.8913
 Adjusted R Square 0.8882
 Standard Error 1.1843
 Observations 108

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	3	1196.21	398.74	284.27	0.00
Residual	104	145.88	1.40		
Total	107	1342.09			

	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	105.33	0.12	851.40	0.00	105.08	105.57
time	-1.04	0.09	-11.37	0.00	-1.22	-0.86
cos(wt)	-0.44	0.17	-2.69	0.01	-0.77	-0.12
sin(wt)	4.31	0.16	27.08	0.00	3.99	4.62
magnitude	4.33					
phase	97.30					

phase reference date 7/15/91

Figure B-5. Tank 241-S-102.

Multiple R 0.9199
 R Square 0.8462
 Adjusted R Square 0.8429
 Standard Error 1.6044
 Observations 144

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	3	1983.22	661.07	256.81	0.00
Residual	140	360.38	2.57		
Total	143	2343.60			

	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	80.69	0.14	586.70	0.00	80.41	80.9587
time	-1.39	0.11	-12.38	0.00	-1.61	-1.1672
cos(wt)	0.23	0.20	1.19	0.24	-0.15	0.6217
sin(wt)	4.53	0.18	24.54	0.00	4.17	4.8962
magnitude	4.54					
phase	88.32				phase reference date	7/15/91

Figure B-6. Tank 241-T-101.

Multiple R 0.9020
 R Square 0.8137
 Adjusted R Square 0.8088
 Standard Error 1.7623
 Observations 119

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	3	1559.68	519.89	167.40	0.00
Residual	115	357.16	3.11		
Total	118	1916.83			

	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	67.19	0.17	403.83	0.00	66.86	67.52
time	-0.17	0.17	-1.03	0.31	-0.51	0.16
cos(wt)	0.48	0.23	2.13	0.04	0.03	0.93
sin(wt)	5.31	0.24	22.36	0.00	4.84	5.78
magnitude	5.33					
phase	86					
phase reference date						7/15/91

Figure B-7. Tank 241-U-105.

Multiple R 0.9438
 R Square 0.8907
 Adjusted R Square 0.8875
 Standard Error 1.7181
 Observations 106

Analysis of Variance

	df	Sum of Squares	Mean Square	F	Significance F
Regression	3	2452.90	817.63	277.00	0.00
Residual	102	301.08	2.95		
Total	105	2753.98			

	Coefficients	Standard Error	t Statistic	P-value	Lower 95%	Upper 95%
Intercept	76.33	0.20	373.47	0.00	75.93	76.74
time	-1.49	0.18	-8.29	0.00	-1.84	-1.13
cos(wt)	1.20	0.24	5.08	0.00	0.73	1.68
sin(wt)	6.49	0.24	27.29	0.00	6.02	6.96
magnitude	6.60	0.34				
phase	81				phase reference date	7/15/91

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