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Ferrocyanide Safety Program: Thermal Analysis of Tank 241-BY-106

J. M. McLaren

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FERROCYANIDE SAFETY PROGRAM: THERMAL ANALYSIS OF TANK 241-BY-106

**R. J. Cash
J. M. McLaren**

ABSTRACT

An analysis was conducted of tank 241-BY-106 to determine the conditions required for an uneven distribution of heat generation (e.g., a hotspot) that would produce temperatures of concern (considered to be 220 °C [418 °F]). Two types of hotspots were investigated. One was 1 meter square, 7.62 cm (3 in.) thick, that was placed on the bottom of the tank two-thirds of the radial distance from the center to the edge of the tank. The other was a 1 meter cube placed in the same location. It was found that the concentrations of heat-producing material required to reach a maximum temperature of 220 °C (418 °F) were greater than 160 times that of the material surrounding the hotspot.

A transient case was also studied, where a hotspot was formed over 5 years. The 1 meter cube hotspot was used. It was determined that the maximum temperature reached was less than the steady-state analysis under the same conditions. The maximum temperature was reached in 5.5 years. The change in the surface temperature was slow enough that the hotspot could not be detected in less than 3 years. The steady-state analysis showed that a large pattern of thermocouple trees would be required to detect a hotspot by this means. The steady-state analysis showed that a hotspot with temperatures that approached 220 °C (418 °F) could probably be detected by surface temperature measurements.

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CONTENTS

1.0	INTRODUCTION	1-1
1.1	BACKGROUND	1-2
1.2	SCOPE OF ANALYSIS	1-2
1.3	SUMMARY OF RESULTS	1-2
2.0	METHODOLOGY AND MODELS	2-1
2.1	METHODOLOGY	2-1
2.2	DESCRIPTION OF MODELS	2-1
2.2.1	Description of the Tank	2-1
2.2.2	Models	2-2
3.0	RESULTS	3-1
3.1	DEVELOPMENT OF HOTSPOT MODEL	3-1
3.2	HOTSPOT CONTAINED WITHIN THE BOTTOM LAYER	3-1
3.3	CUBICAL HOTSPOT	3-5
3.4	CUBICAL HOTSPOT TRANSIENT	3-5
4.0	CONCLUSIONS	4-1
5.0	REFERENCES	5-1

LIST OF FIGURES

2-1	General Noding Diagram, Layer Hotspot	2-3
2-2	Noding Diagram, Sludge Region Details, Layer Hotspot	2-4
2-3	General Noding Diagram, Cubical Hotspot	2-5
2-4	Noding Diagram, Sludge Region Details, Cubical Hotspot	2-6
3-1	Surface Temperatures for Stepped-Tank Model, Trial Hotspot	3-2
3-2	Predicted Temperature Versus Depth Versus Data for Stepped-Top Model and Flat-Top Model Using Various Soil Conductivities	3-3
3-3	Surface Temperatures for Flat-Top Model, Trial Hotspot	3-4
3-4	Surface Temperatures in Various Direction, Layer Hotspot	3-6
3-5	Temperature Versus Angular Displacement at Level and Radial Distance of Hotspot Center, Layer Hotspot	3-7
3-6	Surface Temperature in Various Directions, Cubical Hotspot	3-8
3-7	Temperature Versus Angular Displacement at Level and Radial Distance of Hotspot Center, Cubical Hotspot	3-9
3-8	Temperature of Hotspot Center, 5-Year Hotspot Growth Transient	3-11
3-9	Surface Temperature of Saltcake Over the Hotspot, 5-Year Hotspot Growth Transient	3-12

FERROCYANIDE SAFETY PROGRAM: THERMAL ANALYSIS OF TANK 241-BY-106

1.0 INTRODUCTION

The radioactive waste storage tanks at the Hanford Site have been in use since the 1940s. These tanks have recently been subjected to extensive attention as a result of problems that have occurred or been postulated to occur within the tanks. Some of these problems have been identified for some time, but for various reasons have remained unresolved; others have been identified only recently.

One of the problems involves the potential interaction of ferrocyanide with nitrates in the presence of high temperatures. This is a postulated condition that might exist in some of the tanks (Burger 1989; Burger and Scheele 1988). As a result, it was considered advisable to determine the heat loads of these tanks.

The heat loads of the ferrocyanide-bearing tanks were determined in the 1970s by using psychrometric data. More recently, a thermal analysis of tank 241-BY-106 was performed using the HEATING7* code (Childs 1991). This analysis determined that the heat load of this tank was markedly less than the published value of 12,200 Btu/hr (McLaren 1992; Hanlon 1991). The heat load of this tank was estimated to be 1.61 kw (5500 Btu/hr). The concentrations of heat generating material in this tank necessary to reach temperatures of concern, and the transient behavior of the tank contents resulting from such concentrations being formed, were of considerable interest. Accordingly, an analysis to determine these parameters was conducted. This report describes the results of that analysis.

The objectives of the analysis were as follows.

- a. Determine the concentration of heat-generating material that would produce a maximum temperature of 220 °C in the waste.
- b. Determine the thermal response of the tank to formation of a hotspot.
  1. Determine the maximum temperature reached using the concentration determined above.
  2. Determine the time to maximum temperature in the waste for this hotspot.
  3. Determine the temperature changes on the surface of the waste resulting from the formation of this hotspot.

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*HEATING7 is a trademark of Martin Marietta Corporation.

1.1 BACKGROUND

It has been postulated for waste storage tanks containing ferrocyanide that an uneven distribution of heat generating materials might exist. The probable vertical distribution of heat generating materials in the tanks was developed using thermal analysis; however, thermal analysis could not determine the horizontal distribution of materials. Horizontal distribution analysis was limited by the number of thermocouple trees installed in the tank. Consequently, an additional analysis was done to determine the degree of concentration that would have caused localized temperatures high enough ($> 220^{\circ}\text{C}$ [418°F]) to produce and propagate a thermal reaction.

The heat generating analyses would then provide a tool for estimating (1) the possibilities of hotspot formation; and (2) the time for the temperature to reach a hazardous condition. Any change in surface temperature over time may be detectable using infrared scanning techniques (Morris and Mailhot 1993) before the hotspot temperature became a potential concern.

1.2 SCOPE OF ANALYSIS

The analysis performed for this report was designed to determine the concentrations of heat-producing materials within the waste of tank 241-BY-106 that could produce a maximum temperature of 220°C (418°F). Because this tank appears to have a distribution of heat-generating material that is partially concentrated on the bottom of the tank in a thin 7.62-cm (3-in.) layer, two postulated hotspots were analyzed. One postulated hotspot was totally within the bottom layer; the other included the waste above the bottom layer. The analysis also determined the temperature response over time to a hotspot within the waste that takes 5 years to form, and the response over time of the surface temperature of the tank to this forming hotspot.

1.3 SUMMARY OF RESULTS

This analysis determined that, for a 1-meter-square hotspot with the thickness of the concentrated heat-producing layer, a concentration of 162 times is required to reach a maximum temperature of 220°C (418°F). For a 1-meter-cube hotspot resting on the bottom of the tank, 21 percent of the total heat of the tank must be concentrated in the hotspot to raise the maximum temperature to 220°C (418°F).

Using the cubical hotspot and the concentration determined above, with a time period of 5 years to raise the hotspot to full intensity, the maximum temperature reached is 155°C . Three years are required for the surface temperature over the hotspot to rise 1°C , and 9.5 years are required for the maximum surface temperature increase to occur.

2.0 METHODOLOGY AND MODELS

2.1 METHODOLOGY

A heat transfer code was used in the analysis to determine the heat flow and temperatures in tank 241-BY-106. This approach requires that a three-dimensional model be created to determine the heat concentration and transient response to a hotspot formation within the tank.

The computer code used to determine the heat concentration and thermal transient response is HEATING7 (Childs 1991). The HEATING7 code is a heat transfer analysis code used to determine steady-state and transient temperature distributions within a described structure. The code uses heat conduction, convection, and radiant heat transfer parameters, as well as iterative solution techniques, on a model of the structure to determine the temperatures at nodes described by the model. The code does not have the capability to determine (1) flow patterns resulting from convective heat transfer; or (2) the temperature distribution in the convecting region. Instead, convective heat transfer is calculated by standard empirical correlations. The HEATING7 code uses an improved iterative solution technique for steady-state solutions compared to previous versions, and also has a graphical interface. In this analysis, the conductivities and heat-source distribution used were previously developed from a steady-state analysis of the tank (McLaren 1992). It should be noted that the results of these analyses are dependent on the boundary conditions used. Data available at the time of the analysis were used to set boundary conditions.

2.2 DESCRIPTION OF MODELS

Sections 2.2.1, and 2.2.2 describe the single-shell waste storage tanks and the models used to analyze the hotspot heat distribution and transient response. Section 2.2.1 describes the tank and its contents. Section 2.2.2 describes the three-dimensional models used to determine the heat concentration for the postulated two hotspots, and the thermal transient response to a hotspot taking 5 years to form. These models assume (1) the outside air temperature is 12.2 °C (54 °F); (2) the water table is located 61 m (200 ft) below the surface, and that its temperature is 12.8 °C (55 °F); and (3) the thermal conductivity of the soil surrounding the tank is 0.43 W/m-°C (0.25 Btu/hr-ft-°F).

2.2.1 Description of the Tank

Tank 241-BY-106 is a single-shell waste storage tank, located in the Hanford Site BY Tank Farm. It is a cylindrical concrete tank with a domed concrete top. The tank is set on a concrete slab that is dished so that the center is approximately 0.30 m (1 ft) below the edges. The tank is 22.86 m (75 ft) in diameter and approximately 12.2 m (40 ft) high in the center, with the center of the top 2.13 m (7 ft) below the surface of the soil. The tank has a steel liner made of plates welded together that covers the bottom and

sides of the tank up to the wall-dome intersection. There are a number of piping penetrations in the top of the tank as well as in the sides.

The tank was periodically filled with a slurry of radioactive waste that was allowed to settle. During this periodic filling process, the excess liquid was removed after reaching a certain level. After the periodic filling, settling, and liquid removal processes were complete, other waste additions were made of evaporator concentrates saturated at the boiling temperature. As the solution cooled this waste precipitated out as crystals on top of the waste that was already in place. As a result, there are two layers of different waste in the tank. The crystalline layer is the "crust" or "saltcake," 45 cm (1.5 ft) thick and the lower layer is "sludge" 5.46 m (17.9 ft) thick. The tank was stabilized by pumping out all the liquid possible, so no liquid layer exists on the surface of the tank waste; however, dampness within the saltcake sludge regions exists in varying degrees.

Previous analysis (McLaren 1992) estimated that the heat load of tank 241-BY-106 is 1.612 kW (5,500 Btu/hr). The estimated conductivities of the waste are 0.43 W/m-°C (0.27 Btu/hr-ft-°F) for the sludge below the saltcake, and 0.28 W/m-°C (0.16 Btu/hr-ft-°F) for the saltcake. The heat distribution for this tank was estimated to be one half of the total heat load in a layer 7.62 cm (3 in.) thick on the bottom of the tank, and one half of the total heat load homogeneously distributed in the rest of the sludge, excluding the saltcake.

2.2.2 Models

The models used for the HEATING7 codes were three-dimensional. Parameters developed from a previous analysis were used as starting points (McLaren 1992). The models consist of regions, connected together by boundaries, with the appropriate heat transfer conditions describing these boundaries and regions. The heat sources, described by tabular functions, can represent a uniform or non-uniform distribution.

These models are made up of 22 to 31 regions and 4 boundary conditions. Three regions describe the soil over, around, and under the tank. Three regions describe the concrete bottom and sides of the tank. The concrete tank top is not separately modeled; its volume is included in the soil top cover. One region describes the air space in the tank. One region describes the crust of the waste in the tank, and 15 to 24 regions describe the sludge under the crust, depending upon the hotspot modeled.

Two hotspots were modeled. The first was a 1 meter square 7.62 cm (3 in.) thick, placed on the bottom of the tank with the center two-thirds of the radial distance from the center to the edge of the tank. This thickness is the thickness of the heat-producing layer on the bottom of the tank. The second hotspot was a 1 meter cube placed on the bottom of the tank two-thirds of the radial distance from the center to the edge of the tank. The noding diagrams of these models are shown in Figures 2-1 and 2-2 for the first hotspot modeled, and Figures 2-3 and 2-4 for the second hotspot modeled.

Figure 2-1. General Noding Diagram, Layer Hotspot.

REGIONS	CONDUCTIVITY (Btu/hr ft-°F)	HEAT GENERATION RATE (Btu/hr-ft ³)
1,2,3	.25	0.0
5,6,7	.54	0.0
8	.16	0.0
9,10,12	.27	0.0214
11	.16	0.0214
18,22	.27	2.4898
19,21	.16	2.4898
20	.16	403.23

Figure 2-2. Noding Diagram, Sludge Region Details, Layer Hotspot.

REGIONS	CONDUCTIVITY (Btu/hr-ft-°F)	HEAT GENERATION (Btu/hr-ft ³)
2,3	.25	0.0
5,6,7	.54	0.0
8	.16	0.0
9,10,12,13	.27	0.0214
11	.16	0.0214
14,16,17	.27	2.4898
15	.16	2.4898

Figure 2-3. General Noding Diagram, Cubical Hotspot.

REGIONS	CONDUCTIVITY (Btu/hr-ft-°F)	HEAT GENERATION (Btu/hr-ft ³)
1,2,3	.25	0.0
5,6,7	.54	0.0
8	.16	0.0
9,10,12,18,22	.27	0.0278
11,19,21	.16	0.0278
20,29	.16	32.861
27,31	.27	1.9695
28,30	.16	1.9695

Figure 2-4. Noding Diagram, Sludge Region Details, Cubical Hotspot.

REGION	CONDUCTIVITY (Btu/hr-ft-°F)	HEAT GENERATION (Btu/hr-ft ³)
2,3	.25	0.0
5,6,7	.54	0.0
8	.16	0.0
9,10,12,13,14,16,17	.27	0.0278
11,15	.16	0.0278
23,25,26	.27	1.9695
24	.16	1.9695

Four boundary conditions were modeled. The first was a surface of constant temperature describing the temperature of the soil at the water table. That boundary was considered to be 12.8 °C (55 °F) at 61 m (200 ft) below the surface. The second boundary was a surface-to-boundary condition with forced convection heat transfer to a boundary of constant temperature that describes the soil-to-atmospheric air interface. Forced convection heat transfer was used to account for the wind, which is common throughout most of the year in the tank farm areas. The heat transfer coefficient for this condition is $1.136 \times 10^{-3} \text{ W/hr-cm}^2\text{-}^\circ\text{C}$ ($2.0 \text{ Btu/hr-ft}^2\text{-}^\circ\text{F}$), based on an average wind speed of 12.39 km/hr (7.7 miles/hr) across the surface. The third boundary condition was a surface-to-surface condition, with convective and radiative heat transfer coefficients describing the interface between the waste surface and the air space in the tank, and between the air space and the top of the tank. The fourth boundary condition was a surface-to-insulator condition (i.e., a reflection), and was used to describe the boundary in the soil between one tank and another.

The thermal conductivity used for the concrete sides and bottom of the tank is $0.93 \text{ W/m-}^\circ\text{C}$ ($0.54 \text{ Btu/hr-ft-}^\circ\text{F}$). The conductivity of the soil used was $0.43 \text{ W/m-}^\circ\text{C}$ ($0.25 \text{ Btu/hr-ft-}^\circ\text{F}$). These values were used in the previous analysis (McLaren 1992), and the soil value was verified by data from laboratory samples (Bouse 1975).

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3.0 RESULTS

This section discusses the procedure used to analyze the hotspots and the results of the analysis.

3.1 DEVELOPMENT OF HOTSPOT MODEL

The model developed for the hotspot analysis was taken from the model previously used to analyze for the heat load and thermal characteristics of tank 241-BY-106 (McLaren 1992). In order to model the curved dome of the tank, this model was constructed with a stepped tank top. When a trial hotspot was modeled in the sludge regions, the resulting surface temperature plots were distorted by the stepping effect of the tank top (Figure 3-1). To remove this effect, the model was changed to a flat top.

In order to model the flat top, the total volume of the soil over the tank proper was calculated, and an average depth computed. This depth was then placed in a single region over the tank. This new depth was deeper over the center where the data temperature measurements were taken; therefore, the temperatures in the waste were raised. To remove this error, the conductivity of the soil over the tank was altered until the steady-state temperature at the point where the data were taken agreed with the data. The new conductivity of the soil over the tank is $0.606 \text{ W/m-}^\circ\text{C}$ ($0.35 \text{ Btu/hr-ft-}^\circ\text{F}$).

This new conductivity was applied only to the soil over the tank. The soil under and around the tank all the way to the surface remained at its original value, $0.43 \text{ W/m-}^\circ\text{C}$. Figure 3-2 shows the plots of the temperature versus depth at the location of the thermocouple tree for the original model (stepped), and the flat-top model having soil over the tank with conductivities of $0.25 \text{ Btu/hr-ft-}^\circ\text{F}$ and $0.35 \text{ Btu/hr-ft-}^\circ\text{F}$. Figure 3-3 shows the surface-temperature plots for the trial hotspot case. The hotspots were created and analyzed with this new model.

The hotspots used in this analysis were chosen because of the heat distribution indicated by previous analysis. Because one half of the heat of the tank was considered to be concentrated in the bottom layer, a hotspot within that layer was investigated. Previous hotspot analyses used a cubical-3-ft hotspot, a spot of very nearly the same size, 1 m, was investigated. No mechanism for the formation of any hotspot was postulated.

3.2 HOTSPOT CONTAINED WITHIN THE BOTTOM LAYER

The first hotspot modeled was a 1 meter square, 7.62 cm (3 in.) thick, located two-thirds of the radial distance from the center of the tank to the edge. This thickness was chosen because it was the thickness of the concentrated heat-producing layer determined by the heat-load analysis of the tank (McLaren 1992). The heat load in this hotspot was increased by taking heat from the upper heat-producing region and adding it to the hotspot. This maintained the overall heat load of the tank at 1.612 kW. It was assumed that sludge having temperatures greater than $82.2 \text{ }^\circ\text{C}$ ($180 \text{ }^\circ\text{F}$) will have the

Figure 3-1. Surface Temperatures for Stepped-Tank Model, Trial Hotspot.

Tank 241-BY-106 Surface Temperatures **Hotspot 50 Percent Heat 1 m² 7.62 cm Thick**

29211065.9

Figure 3-2. Predicted Temperature Versus Depth Versus Data for Stepped-Top Model and Flat-Top Model Using Various Soil Conductivities.

Tank 241-BY-106 Data Versus Predictions 5,500 Btu/hr Stepped Top Versus Flat Top

Figure 3-3. Surface Temperatures for Flat-Top Model, Trial Hotspot.

Tank 241-BY-104 Surface Temperature
Hotspot 50 Percent Heat 1 m² 7.62 cm Thick

29211065.7

conductivity of the saltcake layer, based on the assumption that sludge at those temperatures was dry. The conductivity of the saltcake layer was used for dry sludge because it was very close to the lowest conductivity measured in a laboratory analysis (Bouse 1975). No other data were available. Using these parameters, a heat load of 19.6 percent of the total heat of the tank in the hotspot was needed to raise the maximum temperature to 220 °C. This required a concentration of the heat generation rate of 162 times that of the lower heat-producing layer. A plot of the surface temperatures of the saltcake on 0 radian (0 degree), pi radian (180 degree), and pi/2 radian (90 degree) lines is shown in Figure 3-4. This plot shows that there is a definitely discernable temperature change on the surface over the hotspot. Figure 3-5 shows the temperature versus angular displacement away from the hotspot on a circumferential line at the level and radial distance to the center of the hotspot. It shows how rapidly the temperature drops as the distance from the hotspot increases. This illustrates why many thermocouple trees in a pattern would be required for accurate detection of a hotspot using only thermocouples.

3.3 CUBICAL HOTSPOT

The second hotspot modeled was a piece of a wedge 1 m high and 1 m in arc length at the centerline. This approximated a 1-m cube. This hotspot was placed on the bottom of the tank, with its center located two-thirds of the radial distance from the center of the tank to the edge. To concentrate heat in this hotspot, the heat load for the spot was determined, and the remaining heat (1.612 kW less the hotspot heat load) was split between the bottom layer and the rest of the sludge. This maintained the total heat load and the heat distribution previously determined for the rest of the tank.

The hotspot and the regions around the hotspot that were above 82.2 °C were given the conductivity of the saltcake as before. This hotspot requires a heat load of 340 W (1,160 Btu/hr) to reach a maximum temperature of 220 °C. This is a concentration of 21 percent of the total heat of the tank into 0.04 percent of the total volume of the sludge. Figure 3-6 shows a plot of the surface temperatures of the saltcake on 0 radian, pi radian, and pi/2 radian lines for this hotspot. The temperature increase over the hotspot is readily discernable. Figure 3-7 shows the temperature versus angular displacement away from the hotspot on a circumferential line at the level and radial distance to the center of the hotspot. This again illustrates that many thermocouple trees would be necessary for accurate thermocouple detection of a hotspot.

3.4 CUBICAL HOTSPOT TRANSIENT

The cubical hotspot was used for the transient study. This transient used the cubical hotspot with the concentration factors determined in the above analysis. Because the problem started from a non-hotspotted condition, the thermal conductivities of the layers were initially constant throughout the layer. As the temperature increased, the thermal conductivity was changed to reflect dryout of the sludge. This change in conductivity was incorporated

Figure 3-4. Surface Temperatures in Various Direction, Layer Hotspot.

Tank 241-BY-106 Surface Temperature **Hotspot 19.6 Percent Heat 1 m² 7.62 cm Thick**

Figure 3-5. Temperature Versus Angular Displacement at Level and Radial Distance of Hotspot Center, Layer Hotspot.

Tank 241-BY-106 Temperature Versus Angle Level and Distribution of Hotspot Center

20211065.5

Figure 3-6. Surface Temperature in Various Directions, Cubical Hotspot.

Tank 241-BY-106 Surface Temperature **Hotspot 21.1 Percent Heat 1 m³**

Figure 3-7. Temperature Versus Angular Displacement at Level and Radial Distance of Hotspot Center, Cubical Hotspot.

Tank 241-BY-106 Temperature Versus Angle Level and Distribution of Hotspot Center

29211065.3

into the model by using a table of a linear function that decreased the conductivity from 0.43 W/cm-°C at 40.5 °C (105 °F) to 0.28 W/cm-°C at 100 °C. The conductivity did not change below 40.5 °C or above 100 °C. The lower limit was chosen because the results from Bouse (1975) indicated that there was little conductivity change below this temperature. The hotspot consisted of two regions, as in the steady-state study, one in the lower layer, and one in the larger layer above it. These hotspot regions were started at time zero with the same power and concentrations as the sludge surrounding them. The lower part started the same as the layer, and the upper started the same as the remaining bulk of the sludge. The heat load of the hotspot was increased to 340 W linearly over 5 years, and was allowed to decrease commensurate with radioactive decay after that. The thermal conductivity of the hotspot and the surrounding sludge was changed as the temperature increased. The results of this transient showed that the maximum temperature reached was 155.3 °C (311 °F) at 5.5 years (Figure 3-8). The maximum surface temperature reached was 27.6 °C (81.7 °F) at 9 years, an increase of 3.4 °C (Figure 3-9). The surface temperature over the hotspot increased 1 °C in 3 years.

The maximum temperature reached after a 10-year transient study was lower than that reached by a steady-state analysis using the same conditions: 155.3 °C versus 220 °C. This was a result of the large heat capacitance of the tank. The steady-state analysis allowed the entire tank to reach equilibrium with the hotspot condition, while the transient had to heat waste that was initially cooler than the steady-state hotspot condition. Consequently, the maximum temperature reached was lower. If the transient was carried out to equilibrium and the heat sources not allowed to change commensurate with radioactive decay, the temperatures of the two cases would be equal. This result showed the large time constant of the tank.

Figure 3-8. Temperature of Hotspot Center, 5-Year Hotspot Growth Transient.

Tank 241-BY-106 Transient Hotspot Hotspot Center Temperature

Figure 3-9. Surface Temperature of Saltcake Over the Hotspot, 5-Year Hotspot Growth Transient.

Tank 241-BY-106 Transient Hotspot Surface Over Hotspot Temperature

29211065.2

4.0 CONCLUSIONS

The following conclusions are drawn from these analyses.

1. Concentrations of heat-generating material required to raise the maximum temperature to 200 °C are unreasonably high. The lowest concentration required is 162 times the average concentration in the surrounding sludge. It is difficult to envision a method that would cause this kind of concentration, especially in view of the way the tank was filled.
2. A large number of thermocouple trees placed in a specific pattern would be required to identify a possible hotspot with the tank. This would require drilling holes through the top of the tank to achieve the proper pattern. Currently, there are not enough penetrations in the tank dome to allow full coverage, and anything less than full coverage would not be definitive.
3. A hotspot that takes 5 years to produce temperatures approaching 220 °C (418 °F) cannot be detected by periodic surface temperature measurements in less than three years. This may not provide enough time to take remedial action to reduce the maximum temperature of the hotspot. It should be noted that no mechanism for the growth of a hotspot has been studied to determine its probability.
4. The thermal capacitance of the tank is so large that, to reach a maximum temperature of 220 °C (418 °F), even greater concentrations than those determined by steady-state analysis would be required. Consequently, the steady-state analysis is conservative.
5. A hotspot under steady-state conditions (or nearly so) with a maximum temperature approaching 220 °C (418 °F), can be detected by surface temperature measurements. This report shows that the temperature difference over the hotspot compared to the surrounding area should be detectable by existing methods; i.e., the infrared scanning system (Morris and Mailhot 1993).

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